A SURVEY OF $z \sim 6$ QUASARS IN THE SLOAN DIGITAL SKY SURVEY DEEP STRIPE. I. A FLUX-LIMITED SAMPLE AT $z_{AB} < 21^\ast$

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**ABSTRACT**

We present the discovery of five quasars at $z \sim 6$ selected from 260 deg\(^2\) of the Sloan Digital Sky Survey (SDSS) southern survey, a deep imaging survey obtained by repeatedly scanning a stripe along the celestial equator. The five quasars with $20 < z_{AB} < 21$ are 1–2 magnitudes fainter than the luminous $z \sim 6$ quasars discovered in the SDSS main survey. One of them was independently discovered by the UKIRT Infrared Deep Sky Survey. These quasars, combined with another $z \sim 6$ quasar known in this region, make a complete flux-limited quasar sample at $z_{AB} < 21$. The sample spans the redshift range $5.85 < z < 6.12$ and the luminosity range $-26.5 \leq M_{1450} \leq -25.4$ ($H_0 = 70$ km s\(^-1\) Mpc\(^-1\), $\Omega_m = 0.3$, and $\Omega_L = 0.7$). We use the $1/V_\text{e}$ method to determine that the comoving quasar spatial density at $\langle z \rangle = 6.0$ and $(M_{1450}) = -25.8$ is $(5.0 \pm 2.1) \times 10^{-9}$ Mpc\(^-3\) mag\(^-1\). We model the bright-end quasar luminosity function (QLF) at $z \sim 6$ as a power law $\Phi(L_{1450}) \propto L_{1450}^{-\beta}$. The slope $\beta$ calculated from a combination of our sample and the luminous SDSS quasar sample is $-3.1 \pm 0.4$, significantly steeper than the slope of the QLF at $z \sim 4$. Based on the derived QLF, we find that the quasar/active galactic nucleus (AGN) population cannot provide enough photons to ionize the intergalactic medium (IGM) at $z \sim 6$ unless the IGM is very homogeneous and the luminosity ($L_{1450}$) at which the QLF power law breaks is very low.

**Key words:** galaxies: active − quasars: emission lines − quasars: general

1. INTRODUCTION

High-redshift quasars are among the most luminous objects known and provide direct probes of the distant universe when the first generation of galaxies and quasars formed. In recent years, over twenty $z \sim 6$ quasars with $z_{AB} \lesssim 20$ have been discovered (e.g. Fan et al. 2000, 2001a, 2003, 2004, 2006a; Goto 2006). These luminous quasars are essential for understanding the accretion history of black holes (BHs), galaxy formation, and chemical evolution at very early epochs. They harbor supermassive BHs with masses higher than $10^9 M_\odot$ and emit near the Eddington limit (e.g. Barth et al. 2003; Vestergaard 2004; Jiang et al. 2006a; Kurk et al. 2007), revealing the rapid growth of central BHs at high redshift. Their emission lines show solar or supersolar metallicity in the broad line regions, indicating that there was vigorous star formation and element enrichment in the first gigayear of cosmic time (e.g. Barth et al. 2003; Maiolino et al. 2003; Jiang et al. 2007; Kurk et al. 2007). Their absorption spectra show that the intergalactic medium (IGM) at $z \sim 6$ is close to the re-ionization epoch (e.g. Becker et al. 2001; Djorgovski et al. 2001; Fan et al. 2006b, 2006c).

The majority of the currently known $z \sim 6$ quasars were discovered from $\sim$8000 deg\(^2\) of imaging data of the Sloan Digital Sky Survey (SDSS; York et al. 2000). They were selected as $i$-dropout objects using optical colors. Several other high-redshift quasars were discovered based on their infrared or radio emission. For example, Cool et al. (2006) discovered one quasar at $z = 5.85$ in the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999) Bootes Field using the active galactic nuclei (AGNs) and Galaxy Evolution Survey (AGES) spectroscopic observations. The quasar was selected from a Spitzer mid-infrared quasar sample and has a $z_{AB}$ magnitude of 20.68 and an optical luminosity of $M_B = -26.52$. By matching the FLAMINGOS Extragalactic Survey IR survey (Elston et al. 2006) data to the Faint Images of the Radio Sky at Twenty cm (FIRST; Becker et al. 1995) data, McGreer et al. (2006) discovered a radio-loud quasar at $z = 6.12$ in 4 deg\(^2\) of the NDWFS region. This quasar is a broad absorption line (BAL) quasar with an optical luminosity of $M_B = -26.9$, comparable to the luminous SDSS quasars at $z \sim 6$. Despite the high-redshift quasar surveys mentioned above, very little is known about faint quasars ($z_{AB} > 20$) at $z \sim 6$. The SDSS main survey only probes the most luminous quasars, and with a density of 1/470 deg\(^2\) (Fan et al. 2006a). The Cool et al. (2006) quasar at $z = 5.85$ was $z_{AB} > 20$, but the sample contains a single object and is selected from an area of less than 10 deg\(^2\). Mahabal et al. (2005) found a
very faint quasar with \( z_{\text{AB}} = 23.0 \) at \( z = 5.70 \) in a 2.5 deg\(^2\) field around the luminous quasar SDSS J114816.64+525150.3\( ^{11} \) at \( z = 6.42 \). Willott et al. (2005) imaged a 3.83 deg\(^2\) region down to \( z_{\text{AB}} = 23.35 \) in the first results of the Canada–France High-Redshift Quasar Survey (CFHQS) and did not find any quasars at \( z > 5.7 \). In these surveys both the quasar samples and the survey areas are very small, thus they do not provide a good statistical study of high-redshift quasars at \( z_{\text{AB}} > 20 \). Recently, Willott (2007) discovered four quasars at \( z > 6 \) from about 400 deg\(^2\) of the CFHQS, including the most distant known quasar at \( z = 6.43 \). Three of these quasars have \( z_{\text{AB}} \) magnitudes fainter than 21. Since their follow-up observations are not yet complete, they did not determine the spatial density of these quasars.

Finding faint quasars at \( z \sim 6 \) is important for studying the evolution of the quasar population and quasars’ impact on their environments. Fan et al. (2004) obtained the bright-end quasar luminosity function (QLF) at \( z \sim 6 \), but the slope, \(-3.2 \pm 0.7 \), was very uncertain due to the small luminosity range of the sample. Richards et al. (2004) put a broad constraint on the bright-end slope of \( > -4.63 (3 \sigma) \) from the absence of lenses in four quasars at \( z \sim 6 \). With the discovery of faint high-redshift quasars, the QLF can be well determined. The QLF at \( z \sim 6 \) is important to understand BH growth at early epochs (e.g. Volonteri & Rees 2006; Wyithe & Padmanabhan 2006). While bright quasars at high redshift have central BH masses between \( 10^9 \) and \( 10^{10} M_\odot \), fainter quasars with \( z_{\text{AB}} > 20 \) are expected to harbor BHs with masses of a few times \( 10^9 M_\odot \) or below (e.g. Kurk et al. 2007), which can be associated with galaxies of lower masses. The QLF also enables us to determine the quasar contribution to the UV background at \( z \sim 6 \). Detection of complete Gunn–Peterson troughs (Gunn & Peterson 1965) among the highest-redshift quasars indicates a rapid increase of the IGM neutral fraction at \( z \sim 6 \), and suggests that we have reached the end of the re-ionization epoch (e.g. Becker et al. 2001; Djorgovski et al. 2001; Fan et al. 2006c). It is unclear what individual contributions of galaxies and quasars to the re-ionization are. Although there is evidence showing that quasars are probably not the main contributor to re-ionization (e.g. Salvaterra et al. 2007; Srbinsonsky & Wyithe 2007; Shankar & Mathur 2007), a proper determination of the QLF at \( z \sim 6 \) is needed to constrain the quasar contribution.

In this paper we present the discovery of five \( z \sim 6 \) quasars with \( 20 < z_{\text{AB}} < 21 \) selected from 260 deg\(^2\) of the SDSS southern survey, a deep imaging survey obtained by repeatedly scanning a 300 deg\(^2\) area in the Fall Celestial Equatorial Stripe (Adelman-McCarthy et al. 2007a). One of the five quasars, SDSS J020332.39+001229.3 (hereafter SDSS J0203+0012), was independently discovered by matching the UKIRT Infrared Deep Sky Survey (UKIDSS; Warren et al. 2007) data to the SDSS data (Venemans et al. 2007). These five quasars, together with another quasar, SDSS J005552.34–000655.8 (hereafter SDSS J0055–0006) previously discovered in this region (Fan et al. 2004), form a well-defined low-luminosity quasar sample at high redshift. We use this sample and the luminous SDSS quasar sample to measure the QLF and constrain the quasar contribution to the re-ionization of the universe at \( z \sim 6 \).

The structure of the paper is as follows. In Section 2, we introduce the quasar selection criteria and photometric and spectroscopic observations of quasar candidates. In Section 3, we describe the properties of the five new quasars. We derive the QLF at \( z \sim 6 \) in Section 4, and discuss the contribution of quasars to the ionizing background in Section 5. We give a brief summary in Section 6.

11 The naming convention for SDSS sources is SDSS JHHMMSS.S ± DDMMSS.S, and the positions are expressed in J2000.0 coordinates. We use SDSS JHHMM ± DDMM for brevity.
In this paper we used the data in the range $310^\circ < \text{R.A.} < 60^\circ$, as there were significantly fewer than ten runs covering the range $300^\circ < \text{R.A.} < 310^\circ$. The data also contain some “holes” in which the co-added images were not available. The effective area for this work is $260 \text{ deg}^2$. The median seeing as measured in the $riz$ bands was $1.2'' \pm 0.05''$, where the error is the standard deviation of the seeing measured by PHOTO across the co-added images on Stripe 82.

### 2.2. Quasar Selection Procedure

Because of the rarity of high-redshift quasars and overwhelming number of contaminants, our selection procedure of $z > 5.7$ faint quasars from the multi-epoch SDSS imaging data contains the following separate steps (see also Fan et al. 2001a; Fan et al. 2003).

1. Select $i$-dropout sources from the SDSS deep stripe. Objects with $i_{\text{AB}} - z_{\text{AB}} > 2.2$ and $z_{\text{AB}} < 21$ that were not detected in the $ugr$ bands were selected as $i$-dropout objects. We rejected sources with one or more of the following SDSS processing flags: BRIGHT, EDGE, BLENDED, SATUR, MAYBE_CR, and MAYBE_EGHOST (see Stoughton et al. 2002). At $z > 5.7$, the Ly$\alpha$ emission line begins to move out of the SDSS $i$ filter, so a simple cut of $i_{\text{AB}} - z_{\text{AB}} > 2.2$ is used to separate high-redshift quasars (and cool brown dwarfs) from the majority of stellar objects (e.g. Fan et al. 2001a). At $z_{\text{AB}} = 21$, the photometric errors of the co-added data reach $\sigma(z_{\text{AB}}) \sim 0.1$ as shown in Figure 1, so the $z_{\text{AB}} < 21$ criterion guarantees a high quasar selection efficiency due to small photometric errors.

2. Remove false $i$-dropout objects. All $i$-dropout objects were visually inspected, and false detections were deleted from the list of candidates. The majority of the contaminants are cosmic rays. Although the SDSS photometric pipeline effectively rejects cosmic rays, the leakage of a tiny fraction of cosmic rays will contribute a large contamination to our sample. Cosmic rays were recognized by comparing the individual multi-epoch images making up the co-adds. Brown dwarfs with high proper motions can be removed in a similar way, since the multi-epoch images were taken over a period of five years. In the selection of luminous $z \sim 6$ quasars in the SDSS main survey, Fan et al. (2001a) used an additional step, $z$-band photometry of $i$-dropout objects, to eliminate cosmic rays and improve the photometry of potential candidates. In this work we did not use this step, as the photometry of the co-adds is robust. About 60 $i$-dropout objects remained in this step.

3. Near-infrared (NIR) photometry of $i$-dropout objects. We then carried out NIR ($J$ or $H$ band) photometry of $i$-dropout objects selected from the previous step. The details of the NIR observations are described in Section 2.3. Using the $i_{\text{AB}} - z_{\text{AB}}$ versus $z_{\text{AB}} - J$ ($J$ or $H$) color–color diagrams (Figure 2), high-redshift quasar candidates were separated from brown dwarfs (L and T dwarfs), which have more than ten times higher surface density. The open circles in Figure 2 represent known L/T dwarfs from Golimowski et al. (2004), Knapp et al. (2004), and Chiu et al. (2006). The crosses represent simulated quasars at $5.8 < z < 6.6$. Although there is no clear separation between the dwarf locus and the quasar locus due to photometric errors, we selected quasars with the following criteria:

$$i_{\text{AB}} - z_{\text{AB}} > 2.2 \quad \text{and} \quad z_{\text{AB}} - J < 0.5(i_{\text{AB}} - z_{\text{AB}}) + 0.5,$$

(1)
2.3. NIR Photometry and Optical Spectroscopic Observations

In the first two steps we described above, we selected about 60 $i$-dropout objects with $i_{AB} - z_{AB} \geq 2.2$ and $z_{AB} < 21$ from 260 deg$^2$ of the SDSS co-added imaging data. After the selection of $i$-dropouts, we carried out $J$- or $H$-band photometry of these $i$-dropouts using the SAO Widefield InfraRed Camera (SWIRC) on the MMT in 2005 November and 2006 October to separate quasar candidates and cool dwarfs. We used a $5 \times 5$ dither pattern to obtain good sky subtraction and to remove cosmic rays. The exposure time at each dither position was 30 s. The total exposure time for each target was calculated to achieve an uncertainty of 0.5 in $i_{AB} - z_{AB}$. The exposure time for each target was 20 min, which is sufficient to identify $z \sim 6$ quasars in our sample. If a target was identified as a quasar, several further exposures were taken to improve the spectral quality. The quasar data were reduced using standard routines. After bias subtraction, flat fielding, and wavelength calibration were applied to the frames, one-dimensional spectra were extracted, and we flux calibrated using the spectra of spectroscopic standard stars.

The NIR photometry of the six quasars is shown in Figure 3. The optical and NIR properties of the quasars are given in Table 1. The $i_{AB}$ and $z_{AB}$ magnitudes of the newly discovered quasars are taken from the SDSS deep imaging data, and their $J$ and $H$ magnitudes are obtained from our MMT/SWIRC observations. All the quasars have $z_{AB}$ magnitudes between 20 and 21. The surface density of $z \sim 6$ quasars with $z_{AB} < 20$ is about 1/470 deg$^2$ (Fan et al. 2006a), so it is reasonable to find no quasars with $z_{AB} < 20$ in a 260 deg$^2$ area.

The optical spectra of the six quasars are shown in Figure 4. The spectrum of SDSS J0005–0006 was taken from Fan et al. (2004). The spectra of SDSS J035349.72+010404.4 (hereafter SDSS J0353+0104) and SDSS J231546.57–002358.1 (hereafter SDSS J2315–0023) were taken on Keck/ESI with a total exposure time of 60 min on each source. The spectra of the other three quasars were obtained with Magellan/LDSS-3, and the total exposure time on each source was 100 min. Each spectrum shown in Figure 4 has been scaled to the corresponding $z_{AB}$ magnitude given in Table 1, thereby placed on an absolute flux scale. We estimate the redshifts for the new quasars from either the Ly$\alpha$, N\,\textsc{v} $\lambda 1240$ (hereafter N\,\textsc{v}), or the O\,\textsc{i} $\lambda 1304$ (hereafter O\,\textsc{i}).

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OⅠ emission line. For each quasar, we measure the line center of one strong emission line using a Gaussian profile to fit the top ∼50% of the line. This provides a rough estimate of the redshift. Using this redshift we subtract the power-law continuum and decompose the blended Lyα and NⅤ emission lines into individual components. The details are described in the next paragraph. Then we determine the redshifts from individual emission lines. The redshift of SDSS J030331.40–001912.9 (hereafter SDSS J0303–0019) is measured from the NⅤ emission line, which is well separated from Lyα due to the narrow line width. The measured redshift 6.070 ± 0.001 is consistent with the redshift 6.069 ± 0.002 determined from the weak OⅠ emission line. SDSS J0353+0104 is a BAL quasar as seen from strong absorption features around Lyα, so its redshift is measured from the OⅠ emission line. The redshifts of the other three quasars are estimated from the Lyα emission lines. They are usually biased because the blue side of Lyα is affected by the Lyα forest absorption (Schneider et al. 1991). The mean shift with respect to the systemic redshift at z > 3 is about 600 km s⁻¹ (Shen et al. 2007), corresponding to δz ∼ 0.015 at z ∼ 6. We correct for this bias for the redshifts measured from Lyα. The results are listed in Column 2 of Table 1. The errors in the table are the uncertainties obtained from our fitting process. For the redshifts measured from Lyα, their real errors could be much larger due to the scatter in the relation between Lyα redshifts and systemic redshifts (Shen et al. 2007). In our sample four quasars have redshifts greater than 6. The most distant quasar, SDSS J2315–0023, is at z = 6.12.

We measure the rest-frame equivalent width (EW) and full width at half maximum (FWHM) of Lyα and NⅤ for each quasar except the BAL quasar SDSS J0353+0104. To allow the analysis of the emission lines we first fit and subtract the continuum. The wavelength coverage of each spectrum is too short to fit the continuum slope, so we assume it is a power law with a slope αν = −0.5 (fν ∝ ν^α), and normalize it to the spectrum at rest-frame 1275–1295 Å, a continuum window with little contribution from line emission. Lyα and NⅤ are usually blended with each other, so we use three Gaussian profiles to simultaneously fit the two lines, with the first two profiles representing broad and narrow components of Lyα and the third representing NⅤ. Since the blue side of the Lyα emission line is strongly absorbed by Lyα forest absorption systems, we only fit the red side of the line and assume that the line is symmetric. We ignore the weak SiⅡ λ1262 emission line on the red side of

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**Table 1**

| Quasar (SDSS) | Redshift a | iAB (mag) | zAB (mag) | J (mag) | H (mag) |
|--------------|------------|-----------|-----------|---------|---------|
| J000552.34−000655.8 b | 5.850 ± 0.003 | 23.40 ± 0.34 | 20.54 ± 0.10 | 19.87 ± 0.10 | … |
| J02032.39+012229.3 c | 5.854 ± 0.002 | 23.72 ± 0.22 | 20.87 ± 0.10 | 19.05 ± 0.08 | … |
| J030331.40−001912.9 | 6.070 ± 0.001 | 23.92 ± 0.23 | 20.85 ± 0.07 | … | 19.46 ± 0.10 |
| J0353+0104.4 | 6.049 ± 0.004 | 24.03 ± 0.30 | 20.54 ± 0.08 | … | 18.55 ± 0.06 |
| J2054+0104.8 | 6.062 ± 0.004 | 23.30 ± 0.22 | 20.72 ± 0.09 | 19.18 ± 0.06 | … |
| J2315-0023 | 6.117 ± 0.006 | 24.90 ± 0.28 | 20.88 ± 0.08 | 19.94 ± 0.08 | … |

Notes.

a The errors of the redshifts are the uncertainties obtained from our fitting process.

b This quasar was discovered by Fan et al. (2004). The magnitudes were taken from Fan et al. (2004), and the redshift was determined from the MgⅡ emission line by Kurk et al. (2007).

c This quasar was independently discovered by Venemans et al. (2007).

The iAB and zAB magnitudes are AB magnitudes and the J and H magnitudes are Vega-based magnitudes.
We emphasize that the EW and FWHM of Lyα SDSS deep stripe. The spectra of SDSS J0005–0006, J0203+0012, J0303–0019, J0353+0104, J2054–0005, and J2315–0023 were taken on Keck/ESI with a total exposure time of 100 min on each source. The spectra of the other three quasars were taken on Magellan/LDSS-3 with a total exposure time of 60 min on each source. The spectra of the other three quasars were taken on Magellan/LDSS-3 with a total exposure time of 100 min on each source. The ESI spectra have been binned by ten pixels and the LDSS-3 spectra been smoothed by five pixels. Four quasars in this sample are at z > 6. Three quasars have narrow Lyα emission lines. SDSS J0353+0104 is a BAL quasar.

N v. The measured EW and FWHM in units of Å are shown in Table 2. We also give the FWHM of Lyα in units of km s$^{-1}$. We emphasize that the EW and FWHM of Lyα in the table have taken into account the absorbed emission by the Lyα forest, while most previous studies did not take this absorption into account.

The distributions of the Lyα EW and FWHM are broad. The average Lyα EW and FWHM measured from the low-redshift SDSS composite spectrum of Vanden Berk et al. (2001) are about 90 Å and 20 Å ($\sim$5000 km s$^{-1}$), respectively. The EW of Lyα+N v from a sample of quasars at 3.6 < z < 5.0 is 69 ± 18 Å (Fan et al. 2001b), although this is affected by the Lyα forest absorption. We analyzed a sample of 20 luminous SDSS quasars at z ~ 6, and find that the mean Lyα EW and FWHM are 56 Å and 25 Å (also corrected for the Lyα forest absorption) with large scatters of 40 Å and 11 Å, respectively. In Table 2, three of our quasars (SDSS J0005–0006, SDSS J0303–0019, and SDSS J2315–0023) have Lyα FWHM less than half of the typical value. The Lyα FWHM in both SDSS J0005–0006 and SDSS J0303–0019 is only ~1600 km s$^{-1}$. However, their EW are close to or stronger than the typical Lyα EW. In contrast, the other two quasars, SDSS J0203+0012 and SDSS J205406.49–000514.8 (hereafter SDSS J2054–0005), have typical Lyα FWHM, but very weak Lyα EW.

The best-fitting power-law continuum is also used to calculate $m_{1450}$ and $M_{1450}$, the apparent and absolute AB magnitudes of the continuum at rest-frame 1450 Å. The results are given in Table 3. The sample spans a luminosity range of $\sim$26.5 $\leq M_{1450} \leq$ 25.4. Because the Lyα emission usually consists of a large fraction of the total emission in the z-band spectra of these quasars, the large scatter in the Lyα EW results in a large scatter in the distributions of $m_{1450}$ and $M_{1450}$, even though the $z_{AB}$ magnitudes lie in the small range 20.5 < $z_{AB}$ < 20.9.

### 3.1. Notes on Individual Objects

**SDSS J0005–0006** (z = 5.850). SDSS J0005–0006 was discovered by Fan et al. (2004). This quasar has a very narrow Lyα emission line. The rest-frame FWHM of Lyα is only 1680 km s$^{-1}$ (after being corrected for the Lyα forest absorption). The strong N v emission line is well separated from Lyα. The central BH mass is 3.10$^8$ M$_\odot$ (Kurk et al. 2007), an order of magnitude lower than the BH masses in luminous quasars at z ~ 6 (e.g. Barth et al. 2003; Vestergaard 2004; Jiang et al. 2007; Kurk et al. 2007). SDSS J0005–0006 was marginally detected in the Spitzer IRAC 8.0 $\mu$m band and was not detected in the Spitzer MIPS 24 $\mu$m band, indicating that there is no hot dust emission in this quasar (Jiang et al. 2006a).

**SDSS J0203+0012** (z = 5.854). SDSS J0203+0012 was independently discovered by matching the UKIDSS data to...
the SDSS data (Venemans et al. 2007). Its Lyα emission line is broad but weak. The Lyβ and O vi λ1033 (hereafter O vi) emission lines are clearly seen at ∼7000 Å. A C iv λλ1548,1550 absorption doublet is detected at $\lambda \lambda = 8480.1, 8494.3$ Å; this was also noticed by Venemans et al. (2007).

SDSS J0303–0019 ($z = 6.070$), SDSS J0303–0019 also has a very narrow Lyα emission line. The rest-frame FWHM of Lyα is 1580 km s$^{-1}$, similar to the Lyα width of SDSS J0005–0006. The strong N v emission line is well separated from Lyα. The Lyβ and O vi emission lines are clearly detected at ∼7300 Å. The continuum emission in this quasar is very weak. The absolute magnitude $M_{1450}$ is $-25.43$, roughly two magnitudes fainter than the luminous SDSS quasars at $z \sim 6$.

SDSS J0353+0104 ($z = 6.049$), SDSS J0353+0104 is a BAL quasar, as seen from strong absorption features around the Lyα emission line. Its redshift was measured from O i. The fraction of BAL quasars in this small sample is one out of six, similar to the low-redshift fraction (Trump et al. 2006), although C iv observations may yield further BAL examples. The Lyβ and O vi emission lines are seen at ∼7300 Å.

SDSS J2054–0005 ($z = 6.062$), SDSS J2054–0005 has a very weak Lyα emission line. The rest-frame EW of Lyα is only 17.0 Å, significantly smaller than the typical EW. But the FWHM of Lyα, ∼30 Å, is similar to the mean value of Lyα FWHM.

SDSS J2315–0023 ($z = 6.117$). SDSS J2315–0023 is the most distant quasar in this sample. The properties of the Lyα and N v emission lines are similar to those of SDSS J0005–0006 and SDSS J0303–0019. It has a narrow but strong Lyα emission line. The rest-frame EW and FWHM of Lyα are 127 Å and 2420 km s$^{-1}$, respectively. It also has a very strong N v emission line.

4. QLF AT $z \sim 6$

The six quasars presented in this paper provide a flux-limited quasar sample at $z > 5.8$. The survey area is 260 deg$^2$ and the magnitude limit is $z_{AB} = 21$. In this section we calculate the spatial density of the $z > 5.8$ quasars in the SDSS deep stripe, and combine this faint quasar sample with the SDSS bright quasar sample to derive the QLF at $z \sim 6$.

We use the selection function to correct the sample incompleteness due to the selection criteria we applied. The selection function is defined as the probability that a quasar with a given magnitude, redshift, and intrinsic spectral energy distribution (SED) meets our selection criteria. 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 calculate the synthetic distribution of quasar colors for a given ($M_{1450}, z$), following the procedures in Fan (1999) and Fan et al. (2001a). Then we calculate the SDSS magnitudes from the model spectra and incorporate photometric errors into each band. For an object with given ($M_{1450}, z$), we generate a database of model quasars with the same ($M_{1450}, z$). The detection probability for this quasar is then the fraction of model quasars that meet the selection criteria. The details of the model and simulation are described in Fan (1999) and Fan et al. (2001a).

Figure 5 shows the selection function as a function of $M_{1450}$ and $z$ for the two selection criteria (Equations (1) and (2)) based on $J$ and $H$ bands. The contours in the figure are selection probabilities from 0.9 to 0.1 with an interval of 0.1. The sharp decrease of the probability at $z \sim 5.8$ is due to the color cut of $i_{AB} - z_{AB} > 2.2$. The two selection functions are slightly different. Due to smaller photometric errors in the $i$ and $z$ bands, our survey probes ∼1.5 magnitude deeper than the SDSS main survey (see Fan et al. 2001a). The solid circles are the locations of the six $z \sim 6$ quasars in our sample.

We derive the spatial density of the $z > 5.8$ quasars using the traditional $1/V_{\Delta z}$ method (Avni & Bahcall 1980). The available volume for a quasar with absolute magnitude $M_{1450}$ and redshift $z$ in a magnitude bin $\Delta M$ and a redshift bin $\Delta z$ is

$$V_{\Delta} = \int_{V_{\Delta M}} \int_{\Delta z} p(M_{1450}, z) \frac{dV}{dz} dM,$$

where $p(M_{1450}, z)$ is the selection function used to correct the sample incompleteness. We use one $M_{1450}$–$z$ bin for our small sample. The redshift integral is over the redshift range $5.7 < z < 6.6$ and the magnitude integral is over the range that the sample covers. The spatial density and its statistical uncertainty can be written as

$$\rho = \frac{1}{V_{\Delta}} \sum_i \rho_i, \quad \sigma(\rho) = \left[ \sum_i \left( \frac{1}{V_{\Delta}} \right)^2 \right]^{1/2},$$

where the sum is over all quasars in the sample. This is similar to the revised $1/V_{\Delta}$ method of Page & Carrera (2000), since $p(M_{1450}, z)$ has already corrected the incompleteness at the
stress that the flattening is seen at high significance. The lack of flattening claimed by Fontanot et al. (2007) would be real only if the distribution of quasar SEDs was redshift dependent, contrary to what is found in most observations. Hence, the slope change from $z \sim 4$ to $z \sim 6$ is highly likely to be physical. The steepening of the slope at $z \sim 6$ has important consequences in understanding early BH growth in quasars. Quasar evolution at $z \sim 6$ is limited by the number of $e$-folding times available for BH accretion, therefore the shape of the QLF at $z \sim 6$ puts strong constraints on models of BH growth (e.g. Wyithe & Loeb 2003; Hopkins et al. 2005; Volonteri & Rees 2006; Wyithe & Padmanabhan 2006; Li et al. 2007), and helps determine whether standard models of radiatively efficient Eddington accretion from stellar seeds are still allowed, or alternative models of BH birth (e.g. from intermediate-mass BHs) and BH accretion (super-Eddington or radiatively inefficient) are required (e.g. Volonteri & Rees 2006).

The steepening of the QLF slope also has a strong impact on the quasar contribution to the ionizing background at $z \sim 6$. The re-ionization of the universe occurs at $z = 11 \pm 4$ (Spergel et al. 2007) and ends at $z \sim 6$ (Fan et al. 2006b). Studies have shown that quasars/AGN alone are not likely to ionize the IGM at $z \sim 6$ (e.g. Dijkstra et al. 2004; Meiksin 2005; Willott et al. 2005; Douglas et al. 2007; Salvaterra et al. 2007; Srianthavorn & Wyithe 2007; Shankar & Mathur 2007), and galaxies probably can provide enough photons for the re-ionization (e.g. Yan & Windhorst 2004; Bouwens et al. 2006; Kashikawa et al. 2006; McQuinn et al. 2007). However, the individual contributions of galaxies and quasars to the re-ionization are not well determined. The galaxy contribution is uncertain due to our lack of knowledge of factors such as the star-formation rate, the faint-end slope of the galaxy luminosity function, and the escape fraction of ionizing photons from galaxies (e.g. Bunker et al. 2004; Bouwens et al. 2006; Gnedin 2007); while the quasar contribution is poorly determined because the total number of known quasars at $z \sim 6$ was only $\sim 20$ so that even the QLF at the bright end was not well established before this study.

A few small-area deep observations with one or no quasar detections have put strong constraints on the ionizing photon density from $z \sim 6$ quasars. For example, Willott et al. (2005) did not find any quasars at $z > 5.7$ down to $z_{AB} = 23.35$ in a 3.83 deg$^2$ area of CFHQS, and thus concluded that the quasar population makes a negligible contribution to re-ionization. Shankar & Mathur (2007) have considered the implications of all existing $z \sim 6$ quasar observations, including deep X-ray surveys, for the faint end of the high-redshift QLF. Based predominantly on the X-ray surveys, they argue that there is a flattening of the QLF at $M_{1450} \approx -24.67$. Although our sample is not deep enough to reach the break luminosity of the QLF, the combination of our sample and the SDSS luminous sample with more than 20 quasars allows us to improve these constraints.

We estimate the rate at which quasars emit ionizing photons at $z \sim 6$ from the QLF derived above. We assume that the QLF at $z \sim 6$ has a double power-law form with a characteristic luminosity $M_{1450}^*$, a bright-end slope $\beta = -3.1$, and a faint-end slope $\alpha$. At low redshift $\alpha$ is between $-1.2$ and $-2.2$ (e.g. Boyle et al. 2000; Richards et al. 2005; Jiang et al. 2006b); while at $z > 4$ little is known about $\alpha$ and $M_{1450}^*$. Following Fan et al. (2001a), we calculate the photon emissivity of quasars at $z \sim 6$ for a range of $\alpha$ and $M_{1450}^*$. The results are shown in Figure 7. The solid lines represent the photon emissivity per unit comoving volume from quasars as a function of $\alpha$ and $M_{1450}^*$. The dashed lines represent the photon emissivity required to ionize the IGM.
about Shankar & Mathur (2007), the range is between –23 and –21. At the SDSS deep stripe, including one previously discovered by Willott et al. (2005), a flux-limited quasar sample with $z_{AB} < 21$ at $z \sim 6$ over 260 deg$^2$. The sample covers the luminosity range $–26.5 \leq M_{1450}^{\ast} \leq –25.4$. The spatial density of the quasars at $(z) = 6.0$ and $(M_{1450}^{\ast}) = –25.8$ is $(5.0 \pm 2.1) \times 10^{-9}$ Mpc$^{-3}$ mag$^{-1}$. We use a single power-law form to model the bright-end QLF at $z \sim 6$ and find a slope of $–3.1 \pm 0.4$, which is significantly steeper than the slope of the QLF at $z \sim 4$. Using the derived QLF, we find that the quasar/AGN population can provide enough photons required to ionize the IGM at $z \sim 6$ only if the IGM is very homogeneous and the characteristic luminosity of the QLF is very low. To put better constraints on the quasar contribution, much deeper surveys are needed.

The quasars in this paper were selected from the SDSS co-added images with 5–18 runs. Currently the SDSS deep stripe has been scanned between 40 and 50 times, reaching $2 \sim 3$ magnitudes deeper than the main survey when co-added. We are performing a deeper survey of $z \sim 6$ quasars down to $z_{AB} \sim 22$ in this region. We expect to obtain a flux-limited sample with $z_{AB} \sim 22$ in the next few years.

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