We report the discovery of five gravitationally lensed quasars from the Sloan Digital Sky Survey (SDSS). All five systems are reported as two-image lensed quasar candidates from a sample of high-redshift ($z > 2.2$) SDSS quasars. We confirmed their lensing nature with additional imaging and spectroscopic observations. The new systems are SDSS J0819+5356 ($z_s = 2.237$, lens redshift $z_l = 0.294$, and image separation $\theta = 4''.04$), SDSS J1254+2235 ($z_s = 3.626$, $\theta = 1''.56$), SDSS J1258+1657 ($z_s = 2.702$, $\theta = 1''.28$), SDSS J1339+1310 ($z_s = 2.243$, $\theta = 1''.69$), and SDSS J1400+3134 ($z_s = 3.317$, $\theta = 1''.74$). We estimate the lens redshifts of the latter four systems to be $z_l = 0.2$--0.8 from the colors and magnitudes of the lensing galaxies. We find that the image configurations of all systems are well reproduced by standard mass models. Although these lenses may not be in our statistical sample of $z_s < 2.2$ lenses, they expand the number of lensed quasars which can be used for high-redshift galaxy and quasar studies.

**Key words:** gravitational lensing – quasars: individual (SDSS J081959.79+535624.3, SDSS J125418.95+223536.5, SDSS J125819.24+165717.6, SDSS J133907.13+31039.6, SDSS J140012.77+313454.1)

1. **INTRODUCTION**

Gravitationally lensed quasars are unique astronomical and cosmological tools, as described in the review of Kochanek et al. (2006). We can study the mass distributions of lensing objects from individual mass modeling, as well as the substructures in lensing objects (e.g., Kochanek 1991; Mao & Schneider 1998). We can also investigate their interstellar media from dust extinction (e.g., Falco et al. 1999; Muñoz et al. 2004) or absorption lines appearing in spectra of multiple quasar images (e.g., Curran et al. 2007). The statistics of lensed quasars and the measurement of time delays between lensed images are useful tools to constrain cosmological parameters (e.g.,Refsdal 1964; Turner 1990; Fukugita et al. 1990). In addition, lensed quasars sometimes provide opportunities to study the central structures of quasar host galaxies in detail through microlensing events (e.g., Richards et al. 2004; Poindexter et al. 2008).

Motivated by these ideas, astronomers have searched for lensed quasars using various methods and wavebands. Roughly 100 lensed quasars have been identified to date (Kochanek et al. 2006). A number of homogeneously selected samples have been constructed (e.g., Maoz et al. 1993), allowing statistical studies to be done. For example, the Cosmic Lens All Sky Survey (CLASS; Myers et al. 2003; Browne et al. 2003) has created a sample of 22 lensed objects selected from ~16,000 radio sources. This sample has been used to obtain a variety of cosmological and astrophysical results (e.g.,Rusin & Tegmark 2001; Mitchell et al. 2005; Chae et al. 2006).

The Sloan Digital Sky Survey (SDSS; York et al. 2000) has discovered ~80,000 spectroscopically identified quasars (Schneider et al. 2007). We are conducting a survey of lensed quasars selected from the large data set of the SDSS. The survey, the SDSS Quasar Lens Search (SQLS; Oguri et al. 2006, 2008a; Inada et al. 2008) has discovered more than 30 lensed quasars (e.g., Kayo et al. 2007; Oguri et al. 2008b, and references therein), making it the current largest lensed quasar survey. The SQLS also recovered nine previously known lensed quasars included in the SDSS footprint (Walsh et al. 1979; Weymann et al. 1980; Surdej et al. 1987; Bade et al. 1997; Oscoz et al. 1997; Schechter et al. 1998; Myers et al. 1999; Morgan et al. 2001; Magain et al. 1988). The first statistical sample of 11 SQLS lenses (Inada et al. 2008) was constructed from the SDSS Data Release 3 quasar catalog (4188 deg$^2$; Schneider et al. 2005), and used to constrain dark energy (Oguri et al. 2008a).

The SQLS restricts the statistical lens sample to $z_s < 2.2$ because we cannot make a well-defined quasar sample for homogeneous lens surveys at higher redshifts. The SDSS quasars at $z_s > 2.2$ are required to be point sources (see Richards et al. 2002), and therefore they have a strong bias against the homogeneous lens candidate selection (Oguri et al. 2006; Inada et al. 2008). However, the SQLS candidate finding algorithm can easily be extended to locate higher redshift lensed quasars (Inada et al. 2008). Such high-redshift lensed quasars can be used as astronomical and cosmological tools to study (high-redshift) lensing galaxies (e.g., Kochanek et al. 2000) and constrain the Hubble constant (e.g., Oguri 2007). They are also useful for detailed studies of (lensed) high-redshift quasars. In this paper, we report the discoveries of five lensed quasars with high source redshifts ($z_s = 2.237$--3.626). They were selected as lensed quasar candidates from the SDSS data, and were confirmed as lenses.
with the observations at the University of Hawaii 2.2 m telescope (UH88), the Astrophysical Research Consortium 3.5 m telescope (ARC 3.5 m), and the 3.58 m Telescopio Nazionale Galileo (TNG 3.6 m). All five candidates are confirmed to be double-image lensed quasars, with image separations of $1\arcsec28–4\arcsec04$.

The structure of this paper is as follows. Brief descriptions of the SDSS data and our lens candidate selection algorithm are presented in Section 2. We present the results of imaging and spectroscopic observations to confirm the lensing hypotheses for the five objects and estimate the redshifts of the lensing galaxies in Section 3. We model the five lensed quasars in Section 4 and summarize our results in Section 5. We use a standard cosmological model with matter density $\Omega_M = 0.27$, cosmological constant $\Omega_{\Lambda} = 0.73$, and Hubble constant $h = H_0 / 100$ km s$^{-1}$ Mpc$^{-1} = 0.71$ (e.g., Spergel et al. 2003) throughout this paper.

2. SDSS DATA AND CANDIDATE SELECTION

SDSS J0819+5356 was selected as a lens candidate in the SDSS-I, and the other four lenses were selected as lens candidates in the SDSS-II Sloan Legacy Survey. The SDSS consists of a photometric (Gunn et al. 1998) and a spectroscopic survey, and has mapped approximately 10,000 deg$^2$ primarily in a region centered on the North Galactic Cap, through the SDSS-I and the subsequent SDSS-II Legacy Surveys. The survey was conducted with a dedicated wide-field 2.5 m telescope (Gunn et al. 2006) at the Apache Point Observatory in New Mexico, USA. The photometric survey uses five broadband optical filters (ugriz; Fukugita et al. 1996). The spectroscopic survey is carried out with a multifiber spectrograph covering 3800–9200 Å with a resolution of $R \sim 1800$. The data in each imaging observation are processed by the photometric pipeline (Lupton et al. 2001), and then the target selection pipelines (Eisenstein et al. 2001; Richards et al. 2002; Strauss et al. 2002) find quasar and galaxy candidates; the candidates are tiled in each plate according to the algorithm of Blanton et al. (2003). The SDSS produces very homogeneous data with an astrometric accuracy better than about 0.1 rms per coordinate (Pier et al. 2003) and photometric zero-point accuracy better than about 0.02 mag over the entire survey area (Hogg et al. 2001; Smith et al. 2002; Ivezić et al. 2004; Tucker et al. 2006; Padmanabhan et al. 2008). The SDSS is continuously making its data public (Stoughton et al. 2002; Abazajian et al. 2003, 2004, 2005; Adelman-McCarthy et al. 2006, 2007, 2008). The final release (Date Release Seven) was made on 2008 October 31.

The lensed quasar candidate selection algorithm of the SQLS (Oguri et al. 2006; Inada et al. 2008) is composed of two parts. One is “morphological selection,” which selects candidates as extended quasars using the difference between the shapes of each quasar and the point-spread function (PSF) in each field. The other method is “color selection,” which finds quasars with objects (usually fainter) within $\lesssim 20\arcsec$, whose colors are similar to the quasars. Although the selection algorithm is basically designed for quasars with $z_s < 2.2$, we can easily extend it to target higher redshift quasars by shifting to longer wavelength bands, as H I absorption significantly reddens colors at wavelengths shortward of the Ly$\alpha$ emission line (Schneider et al. 1991; Fan 1999; Richards et al. 2002). For example, we can search for quasars with $z_s \lesssim 3.5$ using information from the griz bands rather than the ugr$i$ bands used at lower redshifts (Inada et al. 2008), and $z_l \lesssim 4.8$ using the riz bands. We selected SDSS J0819+5356, SDSS J1258+1657, and SDSS J1400+3134 as lens candidates by morphological selection with griz (or riz for SDSS J1400+3134), and SDSS J1254+2235 and SDSS J1339+1310 by color selection with griz. SDSS J0819+5356 was not selected by color selection despite its large image separation, because of the presence of the bright lensing galaxy between the two stellar components. We note that SDSS J0819+5356 was also selected as a possible lensed Ly$\alpha$ emitting galaxy by the algorithm described in Shin et al. (2008) to identify strong galaxy–galaxy lenses.

The SDSS r-band images of the fields around each lensed quasar candidate are shown in Figure 1. The SDSS a sin$h$ magnitudes (Lupton et al. 1999) without Galactic extinction corrections and redshifts of the five objects are summarized in Table 1. The u-band a sin$h$ magnitude of SDSS J1254+2235 is not given because it is undetected in the u band. All five candidates appear to be doubly imaged lenses in the SDSS images, as we will confirm with the imaging and spectroscopic follow-up observations described in the next section.

3. OBSERVATIONS

As described in Inada et al. (2008), our criteria to confirm the lensing hypothesis for a candidate double-image lensed quasar are (1) the existence of a lensing object between the two stellar (quasar) components, and (2) similar spectral energy distributions (SEDs) for the two quasar images. All five candidates are marginally resolved in the SDSS imaging data and spatially unresolved in the SDSS spectroscopic data (the fiber diameter is $3\arcsec$ and the minimum separation between each fiber on a single plate is $\sim 55\arcsec$), and therefore we conducted optical/near-infrared imaging and spectroscopic follow-up observations to confirm their lensing natures, using the UH88, ARC 3.5 m, and TNG 3.6 m telescopes.

3.1. Imaging Observations

We obtained VRI images for all five candidates and B images for SDSS J0819+5356 with the Tektronix 2048 $\times$ 2048 CCD camera (Tek2k, 0.22 pixel$^{-1}$) at the UH88 telescope. The observations were conducted on 2007 April 11, 2007 November 13, and 2008 March 6, with typical seeing of FWHM $\sim 0.8$. The exposures were between 300 and 480 s depending on the magnitudes of the objects and the observing conditions in each night, and 800 s for the B-band image of SDSS J0819+5356. The instruments, observing dates, and exposure times for these observations are summarized in Tables 2 and 3. The I-band images of all five candidates are shown in the left column of Figure 2. In each image, we clearly detect two stellar components (denoted as A and B, A being the brighter component) with typical separations of $\sim 1.5\arcsec$, except for SDSS J0819+5356, which has a larger image separation of $4\arcsec04$. The BVRI images for SDSS J0819+5356 clearly show an extended object (component G) between components A and B, which we interpret as the lensing galaxy. To see whether the other four candidates also have lensing galaxies between the stellar components, we subtracted two PSFs from the VRI images of each candidate, using nearby stars as PSF templates. In all 12 images, the VRI images of the four candidates, there is extended residual flux between components A and B that we designate component G. The I-band PSF-subtracted images are shown in the lower four panels of the middle column of Figure 2. The morphology of the lensing galaxy of SDSS J1400+3134 appears...
Figure 1. Finding charts (SDSS $r$-band images) for the five lensed quasars. See Table 1 for the celestial coordinates of each object. Note that SDSS J0819+5356 is located at the edge of the field. The pixel scale is 0.396. North is up and east is to the left.

Table 1
SDSS Data of Lenses

| Object          | R.A. (J2000) | Decl. (J2000) | $u$   | $g$    | $r$    | $i$    | $z$    | Redshift        |
|-----------------|--------------|---------------|-------|--------|--------|--------|--------|-----------------|
| SDSS J0819+5356 | 124:99913    | +53:94008     | 19.49 | ±0.15 | 18.63  | ±0.03  | 17.66  | ±0.02           |
| SDSS J1254+2235 | 193:57896    | +22:59350     | ...   | ...    | 20.30  | ±0.04  | 18.95  | ±0.02           |
| SDSS J1258+1657 | 194:58019    | +16:95491     | 19.25 | ±0.05 | 18.55  | ±0.01  | 18.40  | ±0.01           |
| SDSS J1339+1310 | 204:77974    | +13:17768     | 18.51 | ±0.03 | 18.05  | ±0.01  | 17.98  | ±0.02           |
| SDSS J1400+3134 | 210:05322    | +31:58170     | 21.28 | ±0.45 | 19.26  | ±0.02  | 18.96  | ±0.03           |

Notes. Celestial coordinates (J2000), total a sin h magnitudes (Lupton et al. 1999) without Galactic extinction correction inside aperture radii (5.4, 2.1, 2.4, and 7.3 for SDSS J0819+5356, SDSS J1254+2235, SDSS J1258+1657, SDSS J1339+1310, and SDSS J1400+3134, respectively), and quasar emission redshifts from the SDSS data.

Table 2
Summary of Follow-up Observations 1

| Object          | Facilities for Imaging | Date of Imaging | Facilities for Spectroscopy | Date of Spectroscopy |
|-----------------|-------------------------|-----------------|-----------------------------|----------------------|
| SDSS J0819+5356 | UH88 Tek2k ($BVRI$)     | 2007 Nov. 13 ($B$), 2007 Apr. 11 ($VRI$) | ARC 3.5 m DIS         | 2007 Oct. 20         |
| SDSS J1254+2235 | UH88 Tek2k ($VRI$)      | 2008 Mar. 6 ($VRI$) | UH88 WFGS2                 | 2008 Mar. 5          |
| SDSS J1258+1657 | UH88 Tek2k ($VRI$)      | 2007 Apr. 11 ($V$), 2008 Mar. 6 ($R$) | TNG 3.6 m DOLORES      | 2008 Apr. 14         |
| SDSS J1339+1310 | UH88 Tek2k ($VRI$), ARC 3.5 m NICFPS ($H$) | 2007 Apr. 11 ($VRI$), 2007 Apr. 5 ($H$) | UH88 WFGS2            | 2007 May 13          |
| SDSS J1400+3134 | UH88 Tek2k ($VRI$), ARC 3.5 m NICFPS ($H$) | 2007 Apr. 11 ($VRI$), 2007 Mar. 8 ($H$) | UH88 WFGS2            | 2007 May 13          |

Table 3
Summary of Follow-up Observations 2

| Object          | Exposure ($B$) | Exposure ($V$) | Exposure ($R$) | Exposure ($I$) | Exposure ($H$) | Exposure (spec) |
|-----------------|----------------|----------------|----------------|----------------|----------------|-----------------|
| SDSS J0819+5356 | 800 s          | 300 s          | 300 s          | 300 s          | ...            | 1800 s          |
| SDSS J1254+2235 | ...            | 400 s          | 400 s          | 400 s          | ...            | 4800 s          |
| SDSS J1258+1657 | ...            | 300 s          | 400 s          | 480 s          | ...            | 1200 s          |
| SDSS J1339+1310 | ...            | 300 s          | 300 s          | 480 s          | 900 s          | 3600 s          |
| SDSS J1400+3134 | ...            | 300 s          | 400 s          | 900 s          | 4500 s         |                 |
to be unusual due to its low signal-to-noise ratio (S/N). Finally, we subtracted two PSFs plus an extended component modeled by a Sérsic profile using GALFIT (Peng et al. 2002) from the VRI images of the four candidates; the resulting images show virtually no residuals (see the lower four panels of the right column in Figure 2). We also subtracted two PSFs, and two PSFs plus a galaxy component, from the BVRi images of SDSS J0819+5356. The results from the I-band image are shown in the top panels of the middle and right columns of Figure 2. We detect a residual flux (component C) around component A in the “2PSFs+1G” subtracted images (in all BVRi bands). This component appears to be distorted along the critical curve of the system, and therefore might be the lensed host galaxy of the source quasar. We summarize the parameters of the best-fitting Sérsic profiles (in the I-band images) of each lensing galaxy in Table 4. The very large $n$ parameter for SDSS J0819+5356
Figure 3. ARC 3.5 m NICFIPS H-band images of SDSS J1339+1310 and SDSS J1400+3134. The lensing galaxies are bright in H-band images, and therefore we can see them even in the original images. The left, middle, and right panels show the original images, residuals after subtracting two PSFs, and images after subtracting two PSFs plus one galaxy component, respectively. The image scale is 0.273 pixel$^{-1}$. North is up and east is to the left. See Tables 2 and 3 for observation information.

Table 4

| Object             | $r_e$ (r) | $n$  | $e^2$ | $\theta_e$ (°) |
|--------------------|-----------|------|-------|----------------|
| SDSS J0819+5356    | 5.84 ± 0.44 | 7.37 ± 0.22 | 0.22 ± 0.01 | −40.33 ± 0.97 |
| SDSS J1254+2255    | 0.70 ± 0.05  | 1.49 ± 0.45  | 0.55 ± 0.07  | −18.81 ± 6.55  |
| SDSS J1258+1657    | 0.35 ± 0.05  | 2.43 ± 0.80  | 0.23 ± 0.08  | −54.42 ± 17.12 |
| SDSS J1339+1310    | 0.86 ± 0.09  | 3.21 ± 0.59  | 0.17 ± 0.06  | −18.90 ± 14.41 |
| SDSS J1400+3134    | 1.08 ± 0.04  | 0.21 ± 0.07  | 0.43 ± 0.03  | −38.57 ± 3.58  |

Notes. Sérsic parameters measured in the I-band images using GALFIT. For SDSS J1400+3134, the shape of the lensing galaxy is not correctly measured because of the low S/N ratio.

- $r_e$: Effective radius of the Sérsic profile.
- $n$: Sérsic concentration index.
- $e^2$: Ellipticity and its position angle. Each position angle is measured east of north.

implies that the lensing galaxy has a steep inner profile. For SDSS J1400+3134, we cannot measure the correct shape of the residual flux (after subtracting two PSFs) even in the I-band image due to its faintness.

Additional near-infrared (H-band) images for SDSS J1339+1310 and SDSS J1400+3134 were taken with the Near-Infrared Camera and Fabry-Perot Spectrometer (NICFIPS, 0.273 pixel$^{-1}$) at the ARC 3.5 m telescope, on 2007 March 8 and 2007 April 5. The exposures were 900 s for both objects (see also Tables 2 and 3). The lensing galaxies are easily detected in the H-band images; we can see them even in the original images shown in the left column of Figure 3. We again subtracted two PSFs and two PSFs plus a galaxy component using GALFIT. The results are shown in the middle and right columns of Figure 3. The results further support the existence of the lensing objects for SDSS J1339+1310 and SDSS J1400+3134.

The relative astrometry (from the Tek2k I-band images) and the absolute photometry (Landolt–Vega system; Landolt 1992) for the BVRI-band observations of the five candidates are summarized in Table 5. For all candidates, the differences of the relative positions among each filter are less than ∼0.05 for the stellar components and ∼0.15 for the extended components. We used the standard star PG 0918+029 (Landolt 1992) for the optical (BVRI) magnitude calibration. We estimated the H magnitudes using the Two Micron All Sky Survey (2MASS) data (Skrutskie et al. 2006) of nearby stars.

To summarize the imaging observations, we detect extended objects between the two stellar components in all five candidates, which we naturally interpret as the lensing galaxies.

3.2. Spectroscopic Observations

To determine the SEDs of the stellar components of each candidate, we conducted spectroscopic observations using the Wide Field Grism Spectrograph 2 (WFGS2; Uehara et al. 2004) at the UH88 telescope, the Dual Imaging Spectrograph (DIS) at the ARC 3.5 m telescope, and the Device Optimized for the Low Resolution (DOLORES) at the TNG 3.6 m telescope. We used a 0′.9 long slit and the 300 gr mm$^{-1}$ grism (spectral resolution of $R ∼ 600$ and spatial scale of the CCD detector of 0′.34 pixel$^{-1}$) for WFGS2, a 1′.5 long slit and the B400 grism ($R ∼ 500$ and 0′.40 pixel$^{-1}$) for DIS, and a 1′.0 long slit and the LR-B grism ($R ∼ 600$ and 0′.252 pixel$^{-1}$) for DOLORES. We aligned each slit direction to observe components A and B simultaneously. The exposures were typically ∼2000 s for the ARC 3.5 m and TNG 3.6 m telescopes and ∼5000 s for the UH88 telescope. The instruments, observing dates, and exposures for the spectroscopic observations are also summarized in Tables 2 and 3.

All spectroscopic observations were conducted under good seeing conditions (FWHM ≤ 1″). The spectrum of each component was extracted by the standard IRAF tasks, and are shown in Figure 4. The data show that the two stellar components of each candidate have quite similar SEDs. In particular, the two quasar components of SDSS J0819+5356 and SDSS J1254+2235 have similar broad absorption line features. Therefore, together with the existence of the extended objects between the stellar components, we unambiguously conclude that SDSS J0819+5356, SDSS J1254+2235,
SDSS J1258+1657, SDSS J1339+1310, and SDSS J1400+3134 are all lensed quasars.

3.3. Lens Redshifts

Measurements of lens galaxy redshifts are important, because both source (quasar) and lens (galaxy) redshifts are necessary to convert dimensionless lensing quantities to physical units. Although source redshift measurements of lensed quasar systems are relatively easy because of prominent quasar emission lines (see Figure 4), this is not the case for direct measurements of lens galaxy redshifts (Eigenbrod et al. 2006, 2007). Indeed, we were not able to find any signal from the lensing galaxies in our spectra, except in SDSS J0819+5356, for which we measure the redshift of the bright lensing galaxy to be $z_l = 0.294$ from the Ca II H&K, G-band, Mg, and Na absorption lines, appearing in the SDSS spectrum (see Figure 5). The lens redshift of SDSS J0819+5356 is also confirmed in the DIS spectrum of component B, which shows the Ca II H&K lines at $\sim 5300$ Å (see Figure 4).

For the remaining objects, we roughly estimate the redshifts of the lensing galaxies by comparing the observed colors with the results of Fukugita et al. (1995). We particularly use the $R - I$ colors (Table 5), since the lensing galaxies are faint in the $V$ band. For SDSS J1254+2235, the $R - I$ color of 0.32 indicates that the redshift of the lensing galaxy is not high. Therefore, combined with its Sérsic concentration index (Table 4), we estimate that the lensing galaxy is a late-type galaxy at $z_l \sim 0.2$, rather than $z_l \sim 0.5$. For SDSS J1258+1657 and SDSS J1339+1310, their Sérsic index and $R - I$ colors of $\sim 1.0$ (Tables 4 and 5) suggest that the lensing galaxies might be early-type galaxies at $z_l \sim 0.5$. Assuming the early-type, we can further constrain the lens redshifts by comparing the observed magnitudes with the predicted magnitudes from the Faber–Jackson relation (Faber & Jackson 1976) adopted by Rusin et al. (2003). The predicted magnitudes ($R \sim 20.8 \pm 0.7$ and $R \sim 20.2 \pm 0.6$ for SDSS J1258+1657 and SDSS J1339+1310, respectively) assuming $z_l \sim 0.4$ and using the observed image separations and Table 3 of Rusin et al. (2003) imply that the lens redshifts are less than $z_l \sim 0.5$ and probably $z_l \sim 0.4$. Although the morphology of the lensing galaxy of SDSS J1400+3134 is unknown, we estimate the lens redshift to be $z_l \sim 0.8$ from the $R - I$ colors of $\sim 1.5$. To summarize, we estimate the lens redshifts to be $z_l \sim 0.2$, $z_l \sim 0.4$, and $z_l \sim 0.8$ for SDSS J1254+2235, SDSS J1258+1657, SDSS J1339+1310, and SDSS J1400+3134, respectively.

In this paper, we use these results to derive the predicted time delays of each system (see Section 4). These estimates should also provide a useful guidance for the future direct measurements of the lens redshifts. In particular, the direct measurement of the lens redshift of SDSS J1339+1310 might be easy, both because it has the relatively large image separation ($\theta = 1\arcsec 7$) and because the lensing galaxy is bright.

4. MASS MODELING

We modeled the five systems using a mass model of a Singular Isothermal Ellipsoid (SIE). The number of the model parameters (eight parameters; the Einstein radius $R_E$, the ellipticity $e$ and its position angle $\theta_e$, the position of the mass center, and the position and flux of the source quasar) is the same as the number of the constraints from the observations (eight constraints; the positions and fluxes of the two quasar components, and the position of the lensing galaxy), both because all five objects are...
Figure 4. Spectra of the stellar components of the five lensed quasars. We used the DIS at the ARC 3.5 m telescope for SDSS J0819+5356, the WFGS2 at the UH88 telescope for SDSS J1254+2235, SDSS J1339+1310, and SDSS J1400+3134, and the DOLORES at the TNG 3.6 m telescope for SDSS J1258+1657. In each panel, the spectra of brighter components (component A) are shown by the black solid lines, and those of fainter components (component B) are shown by the gray solid lines. The vertical gray dotted lines indicate the positions of the redshifted quasar emission lines. For SDSS J0819+5356, the spectra show broad absorption lines shifted shortward of the N V and C IV emission lines and the Ca II H&K absorption lines from the lensing galaxy (marked by the gray solid symbol at ~5100 Å). The two quasar components of SDSS J1254+2235 also have broad absorption line features. For SDSS J1400+3134, the absorption features around 5400 Å are real but their origin is unknown. The SEDs of each pair are very similar, supporting the lensing hypotheses for all objects.

Figure 5. SDSS spectrum of SDSS J0819+5356. The absorption lines from the lensing galaxy at $z = 0.294$ are marked by the dark gray symbols. The C IV emission line from the source quasar at $z = 2.237$ is marked by the light gray symbol.
In addition to the parameters of the best-fitting models, we summarize the predicted time delays and total magnifications in Table 6. We estimated the uncertainties of the predicted time delays for the 1σ uncertainties of the parameters, and summarized them in Table 6. The measured lens redshift for SDSS J0819+5356 and the estimated lens redshifts for the other four lenses are used to calculate the time delays.

5. SUMMARY

We discovered five high-redshift (zs > 2.2) lensed quasars, SDSS J0819+5356, SDSS J1254+2225, SDSS J1258+1657, SDSS J1339+1310, and SDSS J1400+3134 from the SDSS. They were confirmed to be lenses by the imaging and spectroscopic observations at the UH88, ARC 3.5 m, and TNG 3.6 m telescopes. All five objects are two-image lensed quasars, with image separations of 1″28–4′0. The source redshifts range from 2.24 to 3.63. The lens redshift of SDSS J0819+5356 is measured to be zl = 0.294 from the Ca II H&K absorption lines, whereas the lens redshits of the other four objects are estimated to be 0.2–0.8 from the colors and magnitudes of the lensing galaxies. The image configurations and fluxes of all the lenses are well reproduced by standard lens models. We find signatures of strong external shears for SDSS J1258+1657 and SDSS J1339+1310, presumably coming from nearby galaxies whose redshifts are estimated to be similar to that of the lensing galaxy.

The statistical lensed quasar sample of the SQLS is restricted to zs < 2.2, and therefore all the lensed quasars discovered here will not be included in the SQLS statistical sample. The reason is that the SDSS quasars at zs > 2.2 are selected only from point sources and therefore the SDSS-selected quasars have a strong bias against our “morphological selection.” Thus, the five lenses will be included in a statistical sample when a homogeneous catalog with quasars at zs > 2.2 is constructed. However, the five lenses will definitely be useful for detailed future studies, such as deep spectroscopy for the lensing galaxies to measure their redshifts and velocity dispersions and for the quasar images to study the transverse structure in the Lyα forest, and the high-resolution imaging to see the structure of the systems. In addition, monitoring observations to measure time delays and microlensing events will provide useful opportunities to study the central structures of the quasars and to constrain the Hubble constant. These high-redshift lensed quasars will also be important to extend the redshift range of the lens applications; only about 30 objects out of the ~100 lensed quasars identified to be lenses at zs > 2.2.

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14 Currently, the measurement of velocity dispersions is probably possible only for the lensing galaxy of SDSS J0819+5356.

15 CASTLES Web page (C. S. Kochanek et al., http://cfa-www.harvard.edu/castles/).
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