EIGHT NEW QUASAR LENSES FROM THE SLOAN DIGITAL SKY SURVEY QUasar Lens SEARCH

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ABSTRACT

We report the discovery and confirmation of eight new two-image lensed quasars by the Sloan Digital Sky Survey (SDSS) Quasar Lens Search. The lenses are SDSS J0904+1512 (image separation θ′ = 1′′13, source redshift zΛ = 1.826), SDSS J1054+2733 (θ′ = 1′′27, zΛ = 1.452), SDSS J1055+4628 (θ′ = 1′′15, zΛ = 1.249), SDSS J1131+1915 (θ′ = 1′′46, zΛ = 2.915), SDSS J1304+2001 (θ′ = 1′′87, zΛ = 2.175), SDSS J1349+1227 (θ′ = 3′′00, zΛ = 1.722), SDSS J1455+1447 (θ′ = 1′′73, zΛ = 1.424), and SDSS J1620+1203 (θ′ = 2′′77, zΛ = 1.158). Three of them, SDSS J1055+4628, SDSS J1455+1447, and SDSS J1620+1203, satisfy the criteria for constructing our statistical sample for studying the cosmological model. Based on galactic absorption lines of the lenses, we also derive lens redshifts of zL = 0.398 and zL = 0.513 for SDSS J1620+1203 and the previously discovered lens SDSS J0746+4403, respectively.

Key words: gravitational lensing: strong – quasars: general

Online-only material: color figure

1. INTRODUCTION

Gravitationally lensed quasars play important roles not only in investigating the physical properties of lens galaxies but also in extracting cosmological information and constraining the structure of quasar accretion disks (e.g., see Schneider et al. 2006; Kochanek 2006, for reviews). To use lensed quasars for these studies, it is important to construct large samples, especially for cosmological purposes. The Cosmic Lens All-Sky Survey (CLAS; Myers et al. 2003; Browne et al. 2003) is one of the largest, with 22 lenses drawn from a sample of ~16,000 radio sources, and has provided useful constraints on the evolution of galaxies and cosmology. We are performing a systematic lensed quasar survey, the Sloan Digital Sky Survey Quasar Lens Search (SQLS; Oguri et al. 2006; Inada et al. 2008), to construct a larger sample of lensed quasars in the optical. Thus far, we have discovered 28 lensed quasars (26 are galaxy-scale lenses and two are cluster-scale lenses) and rediscovered 11 known lenses (e.g., Oguri et al. 2008b; Inada et al. 2009, and references therein). Our current sample is now large enough for the statistical errors on cosmological parameters to be comparable to the present level of the systematic uncertainties (Oguri et al. 2008a). Larger samples of lensed quasars also allow an increasing level of “self-calibration” to constrain many of these uncertainties, particularly the velocity dispersion function of the lens galaxies and its evolution as one of the largest contributors to these systematic uncertainties (e.g., Choi et al. 2007; Matsumoto & Futamase 2008; Chae 2008).

In this paper, we report the discovery of new eight galaxy-scale lenses done by early 2009, bringing our total sample to 47.10 We briefly describe the selection of lens candidates from the Sloan Digital Sky Survey (SDSS; York et al. 2000) in the following section, and then present the imaging and spectroscopic observations needed to confirm these candidates in Section 3. Simple mass models of the eight lenses are made in Section 4 to see whether the lensing interpretation is reasonable. Throughout the paper, we assume a standard cosmological model with matter density ΩM = 0.26, cosmological constant ΩΛ = 0.74, and Hubble constant H0 = 72 km s^{-1} Mpc^{-1}.

2. SDSS DATA AND SELECTION OF CANDIDATES

The SDSS-I and SDSS-II Sloan Legacy Surveys are photometric and spectroscopic surveys (Fukugita et al. 1996; Gunn et al. 1998; Gunn et al. 1998; Blanton et al. 2003; Tucker et al. 2006) covering a quarter of the all sky, using a dedicated telescope (Gunn et al. 2006) at the Apache Point Observatory in New Mexico. The imaging data were processed by the photometric pipeline (Lupton et al. 2001) and carefully calibrated (Hogg et al. 2001; Smith et al. 2002; Pier et al. 2003; Ivezic et al. 2004). The spectroscopic quasar targets were selected from the imaging data according to the algorithm described by Richards et al. ( 2002) and cataloged in Schneider et al. ( 2007) and D. P. Schneider et al. ( 2010, in preparation). All the SDSS data are publicly available in the final Data Release 7 (Abazajian et al. 2009).

From the spectroscopically confirmed quasar catalogs, we select candidates for lensed quasars using two different methods based on morphologies (morphological selection) and color (color selection). The details of the two selection methods are found in Inada et al. ( 2008) and Oguri et al. ( 2006). Morphological selection is used to find lenses with small image separations, ≤ 2′′.5, which are not deblended by the SDSS pipeline, and color selection is for lenses with larger separations. Of the eight systems reported in this paper, five systems (SDSS J0904+1512, SDSS J1054+2733, SDSS J1055+4628, 9 Research Fellow of the Japan Society for the Promotion of Science.
10 Visit http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls/ for a list of lensed quasars in the SQLS.
3. ADDITIONAL IMAGING AND SPECTROSCOPY

The imaging observations for these lenses were performed using four instruments on the University of Hawaii 2.2 m telescope (UH88): the Tektronix 2048 × 2048 CCD camera (Tek2k; the pixel size is 0.2195 pixel⁻¹), the UH8k wide-field imager (UH8k; 0.235 pixel⁻¹), the Orthogonal Parallel Transfer Imaging Camera (OPTIC; 0.1374 pixel⁻¹), and the Quick Infrared Camera (QUIRC; 0.189 pixel⁻¹). The spectroscopic data and some images were taken with the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) on the Subaru telescope. The FOCAS data were binned 2 × 2 on the detector leading to a spatial resolution of 0.′208 pixel⁻¹. The spectral resolution is $R \sim 400–500$. Tables 2 and 3 summarize the observations.

We analyzed the imaging data using GALFIT (Peng et al. 2002). First, we fit each system with two stellar components using stars near the systems as point-spread function (PSF) templates. There remained significant extended residuals between the point sources after subtracting the best-fit model for all systems. We then added a galaxy modeled by a Sérsic profile to the fit and found virtually no residuals. In the left panels of Figure 2, we show the original $I$-band images ($R$-band image for SDSS J1055+4628). Most of the signal in the images arises from two point-like objects, labeled “A” and “B.” In the right panels we show the residuals, labeled “G1” or “G2,” after subtracting the two best-fit PSFs. The astrometry and photometry of the components are listed in Table 4, and the best-fit Sérsic parameters are shown in Table 5. The differences in the relative positions of these components between bands are below 0′05 for the stellar components and 0′2 for the extended components.

The one-dimensional spectra of the stellar components were extracted using standard IRAF11 tasks. The spectra shown in Figure 3 and the results of the imaging observations unambiguously confirm that the eight systems are gravitationally lensed systems. The shapes of the various emission lines and continua are almost perfectly identical between the two quasars of each system. The spectrum of the fainter quasar of SDSS J1620+1203 is contaminated with the relatively bright lens galaxy, and we clearly detect some galactic absorption lines of the lens galaxy. We conclude with comments on individual lens system.

SDSS J0904+1512. The $I$-band image shows that the lens galaxy is located near the brighter lens image, like HE1104–1805 (Wisotzki et al. 1993) or SDSS J1226–0006 (Inada et al. 2008), and a fit to the galaxy profile yields the Sérsic index of 4.1. When analyzing $V$- and $R$-band images, we fixed the galaxy profile to the $I$-band profile because the galaxy is too faint to fit the galaxy profile correctly. The image separation is $\theta = 1′.128 \pm 0′007$, and the source redshift is $z_s = 1.826 \pm 0.002$. This lens system is not included in the SQLS statistical sample because of the large flux ratio between the quasar images ($\Delta I > 1.25$; Inada et al. 2008).

SDSS J1054+2733. The best-fit Sérsic index to the galaxy is 3.7 in the $I$ band, and the lens galaxy is likely to be early-type. For the $R$-band analysis, we fixed the galaxy profile to that from the $I$-band fit. Although there remain some residuals in the 2PSFs model of the $V$-band image, we could not fit the residuals well because of a lack of bright enough PSF templates to fit the weak residuals. The image separation is $\theta = 1′.269 \pm 0′004$ and the source redshift is $z_s = 1.452 \pm 0.002$. This system is

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11 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
SDSS J1131+1915. The lens galaxy was successfully fit in the I-band image with the Sérsic profile (the best-fit index is 2.4), but the V-band residuals after subtracting two PSFs are faint and we could not estimate the parameters of the galaxy. We did not take R-band images. The image separation is $\theta = 1''146 \pm 0''004$ and the source redshift is $z_s = 2.915 \pm 0.007$. This system is not included in the SQLS statistical sample because the redshift is outside of our selection criteria ($z_s < 2.2$).

SDSS J1304+2001. We fit the images with two PSFs (A and B) and two Sérsic profiles (G1 and G2), and the best-fit Sérsic indices are 2.9 and 6.0, respectively. Galaxy G1 lies between the two quasars and galaxy G2 is located about 3''5 to the south of G1. G1 and G2 have similar, red colors ($R - I = 0.7 - 1.0$ and $V - R = 0.8 - 0.9$), suggesting that they are probably associated with each other. The image separation is not included in the SQLS statistical sample because of the large flux ratio between the images.

**SDSS J1055+4628.** The FOCAS R-band image was used for astrometric measurements because it is the deepest. In addition to the two quasars (A and B) and the lens galaxy (G1 with a best-fit Sérsic index of 5.4), we also found two extended objects located 3''5 to the north and 4''5 to the south of the system. The northern object has $R - I \sim 1.0$, which is similar to the lens galaxy G1 ($R - I = 0.87$), but the southern one is much bluer than the two galaxies. In the V-band image we could not find any galaxy components. The image separation is $\theta = 1''146 \pm 0''004$ and the source redshift is $z_s = 1.249 \pm 0.001$. This system satisfies our statistical sample criteria and is included in SQLS statistical sample from DR5 (N. Inada et al. 2010, in preparation).
Figure 2. Images taken by the UH88 and Subaru telescopes (left panels of each) and the residuals after fitting and subtracting two PSFs using GALFIT (right panels of each). The residual objects labeled by “G1” or “G2” are the lens galaxies. These are Tek2k I-band images except for SDSS J0904+1512 (I band, OPTIC) and SDSS J1055+4628 (R band, FOCAS). The size of the images is approximately 8′ × 8′, and north is up and east is left.

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

\[ \theta = 1\farcs865 \pm 0\farcs004 \text{ and the source redshift is } z_s = 2.175 \pm 0.002. \]

This system is not included in the SQLS statistical sample because of the large flux ratio between the images.

**SDSS J1349+1227.** Although this system had been reported as a binary quasar in Hennawi et al. (2006), our new observations suggest that it is a gravitational lens rather than a binary quasar. We detected a lens galaxy very close to the fainter quasar component with a best-fit Sérsic index of 1.7. Because the galaxy is faint in the R and V bands, we fixed the galaxy parameters to the best-fit values from the I band. The image separation is \( \theta = 3\farcs002 \pm 0\farcs004 \) and the source redshift is \( z_s = 1.722 \pm 0.002 \). This system will be included in the SQLS DR7 statistical sample (N. Inada et al. 2010, in preparation).

**SDSS J1455+1447.** We fit the I-band image with two PSFs and a galaxy, and the best-fit Sérsic index was 3.5. As in the case of SDSS J1349+1227, we fixed the galaxy profile in R and V to the best-fit values from the I band. The image separation is \( \theta = 1\farcs727 \pm 0\farcs004 \) and the source redshift is \( z_s = 1.424 \pm 0.001 \). This system will be included in the SQLS DR7 statistical sample (N. Inada et al. 2010, in preparation).

**SDSS J1620+1203.** The lens galaxy is bright and close to the faint quasar, and the spectral features of the galaxy are seen in the spectrum of the faint quasar. In fact, the fainter quasar image was classified as a galaxy in the SDSS due to the bright lens galaxy. Ca H\&K, Mg, and Na galactic absorption lines are observed, giving a lens galaxy redshift of \( z_l = 0.398 \pm 0.001 \). The image separation is \( \theta = 2\farcs765 \pm 0\farcs011 \) and the source redshift is \( z_s = 1.158 \pm 0.002 \). The best-fit Sérsic index of 6.62 \( \pm 2.53 \) is larger than is expected (Blanton et al. 2005), but we do not take it seriously because of the large error. This system will be included in the SQLS DR7 statistical sample (N. Inada et al. 2010, in preparation).
in Table 6. As expected, the fitting was done with 

\[ \Delta X (\text{arcsec}) \quad \Delta Y (\text{arcsec}) \quad V \quad R \quad I \]

| Component | \( \Delta X (\text{arcsec}) \) | \( \Delta Y (\text{arcsec}) \) | \( V \) | \( R \) | \( I \) |
|-----------|----------------|----------------|---|---|---|
| SDSS J0904+1512 (\( \theta = 1\text{^h}28\text{^m}12\text{.0} \)) | 0.000 ± 0.003 | 0.000 ± 0.003 | 18.18 ± 0.01 | 17.88 ± 0.01 | 17.71 ± 0.04 |
| A | 0.000 ± 0.002 | 0.000 ± 0.002 | 17.21 ± 0.01 | 17.09 ± 0.01 | 16.94 ± 0.01 |
| B | 0.260 ± 0.004 | 0.149 ± 0.004 | 19.22 ± 0.01 | 18.98 ± 0.01 | 18.82 ± 0.02 |
| G1 | 0.000 ± 0.002 | 0.000 ± 0.002 | 20.02 ± 0.01 | 19.17 ± 0.01 | 18.98 ± 0.01 |
| G2 | 1.225 ± 0.015 | 20.68 ± 0.16 | 20.42 ± 0.14 | 19.58 ± 0.23 | 18.96 ± 0.17 |

**Notes.** Positions of each component were derived from the \( I \)-band images, except for the \( R \)-band image used for SDSS J1055+4628. The positive directions of \( X \) and \( Y \) are west and north, respectively. SDSS J1311+1915 was not observed in the \( R \) band. The \( V \)-band fluxes of the lens galaxies of SDSS J1054+2733, SDSS J1055+4628, and SDSS J1311+1915 are too faint to be measured. The errors on the positions and fluxes include only statistical errors reported by GALFIT. The errors on the image separation were calculated on the assumption that the position uncertainties are all uncorrelated.

### 4. MASS MODELING

We modeled all eight systems to see whether the lensing hypothesis is reasonable from the theoretical point of view. Because of the small number of observational constraints for two image lenses, we limited the model to a singular isothermal ellipsoid (SIE) without any external shear. This mass model has five parameters: the lens position, the Einstein radius \( R_E \), ellipticity \( e \), and position angle \( \theta_e \) (measured east of north). If we fit the relative positions and the image flux ratio, these two image lenses provide only five constraints, so our model has no degrees of freedom and we can find a perfectly fitting model with \( \chi^2 \sim 0 \) as long as the model is reasonable. To find the best-fit mass models, we used the *glafic* software (M. Oguri 2010, in preparation; version 1.0). We used the positions and \( I \)-band fluxes in Table 4. Only one lens galaxy was considered even if there are nearby galaxies that could appreciably affect the lens potentials, as in the case of SDSS J1055+4628 and SDSS J1304+2001. The resulting parameters are summarized in Table 6. As expected, the fitting was done with \( \chi^2 \sim 0 \) for all lens systems.

### Table 4

| Object | \( r_{e}^{2}(c) \) | \( n^b \) | \( e^s \) | \( \theta_{e}^d(\text{deg}) \) |
|--------|----------------|---|---|---|
| SDSS J0904+1512 | 0.26 ± 0.03 | 4.11 ± 1.04 | 0.49 ± 0.04 | −20 ± 5 |
| SDSS J1054+2733 | 0.42 ± 0.04 | 3.67 ± 0.75 | 0.42 ± 0.04 | −88 ± 5 |
| SDSS J1055+4628 | 0.53 ± 0.05 | 5.42 ± 1.53 | 0.07 ± 0.04 | +28 ± 22 |
| SDSS J1131+1915 | 0.14 ± 0.04 | 2.38 ± 1.22 | 0.82 ± 0.82 | −15 ± 11 |
| SDSS J1304+2001 | 0.54 ± 0.02 | 2.90 ± 0.45 | 0.42 ± 0.03 | +58 ± 4 |
| SDSS J1349+1227 | 1.06 ± 0.13 | 1.69 ± 0.52 | 0.24 ± 0.06 | +71 ± 11 |
| SDSS J1455+1447 | 1.49 ± 0.20 | 3.50 ± 0.54 | 0.28 ± 0.04 | −76 ± 5 |
| SDSS J1620+1203 | 3.70 ± 3.20 | 6.62 ± 2.53 | 0.25 ± 0.03 | −21 ± 4 |

**Notes.** Sérsic parameters measured in the \( I \)-band images (\( R \) band for SDSS J1055+4628) using GALFIT.

| \( r_{e}^{2}(c) \) | \( n^b \) | \( e^s \) | \( \theta_{e}^d(\text{deg}) \) |
|----------------|---|---|---|
| \( r_{e}^{2}(c) \) | \( n^b \) | \( e^s \) | \( \theta_{e}^d(\text{deg}) \) |
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| SDSS J1131+1915 | 0.14 ± 0.04 | 2.38 ± 1.22 | 0.82 ± 0.82 | −15 ± 11 |
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**Notes.** Sérsic parameters measured in the \( I \)-band images (\( R \) band for SDSS J1055+4628) using GALFIT.

* Effective radius of the Sérsic profile.
* Sérsic index.
* Ellipticity.
* Major axis position angle measured east of north.

We estimated likely redshifts of the lens galaxies from the observed \( I \)-band magnitudes using the modified Faber–Jackson
Figure 3. FOCAS spectra of the eight lens systems. The flux density units are \(10^{-17}\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\). For SDSS J1055+4628, two exposures were merged at \(\sim 5850\) Å. Absorption lines from the lens galaxy are observed in the spectrum of the fainter image of SDSS J1620+1203. Absorption lines by some intervening systems are also observed in SDSS J0904+1512 (Mg\(\text{II}\) and Fe\(\text{II}\) at \(z = 1.2168 \pm 0.0002\)), SDSS J1054+2733 (Mg\(\text{II}\) and Fe\(\text{II}\) at \(z = 0.6794 \pm 0.0002\)), SDSS J1131+1915 (Fe\(\text{II}\) at \(z = 1.1890 \pm 0.0005\) and a DLA at \(z = 2.6025 \pm 0.0002\) with Si\(\text{II}\), O\(\text{I}\), and C\(\text{II}\)), and SDSS J1349+1227 (Fe\(\text{II}\) at \(z = 1.2347 \pm 0.0002\) and \(z = 1.2385 \pm 0.0002\)). The features at \(\sim 6900\) Å and \(\sim 7600\) Å are telluric.

Table 6

| Object                  | \(R_{\text{lim}}(\prime)\) | \(\theta_\epsilon(\deg)\) | \(\mu_{\text{tot}}\) | \(\Delta t\) \(\text{(b)}\) |
|-------------------------|----------------------------|-----------------------------|----------------------|--------------------------|
| SDSS J0904+1512         | 0.529 \(\pm 0.007\)       | 0.72 \(\pm 0.05\)          | +31 \(\pm 2\)       | 6.9 \(\pm 1.0\)          |
| SDSS J1054+2733         | 0.598 \(\pm 0.004\)       | 0.52 \(\pm 0.06\)          | -14 \(\pm 1\)       | 12.7 \(\pm 2.2\)         |
| SDSS J1055+4628         | 0.600 \(\pm 0.016\)       | 0.37 \(\pm 0.08\)          | -49 \(\pm 7\)       | 3.4 \(\pm 0.5\)          |
| SDSS J1131+1915         | 0.680 \(\pm 0.006\)       | 0.58 \(\pm 0.09\)          | +5 \(\pm 1\)        | 10.2 \(\pm 1.9\)         |
| SDSS J1304+2001         | 0.987 \(\pm 0.008\)       | 0.23 \(\pm 0.02\)          | +27 \(\pm 3\)       | 7.9 \(\pm 0.8\)          |
| SDSS J1349+1227         | 1.399 \(\pm 0.010\)       | 0.57 \(\pm 0.09\)          | -42 \(\pm 4\)       | 2.0 \(\pm 0.1\)          |
| SDSS J1455+1447         | 0.853 \(\pm 0.004\)       | 0.16 \(\pm 0.03\)          | +10 \(\pm 2\)       | 12.7 \(\pm 2.0\)         |
| SDSS J1620+1203         | 1.353 \(\pm 0.021\)       | 0.23 \(\pm 0.06\)          | +21 \(\pm 10\)      | 2.8 \(\pm 0.1\)          |

Notes. Errors are estimated from 1000 random data for each system with scatter in Table 4 for positions and 0.2 mag for image magnitudes. We used the redshifts estimated by the Faber–Jackson relation in Table 7 to compute the predicted time delays, or the measured redshift for SDSS J1620+1203. We do not include the uncertainty of the redshift for the error estimate.

\(a\) Total magnification.

\(b\) Time delay.

The lens galaxy of SDSS J0904+1512 is bright in the \(I\) band, which makes the expected redshift lower than suggested by the colors. The red colors of the lens galaxy, \(R – I = 1.13\) and \(V – R = 1.46\), suggest that it is an early-type galaxy at \(z \sim 0.5\) (Fukugita et al. 1995). For SDSS J1349+1227, luminosity profile indicates that it might...
Table 7
Predicted Redshifts and Apparent V and R Magnitudes of Lens Galaxies

| Object               | V       | R       | Redshift (FJ) | Redshift (R - I) |
|----------------------|---------|---------|---------------|-----------------|
| SDSS J0904+1512      | 20.1    | 19.1    | 0.19          | 0.54            |
| SDSS J1054+2733      | 20.3    | 19.3    | 0.23          | 0.43            |
| SDSS J1055+4628      | 21.6    | 20.5    | 0.39          | 0.38            |
| SDSS J1131+1915      | 21.2    | 20.1    | 0.32          | 0.32            |
| SDSS J1304+2001      | 20.5    | 19.3    | 0.32          | 0.46            |
| SDSS J1349+1227      | 21.7    | 20.3    | 0.63          | 0.66            |
| SDSS J1455+1447      | 20.2    | 19.0    | 0.27          | 0.53            |
| SDSS J1620+1203      | 20.2    | 18.9    | 0.39          | 0.41            |

Notes. Values in parenthesis are the observed magnitude in Table 4. The typical uncertainties of redshift (FJ) and redshift (R - I) are ~0.1, considering 0.5 mag and 0.1 mag scatter for luminosity and color of galaxies, respectively.

a R - I color is too blue to match the template.

b Redshift of SDSS J1620+1203 is measured spectroscopically and I-band magnitude is estimated to be 18.3 at this redshift. FJ estimate will be 0.27 to recover the observed I-band magnitude of 17.59.

be a late-type galaxy, which may cause the discrepancy. For comparison, we also list redshifts estimated by matching R - I color of the lens galaxies to the Coleman et al. (1980) early-type galaxy template. The results are fairly consistent with the estimates from the Faber–Jackson relation except for SDSS J1455+1447, where the disagreement would be solved if the observed R-band magnitude were ~0.5 brighter. We did not pursue these discrepancies further because the image quality is not adequate for a detailed investigation. In Table 6, we list the predicted time delays using the Faber–Jackson redshift estimates from Table 7 and the measured redshift for SDSS J1620+1203.

5. SUMMARY

As part of the SQLS project we discovered eight new gravitationally lensed quasars: SDSS J0904+1512, SDSS J1054+2733, SDSS J1055+4628, SDSS J1131+1915, SDSS J1304+2001, SDSS J1349+1227, SDSS J1455+1447, and SDSS J1620+1203. All eight lenses are two-image quasar lenses produced by galaxy-scale lens potentials. They were confirmed to be lenses by imaging and spectroscopic observations using the UH88 and Subaru telescopes. Simple mass models also suggest that the observed image configurations and fluxes are reasonable for lens systems. For SDSS J1620+1203, the redshift of the lens galaxy was determined from the absorption lines in the spectrum of the fainter quasar. The system configuration is summarized in Table 4.

Adding the eight systems reported in this paper, the SQLS has discovered 36 quasar lenses and rediscovered 11 known lenses. Among the eight new lenses, SDSS J1055+4628 will be included in the DR5 statistical lens catalog (N. Inada et al. 2010, in preparation), and SDSS J1455+1447 and SDSS J1620+1203 will be in the final DR7 statistical lens catalog of the SQLS (N. Inada et al. 2010, in preparation).

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Figure 4. Section of the two-dimensional FOCAS spectrum (left) of SDSS J0746+4403 (Inada et al. 2007) and the one-dimensional spectrum (right) extracted from the central region shown in the left panel, denoted by the two dashed lines. We can clearly see the CaII H&K and G-band absorption lines from the lens galaxy at z_l = 0.513, in the right panel.
APPENDIX
LENS REDSHIFT OF SDSS J0746+4403

We also measured the lens redshift of SDSS J0746+4403 (Inada et al. 2007), one of the lensed quasars included in our statistical lens sample, using the Subaru telescope. We obtained a deep (total 2700 s exposure) spectrum of this lens with FOCAS on 2007 January 21. We used the 300B grism, the SY47 filter, and a 1.0′′ width slit aligned along the A and B lensed images. The data were binned 2×2 on-chip. The seeing was less than 1.0″ during the exposure. The two-dimensional spectrum of the system is shown in the left panel of Figure 4. In order to minimize the influence of the lensed images, we extracted a one-dimensional spectrum between the peaks of lensed images A and B (see Figure 4), using standard IRAF tasks. Although there remains some contamination from the lensed quasar images, we can clearly see galactic absorption lines of the lensing galaxy. The lens redshift is measured to be $z_L = 0.513$ from the redshifted Ca II H&K and G-band absorption lines at about 5950 Å, 6000 Å, and 6500 Å, respectively.

REFERENCES
Abazajian, K. N., et al. 2009, ApJS, 182, 543
Blanton, M. R., Eisenstein, D., Hogg, D. W., Schlegel, D. J., & Brinkmann, J. 2005, ApJ, 629, 143
Blanton, M. R., Lin, H., Lupton, R. H., Maley, F. M., Young, N., Zehavi, I., & Loveday, J. 2003, AJ, 125, 2276
Browne, I. W. A., et al. 2003, MNRAS, 341, 13
Chae, K.-H. 2008, MNRAS, 402, 2031
Choi, Y.-Y., Park, C., & Vogeley, M. S. 2007, ApJ, 658, 884
Coleman, G. D., Wu, C.-C., & Weedman, D. W. 1980, ApJS, 43, 393
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Gunn, J. E., et al. 1998, AJ, 116, 3040
Gunn, J. E., et al. 2006, AJ, 131, 2332
Hennawi, J. F., et al. 2006, AJ, 131, 1
Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, AJ, 122, 2129
Inada, N., et al. 2007, AJ, 133, 206
Inada, N., et al. 2008, AJ, 135, 496
Inada, N., et al. 2009, AJ, 137, 4118
Ivezić, Ž, et al. 2004, Astron. Nachr., 325, 583
Kashikawa, N., et al. 2002, PASJ, 54, 819
Kochanek, C. S. 2006, in Gravitational Lensing: Strong, Weak and Micro, Saas-Fee Advanced Course 33, ed. G. Meylan, P. North, & P. Jetzer (Berlin: Springer), 91
Lupton, R., Gunn, J. E., Ivezić, Z., Knapp, G. R., Kent, S., & Yasuda, N. 2001, in ASP Conf. Ser. 238, Astronomical Data Analysis Software and Systems X, ed. F. R. Hamden, Jr., F. A. Primini, & H. E. Payne (San Francisco, CA: ASP), 269
Lupton, R. H., Gunn, J. E., & Szalay, A. S. 1999, AJ, 118, 1406
Matsumoto, A., & Futamase, T. 2008, MNRAS, 384, 843
Myers, S. T., et al. 2003, MNRAS, 341, I
Oguri, M., et al. 2006, AJ, 132, 999
Oguri, M., et al. 2008a, AJ, 135, 512
Oguri, M., et al. 2008b, MNRAS, 391, 1973
Peng, C. Y., Ho, L. C., Impey, C. D., & Riis, H.-W. 2002, AJ, 124, 266
Pier, J. R., Munn, J. A., Hindsley, R. B., Hennessy, G. S., Kent, S. M., Lupton, R. H., & Ivezić, Z. 2003, AJ, 125, 1559
Richards, G. T., et al. 2002, AJ, 123, 2945
Rusin, D., et al. 2003, ApJ, 587, 143
Schneider, P., Kochanek, C. S., & Wambsganss, J. 2006, in Gravitational Lensing: Strong, Weak and Micro, Saas-Fee Advanced Courses 33, ed. G. Meylan, P. North, & P. Jetzer (Berlin: Springer)
Schneider, D. P., et al. 2007, AJ, 134, 102
Smith, A., et al. 2002, AJ, 123, 2121
Stoughton, C., et al. 2002, AJ, 123, 485
Tucker, D. L., et al. 2006, Astron. Nachr., 327, 821
Wisotzki, L., Koehler, T., Kayser, R., & Reimers, D. 1993, A&A, 278, L15
York, D. G., et al. 2000, AJ, 120, 1579