

Five New High-Redshift Quasar Lenses from the Sloan Digital Sky Survey

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ABSTRACT

We report the discovery of five gravitationally lensed quasars from the Sloan Digital Sky Survey (SDSS). All five systems are selected 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 (source redshift $z_s = 2.237$, 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 $z_l = 0.4 - 0.6$ 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

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these lenses will not be included 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.

Subject headings: gravitational lensing — quasars: individual (SDSS J081959.79+535624.3, SDSS J125418.95+223536.5, SDSS J125819.24+165717.6, SDSS J133907.13+131039.6, SDSS J140012.77+313454.1)

1. Introduction

Gravitationally lensed quasars are unique astronomical and cosmological tools, as described in the review of Kochanek (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 extinctions (e.g., Falco et al. 1999; Muñoz et al. 2004) or absorption lines appeared 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 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 $\sim 16,000$ 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 over $\sim 100,000$ spectroscopically identified quasars (Schneider et al. 2007). We are conducting a survey of lensed quasars selected from the large dataset 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 deg²; 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 are useful for detailed studies of lensing galaxies and lensed high-redshift quasars. They can also be used as astronomical and cosmological tools to study lensing galaxies (e.g., Kochanek et al. 2000) and constrain the Hubble constant (e.g., Oguri 2007). In this paper, we report the discoveries of five lensed quasars with high source redshifts ($z_s = 2.237\text{--}3.626$). 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-meter telescope (UH88), the Astrophysical Research Consortium 3.5-meter telescope (ARC 3.5m), and the 3.58-meter Telescopio Nazionale Galileo (TNG 3.6m). All five candidates are confirmed to be double-image lensed quasars, with image separations of $1''.28\text{--}4''.04$.

The structure of this paper is as follows. Brief descriptions of the SDSS data and our lens candidate selection algorithm are presented in § 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 § 3. We model the five lensed quasars in § 4 and summarize our results in § 5. We use a standard cosmological model with matter density $\Omega_M = 0.27$, cosmological constant $\Omega_\Lambda = 0.73$, and Hubble constant $h = H_0/100\text{km sec}^{-1}\text{Mpc}^{-1} = 0.71$ (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 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 square degrees primarily in a region centered on the North Galactic Cap, through SDSS-I and the subsequent SDSS-II Legacy Survey. 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 broad-band optical filters (*ugriz*, Fukugita

et al. 1996). The spectroscopic survey is carried out with a multi-fiber spectrograph covering 3800 Å to 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 zeropoint accuracy better than about 0.02 magnitude 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 2006, 2007, 2008). The final release (Data Release Seven) is now being prepared.

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 $\lesssim 20''$, 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 α 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 *ugri* bands used at lower redshifts (Inada et al. 2008), and $z_s \lesssim 4.8$ 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 α 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 luminosities (Lupton et al. 1999) without Galactic extinction corrections and redshifts of the five objects are summarized in Table 1. The *u*-band luminosity 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 ($3''$ fiber diameter), and therefore we conducted optical/near-infrared imaging and spectroscopic follow-up observations to confirm their lensing natures, using the UH88, ARC 3.5m, and TNG 3.6m telescopes.

3.1. Imaging Observations

We obtained *VRI* images for all five candidates and *B* images for SDSS J0819+5356 with the Tektronix 2048×2048 CCD camera (Tek2k, $0''.22 \text{ pixel}^{-1}$) at the UH88 telescope. The observations were conducted on 2007 April 11, 2007 November 13, and 2008 March 6, with typical seeing of $\text{FWHM} \sim 0''.8$. The exposures were between 300 and 480 sec depending on the magnitudes of the objects and the observing conditions in each night, and 800 sec 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 $\sim 1.5''$, except for SDSS J0819+5356, which has a larger image separation of $4''.04$. 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 to be unusual due to its low signal-to-noise ratio. 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 *I*-band images) of each lensing galaxy in Table 4. The very large n parameter for SDSS J0819+5356 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 (NICFPS, $0''.273$ pixel $^{-1}$) at the ARC 3.5m telescope, on 2007 March 8 and 2007 April 5. The exposures were 900 sec 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 for the *BVRIH*-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 $\sim 0''.05$ (for the stellar components) and $\sim 0''.15$ (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 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 3.5m telescope, and the Device Optimized for the LOw RESolution (DOLORES) at the TNG 3.6m telescope. We used a $0''.9$ long slit and the 300 gr/mm grism (spectral resolution of $R \sim 600$ and spatial scale of the CCD detector of $0''.34$ pixel $^{-1}$) for WFGS2, a $1''.5$ long slit and the B400 grism ($R \sim 500$ and $0''.40$ pixel $^{-1}$) for DIS, and, a $1''.0$ long slit and the LR-B grism ($R \sim 600$ and $0''.252$ pixel $^{-1}$) for DOLORES. We aligned each slit direction to observe

components A and B simultaneously. The exposures were typically ~ 2000 sec for the ARC 3.5m and TNG 3.6m telescopes and ~ 5000 sec 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 ($\text{FWHM} \lesssim 1''.0$). The spectra of each component were extracted by the standard IRAF¹ 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 lines at $\sim 5300\text{\AA}$ in the spectrum of component B. The lens redshift of SDSS J0819+5356 is also confirmed in its SDSS spectrum (see Figure 5), which shows G-band, Mg, and Na absorption lines as well as the Ca II H&K lines.

For the remaining objects, we estimated redshifts for the lensing galaxies using the observed magnitudes and colors. For SDSS J1400+3134, the $V-R$ and $R-I$ colors (Table 5) are roughly consistent with a $z \sim 0.6$ elliptical galaxy (Fukugita et al. 1995), and the predicted magnitude of $R \sim 21.4$ (assuming this redshift) from the Faber-Jackson relation (Faber & Jackson 1976) adopted by Rusin et al. (2003) is also consistent with the observed magnitude ($R \sim 21.5$). For the lensing galaxies of the other three lensed quasars, it is difficult to estimate the redshifts from their colors alone. However, comparing the predicted magnitudes ($R \sim 20.5$,

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$R \sim 20.8$, and $R \sim 20.2$ for SDSS J1254+2235, SDSS J1258+1657, and SDSS J1339+1310, respectively) with the observed R magnitudes (Table 5) implies that the redshifts of all three lensing galaxies are $z_l \sim 0.4$. For SDSS J1254+2235, although the Sérsic concentration index (Table 4) indicates the lensing galaxy might be a late-type galaxy, we used the Faber-Jackson relation as well since the residual flux after subtracting two PSFs is also well fitted by a de Vaucouleurs profile (Sérsic profile with a fixed index of $n = 4$).

In this paper, we use these results to derive the predicted time delays of each system (see § 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 ($\theta = 1''.7$) 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). Since all five objects are doubly-imaged lenses, the number of the model parameters (8 parameters; the Einstein radius R_E , the ellipticity e and its position angle θ_e , the position of the lens galaxy, and the position and flux of the source quasar) is the same as the number of the constraints from the observations (8 constraints; the positions and fluxes of the two quasar components, and the position of the lensing galaxy). We adopt the observables from the I -band images as the constraints, and used *lensmodel* (Keeton 2001) for modeling. The parameters of the best-fitting models are summarized in Table 6. As expected from the zero degree of freedom for these models, we obtained models that fit the data perfectly ($\chi^2 \sim 0$).

For SDSS J0819+5356, the model ellipticity e and its position angle θ_e (Table 6) agree with those observed for the lensing galaxy (Table 4). Except for SDSS J0819+5356, however, the predicted values of e and θ_e are in poor agreement with the observed values. Such differences are common in lensed quasar systems when there are other nearby potentials producing a strong tidal shear (Keeton et al. 1998). Indeed, the predicted θ_e of SDSS J1258+1657 is aligned well with directions to the nearby two galaxies ($5''.0$ north and $7''.0$ south from the object), whose photometric redshifts (Csabai et al. 2003) of $z \sim 0.48$ are similar to the estimated lens redshift. A large misalignment is also seen in SDSS J1339+1310, which have some nearby galaxies with the photometric redshifts of $z \sim 0.4$. We could not test the alignment for SDSS J1400+3134, because we could not measure the shape of its lens galaxy in our images.

In addition to the parameters of the best-fitting models, we summarize the predicted

time delays and total magnifications 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 ($z_s > 2.2$) lensed quasars, SDSS J0819+5356, SDSS J1254+2235, 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 3.5m, and TNG 3.6m telescopes. All five objects are two-image lensed quasars, with image separations of $1''.28$ – $4''.04$. The source redshifts range from 2.24 to 3.63. The lens redshift of SDSS J0819+5356 is measured to be $z_l = 0.294$ from the Ca II H&K absorption lines, whereas the lens redshifts of the other four objects are estimated to be 0.4–0.6 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 $z_s < 2.2$, 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 $z_s > 2.2$ 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 $z_s > 2.2$ 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, spectroscopy for the quasar images to study the transverse structure in the Ly α forest, and 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 quasar lenses will also be important to extend the redshift range of the lens applications; only about 30 objects out of the ~ 100 lensed quasars² are identified to be lenses at $z_s > 2.2$.

Use of the UH 2.2-m telescope for the observations is supported by NAOJ. Based in part on observations obtained with the Apache Point Observatory 3.5-meter telescope, which is owned and operated by the Astrophysical Research Consortium, and on observations made

²CASTLES webpage (C. S. Kochanek et al., <http://cfa-www.harvard.edu/castles/>.)

with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundacion Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. N. I. acknowledges support from the Special Postdoctoral Researcher Program of RIKEN and RIKEN DRI research Grant. This work was supported in part by Department of Energy contract DE-AC02-76SF00515 and NSF grant AST-0707266. I. K. acknowledges support from the JSPS Research Fellowships for Young Scientists and Grant-in-Aid for Scientific Research on Priority Areas No. 467.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, Cambridge University, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

Facilities: UH88 Tek2k, UH88 WFGS2, ARC 3.5m NICFPS, ARC 3.5m DIS, TNG 3.6m DOLORES.

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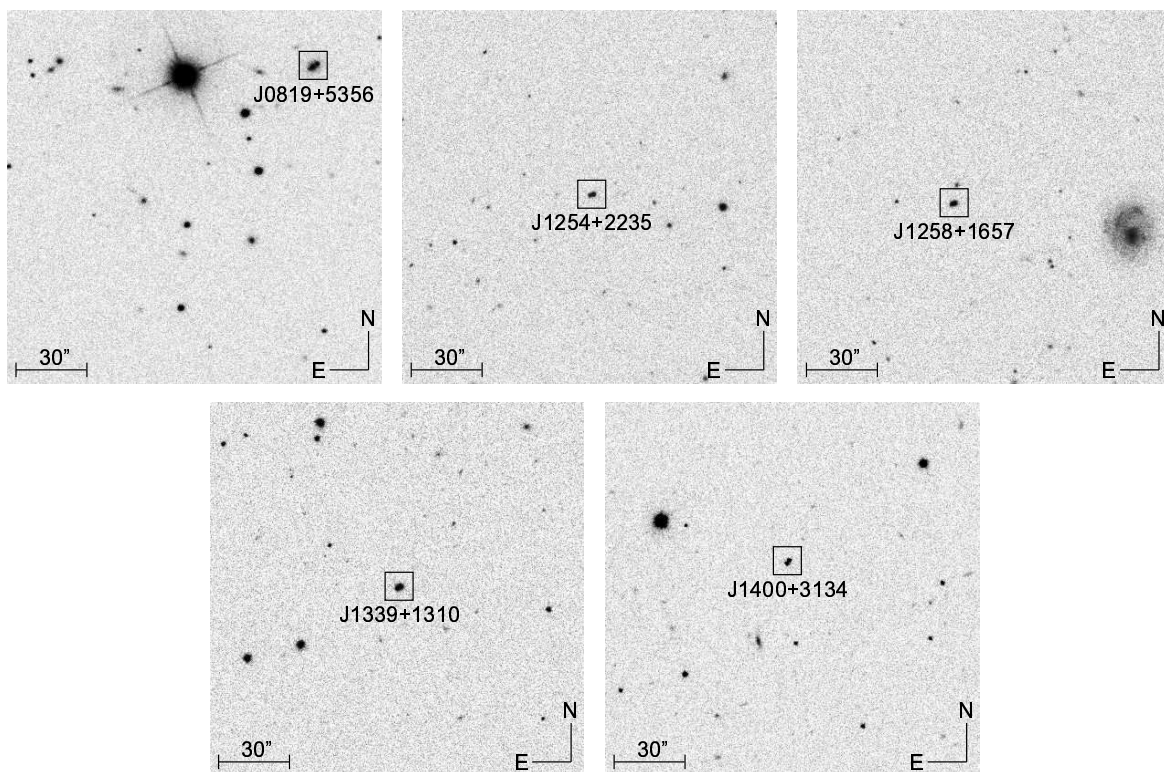


Fig. 1.— Finding charts (SDSS r -band images) for the five lensed quasars. See Table 1 for the celestial coordinates of each object. Note that SDSS J0819+5356 is located at the edge of the field. The pixel scale is $0''.396$. North is up and East is to the left.

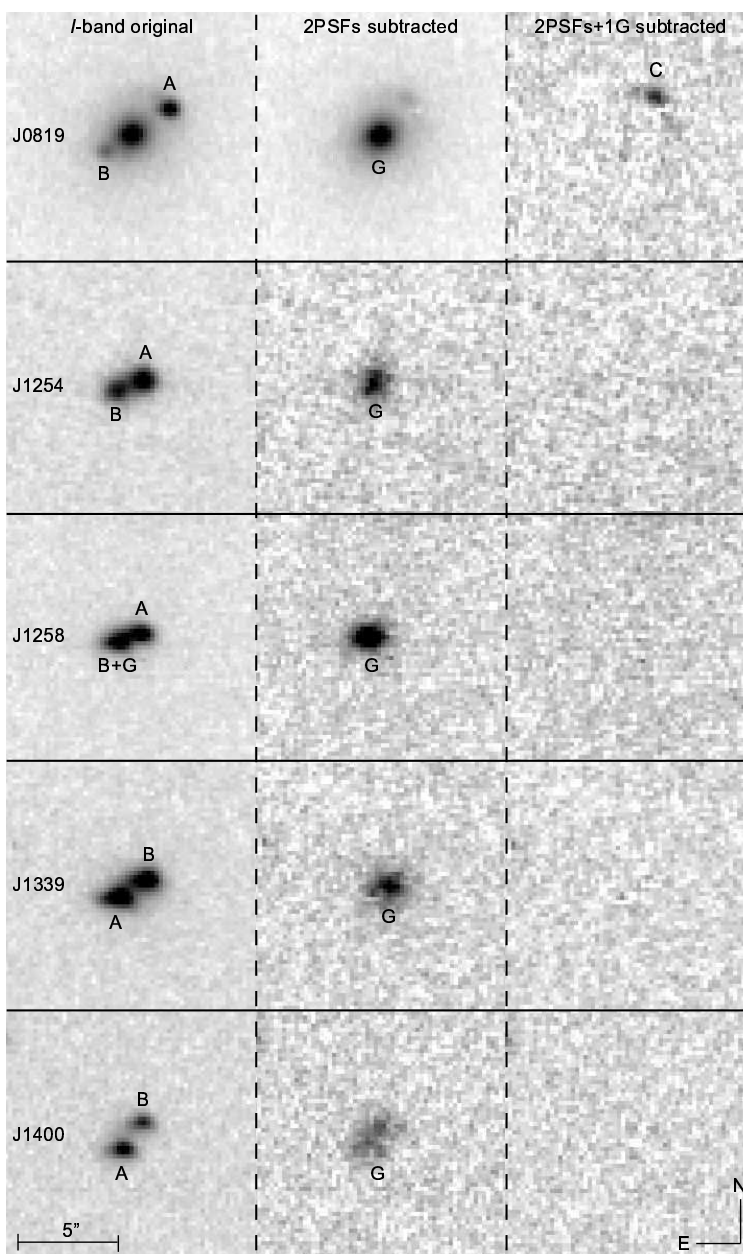


Fig. 2.— The UH88 Tek2k *I*-band images of the five lensed quasars. The left panels show the original image of each object. The middle panels and the right panels show the residual fluxes after subtracting two PSFs, and two PSFs plus one galaxy component, respectively, from each original image. All fits were carried out using GALFIT (Peng et al. 2002). For SDSS J0819+5356, the residual (component C) after subtracting two PSFs plus one galaxy component may be the lensed host galaxy of the source quasar. The image separations are corresponding to the physical scales (at the lens redshift) of about 18 kpc, 9 kpc, 7 kpc, 9 kpc, and 12 kpc for SDSS J0819+5356, SDSS J1254+2235, SDSS J1258+1657, SDSS J1339+1310, and SDSS J1400+3134, respectively. The image scale is $0''.22 \text{ pixel}^{-1}$. North is up and East is to the left. See Tables 2 and 3 for observation information.

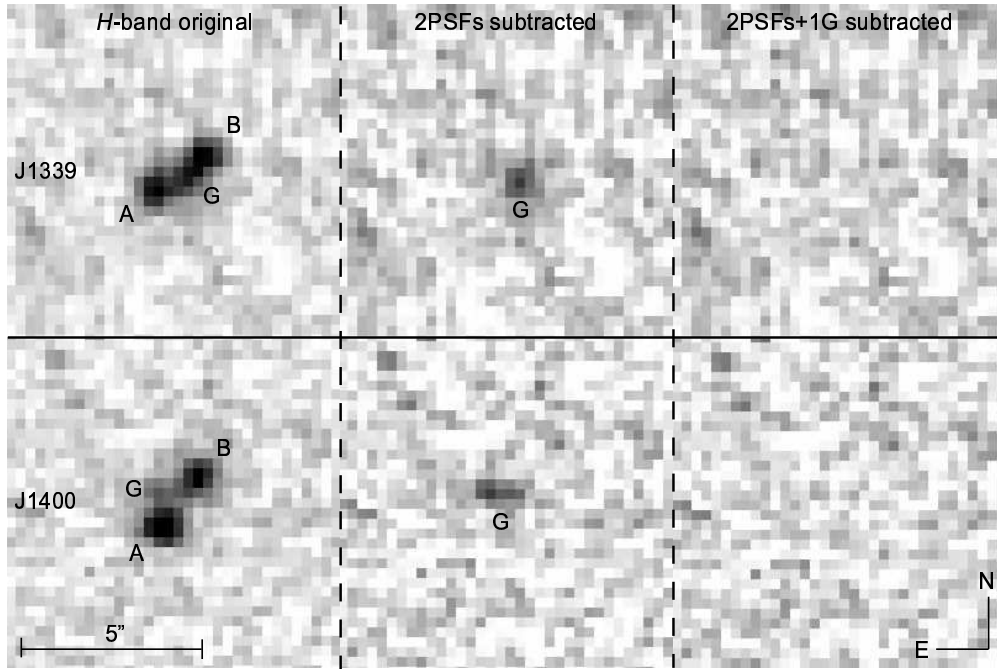


Fig. 3.— The ARC 3.5m NICFPS H -band images of SDSS J1339+1310 and SDSS J1400+3134. The lensing galaxies are bright in H -band images, and therefore we can see them even in the original images. The left, middle, and right panels show the original images, residuals after subtracting two PSFs, and images after subtracting two PSFs plus one galaxy component, respectively. The image scale is $0''.273 \text{ pixel}^{-1}$. North is up and East is to the left. See Tables 2 and 3 for observation information.

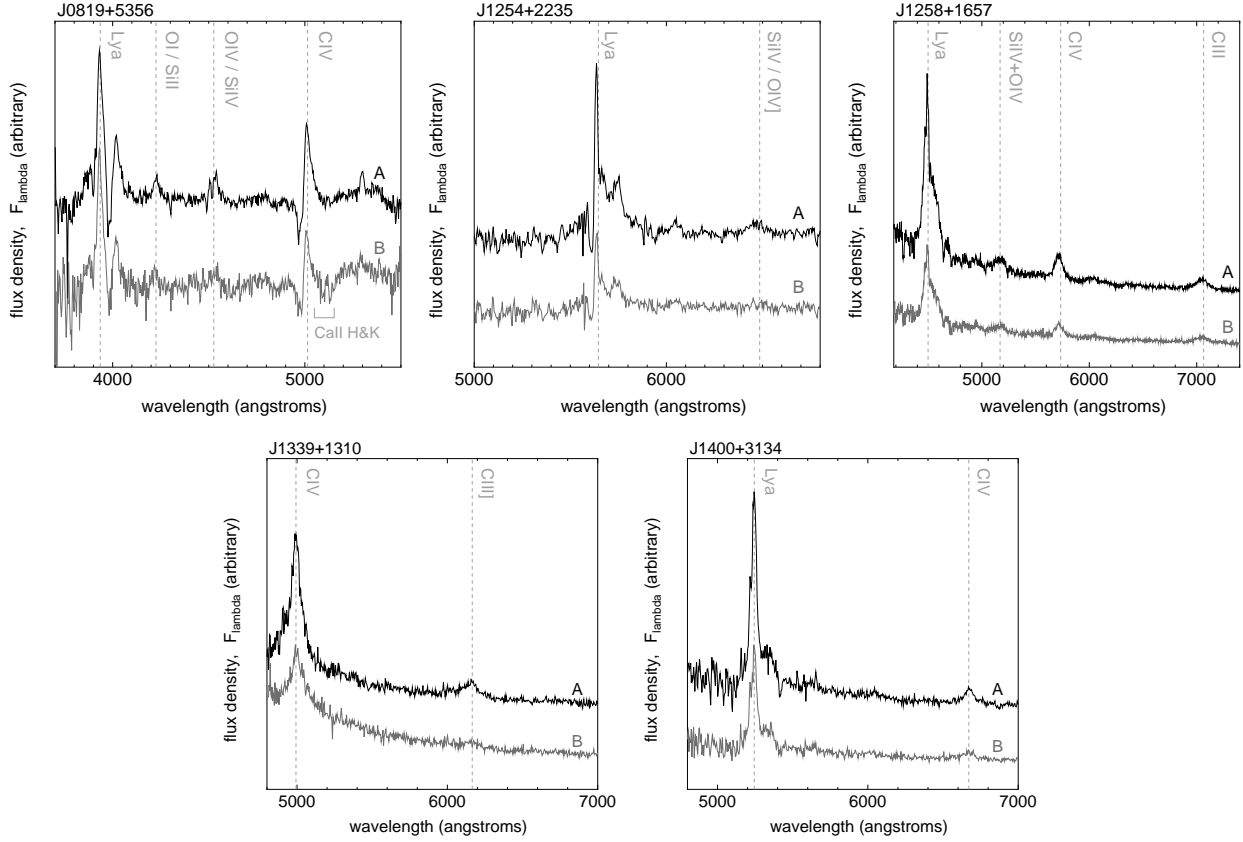


Fig. 4.— Spectra of the stellar components of the five lensed quasars. We used the DIS at the ARC 3.5m telescope for SDSS J0819+5356, the WFGS2 at the UH88 telescope for SDSS J1254+2235, SDSS J1339+1310, and SDSS J1400+3134, and the DOLORES at the TNG 3.6m telescope for SDSS J1258+1657. In each panel, 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 line features and the Ca II H&K absorption lines from the lensing galaxy (marked by the gray solid symbol at $\sim 5100\text{\AA}$). The two quasar components of SDSS J1254+2235 also has broad absorption line features. For SDSS J1400+3134, the absorption features around 5400\AA are real but their origin is unknown. The SEDs of each pair are very similar, supporting the lensing hypotheses for all objects.

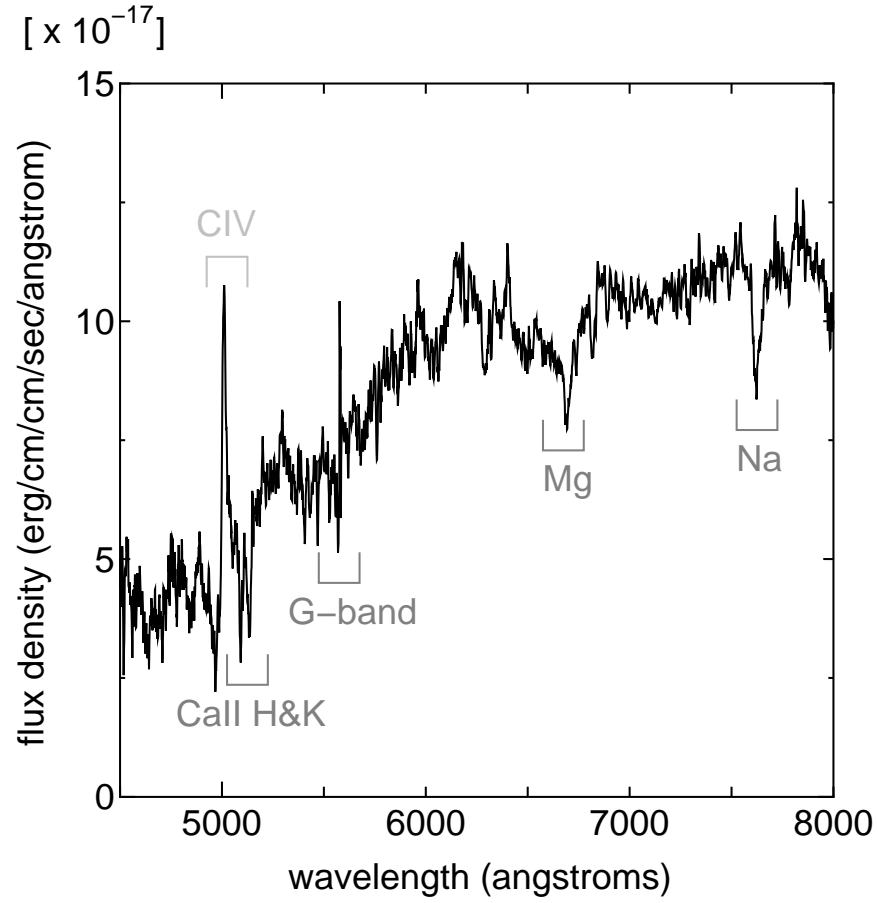


Fig. 5.— The SDSS spectrum of SDSS J0819+5356. The absorption lines from the lensing galaxy at $z = 0.294$ are marked by the dark gray symbols. The C IV emission line from the source quasar at $z = 2.237$ is marked by the light gray symbol.

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	17.25±0.02	16.87±0.06	2.2371±0.0016
SDSS J1254+2235	193°57896	+22°59350	...	20.30±0.04	18.95±0.02	18.68±0.02	18.32±0.09	3.6256±0.0019
SDSS J1258+1657	194°58019	+16°95491	19.25±0.05	18.55±0.01	18.40±0.01	18.26±0.02	18.15±0.06	2.7015±0.0015
SDSS J1339+1310	204°77974	+13°17768	18.51±0.03	18.05±0.01	18.06±0.01	17.98±0.02	17.69±0.05	2.2429±0.0028
SDSS J1400+3134	210°05322	+31°58170	21.28±0.45	19.26±0.02	18.96±0.03	18.82±0.04	18.99±0.19	3.3166±0.0007

Note. — Celestial coordinates (J2000), total luminosities (Lupton et al. 1999) without Galactic extinction correction inside aperture radii (5''4, 2''1, 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 FOLLOWUP OBSERVATIONS 1

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

Table 3. SUMMARY OF FOLLOWUP OBSERVATIONS 2

Object	Exposure (B)	Exposure (V)	Exposure (R)	Exposure (I)	Exposure (H)	Exposure (spec)
SDSS J0819+5356	800s	300s	300s	300s	...	1800s
SDSS J1254+2235	...	400s	400s	400s	...	4800s
SDSS J1258+1657	...	300s	400s	480s	...	1200s
SDSS J1339+1310	...	300s	300s	480s	900s	3600s
SDSS J1400+3134	...	300s	300s	400s	900s	4500s

Table 4. PARAMETERS OF THE BEST-FITTING SÉRSIC PROFILES

Object	n^a	e^b	$\theta_e(^{\circ})^b$
SDSS J0819+5356	7.37 ± 0.22	0.22 ± 0.01	-40.33 ± 0.97
SDSS J1254+2235	1.49 ± 0.45	0.55 ± 0.07	-18.81 ± 6.55
SDSS J1258+1657	2.43 ± 0.80	0.23 ± 0.08	-54.42 ± 17.12
SDSS J1339+1310	3.21 ± 0.59	0.17 ± 0.06	-18.90 ± 14.41
SDSS J1400+3134	0.21 ± 0.07	0.43 ± 0.03	-38.57 ± 3.58

Note. — 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 signal-to-noise ratio.

^aSérsic concentration index.

^bEllipticity and its position angle. Each position angle is measured East of North.

Table 5. RELATIVE ASTROMETRY AND PHOTOMETRY OF THE FIVE LENSES

Component	ΔX (arcsec)	ΔY (arcsec)	B	V	R	I	H
SDSS J0819+5356 ($\theta = 4''04$)							
A	$\equiv 0$	$\equiv 0$	20.64 ± 0.01	20.24 ± 0.01	19.92 ± 0.01	19.39 ± 0.01	...
B	-3.367 ± 0.006	-2.226 ± 0.006	22.16 ± 0.02	21.84 ± 0.01	21.50 ± 0.02	20.97 ± 0.02	...
C	-0.598 ± 0.020	0.656 ± 0.020	22.76 ± 0.04	22.77 ± 0.03	22.30 ± 0.02	21.84 ± 0.04	...
G	-1.980 ± 0.002	-1.348 ± 0.002	19.44 ± 0.27	18.41 ± 0.13	17.61 ± 0.03	16.54 ± 0.04	...
SDSS J1254+2235 ($\theta = 1''56$)							
A	$\equiv 0$	$\equiv 0$	...	20.07 ± 0.01	19.91 ± 0.01	19.33 ± 0.01	...
B	-1.460 ± 0.006	-0.553 ± 0.006	...	20.71 ± 0.04	20.38 ± 0.01	19.94 ± 0.04	...
G	-0.931 ± 0.036	-0.259 ± 0.036	...	21.69 ± 0.04	20.50 ± 0.03	20.18 ± 0.04	...
SDSS J1258+1657 ($\theta = 1''28$)							
A	$\equiv 0$	$\equiv 0$	...	19.34 ± 0.01	18.99 ± 0.01	18.58 ± 0.01	...
B	-1.183 ± 0.006	-0.481 ± 0.006	...	19.78 ± 0.03	19.29 ± 0.04	19.02 ± 0.04	...
G	-0.970 ± 0.035	-0.274 ± 0.035	...	20.67 ± 0.07	20.38 ± 0.09	19.23 ± 0.05	...
SDSS J1339+1310 ($\theta = 1''69$)							
A	$\equiv 0$	$\equiv 0$	...	19.25 ± 0.01	19.12 ± 0.01	18.28 ± 0.01	17.3 ± 0.1
B	1.400 ± 0.002	0.942 ± 0.002	...	19.13 ± 0.01	19.07 ± 0.01	18.46 ± 0.01	17.3 ± 0.1
G	1.058 ± 0.018	0.384 ± 0.018	...	20.79 ± 0.06	20.16 ± 0.02	19.25 ± 0.05	17.2 ± 0.4
SDSS J1400+3134 ($\theta = 1''74$)							
A	$\equiv 0$	$\equiv 0$	...	19.84 ± 0.01	19.74 ± 0.01	19.37 ± 0.01	17.9 ± 0.1
B	1.021 ± 0.004	1.414 ± 0.004	...	20.47 ± 0.01	20.32 ± 0.01	19.87 ± 0.02	18.3 ± 0.1
G	0.125 ± 0.033	0.566 ± 0.033	...	22.51 ± 0.51	21.51 ± 0.07	20.01 ± 0.04	18.0 ± 0.3

Note. — Measurements are done in the Tek2k images using GALFIT. The positions of each component are derived in the I -band images. The positive directions of X and Y are defined by west and north, respectively.

Table 6. RESULTS OF MASS MODELING

Object	$R_E(\prime\prime)$	e	$\theta_e(^{\circ})$	$\Delta t(h^{-1}\text{day})$	μ_{tot}
SDSS J0819+5356	2.057	0.123	−58.6	44.6	15.5
SDSS J1254+2235	0.787	0.081	−29.2	11.2	8.5
SDSS J1258+1657	0.565	0.481	−3.6	19.0	3.0
SDSS J1339+1310	0.853	0.287	29.7	17.7	5.6
SDSS J1400+3134	0.790	0.448	37.6	38.6	5.4

Note. — Each position angle is measured East of North. In order to calculate the predicted time delays (Δt), we use the measured lens galaxy redshift of $z_l = 0.294$ for SDSS J0819+5356, and the estimated lens galaxy redshifts of $z_l = 0.4$ (for SDSS J1254+2235, SDSS 1258+1657 and SDSS J1339+1310) and $z_l = 0.6$ (for SDSS J1400+3134). μ_{tot} represents the predicted total magnification.