Mass models and environment of the new quadruply lensed quasar SDSS J1330+1810*

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ABSTRACT

We present the discovery of a new quadruply lensed quasar. The lens system, SDSS J1330+1810 at \(z_s = 1.393\), was identified as a lens candidate from the spectroscopic sample of the Sloan Digital Sky Survey. Optical and near-infrared images clearly show four quasar images with a maximum image separation of 1.76 arcsec, as well as a bright lensing galaxy. We measure a redshift of the lensing galaxy of \(z_l = 0.373\) from absorption features in the spectrum. We find a foreground group of galaxies at \(z = 0.31\), centred at \(\sim 120\) arcsec southwest of the lens system. Simple mass models fit the data quite well, including the flux ratios between images, although the lens galaxy appears to be \(\sim 1\) mag brighter than expected by the Faber–Jackson relation. Our mass modelling suggests that shear from nearby structure is affecting the lens potential.

Key words: gravitational lensing – quasars: individual: SDSS J133018.65+181032.1.

1 INTRODUCTION

Thus far about 100 gravitationally lensed quasars are known, of which nearly 30 are quadruple (four-image) lenses. The number ratio of quadruple lenses to double (two-image) lenses contains information on both the shapes of lensing galaxies and the luminosity function of source quasars (Rusin & Tegmark 2001; Chae 2003; Hutemer, Keeton & Ma 2005; Oguri 2007b; Mandelbaum, van de Ven & Keeton 2008). In addition, quadruple lenses allow more detailed mass modelling of individual lenses. For instance, the larger number of images provides more constraints on the lens potential, which is essential in probing the effects of external perturbations on primary lenses (Keeton, Kochanek & Seljak 1997) and constraining the Hubble constant from time-delay measurements (e.g. Suyu & Blandford 2006). Magnifications of merging image pairs in quadruple lenses satisfy distinct relations if the lens potential is smooth, but small-scale structures near the image can violate the relations. Thus, flux ratios of quadruple lens images serve as the unique probes of substructure or microlensing in lens galaxies (Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002; Dalal & Kochanek 2002; Schechter & Wambsganss 2002).

In this paper, we present the discovery of a new gravitationally lensed quasar with four lensed images, SDSS J133018.65+181032.1 (SDSS J1330+1810). It was discovered as part of the Sloan Digital Sky Survey Quasar Lens Search (SDSS QLS; Oguri et al. 2006, 2008; Inada et al. 2008), which takes advantage of the large spectroscopic quasar catalogue (see Schneider et al. 2007) of the Sloan Digital Sky Survey (SDSS; York et al. 2000) to locate new lensed quasars. We place particular emphasis on mass modelling and the investigation of the structure around the lens.

The outline of this paper is as follows. We describe the SDSS and follow-up data in Sections 2 and 3, respectively. The environment

*This paper includes data gathered with the 6.5-m Magellan telescopes located at Las Campanas Observatory, Chile. Based on observations obtained with the Apache Point Observatory 3.5-m telescope, which is owned and operated by the Astrophysical Research Consortium. Use of the University of Hawaii 2.2-m telescope for the observations is supported by National Astronomical Observatory of Japan (NAOJ).
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of the lens is discussed in Section 4. Section 5 is devoted to mass modelling. Our results are summarized in Section 6. Throughout this paper, we adopt the standard Lambda-dominated flat universe cosmology with matter density $\Omega_M = 0.26$ and the Hubble constant $h = 0.72$ (Dunkley et al. 2008).

2 THE SDSS DATA

The lens system SDSS J1330+1810 was first identified in the data of the SDSS-II (Adelman-McCarthy et al. 2008). The SDSS-II is a survey to map 10 000 deg$^2$ of the northern sky with a dedicated wide-field 2.5-m telescope (Gunn et al. 2006) at the Apache Point Observatory in New Mexico, USA. It consists of a photometric survey (Gunn et al. 1998) with five broad-band optical filters (Fukugita et al. 1996) and a spectroscopic survey of quasars and galaxies selected by a series of target selection algorithms. Richards et al. (2002) present the SDSS quasar selection technique, and Blanton et al. (2003) describe the generation of the final SDSS spectroscopic targets. The homogeneity and good quality of the data, with an astrometric accuracy better than 0.1 arcsec rms per coordinate (Pier et al. 2003) and a photometric zero-point accuracy better than 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), are essential for various statistical studies.

The SQLS identifies gravitationally lensed quasar candidates using a well-defined algorithm (Oguri et al. 2006) applied to the spectroscopic SDSS quasars. The algorithm has two parts: morphological selection, which identifies quasars that are poorly fitted by the point spread function (PSF), and colour selection, which examines objects near each spectroscopic quasar and selects those with colours similar to the quasar as lens candidates. These two selections are designed to locate small- ($\sim 1$ arcsec) and large-separation ($\gtrsim 3$ arcsec) lensed quasars, respectively. The SQLS has already discovered >20 new gravitationally lensed quasars from the SDSS data using this algorithm, including both double and quadruple lenses (e.g. Kayo et al. 2007, and references therein).

The gravitational lens SDSS J1330+1810 was selected as a lens candidate by the morphological selection algorithm. Fig. 1 shows the SDSS $i$-band image of the system (seeing of 1.0 arcsec). The enlarged image clearly indicates that the system, which is classified as a quasar at $z = 1.393$ from the SDSS spectrum (see Fig. 2), is not a point source but consists of multiple components. The morphology of the quasar in the SDSS image is similar to that of SDSS J0924+0219 (Inada et al. 2003), suggesting that this is likely to be a fold-type quadruple lens. We find no bright radio [Faint Images of the Radio Sky at Twenty-centimeters (FIRST); Becker, White & Helfand 1995] or X-ray [ROSAT All Sky Survey (RASS); Voge et al. 1999] source in the vicinity of SDSS J1330+1810. In the SDSS spectrum, we find absorption lines at $\sim 3850$ and $\sim 5400$ Å, consistent with Mg II and Ca lines due to a galaxy at $z = 0.373$. We interpret these features as absorptions by the lensing galaxy. In addition, a Mg/Fe absorption system at $z = 1.054$ is seen in the spectrum. Since its redshift is quite close to the source redshift, the effect of the absorber at $z = 1.054$ on the lens potential is expected to be small.

The SDSS image shows a concentration of red galaxies $\sim 120$ arcsec south-west of SDSS J1330+1810 (see Fig. 2; around G1 and G2). One of the galaxies, G2, was targeted by the luminous red galaxy program (Eisenstein et al. 2001) and has been observed spectroscopically in the SDSS (Fig. 2), with a redshift of $z = 0.3126$. The presence of the [O ii] emission line (rest-frame equivalent width of $\sim 9$ Å) suggests an ongoing star formation activity in the galaxy G2. We explore the possible group further in Section 4.
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The total exposure time was 405 s in J, 540 s in H and 360 s in K$_s$. The seeing was 0.74–0.82 arcsec. We also obtained H-band images with the Near-Infrared Camera and Fabry–Perot Spectrometer at the Astrophysical Research Consortium 3.5-m (ARC 3.5 m) Telescope on 2007 June 1. The total exposure time was 1200 s and the seeing was 0.88 arcsec. Optical imaging was conducted with the Tektronix 2048 × 2048 CCD camera at the University of Hawaii 2.2-m (UH88) telescope. A 500 s image in V band was taken on 2008 March 6, under 0.81 arcsec seeing. All the data were reduced using standard IRAF tasks. The zero-point magnitudes of the infrared images were estimated using Two-Micron All-Sky Survey (2MASS) data (Skrutskie et al. 2006), whereas the UH88 image was calibrated by the standard star PG0918+029 (Landolt 1992).

The images shown in Fig. 3 confirm that the system is indeed a typical fold-type quadruple lens, with two merging images and the other two images on the other side of the lens. For definiteness, we fit the images using GALFIT (Peng et al. 2002). The assumed model consists of four PSFs and a lens galaxy modelled by a Sersic profile with the convolution of the PSF. We adopt nearby stars as PSF templates. We first left the Sersic index $n$ as a free parameter and found the best-fitting value to be $n \approx 3.4$, which is close to the canonical value for early-type galaxies, $n = 4$. Thus in what follows, we fix the Sersic index to $n = 4$. We find that this model fits the data quite well. The subtracted images shown in Fig. 3 show virtually no residuals.

Table 1 summarizes the relative astrometry and photometry from the fitting. Following convention, we name four quasar components A–D, in decreasing order of their brightnesses, and we name the lensing galaxy G. The relative positions of the four components agree well among the high angular resolution images, with a scatter of $\sim 0.03$ arcsec. The maximum separation between images is 1.76 arcsec. For the NIR images, the lensing galaxy is modelled well by the Sersic profile ($n = 4$) with scale radius $R_e \sim 0.7–0.9$ arcsec, ellipticity $e \sim 0.57$ and position angle (east of north) $\theta_e \sim 24^\circ$. The lensing galaxy has somewhat different...
Table 1. Relative astrometry and photometry from the follow-up images (see Fig. 3). The positive directions of x and y are north and west, respectively. The J2000 coordinates of component A are (RA, Dec.) = (202.577 84, 18.175 62). The positional errors are estimated from the scatter between the five follow-up images. The errors on the magnitudes are statistical errors only and do not include systematic errors coming from uncertainties of PSFs and the galaxy profile. The magnitudes have not been corrected for Galactic extinction. The magnitudes of galaxy G refer to the total magnitudes.

| Name | x (arcsec) | y (arcsec) | V (UH88) (mag) | J (Magellan) (mag) | H (ARC 3.5 m) (mag) | H (Magellan) (mag) | Ks (Magellan) (mag) |
|------|------------|------------|----------------|-------------------|--------------------|--------------------|--------------------|
| A    | ±0         | ±0         | 19.02 ± 0.02   | 18.36 ± 0.05      | 17.32 ± 0.05       | 17.40 ± 0.07       | 17.06 ± 0.04       |
| B    | 0.42 ± 0.03| -0.01 ± 0.03| 19.72 ± 0.03   | 18.68 ± 0.07      | 17.54 ± 0.06       | 17.73 ± 0.09       | 17.30 ± 0.05       |
| C    | 1.30 ± 0.03| 1.19 ± 0.03 | 19.89 ± 0.01   | 19.12 ± 0.02      | 18.18 ± 0.02       | 18.24 ± 0.02       | 17.90 ± 0.03       |
| D    | -0.24 ± 0.04| 1.58 ± 0.04| 21.45 ± 0.04   | 19.83 ± 0.05      | 19.36 ± 0.12       | 19.13 ± 0.05       | 18.62 ± 0.06       |
| G    | 0.24 ± 0.03| 0.97 ± 0.03 | 19.48 ± 0.04   | 16.77 ± 0.01      | 16.00 ± 0.01       | 16.08 ± 0.02       | 15.26 ± 0.01       |

Figure 4. Flux ratios of quasar images from the follow-up images (see also Fig. 3 and Table 1). We plot magnitude differences between images B–D and the brightest image A, Δm ≡ m_A − m_X (X = B–D). Dotted horizontal lines indicate median values of individual ratios, which we adopt for mass modelling.

Figure 5. G band (left-hand panel) and Na (right-hand panel) absorption lines of the lensing galaxy at z = 0.373 from the spectrum of SDSS J1330+1810 obtained with the DIS at the ARC 3.5-m telescope. The feature at 5750 Å is an Mg II doublet at z = 1.054 (see also Fig. 2).
Since these absorptions are weak, they were not seen in the SDSS spectrum. We note that the DIS spectrum exhibits clear emission lines of quasars, which should originate both from images C/D and from scattered fluxes from images A/B.

The redshift of galaxy G3 is $z = 0.311$ (Fig. 6), which is quite close to the redshift of galaxy G2, $z = 0.3126$. The two galaxies have similar spectra, with significant $[\text{O} \, \text{II}]$ emission of the same rest-frame equivalent width. The 4000 Å break of G3 is weaker than that of G2, which implies that star formation happened more recently in G3.

**4 ENVIRONMENT OF THE LENS GALAXY**

The wide-field image suggests a possible group of galaxies located near the lens system (see Section 2). The high incidence of groups near strong lens systems has been noted before (Fassnacht & Lubin 2002; Momcheva et al. 2006; Williams et al. 2006; Auger et al. 2007; Cabanac et al. 2007; Shin et al. 2008; Treu et al. 2008) and is theoretically expected (Keeton, Christlein & Zabludoff 2001; Oguri, Keeton & Dalal 2005). Although the redshift of the possible group, $z = 0.31$, differs from the lens redshift $z_l = 0.373$, a foreground group affects the lens potential in a similar way as does a group at the same redshift. In this section, we study the distribution and properties of galaxies in the field from the SDSS.

First, we extract locations and brightnesses of galaxies in the $12 \times 12$ arcmin$^2$ field centred on the lens system from the SDSS Data Release 6 (Adelman-McCarthy et al. 2008). We adopt the Petrosian (1976) magnitudes in what follows. We restrict our analysis to galaxies brighter than $i = 21$, where star–galaxy separation is reliable. To study the distribution at $z \sim 0.31$, we adopt photometric redshift measurement in the SDSS data bases (Csabai et al. 2003; Adelman-McCarthy et al. 2008). Specifically, we select galaxies whose photometric redshifts are consistent with $z = 0.31$ within their quoted errors. Therefore, our study here is not necessarily restricted to red elliptical galaxies but includes blue galaxies as well. Galaxies with large photometric redshift errors, $\Delta z > 0.2$, are excluded from our analysis.

We show the angular distributions of all galaxies and galaxies at $z \sim 0.31$ in Fig. 7. There is a clear concentration of galaxies to the south-west of the lens. The structure is more pronounced after applying a cut by the photometric redshift. We note that G1 is the brightest among galaxies at $z \sim 0.31$ selected in this way. Together with the agreement of the spectroscopic redshifts of G2 and G3 (Sections 2 and 3.2), we conclude that there is a foreground group of galaxies at $z \sim 0.31$ with its centre $\sim 120$ arcsec south-west of the lens system (corresponding to the transverse physical distances of $390h^{-1}$ kpc at $z = 0.31$ and $440h^{-1}$ kpc at $z = 0.373$), centred around G1 and G2. It is worth noting that a concentration of galaxies can also be seen around G3, which suggests that there might be a subclump of the group around G3.

There is a possibility that a concentration of galaxies at the lens redshift $z = 0.373$ exists in addition to the group at $z = 0.31$. However, most of galaxies examined here are rather faint and have large errors on the photometric redshifts, which prevents us from distinguishing structures at $z = 0.31$ from $z = 0.373$. Additional imaging and spectroscopic follow-up observations are necessary to explore this issue further.

**5 MASS MODELLING**

We constrain the lens potential of this system using the observed image positions and flux ratios. The relative positions of the quasar images and galaxies and their errors are adopted from Table 1. Flux ratios are estimated from the median of the measurements in the five follow-up images (see Fig. 4). Note that the flux ratios agree
Table 2. Best-fitting mass models of SDSS J1330+1810. The column ‘Flux’ shows whether flux ratios are included as constraints or not. The parameter \( \theta_{\text{Ein}}, e \) and \( \gamma \) denote the Einstein radius, ellipticity and external shear, respectively. The position angle of ellipticity and shear, \( \theta_{e} \) and \( \theta_{\gamma} \), are measured east of north. \( x_{\text{pos}}^{\gamma}, x_{\text{gal}}^{\gamma} \) and \( x_{\text{Ein}}^{\gamma} \) indicate chi-square values from image positions, lens galaxy positions and flux ratios. The total chi-square \( \chi^{2} \) is the sum of these three. Also shown are the time delays between images predicted by the best-fitting models, adopting the lens redshift \( z_{l} = 0.373 \).

| Model | Flux | \( \chi^{2}/\text{d.o.f.} \) | \( x_{\text{pos}}^{\gamma} \) | \( x_{\text{gal}}^{\gamma} \) | \( x_{\text{Ein}}^{\gamma} \) | \( e \) | \( \theta_{e}(\text{deg}) \) | \( \gamma \) | \( \theta_{\gamma}(\text{deg}) \) | \( \Delta t_{AB}(\text{d}) \) | \( \Delta t_{AC}(\text{d}) \) | \( \Delta t_{AD}(\text{d}) \) |
|-------|-----|----------------|----------------|----------------|----------------|-----|----------------|-----|----------------|----------------|----------------|----------------|
| SIE   | No  | 2.10/3         | 2.10           | 0.01           | 0.97           | 0.31 | 34             | \( \dot{e} \) | \( \dot{\gamma} \) | -0.15           | 6.04           | -11.68         |
| SIE   | Yes | 7.28/6         | 2.80           | 0.01           | 4.47           | 0.97 | 0.32           | 34             | \( \dot{e} \) | -0.18           | 5.91           | -11.83         |
| SIE\( x \) | No  | 0.33/1         | 0.13           | 0.21           | 0.97           | 0.39 | 25             | 0.05           | \( \dot{e} \) | -0.88           | -0.20          | 6.76           | -12.17         |
| SIE\( x \) | Yes | 1.14/4         | 0.76           | 0.13           | 0.25           | 0.99 | 0.56           | 25             | 0.11           | -0.75          | -0.31          | 10.28          | -12.69         |

Figure 8. The best-fitting model (SIE\( x \), flux ratios are included as constraints) is shown. See Table 2 for best-fitting parameters. The black curve and squares indicate the critical curve of the best-fitting model and the predicted image positions. Observed image positions are within the symbols. Grey curves and the square are the corresponding caustics and source position.

Figure 9. The UH88 V-band image around the lens system. North is up and east is left. Shear directions in our best-fitting models (\( \theta_{\gamma} = -88^\circ \) for the model without flux constraints and \( -75^\circ \) for the model with flux constraints) are shown by thick solid lines. Directions to a nearby bright galaxy (G3) and the centre of the group (G1/G2) are indicated by thin solid lines.
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6 SUMMARY

We have presented the discovery of a new four-image lensed quasar SDSS J1330+1810 ($z_l = 1.393$). This source was selected as a lens candidate by the SQLS due to its extended morphology. Our observations in optical and NIR indicate that it is a typical fold-type quadruple lens, with a maximum separation between images of 1.76 arcsec. From the spectrum we measured a lens redshift of $z_l = 0.373$. Standard simple elliptical mass models fit the data well, including the flux ratios, implying no evidence for substructure. The mass modelling suggests an important contribution of the external shear, probably from a nearby bright galaxy. There is also a foreground group of galaxies whose centre is $\sim 120$ arcsec from the lens. The lens galaxy is $\sim 1$ mag brighter than predicted by mass modelling.

Thus far, the SQLS has discovered 31 lensed quasars including SDSS J1330+1810, of which five are quadruple lenses (e.g. Inada et al. 2003; Kayo et al. 2007). The low fraction of quadruple lenses may imply that the faint end slope of the quasar optical luminosity function is shallow, although it is marginally consistent with standard theoretical expectations (Oguri 2007b). The SQLS has completed $\sim 2/3$ of its survey, implying that a few more quadruple lenses will be discovered by the completion of the survey.

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REFERENCES

Adelman-McCarthy J. K. et al., 2007, ApJS, 172, 634
Adelman-McCarthy J. K. et al., 2008, ApJS, 175, 297
Auger M. W., Fassnacht C. D., Abrahamse A. L., Lubin L. M., Squires G. K., 2007, AJ, 134, 668
Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
Blanton M. R., Lin H., Lupton R. H., Maley F. M., Young N., Zehavi I., Loveday J., 2003, AJ, 125, 2276
Cabanac R. A. et al., 2007, A&A, 461, 813
Chae K.-H., 2003, MNRAS, 346, 746
Chiba M., 2002, ApJ, 565, 17
Csabai I. et al., 2003, AJ, 125, 580
Dalal N., Kochanek C. S., 2002, ApJ, 572, 25
Dunkley J. et al., 2008, preprint (arXiv:0803.0586)
Eisenstein D. J. et al., 2001, AJ, 122, 2267
Faber S. M., Jackson R. E., 1976, ApJ, 204, 668
Falco E. E. et al., 1999, ApJ, 523, 617
Fassnacht C. D., Lubin L. M., 2002, AJ, 123, 627
Fukugita M., Ichikawa T., Gunn J. E., Doi M., Shimasaku K., Schneider D. P., 1996, AJ, 111, 1748
Gunn J. E. et al., 1998, AJ, 116, 3040
Gunn J. E. et al., 2006, AJ, 131, 2332
Hogg D. W., Finkbeiner D. P., Schlegel D. J., Gunn J. E., 2001, AJ, 122, 2129
Huterer D., Keeton C. R., Ma C.-P., 2005, ApJ, 624, 34
Inada N. et al., 2003, AJ, 126, 666
Inada N. et al., 2008, AJ, 135, 496
Ivezić Ž. et al., 2004, Astron. Nachr., 325, 583
Kayo I. et al., 2007, AJ, 134, 1515
Keeton C. R., 2003, ApJ, 584, 664
Keeton C. R., Kochanek C. S., Seljak U., 1997, ApJ, 482, 604
Keeton C. R., Christlein D., Zabludoff A. I., 2000, ApJ, 545, 129
Landolt A. U., 1992, AJ, 104, 340
Mao S., Schneider P., 1998, MNRAS, 295, 587
Mandelbaum R., van de Ven G., Keeton C. R., 2008, preprint (arXiv:0808.2497)
Martini P., Persson S. E., Murphy D. C., Birk C., Shectman S. A., Gunnels S. M., Koch E., 2004, Proc. SPIE, Vol. 5492. SPIE, Bellingham, p. 1653
Metcalf R. B., Madau P., 2001, ApJ, 563, 9
Momcheva I., Williams K., Keeton C., Zabludoff A., 2006, ApJ, 641, 169
Oguri M., 2007a, ApJ, 660, 1
Oguri M., 2007b, NJPh, 9, 442
Oguri M., Keeton C. R., Dalal N., 2005, MNRAS, 364, 1451
Oguri M. et al., 2006, AJ, 132, 999
Oguri M. et al., 2008, AJ, 135, 512
Padmanabhan N. et al., 2008, ApJ, 674, 1217
Pahre M. A., 1999, ApJS, 124, 127
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2002, AJ, 124, 266
Petrosian V., 1976, ApJ, 209, L1
Pier J. R., Munn J. A., Hindsley R. B., Hennessy G. S., Kent S. M., Lupton R. H., Ivezic Ž., 2003, AJ, 125, 1559
Richards G. T. et al., 2002, AJ, 123, 2945
Rusin D., Tegmark M., 2001, ApJ, 553, 709
Rusin D. et al., 2003, ApJ, 587, 143
Schechter P. L., Wambsganss J., 2002, ApJ, 580, 685
Schneider D. P. et al., 2007, AJ, 134, 102
Shin M.-S., Strauss M. A., Oguri M., Inada N., Falco E. E., Broadhurst T., Gunn J. E., 2008, AJ, 136, 44
Skrutskie M. F. et al., 2006, AJ, 131, 1163
Smith J. A. et al., 2002, AJ, 123, 2121
Suyu S. H., Blandford R. D., 2006, MNRAS, 366, 39
Treu T., Gavazzi R., Gorecki A., Marshall P. J., Koopmans L. V. E., Bolton A. S., Moustakas L. A., Burles S., 2008, ApJ, in press (arXiv:0806.1056)
Tucker D. L. et al., 2006, Astron. Nachr., 327, 821
Voges W. et al., 1999, A&A, 349, 389
Williams K. A., Momcheva I., Keeton C. R., Zabludoff A. I., Lehár J., 2006, ApJ, 646, 85
York D. G. et al., 2000, AJ, 120, 1579

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