SDSS J1335 + 0118: A New Two-Image Gravitational Lens

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Abstract

We report on the discovery of the two-image gravitationally lensed quasar SDSS J1335+0118. The object was selected as a lens candidate from the Sloan Digital Sky Survey. The imaging and spectroscopic follow-up observations confirm that the system exhibits two gravitationally lensed images of a quasar at z = 1.57. The image separation is 1″56. We also detect an extended component between the two quasar images, likely to be a lensing galaxy. Preliminary mass modeling predicts a differential time delay, ∆t of ~ 30 h⁻¹ day, assuming the redshift of the lens galaxy to be 0.5.

Key words: galaxies: quasars: individual (SDSS J133534.79+011805.5) — gravitational lensing

1. Introduction

Multiple images of a quasar produced by a foreground galaxy are useful for cosmological and astrophysical applications, such as measuring the cosmological constant through the lensing rate (Turner 1990; Fukugita et al. 1990; Chae et al. 2002), determining the global Hubble constant from time delays between images (Refsdal 1964, 1966), studying the mass distributions of the lensing galaxies (Kochanek 1991; Metcalf, Madau 2001; Chiba 2002; Dalal, Kochanek 2002; Schechter, Wambsganss 2002; Koopmans, Treu 2003; Rusin et al. 2003), and considering the formation and evolution of galaxies (Kochanek et al. 2000; Kochanek, White 2001; Keeton 2001a; Oguri 2002; Ofek et al. 2003). A large homogeneous sample of lensed quasars with a well-understood selection function is essential in these statistical studies. In addition, lensed quasars can be a powerful tool to study a quasar itself through microlensing, spectra, or variabilities of lensed quasars (Chang,Refsdal 1984; Grieger et al. 1991; Mediavilla et al. 1998; Mineshige, Yonehlera 1999; Yonehlera 1999, 2001; Wyithe et al. 2000; Lewis, Ibata 2003). Therefore, it is also important to make a large sample of lensed quasars to find more gravitational lens systems that are suitable for studying quasars.

The Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002; Abazajian et al. 2003) has the potential to provide such a lensed quasar sample. The SDSS is a survey to image 10⁴ deg² of the sky as well as to obtain spectra of galaxies and quasars from the imaging data. The dedicated 2.5 m telescope at Apache Point Observatory is equipped with a multi-CCD camera (Gunn et al. 1998) with five broad bands centered at 3561, 4676, 6176, 7494, and 8873 Å (Fukugita et al. 1996). The imaging data are automatically reduced by a photometric pipeline (Lupton et al. 2001). The astrometric positions are accurate to about 0″1 for sources brighter than r = 20.5 (Pier et al. 2003). The photometric errors are typically less than 0.03 mag (Hogg et al. 2001; Smith et al. 2002). The SDSS quasar selection algorithm is presented in Richards et al. (2002); the SDSS spectra cover 3800–9200 Å at a resolution of 1800–2100. The final spectroscopic quasar sample is expected to comprise 10⁵ quasars, and thus will contain ~ 10² lensed quasars given the typical lensing probability of 0.1% (Turner et al. 1984). Indeed, several new gravitational lens systems have been discovered using SDSS data (Inada et al. 2003a,b, 2004; Morgan et al. 2003; Johnston et al. 2003; Pindor et al. 2004; Oguri et al. 2004).
We report on the discovery of the lensed quasar SDSS J133534.79+011805.5 (SDSS J1335+0118) in the SDSS. This quasar has already been identified in the Large Bright Quasar Survey (LBQS 1333+0133; Hewett et al. 1991), but not as being lensed. A search for lens candidates in the LBQS was carried out by Hewett et al. (1998), but those authors state that their search is not sensitive to lens systems with ≤3″ separations. The quasar was selected as a lens candidate in the course of an ongoing search for strongly lensed quasars in the SDSS. From the results of photometric and spectroscopic follow-up observations, we conclude that the quasar is lensed by an intervening galaxy.

2. Observations

2.1. Candidate Selection

To select SDSS lensed quasar candidates, we examine all spectroscopically confirmed quasars with z > 0.6. Quasars at smaller redshifts have a much lower probability of being lensed, and are also often extended because of their host galaxies, making it more difficult to select lens candidates with our candidate selection algorithm, described below. We search for lens candidates using a combination of SDSS parameters: dev⊥ (the likelihood parameter of fitting by de Vaucouleurs profile), exp⊥ (the likelihood parameter of fitting by exponential disk), and star⊥ (the likelihood parameter of fitting by point spread function). This candidate selection algorithm has already found three new lensed quasar systems (Inada et al. 2003a,2004; Pindor et al. 2004), and can identify gravitationally lensed quasars with image separations of 1″-2″ quite well (N. Inada et al., in preparation). The SDSS ugriz imaging data of SDSS J1335+0118 (see figure 1) clearly show that the system consists of two stellar components with similar colors, making it an excellent lensing candidate. The total magnitudes of this system in the SDSS photometric data are u = 18.21 ± 0.02, g = 17.83 ± 0.01, r = 17.62 ± 0.01, i = 17.26 ± 0.01, and z = 17.14 ± 0.03.

2.2. Additional Imaging Observations

We obtained a deep i-band image on 2003 May 28 using the Subaru Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002) on the Subaru 8.2-m telescope of the National Astronomical Observatory of Japan, which is shown in figure 2. The exposure time was 30 s and the seeing was 0″5-0″6. The image scale was 0″2 pixel−1. Each frame was bias-subtracted and flat-field corrected. Subtraction of the two quasar images using a nearby star as a point-spread function (PSF) template revealed an extended object, denoted as G, located on the line between A and B, and closer to B (see figure 2). This configuration is expected for a standard simple lens model such as singular isothermal sphere model; thus, component G is likely to be a lens galaxy. In table 1,

| Object | x (arcsec) | y (arcsec) | Flux (arbitrary) |
|--------|------------|------------|-----------------|
| A      | 0.000 ± 0.001 | 0.000 ± 0.001 | 1.0 ± 0.2       |
| B      | −1.038 ± 0.002 | −1.165 ± 0.002 | 0.374 ± 0.075  |
| G      | −0.769 ± 0.011 | −0.757 ± 0.011 | ...            |

* The positive directions of x and y are defined by West and North, respectively.
† Errors are broadened to 20% to account for possible systematic effects.
we summarize the position of each component and the relative fluxes of the quasar components that are measured using Subaru Suprime-Cam data. The errors of the galaxy position were determined by Gaussian fits.

We also obtained $J$ and $K$-band data on 2003 April 19 with the Near InfraRed Camera (NIRC; Matthews, Soifer 1994) of the Keck I telescope at the W. M. Keck Observatory on Mauna Kea, Hawaii, USA. The total exposure time was 900 s and the seeing was variable, averaging $\sim 0''6$. Conditions were not photometric, with about 1 mag of variable cloud. The image scale was $0''15$ pixel$^{-1}$. Standard reduction procedures were followed to remove the dark current and to flatten the data. We show the $K$ image in figure 3. Although the galaxy component can be seen in the direct image, we subtracted the PSF of two quasar components by fitting a Gaussian PSF at each quasar location, revealing the lensing galaxy more clearly (see figure 3). As in the $i$-band image shown in figure 2, the galaxy component is seen in the PSF-subtracted $K$-band image. We compare the distance between components A, B, and G in table 2. The differences in the distances are large, but only $\sim 0''1$ at most, and still much smaller than the seeing sizes and the pixel sizes. The position of the lens galaxy is particularly uncertain in the $K$ data because not only is the lensing galaxy relatively faint and extended, but also because the seeing was quite variable on the night when the IR data were obtained, and no suitable PSF star is present in the NIRC field, making it

![Figure 2](https://example.com/fig2.png)

**Fig. 2.** Subaru Suprime-Cam images of SDSS J1335 +0118 in the $i$-band. The image scale is $0''2$ pixel$^{-1}$. Left: Original Suprime-Cam image. Components A and B are lensed quasar components. Right: PSF-subtracted image. The component G is likely to be the lens galaxy.

![Figure 3](https://example.com/fig3.png)

**Fig. 3.** Same as figure 2, but the $K$-band images taken with NIRC on Keck I telescope are shown. The image scale is $0''15$ pixel$^{-1}$. 
difficult to properly subtract the PSF wings which overlap the galaxy. Thus, it may be possible that such residuals systematically affect the estimated positions. We note that the system is detected (but not resolved) by the Two-Micron All-Sky Survey (2MASS) with $z = 1.57 \pm 0.03$ and $z = 1.57 \pm 0.05$, respectively. We cross-correlate the two spectra and estimate the velocity difference between two components A and B, but this is not surprising given the inhomogeneity of the spatial distribution of absorbers (e.g., Petitjean, Bergeron 1990; Steidel, Sargent 1992). We note that the color of component G (see subsection 2.4) is consistent with that of a low-redshift ($z \lesssim 0.5$) early-type galaxy (e.g., McLeod et al. 1995).

2.4. Differential Extinction

We checked colors of the quasar components to see whether the system suffers from differential extinction. The results of photometry from the imaging data of the SDSS, Subaru, and Keck are given in table 3. The relative magnitudes were estimated from Subaru, Keck, and SDSS images. To calibrate total magnitudes, we used measurements of the SDSS, $i = 17.26 \pm 0.01$, and the 2MASS, $K = 15.29 \pm 0.18$. We found that the colors of each component are consistent with a single value, given the errors of $\lesssim 0.1$ mag associated with the deconvolution of two components. The spectra of the quasar components shown in figure 4 also indicate no significant differential extinction. Although it seems that at $\lesssim 4800 \text{ Å}$ the ratio increases as the wavelength decreases, the feature is not significant because of the large errors in those wavelengths arising from the low response at $4000 \text{ Å}$, and shorter. Therefore, we

### Table 2. Comparison of positions between the Subaru $i$-band and the Keck $K$-band images.

| Objects | $i$-band distance (arcsec) | $K$-band distance (arcsec) |
|---------|--------------------------|--------------------------|
| AB      | 1.560 \pm 0.002          | 1.503 \pm 0.002          |
| AG      | 1.079 \pm 0.011          | 0.969 \pm 0.012          |
| BG      | 0.489 \pm 0.011          | 0.542 \pm 0.012          |

### Table 3. Photometry of the Subaru $i$-band, the Keck $K$-band, and SDSS $ugriz$-band images.

| Band   | Total          | A   | B   | B − A | G   |
|--------|----------------|-----|-----|-------|-----|
| $u$ (SDSS) | 18.21 \pm 0.02$ | 18.54 | 19.68 | 1.14  | \cdots |
| $g$ (SDSS) | 17.83 \pm 0.01$ | 18.12 | 19.39 | 1.27  | \cdots |
| $r$ (SDSS) | 17.62 \pm 0.01$ | 17.95 | 19.09 | 1.14  | \cdots |
| $i$ (SDSS) | 17.26 \pm 0.01$ | 17.60 | 18.68 | 1.08  | \cdots |
| $i$ (Subaru) | 17.26 \pm 0.01$ | 17.63 | 18.70 | 1.07  | 20.05 |
| $z$ (SDSS) | 17.14 \pm 0.03$ | 17.49 | 18.54 | 1.05  | \cdots |
| $K$ (Keck) | 15.29 \pm 0.18$ | 15.78 | 16.75 | 0.97  | 17.81 |

* Based on the SDSS.
† Based on the 2MASS.

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conclude that differential reddening is not significant.

3. Mass Modeling

We model the lens system with the simple Singular Isothermal Ellipsoid (SIE) model, assuming that component G is the lens galaxy. The SIE model has the following dimensionless surface mass density:

$$\kappa(r) = \frac{r_{\text{Ein}}}{2\zeta}$$

where $\zeta = r\left\{1 + \frac{[1-q^2]/(1+q^2)}{\cos 2(\theta - \theta_e)}\right\}^{1/2}$, $r_{\text{Ein}}$ is the Einstein ring radius, $q$ is the lens axis ratio, and $\theta_e$ is the position angle of the ellipse. The model includes eight parameters: the galaxy position, $x_g$ and $y_g$; the Einstein ring radius, $r_{\text{Ein}}$; the ellipticity, $e = 1 - q$; the position angle, $\theta_e$; the source position, $x_s$ and $y_s$; and the flux of the quasar, $f$. Since the number of constraints is also eight (see table 1),

the degree of freedom is zero. We use the public software lensmodel (Keeton 2001b) to constrain the models. The results are summarized in table 4. The best-fit parameters predict the time delay between images to be $\Delta t = 29.5 \pm 1.2$ day if we adopt a lens redshift $0.5$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$. The errors on the parameters were estimated from one-dimensional slices of the $\chi^2$ surface. We found that we can fit the lens system with a relatively small lens ellipticity, $e = 0.123^{+0.041}_{-0.024}$, significantly

Table 4. Best-fit SIE model parameters for SDSS J1335 + 0118.

| Parameter  | Value            |
|------------|------------------|
| $r_{\text{Ein}}$ (arcsec) | $0.789^{+0.009}_{-0.011}$ |
| $e$         | $0.123^{+0.041}_{-0.024}$ |
| $\theta_e$ (deg)  | $-7.8^{+19.3}_{-12.0}$ |

We use positions and flux ratios of SDSS J1335 + 0118 in the Subaru $i$-band image (see table 1). Errors are 68% confidence.
smaller than observed ellipticity of the light (≈ 0.3). The derived position angle of the lens galaxy is consistent with that of the light (≈ 7°) within 1σ. These results are in good agreement with previous studies (e.g., Keeton et al. 1998).

4. Conclusion

We have reported the discovery of a new two-image gravitational lens, SDSS J1335 + 0118. The system was identified as a new lens candidate in the SDSS. The image separation is 1′56 ± 0′002 in the i-band image taken with Subaru Suprime-Cam. The spectroscopic observation with ESO NTT has confirmed that both images have an identical redshift of \( z = 1.57 (z = 1.57 ± 0.03 \) and \( z = 1.57 ± 0.05 \) for components A and B, respectively). We have also probably identified the lensing galaxy between two quasar components in the higher resolution imaging data taken with Subaru Suprime-Cam and Keck NIRC. The lens geometry is well reproduced with a simple mass model and reasonable model parameters. Assuming the redshift of the lens galaxy to be 0.5, we have predicted a differential time delay of \( \Delta t \sim 30 h^{-1} \) day.

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