A New Gravitational Lens Candidate with Large Image Separation in the SDSS DR5 Data

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Abstract

The discovery of a gravitational lens candidate is reported. The quasars SDSS J111611.73+411821.5 and SDSS J111610.68+411814.4 are recognized as two images of the same object, being strongly lensed by the closer galaxy SDSS J111611.03+411820.9. The source is located at a redshift of $z \sim 3$, while the redshift of the lens galaxy is $z \sim 0.25$. The separation of the images is large, $\sim 13$ arcsec. Commonly used models of the mass distribution for the lens galaxy with values of the parameters in the expected range describe the positions and fluxes of the images.
Introduction

Gravitational lenses are widely used for astrophysical and cosmological studies. Individually analyzed, they can provide a better understanding of both the lens and the source. The lensing effect depends only on the distribution of mass within the lens, and not on the type of matter, and can be used to study the distribution of dark matter in galaxy or galaxy cluster halos [1]. The statistical properties of the lens systems are sensitive to the cosmological constant [2], the global Hubble constant [3], or the formation and evolution of galaxies [4].

Currently, about 100 lensed quasars have been discovered [4], but the recent development of massive sky surveys is increasing this number quickly. The discovery of a new lens candidate in the Sloan Digital Sky Survey (SDSS) data is reported here. Several gravitational lenses have been discovered previously in the SDSS data [5]. Collecting a large sample of gravitational lenses with well-defined statistical properties is important to obtain consistent cosmological and astrophysical conclusions, and the SDSS gives a good opportunity to obtain such a sample.

In the analysis presented here, the quasars SDSS J111610.8+411814.4 and SDSS J111611.73+411821.5 are identified as two images of the same quasar, being lensed by the closer galaxy SDSSJ111611.03+411820.9. Both quasars are in the spectroscopic catalog of the survey, while the galaxy is a photometric object. The system is studied and modelled to check the consistency of the gravitational lens hypothesis.

Observation of the Lens Candidate

The Sloan Digital Sky Survey

The SDSS [6] is a large-area imaging survey of the north Galactic cap. It has covered nearly a quarter of the Celestial Sphere (8000 square degrees). The survey has recorded around $1.3 \times 10^8$ objects with well-calibrated photometry [7]. The photometric errors are typically less than 0.03 magnitude [8]. In addition to that, there is a spectroscopic survey, that has collected spectra

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1. http://cfa-www.harvard.edu/castles
2. http://www.sdss.org
for roughly $10^6$ galaxies and $10^5$ quasars, and has covered a total area of 5713 square degrees using an optimized tiling algorithm [9].

The survey uses a dedicated telescope [10] of 2.5m, located at the Apache Point Observatory, New Mexico. The imaging survey uses the drift-scan mode of the 142 Mpixel camera [11] to obtain data in five broad bands [12], $u g r i z$, centered at 3561, 4676, 6176, 7494 and 8873 Å respectively. The images are processed automatically by a photometric pipeline [13], and are calibrated astrometrically [14] and photometrically [7].

Some objects are selected from the imaging data for spectroscopy using a variety of algorithms, that include a deeper sample of galaxies [15] and quasars [16]. The spectra are observed by means of a pair of double spectrographs able to take 640 spectra simultaneously. They are fed by optical fibers each 3" in diameter. The spectra cover the wavelength range from 3800 to 9200 Å, with a resolution of $\lambda/\Delta\lambda \sim 2000$.

The results presented here correspond to the Data Release 5 (DR5) of the SDSS [17]. Previous data releases are described elsewhere [18].

**Observation of the Lens Candidate**

The identification of the lens candidate presented here was performed during a study of close quasar pairs. The SDSS image of the system can be seen in Figure 1, where the two images of the quasar are labelled QSO 1 and QSO 2, and are compatible with point-like objects, and the lens galaxy is clearly visible between them as an extended object, labelled GAL. The large separation between the images makes the system a very clear candidate, since the objects are perfectly resolved even in the SDSS spectroscopic sample, and no additional follow-up is necessary. The main astrometric and photometric features of the objects are described in Table 1.

The two images of the quasar are included in the spectroscopic sample of the SDSS. Their spectra can be seen in Figure 2 top. The angular separation between the two quasar images is large, 13.7", and the separation of each image and the lens galaxy is 7.6" and 7.9". The observed redshifts of the two images using the CIV line are $3.01 \pm 0.04$ and $3.01 \pm 0.03$. The optimal redshifts from the SDSS spectroscopic calculations are $2.971 \pm 0.003$ and $2.980 \pm 0.005$. The redshifts are compatible within errors.

Moreover, the shapes of both spectra are very similar. The ratio of spectra is shown in Figure 2 bottom, and it is constant along the full range of considered wavelengths. Considering both quasars as lensed images of a sin-
gle object is then supported both by the similarity of the spectra and by the consistency of the redshifts.

There is no spectrum of the lens galaxy, which is located in the middle of the two images of the quasar, but the photometric redshift computed for it in the SDSS data is $z = 0.18 \pm 0.03$ using the templates algorithm [19] or $z = 0.25 \pm 0.03$ using the modified neural network method [20]. The two values are only marginally compatible, but the lens system is very weakly dependent on this redshift. The most sensitive quantity is the time delay between images, that has not been explored in this analysis. For the other parameters, the full analysis has been performed using both values of the redshift and the conclusions are the same, with compatible values for all the parameters. The numbers quoted in the text are for a redshift of 0.25.

**Lens Model**

The gravitational lens hypothesis is analysed using two mass models, a Singular Isothermal Ellipsoid (SIE) and a Singular Isothermal Sphere with shear (SISS). The *gravlens/lensmodel* software [21] is used. The assumed errors are $\pm 0.1''$ in the positions and $20\%$ in the fluxes. These errors are larger than the actual errors on the measurements, and are adopted to account for possible external perturbations. Both models have 8 parameters (the lens position, the Einstein radius, the ellipticity or shear, the position angle, the source position and the source flux) and the system offers 8 constraints (the image positions, the lens position and the fluxes of the images), what means that the data should be described perfectly in any fit to these models, since there are no degrees of freedom. However, sensible values for the parameters should be obtained from the fits.

The measured positions of the images relative to the central galaxy in the lens plane are shown in Figure 3 as dots, while the fitted positions are shown as open circles. Both models, SIE and SISS are able to describe the observed positions, as expected. Also the fitted source position and the critical curves for the lens system are presented.

The parameters for the lens obtained from each model are shown in Table 2.

The mass of the lens galaxy, defined as all the mass contained inside the Einstein radius, is $M_L = (5.3 \pm 0.1) \times 10^{12} M_\odot$ in both models.

The fitted ellipticity for the lens galaxy in the SIE model is smaller than
the measured ellipticity for the light, which is around 0.3 in all the bands, as presented in Table 3. The fitted shear in the SISS model is in the typical range for lens systems. The fitted position angles are not compatible with the measured angle for the light, shown in Table 3, what means that some slight external perturbation may be present. In fact, there seems to be a group or cluster of galaxies between the source and the lens galaxy, at \( z \sim 0.5 \), that may also contribute to the lensing.

Since the redshifts for the source quasar and the lens galaxy are known, it is possible to compute the angular diameter distances, for a flat cosmology with \( \Omega_\Lambda = 0.7, \Omega_M = 0.3 \) and \( h = 0.71 \). Then, the expected magnifications of the quasar images can be obtained from the lens models. The expected ratio of fluxes of the two images of the quasar is found to be \( 0.38 \pm 0.02 \) for both models, in agreement with the observed value, \( 0.38 \pm 0.01 \), as expected. The observed value has been obtained from a fit to the ratio of spectra of Figure 2-bottom and confirmed from the differences of magnitudes from Table 1.

The velocity dispersion of the mass producing the lens in the SIE model can be determined from the Einstein radius, and it is found to be \( \sigma = 560 \) km/s, higher than expected for a typical elliptical galaxy. This fact is not strange, since the mass distribution producing the lens extends for \( 5.80 \pm 0.11 \) effective radii from the center of the galaxy. The effective radius of the galaxy, taken as the radius that contains half of the petrosian flux of the galaxy in the r-band is read from the SDSS database. Then, using different mass distributions (described in gravlens/lensmodel), the mass inside the effective radius can be inferred from the mass contained inside the Einstein radius. When the SIE model is used to evaluate the mass of the galaxy inside the effective radius, the obtained value is \( M_{R_{eff}}^{SIE} = (0.91 \pm 0.02) \times 10^{12} M_\odot \). The corresponding velocity dispersion for this radius is \( \sigma_{R_{eff}} = 232 \) km/s. These are typical values for an elliptical galaxy. If a NFW profile is used, the mass contained in the effective radius is \( M_{R_{eff}}^{NFW} = (2.33 \pm 0.05) \times 10^{12} M_\odot \).

An extended part of the dark matter halo is contributing to the lens effect. The contribution of the halo is confirmed by the fact that the mass-to-luminosity ratio of the lens galaxy is \( M_L/L_L \sim 170 M_\odot/L_\odot \). This value is in the expected range if the dark matter halo contributes to the lens. The absolute luminosity of the galaxy has been obtained from the SDSS database. The mass-to-luminosity ratios inside the effective radius, are \( \sim 30 M_\odot/L_\odot \) for the isothermal models and \( \sim 100 M_\odot/L_\odot \) for the NFW model. The value for
the NFW is much higher than expected for a typical elliptical galaxy. The value for the isothermal profile is high, but can be still in the expected range for elliptical galaxies.

Conclusions

A candidate to strong lensed quasar by a closer galaxy has been found in the SDSS DR5 data. The system fulfills the conditions to be considered a gravitational lens. There are two point-like images with very similar redshifts (\(\sim 3\)) and spectra and there is a galaxy between the images with a redshift smaller than the images (\(\sim 0.25\)). The angular separation between the two images is large (\(\sim 13''\)).

The fitted Einstein radius for the lens is large, \(\theta_E = 7.68 \pm 0.09''\). The total mass inside the Einstein radius is \(M_L = (5.3 \pm 0.1) \times 10^{12} M_\odot\). The mass-to-luminosity ratio of the lens galaxy at the Einstein radius, or 5.8 effective radii, is high, \(M_L/L_L > 100 M_\odot/L_\odot\). This is compatible with a substantial contribution of the dark matter halo to the lensing mass. The extrapolation of the mass value from the Einstein radius to the effective radius with different mass distributions shows that the isothermal models are a good description for an elliptical galaxy, with mass and velocity dispersion in the expected range. The orientation angle resulting from the fit (in both models) is misaligned with respect to the orientation angle of light, which may indicate some small contribution of an external perturbation. In fact, there seems to be a group or cluster of galaxies at \(z \sim 0.5\) that may have some contribution to the lensing of the quasar.

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Table 1: Astrometry and photometry of the lens objects. The difference in right ascension and declination with respect to the lens galaxy is given in arcsec. The coordinates of the galaxy are $\text{ra}=169.045962^\circ$, $\text{dec}=41.305817^\circ$. The given magnitudes are the SDSS model magnitudes in the five bands.

| Object | GAL | QSO 1 | QSO 2 |
|--------|-----|-------|-------|
| $\Delta \text{ra} (''')$ | 0.0 | 10.541 | 0.590 |
| $\Delta \text{dec} (''')$ | 0.0 | -5.227 | -6.473 |
| $u$ | 21.75 $\pm$ 0.28 | 20.40 $\pm$ 0.05 | 21.36 $\pm$ 0.11 |
| $g$ | 19.79 $\pm$ 0.02 | 18.54 $\pm$ 0.01 | 19.45 $\pm$ 0.01 |
| $r$ | 18.62 $\pm$ 0.01 | 18.15 $\pm$ 0.01 | 19.15 $\pm$ 0.01 |
| $i$ | 18.03 $\pm$ 0.01 | 17.93 $\pm$ 0.01 | 19.00 $\pm$ 0.01 |
| $z$ | 17.64 $\pm$ 0.03 | 17.96 $\pm$ 0.02 | 19.03 $\pm$ 0.04 |

Table 2: Lens parameters obtained from fits to two models of the mass distribution: SIE and SISS. Ellipticity or shear plus orientation angle may indicate some influence of external perturbations.

| Model | $\theta_{\text{Einstein}} (''')$ | Mass ($10^{12} M_\odot$) | Shear | Ellipticity | Angle ($^\circ$) |
|-------|-----------------|-----------------|------|------------|-----------------|
| SIE   | 7.68 $\pm$ 0.07 | 5.3 $\pm$ 0.1   | –    | 0.06 $\pm$ 0.02 | 263 $\pm$ 6    |
| SISS  | 7.68 $\pm$ 0.07 | 5.3 $\pm$ 0.1   | 0.02 $\pm$ 0.01 | –          | 263 $\pm$ 6    |
| Band | Ellipticity | Orientation Angle (°) |
|------|-------------|-----------------------|
| $u$  | 0.41 ± 0.73 | 142                   |
| $g$  | 0.34 ± 0.06 | 156                   |
| $r$  | 0.28 ± 0.03 | 157                   |
| $i$  | 0.30 ± 0.03 | 153                   |
| $z$  | 0.26 ± 0.06 | 157                   |

Table 3: Main physical characteristics of the lens galaxy in the five SDSS bands. The ellipticity and the orientation angle are the De Vacouleurs values read from the SDSS database. The orientation angle is defined in the SDSS standard way, east of north.
Figure 1: SDSS image of the lens candidate. The two images of the quasar are compatible with point-like objects, while the galaxy is an extended object located in the middle of the two quasar images.
Figure 2: Top: Spectra of the two QSO images taken in the SDSS spectroscopic survey. Bottom: Ratio of both spectra. The value is constant along the considered wavelengths range.
Figure 3: Measured (dots) and fitted (open circles) positions of the QSO images and the lens galaxy for the two mass models considered, SIE (top) and SISS (bottom). The size of the dots and the open circles does not correspond to the errors, and is chosen to make them visible. The critical curves for the models and the fitted positions of the source are also plotted.