SDSS J1650+4251: A NEW GRAVITATIONAL LENS

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ABSTRACT

We report that the Sloan Digital Sky Survey quasar SDSS J165043.44+425149.3 is gravitationally lensed into two images, based on observations obtained with the WIYN 3.5 m telescope at the Kitt Peak National Observatory. The lensed quasar, at a redshift of $z = 1.547$, appears as two images separated by 1$''$2 with $B$-band magnitudes of 17.8 and 20.0. The lensing galaxy is clearly detected in $I$-band images obtained in 0$''$3 seeing after point-spread function subtraction of the two quasar images. A strong metal-line absorption system is also identified in the unresolved SDSS spectrum of the double quasar, suggesting a plausible lens redshift of $z = 0.58$. The $UBRI$ flux ratios of the pair vary significantly, from 8.5:1 in the blue to 5.4:1 in the red, a difference of 0.5 mag, and are likely due to differential reddening through the lensing galaxy, microlensing in one or both quasar images, or some combination of the two. Optical monitoring of the quasar pair, particularly at blue wavelengths, will be needed to determine if microlensing is indeed significant. The predicted differential time delay between the quasar images is on the order of 1 month, assuming the intervening absorption system is due to the lensing galaxy.

Key words: gravitational lensing — quasars: individual (SDSS J165043.44+425149.3)

1. INTRODUCTION

Gravitationally lensed quasars are useful for a wide range of applications, such as constraining the cosmological parameters $H_0$ (Koopmans et al. 2000; Kochanek 2002) and $\Lambda$ (Falco, Kochanek, & Muñoz 1998; Chae et al. 2002), mapping the structure of luminous and dark matter in intermediate-redshift galaxies (Koopmans & Treu 2003), and studying the evolution of the lensing galaxies themselves (Kochanek et al. 2000). Owing to a number of large-scale surveys for lensed quasars at both optical and radio wavelengths, there are now well over 70 confirmed systems. In this paper we report that the quasar SDSS J1650+4251 is gravitationally lensed into two images, based on observations obtained with the WIYN 3.5 m telescope. We present the lens discovery data and subsequent detection of the lensing galaxy in §2, assess the SDSS spectrum of the system in §3, and discuss the plausible redshift and potential model of the lensing galaxy in §4. Our findings and possible directions for future work are summarized in §5.

2. OBSERVATIONS AND ANALYSIS

SDSS J1650+4251 (16$^h$50$^m$43$^s$.44, +42$^\circ$51$'$49$''$3; J2000.0) was identified as a $z = 1.547$ redshift quasar from the first data release of the Sloan Digital Sky Survey (SDSS DR1). The target’s blue magnitude is $g = 17.51$, which includes a 0.06 mag correction for foreground Galactic extinction (Schlegel, Finkbeiner, & Davis 1998). In addition, the object does not appear to have been known prior to its Sloan discovery, as queries to the NRAO VLA Sky Survey radio catalog, the ROSAT X-ray database, and the NASA/IPAC Extragalactic Database returned no results within 2$'$ of the quasar’s coordinates. During the nights of 2003 April 24 and 25, approximately 200 DR1 quasars were reimaged under excellent seeing conditions with the WIYN telescope at the Kitt Peak National Observatory, with the goal of identifying multiple-image morphology indicative of gravitational lensing. Our snapshots consisted of 30 s R-band exposures using the Mini-Mosaic direct imager, which has a field of view of 9.6 square and a gain and read noise of 1.5 $e^-$ ADU$^{-1}$ and 5.5 $e^-$, respectively. We operated in 2 $\times$ 2 binning mode to help minimize the readout time, which provided a scale of 0.282 pixel$^{-1}$.

For each target we assigned an a priori lensing probability based on the quasar’s redshift and $g$-band magnitude. These crude probabilities, which are computed using an optical depth calculation and a magnification bias factor (e.g., Kochanek 1996), were used to select targets for reimaging during the observing run. The a priori lensing probability for SDSS J1650+4251 was 0.7%, placing it in the top 2% of the ~8000 DR1 quasars accessible during the WIYN run. The discovery snapshot of the target immediately revealed it to be double, with an image separation of 1$''$2 and an R-band flux ratio of ~5:1. Binned follow-up images were obtained in Harris $UBRI$ filters, as well as several unbinned images in the I band alone, and they revealed a similar separation and flux ratio in the other bandpasses. The seeing during the discovery and follow-up images was exceptional, ranging from 0$''$6 FWHM in $U$ to 0$''$3 FWHM in $I$. A summary of the WIYN data for SDSS J1650+4251 is provided in Table 1. In addition, $UBRI$ images of the Landolt (1992) standard field PG 1633 were also obtained immediately following the quasar observations. A 2$''$5 square region of the target and surrounding field is shown in Figure 1.

The images were bias-subtracted and flat-field-corrected using twilight sky flats taken during the run. To model the
light distribution of the double image, we have simulta-
neously fitted two empirical point-spread functions (PSFs) to components A (brighter) and B (fainter) for each image listed in Table 1 using a Powell minimization routine (Press et al. 1992). For the BRI-band images, star 2 in Figure 1 provided the PSF. This star dropped significantly in brightness toward the blue, so star 1 served as the U-band PSF. After subtracting the best-fit models, no significant structure was detected in the residual image for the UBR data. The average flux ratio for the two components was 5.4 : 1 in R and increased toward bluer wavelengths to 7.3 : 1 in B and 8.5 : 1 in U. Relative astrometry and photometry for the two-component models are reported in Table 2. Magnitudes in Table 2 have been calibrated using zero points (but no color terms) obtained from the PG 1633 standards.

The lack of significant residuals in the UBR data indicates that the system is well modeled by two point sources at these wavelengths. However, significant structure was present at the position of the double image after subtracting the two-component model from the unbinned I-band data, as seen in Figure 2b. The peak of the residual flux is ~15 σ (where σ is the rms noise per pixel) and is peaked roughly collinear and between the brighter two components. This position is what would be expected for a simple singular isothermal sphere (SIS) lens model of the system, assuming the two brighter and pointlike images were lensed components of a single background quasar and the faint residual flux was from a foreground lensing galaxy.

To model the suspected galaxy flux (hereafter, component G), a third component was added to the I-band models and the simultaneous fits were repeated. The galaxy was modeled using a circularly symmetric "pseudo-Gaussian" light profile (Schechter & Moore 1993), which falls off more slowly than a true Gaussian at moderate distances (several pixels) from the profile core. The relative fluxes and positions of the three components were free to vary. Figure 2c shows the stacked residuals from the three-component I-band fits and is free from significant structure above 5 σ at the position of component G. There are still significant residuals (±8 σ) at the cores of component A and B, but this is most likely an artifact of fractional pixel shifts of the undersampled PSF. Figure 2d shows the same fit as in Figure 2c, but with the galaxy model unsubtracted. Results for the three-component fit are also reported in Table 2.

The I-band data place the galaxy closer to component B (θBG = 0''36) than to A (θAG = 0''87) and offset by 0''15 (1 pixel) to the southwest with respect to the quasar AB line. The average I-band flux ratio, 5.75 : 1, is slightly larger than that found at R. To estimate the galaxy magnitude in I, we have performed aperture photometry on the unsubtracted galaxy flux for the three-component model, that is, on

TABLE 1
Log of Observations for SDSS J1650+4251

| Frame | Filter | Exp. (s) | FWHM (arcsec) | Bin Mode |
|-------|--------|----------|---------------|----------|
| 302   | R      | 30       | 0.41          | 2        |
| 304   | U      | 60       | 0.58          | 2        |
| 305   | U      | 90       | 0.60          | 2        |
| 306   | I      | 60       | 0.38          | 2        |
| 307   | B      | 60       | 0.45          | 2        |
| 308   | I      | 60       | 0.32          | 1        |
| 309   | I      | 150      | 0.31          | 1        |
| 310   | I      | 150      | 0.32          | 1        |
| 311   | I      | 150      | 0.33          | 1        |
| 313   | R      | 60       | 0.40          | 2        |
| 314   | B      | 60       | 0.47          | 2        |

Note.—Binning modes 1 and 2 yield a pixel scale of 0''141 and 0''282 pixel⁻¹, respectively.

Fig. 1.—A 2/5 square finding chart for SDSS J1650+4251 and surroundings. The lens and two PSF stars are labeled.

TABLE 2
Astrometry and Photometry for SDSS J1650+4251

| Filter | m_A | m_B | m_G | ΔR.A. (arcsec) | ΔDecl. (arcsec) | ΔR.A. (arcsec) | ΔDecl. (arcsec) |
|--------|-----|-----|-----|----------------|-----------------|----------------|----------------|
| U      | 17.10 | 19.42 | ... | 0.212          | -1.138           | ...             | ...             |
| B      | 17.80 | 19.96 | ... | 0.212          | -1.145           | ...             | ...             |
| R      | 17.44 | 19.26 | ... | 0.223          | -1.147           | ...             | ...             |
| I      | 17.15 | 19.05 | 20.5 | 0.223 ± 0.002  | -1.163 ± 0.001  | 0.017 ± 0.032  | -0.872 ± 0.026  |

Note.—Harris magnitudes for components A, B, and G are denoted by m_A, m_B, and m_G, respectively. Relative astrometry for components B and G are with respect to component A. Error bars for the I-band positions are from the rms dispersion among the four unbinned I-band frames.
D. An aperture radius of 0.71 (5 pixels) was used and yields a calibrated magnitude of $I = 20.5$. Since no aperture correction was applied, this is likely a lower limit to the true galaxy magnitude.

3. SPECTRAL OBSERVATIONS

Unresolved spectra of SDSS J1650+4251 were obtained with the 2.5 m telescope at Apache Point, New Mexico, on 2001 June 19 as part of the standard SDSS spectroscopic follow-up of color-selected quasar candidates (Richards et al. 2002). The spectrum has a wavelength coverage of approximately 3800 to 9200 Å, a dispersion that ranged from 1 to 2 Å pixel$^{-1}$ from blue to red, and a total on-source exposure time of 2700 s. A 5 Å binned sample of the Sloan spectrum is reproduced in the top panel of Figure 3.

The 50% seeing disc was during the exposure, ensuring that light from both components was well mixed. The unresolved spectrum clearly shows broad emission lines of C IV, C III, and Mg II, consistent with at least one object being a $z = 1.5474$ quasar (as determined from a Gaussian fit to the Mg II emission feature). If the remaining component were a foreground star, then one might expect zero-redshift stellar features in the unresolved spectrum. The expected locations of several stellar features are marked by the dashed lines in Figure 3, but none are readily identified with features in the spectrum. (The absorption feature at the expected location of the Na doublet is actually consistent with a Mg II doublet at $z = 1.108$). The lack of significant stellar absorption lines, together with the absence of other quasar emission lines at a redshift different than that quoted above, argues for two similarly redshifted quasars.

There is also evidence for several $z > 0$ absorption systems in the spectrum. The two strongest absorption systems are identified using four doublet features at approximate observed wavelengths of $\lambda\lambda 3945, 4090, 4415$, and 7125. The bluest and reddest of these absorption doublets lie on top of the C IV and Mg II quasar emission lines and are consistent with C IV $\lambda\lambda 1548, 1550$ (bottom left, Fig. 3) and Mg II $\lambda\lambda 2796, 2803$ at redshifts of $z = 1.545$ and 1.546, respectively. These features are clearly associated with the quasar, which supports the idea of Chartas (2000) that quasars with intrinsic absorption (particularly broad absorption–line quasars) may be overrepresented in the sample of known gravitational lenses. The remaining two strong doublets are consistent with an intervening absorption system at $z = 0.577$ arising from Fe II $\lambda\lambda 2587, 2600$ and Mg II $\lambda\lambda 2796, 2803$ (bottom right, Fig. 3). Assuming this absorber redshift, a weak Mg I $\lambda 2853$ absorption singlet was also identified at the same redshift. There is also evidence for two

Fig. 2.—Excised images of SDSS J1650+4251 taken in 0′′3 seeing with WIYN (scale of 0′′141 pixel$^{-1}$). The orientation and angular size of each panel are identical. (a) Stacked I-band image of the lens. (b) Residuals of (a) after fitting and subtracting two empirical PSFs to components A and B. (c) Residuals of (a) after fitting and subtracting two empirical PSFs plus circularly symmetric pseudo-Gaussian profile to model the lensing galaxy (component G). (d) Same as (c), but with the galaxy model unsubtracted. The contrast level for (b), (c), and (d) range from $-3 \sigma$ to $10 \sigma$, where $\sigma$ is the rms noise (Poisson + readout) associated with each pixel. Note the possible companion galaxy (G2) 3″ south of the main lensing galaxy.
weak Mg II systems at redshifts above unity (z = 1.108 and z = 1.323), but their identifications are less secure than the ones for the features above.

4. DISCUSSION

4.1. Plausible Redshift of the Lensing Galaxy

Although the lensing galaxy currently lacks a spectroscopic redshift, a plausible redshift of z = 0.577 is suggested by the intervening Mg II and Fe II absorption system present in the quasar spectrum. One can statistically estimate the redshift of the lensing galaxy following the approach of Kochanek (1992). Using the image separation of 1″ 2 and quasar redshift of z = 1.547, we find a median lens redshift of z = 0.59 with a 1 σ interval of 0.36 < z < 0.82 (assuming matter and energy densities of 0.3 and 0.7 of the closure density, respectively).

An additional estimate of the galaxy redshift can be obtained from the observed I-band magnitude. For a given lens redshift, and assuming an isothermal sphere model for the lensing potential, the galaxy’s velocity dispersion σ is related to the observed image separation Δθ by

\[ \Delta \theta = \frac{D_{ls}}{D_{os}} \frac{8 \pi \sigma^2}{c^2} \]  

(Narayan & Bartelmann 1999), where D_{ls} and D_{os} are angular diameter distances from the lens to the source and from the observer to the source, respectively. The galaxy’s B-band luminosity can be estimated from its velocity dispersion using the Faber-Jackson (1976) relationship, \( L/L_\ast = (\sigma/\sigma_\ast)^\gamma \), where \( L_\ast \) corresponds to a B-band magnitude of \( M_\ast = -19.7 + 5 \log h \) and we adopt \( \sigma_\ast = 225 \) km s\(^{-1}\) and \( \gamma = 4.0 \) appropriate for elliptical galaxies. Finally, the galaxy’s apparent magnitude \( m \) is given by

\[ m_{AB}(\lambda_{obs}) = M_{AB}(\lambda_{rest}) + 5 \log \left( \frac{D_{ol}}{10 \text{ pc}} \right) + 7.5 \log(1 + z) \]  

where \( D_{ol} \) is the angular diameter distance from the observer to the lens. For calculating \( M_{AB}(\lambda_{rest}) \), a spectral energy distribution (SED) for an early-type galaxy was obtained from

![Graphs showing absorption lines and redshifts](image-url)
potential \( \phi \) given by
\[
\phi = br - \frac{\gamma}{2} r^2 \cos 2(\theta - \theta_s).
\] (3)

The major axis of the isopotential lines point along \( \theta_s \) (measured east of north), which is also the direction (modulo 180°) of the perturbing mass responsible for the shear. Note that the sign convention for the shear term is opposite to that adopted by Wisotzki et al. (2002), whose SIS + shear model predicts a perturbing mass at ±90° from \( \theta_s \). In the limit of vanishing shear (\( \gamma \to 0 \)) the strength of the potential, \( b \), corresponds to the Einstein radius of the system, which is also half of the observed image separation. There are five model parameters (including two for the unknown quasar source position) and five constraints (the relative positions of components A and B with respect to the lensing galaxy and the A/B flux ratio). Thus, there are no degrees of freedom and our best fit is characterized by \( \chi^2 = 0 \).

Parameter values were obtained by minimizing residuals in the source plane. For a given parameter set, each quasar image is traced back from the image plane to the source plane using the lens equation, and the optimal model parameters are then found by minimizing residuals between the model source position and the backward projection of the image positions.

Using the \( I \)-band positions and flux ratio as constraints, our best-fit model parameters are \( b = 0\arcsec.665, \gamma = 0.152, \) and \( \theta_s = 136\arcsec.8, \) and a lensed source position of \((\Delta \alpha, \Delta \delta) = (-0\arcsec.136, 0\arcsec.218)\) with respect to the lensing galaxy. The model predicts magnification factors of 4.94 and −0.86 for components A and B, where the negative sign denotes a parity flip, and a differential time delay between quasar images of 33.8 days for a Hubble constant of 75 km s\(^{-1}\) and assumed galaxy redshift of \( z = 0.577 \). At this redshift the corresponding velocity dispersion for the lensing galaxy would be 185 km s\(^{-1}\) for an elliptical galaxy. The Faber-Jackson relationship predicts a \( B \)-band galaxy luminosity of roughly 0.5 \( L_\odot \), which is not unreasonable.

The shear strength is fairly large for a double system. If the source of shear was from a neighboring galaxy with the same velocity dispersion and redshift as the main lensing galaxy, then it would be located 20' away. Indeed, there is a possible companion galaxy 30' south from the lensing galaxy (object G2 in Fig. 2); however, the position angle (P.A.) of the nearby galaxy (171° east of north) differs by 35° from the best-fit shear direction. While this may indicate that the companion is actually a chance projection, it is hard to dismiss the notion that the nearby galaxy and large shear are associated.

In other lensed quasars with large shears a nearby group or cluster of galaxies at moderate distances (10° to 40°) sometimes acts as the source of the shear (Kundic et al. 1997; Schechter et al. 1997; Kneib, Cohen, & Hjorth 2000). For SDSS J1650+4251, there is one faint object 8' from the lensing galaxy at a P.A. of 110°, but the light profile is more consistent with a point source than a galaxy. Otherwise, there are no obvious galaxy concentrations near the shear position angle.

4.3. Flux Ratios

The flux ratios for the system show a significant change with wavelength, ranging from 5.4 : 1 in \( R \) to 7.3 : 1 in \( B \) to

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S. Lilly (1997, private communication), which consisted of interpolated and extrapolated values of the SEDs presented by Coleman, Wu, & Weedman (1980). The SED is then normalized to the Faber-Jackson luminosity at 4400(1 + \( z \)) Å, which yields the predicted AB magnitudes. To transform

Fig. 4.—Predicted \( I \)-band magnitude of the lensing galaxy as a function of the lens galaxy redshift (curved solid line), along with the 1 \( \sigma \) error range (curved dashed lines) expected from the scatter in the Faber-Jackson relationship. The horizontal line marks the observed \( I \)-band magnitude of the lensing galaxy (\( I = 20.5 \)), and the vertical tick marks the location of the intervening absorption system (\( z = 0.577 \)). The shaded region (0.36 < \( z < 0.82 \)) is the 1 \( \sigma \) statistical redshift range for the lensing galaxy.

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8.5 : 1 in U. Since gravitational lensing is achromatic, one would ideally expect the flux ratio to be constant. But in practice the observed fluxes can be affected by dust extinction, microlensing, or flux contamination from the intervening lensing galaxy. For SDSS J1650+4251, significant flux contamination of component B’s light from the lens appears unlikely, as the three component I-band fit (which models the galaxy flux separate from the quasar flux) yields an A : B flux ratio within 0.1 mag of the value found from the two-component R-band fit. Even less galaxy contamination would be expected at bluer wavelengths. However, the trend of increasing flux ratios toward bluer wavelengths is consistent with either differential reddening or microlensing, both of which are expected to produce a chromatic effect.

Could the flux ratios be accounted for by differential reddening? Assuming that dust extinction is the primary cause, we can quantify the amount of differential reddening needed between the two lines of sight using the approach of Falco et al. (1999). If $m_{l}(\lambda)$ is the observed magnitude of the $i$th image, then the magnitude difference between the $i$th and $j$th image is given by

$$m_i(\lambda) - m_j(\lambda) = -2.5 \log \left( \frac{\mu_i}{\mu_j} \right) + (E_i - E_j) R \left( \frac{\lambda}{1+z_i} \right),$$

where $\mu$ is the macro-magnification factor, $E$ is the $E(B-V)$ extinction, and $R(\lambda)$ is the extinction curve. The optical and UV extinction curves were calculated using the parameters from Cardelli, Clayton, & Mathis (1989), and we have set the $R_V$ extinction parameter to the Galactic value of $R_V = 3.1$, and we use a lens redshift of $z_l = 0.58$. Our best-fit solution has $(M, \Delta E) = (4.4, -0.07)$, with image B suffering more extinction than image A, and it reproduced the observed $UBRI$ flux ratios to within 0.02, −0.10, 0.12, and −0.04 mag, respectively. A negative value denotes a predicted flux ratio larger (closer to unity) than observed. As a comparison, the expected magnitude differences with no differential extinction are 0.27, −0.11, 0.23, and 0.15 mag for $UBRI$, respectively.

The required differential extinction of 0.07 mag is not unreasonable; the median differential extinction found by Falco et al. (1999) for their sample of 15 optically selected gravitational lenses is $|\Delta E| = 0.04$, with nearly three out of four flux ratios having $|\Delta E| < 0.1$. Thus, differential reddening is one plausible explanation that can account for the color-dependent flux ratios seen for SDSS J1650+4251.

Microlensing of the source quasar’s continuum by stars in the lensing galaxy is another possible explanation. Since the microlensing caustic pattern has higher contrast on smaller angular scales, one expects larger microlensing amplitudes for smaller source sizes. Thus, the quasar’s blue continuum ought to undergo larger microlensing-induced variations than the red continuum. This argues for either a net microlensing demagnification of image B or amplification of image A, on the order of several tenths of a magnitude, during the WIYN observations. Discriminating between dust extinction and microlensing should be straightforward, since the microlensing pattern is expected to change with time, while extinction due to dust should not. Future monitoring of the quasar pair, particularly in the blue, will help determine if microlensing is indeed significant.

5. CONCLUSIONS

We have reported that the $z = 1.547$ quasar SDSS J1650+4251 is gravitationally lensed into a 1:2 double. The lensing galaxy is clearly detected in $I$ band after PSF subtraction of the two quasar images, and it is located closer to the fainter quasar image, as expected for a simple SIS model of the lensing potential. A strong metal-line absorption system is detected in the unresolved spectrum of the quasar pair, suggesting a plausible lens redshift of $z = 0.577$. Taking this as the lensing galaxy redshift, an SIS plus external shear model predicts a differential time delay of 33.8 days ($H_0 = 75$ km s$^{-1}$). Resolved spectra of the lensing galaxy will be needed to obtain a confident galaxy redshift and precise time delay prediction.

The flux ratios for the system show a change of 0.5 mag with wavelength, ranging from 5.4 : 1 in $R$ to 8.5 : 1 in $U$. The trend of larger flux ratios toward bluer wavelengths can be explained reasonably well by differential dust extinction through the lensing galaxy, although microlensing-induced variations may also be present. For at least one doubly lensed quasar, SBS 0909+532 (Kochanek et al. 1997), the flux ratio is known to vary by up to a full magnitude across optical wavelengths, so the magnitude of variation observed for SDSS J1650+4251 is not unprecedented. Optical monitoring of the double quasar, particularly at blue wavelengths, will help determine if microlensing is significant and if the lensed quasar is sufficiently variable for time delay studies.

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