

MICROLENSING OF THE BROAD EMISSION LINE REGION IN THE QUADRUPLE LENS SDSS J1004+4112

GORDON T. RICHARDS,¹ CHARLES R. KEETON,^{2,3} BARTOSZ PINDOR,^{1,4} JOSEPH F. HENNAWI,¹ PATRICK B. HALL,¹
 EDWIN L. TURNER,¹ NAOHISA INADA,^{5,6} MASAMUNE OGURI,⁵ SHIN-ICHI ICHIKAWA,⁷ ROBERT H. BECKER,^{8,9}
 MICHAEL D. GREGG,^{8,9} RICHARD L. WHITE,¹⁰ J. STUART B. WYTHE,^{1,11} DONALD P. SCHNEIDER,¹²
 DAVID E. JOHNSTON,^{1,2,13} JOSHUA A. FRIEMAN,^{2,13,14} AND J. BRINKMANN¹⁵

Received 2004 February 13; accepted 2004 April 13

ABSTRACT

We present seven epochs of spectroscopy on the quadruply imaged quasar SDSS J1004+4112, spanning observed-frame time delays from 1 to 322 days. The spectra reveal differences in the emission lines between the lensed images. Specifically, component A showed a strong enhancement in the blue wings of several high-ionization lines relative to component B, which lasted at least 28 days (observed frame) and then faded. Since the predicted time delay between A and B is $\lesssim 30$ days, our time coverage suggests that the event was not intrinsic to the quasar. We attribute these variations to microlensing of part of the broad emission line region of the quasar, apparently resolving structure in the source plane on a scale of $\sim 10^{16}$ cm at $z = 1.734$. In addition, we observed smaller differences in the emission-line profiles between components A and B that persisted throughout the time span, which may also be due to microlensing or millilensing. Further spectroscopic monitoring of this system holds considerable promise for resolving the structure of the broad emission line region in quasars.

Subject headings: gravitational lensing — quasars: emission lines — quasars: general —
 quasars: individual (SDSS J100434.91+411242.8)

1. INTRODUCTION

Microlensing in the images of a multiply imaged quasar was first reported by Irwin et al. (1989) for the quadruple lens Q2237+0305 (Huchra et al. 1985). Most quasar microlensing studies have been based on broadband photometric monitoring (e.g., Woźniak et al. 2000; Schechter et al. 2003; Colley & Schild 2003), which is sensitive primarily to variations in the continuum. Microlensing of the continuum is expected, since the optical/UV continuum emission is thought to originate in a region that is comparable in size to the Einstein radius of a typical star in a typical lens galaxy. There have been various attempts to study microlensing with spatially resolved

spectroscopy of several lens systems, and most of them have confirmed variations in the continuum (Fitte & Adam 1994; Lewis et al. 1998; Nadeau et al. 1999; Wisotzki et al. 2003; Wucknitz et al. 2003; Gómez-Álvarez et al. 2004).

Microlensing of the broad emission line region (BELR) is also possible if the BELR has structure on scales comparable to the Einstein radius of a star (Nemiroff 1988; Schneider & Wambsganss 1990). The possibility of BELR microlensing seemed rather remote until recent reverberation mapping work revised the estimate of the BELR size downward from $\sim 10^{18}$ to $\sim 10^{16}$ cm (Wandel et al. 1999; Kaspi et al. 2000). Inspired by these numbers, Abajas et al. (2002) and Lewis & Ibata (2004) revived the idea of looking for microlensing of the BELR and computed possible line profile variations for various BELR models.

Possible examples of microlensing of a quasar emission line have been presented by Filippenko (1989) for Q2237+0305, by Chartas et al. (2002) for MG J0414+0534, and by Chartas et al. (2004) for H1413+117. In particular, Chartas et al. (2004) detected a strong, redshifted Fe K α emission line in the X-ray spectrum of only one of the components in the quadruple lens H1413+117. Although they did not have multiple epochs to look for variability, Chartas et al. (2004) invoked a short predicted time delay between the components to argue that microlensing is the preferred explanation for seeing the Fe K α line in only one component. Chartas et al. (2002) did have multiple epochs of X-ray observations for the quadruple lens MG J0414+0534, and over a 3 month time frame they detected a fivefold increase in the equivalent width of the redshifted Fe K α line in component B but not in component A (components C and D were too faint for the line to be resolved). In other cases, some of the previous resolved spectroscopy observations did reveal apparent changes in the broad emission lines (e.g., Angonin et al. 1990; Lewis et al. 1998; Wisotzki et al. 2003), but the changes were in the

¹ Princeton University Observatory, Peyton Hall, Princeton, NJ 08544.

² Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.

³ Hubble Fellow.

⁴ Department of Astronomy, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada.

⁵ Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan.

⁶ Institute of Astronomy, University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan.

⁷ National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan.

⁸ Physics Department, University of California, 1 Shields Avenue, Davis, CA 95616.

⁹ Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, L-413, 7000 East Avenue, Livermore, CA 94550.

¹⁰ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

¹¹ University of Melbourne, Parkville, VIC 3010, Australia.

¹² Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802.

¹³ Center for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.

¹⁴ Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510.

¹⁵ Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349.

TABLE 1
SUMMARY OF OBSERVATIONS

Date (UT)	Telescope	Components	Exposure Time (s)	Dispersion (\AA pixel^{-1})	λ Range (\AA)
2003 Feb 3	SDSS 2.5 m	B	2700	~ 1	3800–9200
2003 May 3	ARC 3.5 m (DIS III)	A	1800	2.4	3820–5630
2003 May 31	Keck I (LRIS)	ABCD	900	~ 1	3028–9700
2003 Nov 21	ARC 3.5 m (DIS III)	AB	2700+2700	2.4	3890–9350
2003 Nov 30	ARC 3.5 m (DIS III)	AB	2700+2700	2.4	3890–9350
2003 Dec 1	ARC 3.5 m (DIS III)	AB	2400+2400	2.4	3890–9350
2003 Dec 22	ARC 3.5 m (DIS III)	AB	2400+2400	2.4	3890–9350

equivalent width of the lines rather than the line profiles and were probably caused by differential microlensing between the continuum and the BELR (as opposed to microlensing *within* the BELR itself).

In this paper we present results from spectroscopic monitoring of the recently discovered quadruple lens SDSS J1004+4112 (Inada et al. 2003; Oguri et al. 2004). SDSS J1004+4112 is lensed by a cluster and has large image separations, with distances between components ranging from $3''.73$ to $14''.62$. As a result, this system is much easier to resolve from the ground than typical lens systems and is an ideal target for spectroscopic monitoring. We observe variability in the broad emission line profiles of one of the lensed images that provides strong evidence for microlensing within the BELR, suggesting that the theoretical predictions for microlensing were correct and confirming that the BELR has structure on the scale of the Einstein radius of a star.

2. DATA AND SPECTRAL ANALYSIS

Component B of SDSS J1004+4112 was first identified as a quasar by Cao et al. (1999) and was also targeted as a quasar candidate (Richards et al. 2002) as part of the Sloan Digital Sky Survey (SDSS; York et al. 2000); the SDSS spectrum (resolution $R \sim 2000$) was taken on 2003 February 3 (in $1''.6$ seeing), and the object was identified as a $z = 1.734$ quasar. Component A was also identified as a possible quasar candidate based on its colors in the SDSS imaging data (Fukugita et al. 1996; Gunn et al. 1998); it was first confirmed as a quasar (also at $z = 1.734$) from observations taken on 2003 May 3 using the ARC 3.5 m telescope at Apache Point Observatory. Higher quality spectra of each of the four components and the lens galaxy were taken on 2003 May 31 with the LRIS (Oke et al. 1995) spectrograph on the Keck I telescope at the W. M. Keck Observatory. These spectra are further described in Inada et al. (2003), Oguri et al. (2004), and Table 1. Table 1 gives the UT date of the observations, the telescope used, the components observed, the exposure time, the dispersion, and the wavelength range covered.

Inada et al. (2003) and Oguri et al. (2004) noted that the Keck/LRIS spectra showed that all four components had the same redshift and similar spectra, but there are some obvious differences, with component A showing the largest differences relative to the other components (see Fig. 1). Specifically, component A has a much stronger blue emission-line wing in the high-ionization lines (Si IV/O IV], C IV, and He II). Component B appears to have a slightly enhanced red wing as compared with the other three components. In Figure 1, we have sought to emphasize the differences in the C IV emission line profile by subtracting a continuum fit between 1450 and 1690 \AA and then normalizing to the peak of C IV

emission. Other choices in presentation could enhance or reduce the appearance of similarities and differences between the components.

Based on the puzzling differences in the broad emission line profiles of the four components of the Keck/LRIS spectra, in 2003 November and December we obtained additional spectra of images A and B to monitor the differences; see Table 1. We used the DIS III spectrograph on the ARC 3.5 m telescope at Apache Point Observatory, using the same instrument setup and IRAF¹⁶ data reduction for each epoch. The dispersion was $2.4 \text{ \AA pixel}^{-1}$ (with 3.5 pixels per resolution element yielding a resolution of 8.4 \AA), and the spectra cover the range 3890–9350 \AA . Flux calibration was performed with respect to a hot standard star: either Feige 34 or G191-B2B. Wavelength calibration was performed with respect to a helium-neon-argon

¹⁶ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

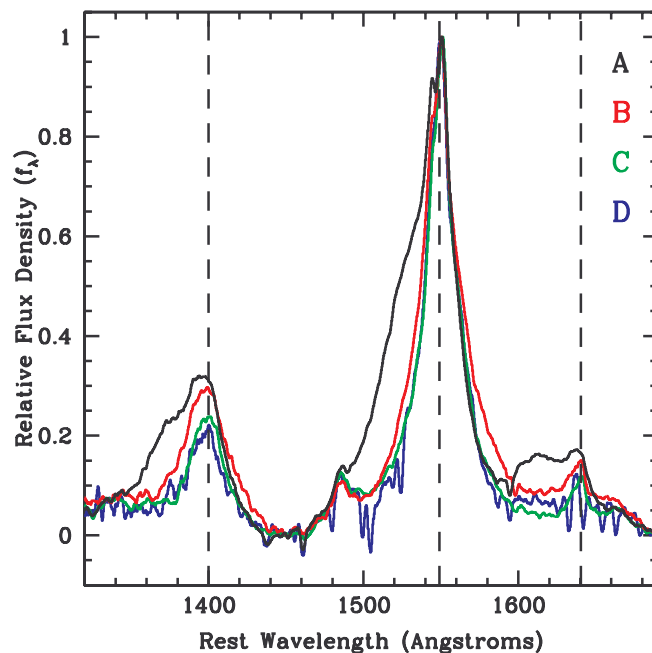


FIG. 1.—Keck/LRIS spectra of components A, B, C, and D of SDSS J1004+4112. Dashed vertical lines indicate the expected peaks of Si IV/O IV], C IV, and He II for $z = 1.734$. A power-law continuum, fitted between 1450 and 1690 \AA , has been subtracted from each spectrum, and the spectra are all normalized to the peak of C IV. The spectra are smoothed by a 7 pixel boxcar filter.

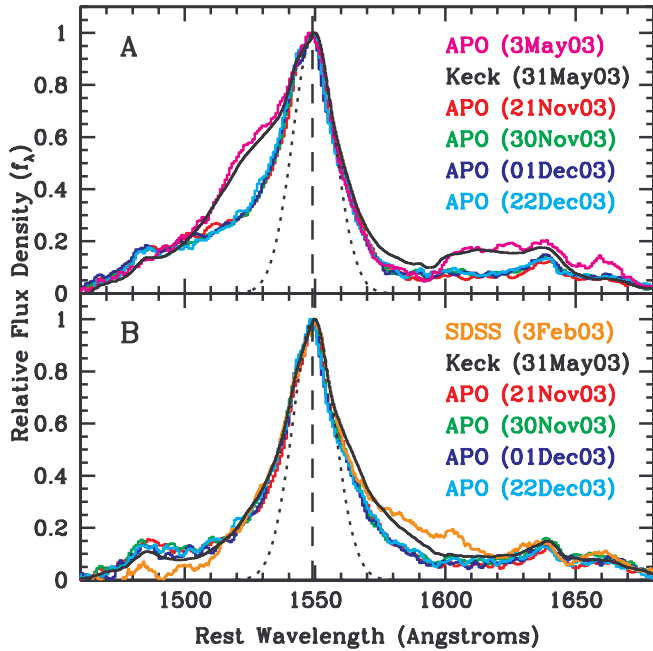


FIG. 2.—Seven epochs of data in the C IV emission line region of SDSS J1004+4112. A power-law continuum, fitted between 1450 and 1690 Å, has been subtracted from each spectrum, and the spectra are all normalized to the peak of C IV. We also overplot a scaled Gaussian at the center of C IV to guide the eye toward emission-line differences that are persistent with time. The dashed vertical line indicates the expected C IV peak at 1549.06 Å. All spectra have been smoothed to similar resolutions. Note that this smoothing hides the associated absorption system that is observed just blueward of the C IV emission line peak.

comparison lamp. Both components (which are separated by $3''.73$) were observed at the same time in order to minimize any differences between them, at the expense of loss of spectrophotometric accuracy (slit not positioned at the parallactic angle). At each epoch we took two spectra of either 40 or 45 minutes each. These spectra were extracted separately and then combined to yield the 2003 November/December epoch spectra shown in Figure 2. The two-dimensional spectra are only moderately resolved (the seeing ranged between $1''.0$ and $1''.8$), so we deblended the two-dimensional spectra by fitting a double Gaussian profile before extracting the spectra. We estimate that contamination of the faint component by the brighter component is less than 3%.

Figure 2 shows all seven epochs of spectroscopic data for components A and B in the C IV emission line region. The 2003 May 3 epoch observation of component A at Apache Point Observatory confirms the reality of the excess emission in the blue wing of component A in the Keck spectrum. The excess emission in He II spans a velocity range ~ 2500 – 8500 km s $^{-1}$ (blueshifted). Both Si IV and C IV have excesses over a slightly higher velocity range. The excess in He II is much stronger in terms of equivalent width than that in C IV.

3. DISCUSSION

3.1. Time-dependent Blue Wing Differences: Microlensing of the BELR

3.1.1. Discounting Alternatives and Objections

To argue that the excess in the blue wings of the high-ionization emission lines of component A is caused by microlensing of the BELR, we must rule out alternative explanations. The first question is whether the flux enhancements

are an artifact of the data acquisition or reduction procedures. We view this explanation as highly unlikely because the enhancement appeared at two different epochs in spectra taken by different observers with different telescopes and reduced independently.

The second question is whether the spectral variations could be intrinsic to the quasar, rather than induced by lensing. If so, then the same variations should be seen in the other lensed images, offset in time by the lens time delays. While the time delays are still uncertain, in nearly all of the lens models presented by Oguri et al. (2004), the delay between components A and B is predicted to be $\lesssim 30$ days. (The Oguri et al. models do not form an exhaustive set, but the prediction of a short time delay between A and B is generic.) In $\sim 10\%$ of the models component A leads component B. In this case, seeing the flux enhancement in the 2003 May 3 and May 31 spectra of component A but not in the 2003 May 31 spectrum of component B means that intrinsic variability cannot explain the data. In the other $\sim 90\%$ of the models component B leads component A. In this case, the intrinsic variability hypothesis would imply that the variations must have appeared in component B sometime after 2003 February 3, been present during 2003 April (in advance of the variations observed in component A in 2003 May), and then disappeared before 2003 May 31. In other words, the event must have lasted less than 117 days in the observed frame, or less than 43 days in the rest frame, and we were fortunate to catch the event in component A just before it disappeared.

Since the time separation of our spectral coverage does not completely rule out intrinsic variability, this issue deserves further discussion. Specifically, we must address the likelihood of intrinsic variability of the BELR on timescales of less than 43 days in the rest frame. Reverberation timescales can be less than 43 days, since the radius of the BELR is likely to be of the order of or less than this size. However, in that case either the entire emission-line profile will vary with respect to any significant change in the continuum or we would expect to see any asymmetric enhancement propagate to the other parts of the emission lines with time. Since we do not observe a significant change in the continuum level (see below) and since the enhancement of the emission lines is only in the blue wing and not over the rest of the line profile, a reverberation effect is unlikely. Thus we are left with the possibility of a dynamical change, such as is seen in the so-called double-peaked emission-line quasars (e.g., Eracleous & Halpern 2003; Strateva et al. 2003), which could better explain the blue-wing-only nature of the enhancement in the high-ionization emission lines. Indeed, the dynamical timescale (~ 6 months; Eracleous 2004) can be in the range needed to explain our observations. However, double-peaked emission is typically only seen in the Balmer lines (and sometimes Mg II) and is absent or weak at best in high-ionization lines like C IV and He II. Furthermore, it would be very unusual for a double-peaked emission-line object to show a blue-wing enhancement in both our 2003 May 3 and 2003 May 31 epochs, but no strong blue- or red-wing enhancement in our four 2003 November/December epochs. Thus, although an explanation of the data in terms of intrinsic variability is not rigorously excluded, such a model would have to be rather improbably contrived.

One possible objection to the microlensing hypothesis is that if the BELR was microlensed, why not the continuum as well? It is difficult to put constraints on any enhancement of the continuum of component A relative to B during the time spanned by our observations because not all of the spectra

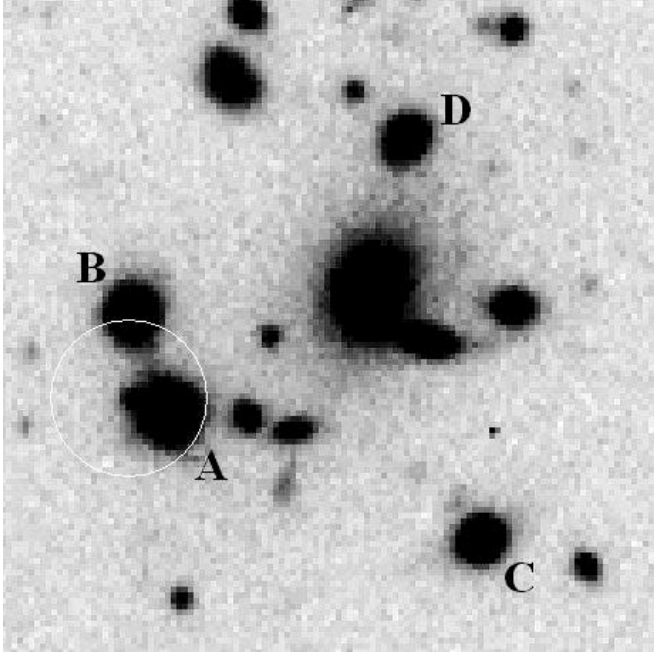


FIG. 3.—Central ($22''6$) region of the 1340 s *i*-band Subaru Prime Focus Camera image from Oguri et al. (2004, Fig. 8). North is up, east is left. Although the image is saturated and proper PSF subtraction of component A is not possible, there appears to be a superimposed galaxy (with an estimated $i \sim 24.5$) just to the northeast of component A that could host the microlensing object. The white circle is centered on the possible microlensing galaxy and represents a $20 h_{70}^{-1}$ kpc radius at $z = 0.68$, assuming $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 h_{70} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

were taken at the parallactic angle. Still, we can estimate that component A was no more than $\sim 20\%$ brighter than B in the continuum in 2003 May (as compared to 2003 November/December). However, this is not obviously inconsistent with the microlensing hypothesis. Because the caustic network may be complicated, it is easy to imagine configurations in which part of the BELR is close enough to a caustic to be microlensed, while the continuum source is far enough to feel little effect. In fact, detailed simulations by Lewis & Ibata (2004) show that there is poor correlation between the magnification of the BELR and the continuum source, so variations in the broad emission lines need not be accompanied by variations in the continuum. Observationally, in previous cases of apparent microlensing of the Fe K α line in lensed quasars, no change in the continuum was noted (Chartas et al. 2002, 2004; Dai et al. 2003). Overall, our general picture is that only *part* of the BELR was being microlensed in 2003 May (see § 3.1.3), and the continuum was not microlensed at that time.

Another possible complication with the microlensing hypothesis is that cluster galaxies tend to be stripped of their halos through mergers and interactions. Microlensing would therefore require either a cluster member very close to the line of sight to component A or a population of intracluster stars or massive compact halo objects (MACHOs; e.g., Totani 2003; Baltz et al. 2004). The presence of intracluster MACHOs might not be surprising, because tidal forces would naturally strip MACHOs from cluster galaxies along with the galaxy halos. On the other hand, there is evidence for a galaxy superimposed on component A that could host the microlensing object, as shown in Figure 3. Proper point-spread function (PSF) subtraction to confirm this hypothesis is not possible since component A is saturated in this image, but our

best efforts do reveal residual flux at the center of the circle in Figure 3 with an estimated magnitude of $i \sim 24.5$.

3.1.2. Examining the Microlensing Hypothesis

We can also reverse the argument and ask whether our microlensing hypothesis makes sense given our current understanding of the structure of quasars and the details of microlensing. Without invoking detailed microlensing and BELR models (which would be premature since we have observed only one microlensing event), we still find that qualitative and quantitative arguments reveal good consistency between the microlensing hypothesis and the data.

The scale for microlensing is given by the Einstein radius of a star (Schneider et al. 1992),

$$R_{\text{Ein},S} = \left(4 \frac{GM}{c^2} \frac{D_s D_{ls}}{D_l} \right)^{1/2}, \quad (1)$$

$$R_{\text{Ein},L} = \frac{D_l}{D_s} R_{\text{Ein},S}, \quad (2)$$

where $R_{\text{Ein},L}$ and $R_{\text{Ein},S}$ are the Einstein radius projected into the lens and source planes, respectively, and D_l , D_s , and D_{ls} are the angular diameter distances to the lens, to the source, and from the lens to the source, respectively. Although the microlensing probability distribution is a complex function of the microlensing parameters (e.g., Wambsganss 1992; Lewis & Irwin 1995), the Einstein radius sets the characteristic scale, and the BELR can be microlensed if it has structure on scales $\lesssim R_{\text{Ein},S}$ (Abajas et al. 2002; Lewis & Ibata 2004). For SDSS J1004+4112, the lens redshift is $z_l = 0.68$ and the source redshift is $z_s = 1.734$, so the Einstein radius of a $0.1 M_\odot$ star associated with the lensing cluster is

$$\begin{aligned} R_{\text{Ein},S} &\sim 1.4 \times 10^{16} \left(\frac{M}{0.1 M_\odot} \right)^{1/2} h_{70}^{-1/2} \text{ cm} \\ &\sim 5.3 \left(\frac{M}{0.1 M_\odot} \right)^{1/2} h_{70}^{-1/2} \text{ lt-days} \end{aligned} \quad (3)$$

in a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 h_{70} \text{ km s}^{-1} \text{ Mpc}^{-1}$. Thus, the typical stellar Einstein radius is indeed comparable to the currently favored size of the BELR, and microlensing is not unexpected.

The variability is caused by relative motion between the caustic network and the source. If the motion is dominated by the proper motion of the lens galaxy (with transverse velocity v_\perp), then the effective transverse velocity projected into the source plane and expressed in distance per unit observed-frame time is

$$v_{\text{eff}} = \frac{v_\perp}{1 + z_l} \frac{D_s}{D_l}. \quad (4)$$

If the microlensing is dominated by caustic crossings, then one characteristic timescale is the time for a caustic to sweep across the source, $t_{\text{src}} \sim 2R_{\text{src}}/v_{\text{eff}}$. If we estimate $v_\perp \sim \sigma$, where σ is the velocity dispersion of the lens, then $\sigma \sim 700 \text{ km s}^{-1}$ for the lensing cluster in SDSS J1004+4112 (Oguri et al. 2004) yields

$$t_{\text{src}} \sim 12.7 \left(\frac{R_{\text{src}}}{10^{16} \text{ cm}} \right) \left(\frac{v_\perp}{700 \text{ km s}^{-1}} \right)^{-1} \text{ yr}. \quad (5)$$

The situation may be more complicated than this, because at any given time the large BELR could be covered by more than

one caustic and the variability would represent their combined effect. In addition, the effective size of the emission region as a function of velocity may be much smaller than the overall size of the BELR (see Fig. 2 of Lewis & Iбата 2004). The fact that we see variability only in the blue wings of the emission lines and on a timescale of ~ 6 months indeed suggests that the microlensing affected a small part of the BELR, resolved in velocity space, that has a characteristic size much smaller than 10^{16} cm.

A second interesting timescale is the typical time between microlensing events. Here the key unit is the time to cross an Einstein radius,

$$t_{\text{Ein}} \sim R_{\text{Ein},S}/v_{\text{eff}} \\ \sim 8.6 \left(\frac{M}{0.1 M_{\odot}} \right)^{1/2} \left(\frac{v_{\perp}}{700 \text{ km s}^{-1}} \right)^{-1} h_{70}^{-1/2} \text{ yr.} \quad (6)$$

If even a few percent of the mass is in stars, microlensing is associated with a caustic network rather than a single star, and so naive estimates of the time between events are difficult. To obtain a better estimate, we have used the standard ray-shooting technique to compute microlensing magnification maps and generate sample light curves (Kayser et al. 1986; Wambsganss et al. 1990). We adopt a convergence $\kappa = 0.392$ and shear $\gamma = 0.642$ at the position of component A, inferred from a lens model consisting of a singular isothermal ellipsoid with an external shear that fits the data well (see Oguri et al. 2004 for modeling details). We assume that all the stars have the same mass and work in units of $R_{\text{Ein},S}$ so we need not specify the mass explicitly. We consider cases in which stars comprise 1%, 5%, 15%, and 25% of the surface mass density. We compute the magnification maps and then convolve them with a source profile. For simplicity, we take the source to be a uniform disk of radius R and consider a range of the ratio $R/R_{\text{Ein},S}$. The source is likely to be much more complicated, especially when its velocity structure is considered, but using more detailed models is beyond the scope of this paper and is not essential for our order-of-magnitude estimates. (See, e.g., Lewis & Iбата 2004 for examples of more sophisticated calculations.)

We find that starting from a nonmicrolensed position, the average wait time until the magnification changes by more than 30% is $\sim (0.2-0.8) \times t_{\text{Ein}}$. The range represents uncertainties in the source size and in the number density of microlenses. Although there are many uncertainties, it seems reasonable to expect that microlensing events could be observed in SDSS J1004+4112 on an approximately yearly basis. Incidentally, if $t_{\text{src}} \gtrsim t_{\text{Ein}}$, then microlensing events will blur together and the light curves will show continuous smooth variations (see, e.g., Kochanek 2004). The apparent lack of microlensing in the 2003 November/December epochs therefore adds further support to the hypothesis that the region being microlensed is smaller than $\sim 10^{16}$ cm.

The microlensing hypothesis nicely explains one of the more interesting observational results, namely, that different emission lines show different amounts of variability. From reverberation mapping results, we know that the BELR is stratified by ionization and that higher ionization lines are found closer to the center (Peterson & Wandel 1999). As a result, the highest ionization regions have the smallest effective sizes and should be the most sensitive to microlensing. Our finding that the excess in the He II line is stronger than the excess in the C IV line (in terms of equivalent width) is

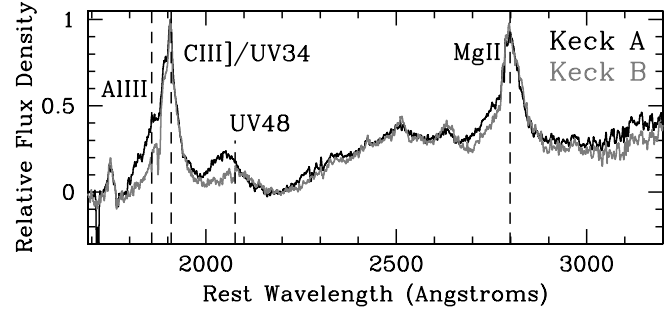


FIG. 4.—Comparison of Keck spectra of components A and B in the C III]/UV34 to Mg II region of the spectra, showing the weaker enhancement (relative to the higher ionization lines) of the blue wings of these emission lines. A power-law continuum, fitted between 1690 and 2200 Å, has been subtracted from each spectrum, and the spectra are all normalized to the peak of C III]. No constraint is placed on Mg II. The dashed vertical lines indicate the expected Al III], C III], and Mg II peaks in addition to the Fe III UV34 and UV48 complexes. The spectra are smoothed by a 7 pixel boxcar filter.

consistent with their relative reverberation mapping sizes (Peterson & Wandel 1999). Furthermore, there is a suggestion of a weaker excess in the blue wings of the C III]/Si III]/Al III]/Fe III UV34 complex, Mg II, and Fe III UV48 (a triplet at 2062.211, 2068.904, and 2079.652 Å; see Figure 4 and also the ratio spectra in Figure 3 of Oguri et al. (2004). All of the above lines are lower ionization lines than C IV and He II, so their weaker excesses are also consistent with being more weakly microlensed as a result of their emitting regions being larger with respect to the projected Einstein radius of the lens.

An obvious question is if the BELR in SDSS J1004+4112 is being microlensed, why should it be seen more robustly in this lens system than in others? One possibility has to do with the quasar's intrinsic luminosity. The observed absolute i magnitude of component A is $M_i = -26.9$, but this component is amplified by a factor of ~ 20 or more,¹⁷ so the intrinsic absolute i magnitude is $M_i \gtrsim -23.8$. Many other lensed quasars have similar observed magnitudes but smaller amplifications and hence higher luminosities. Since the size of the BELR scales as the 0.5–0.7 power of the luminosity (e.g., Kaspi et al. 2000), SDSS J1004+4112 being relatively underluminous would make it more sensitive to microlensing than many other lensed quasars.

The large amplification helps make microlensing unsurprising in another way. Large amplifications are associated with significant distortions that increase the size of the caustics (see Fig. 2 of Schechter & Wambsganss 2002). Thus, with a given star field the microlensing probability increases as the amplification increases. This may explain not only why microlensing has been detected in SDSS J1004+4112 but also why it was seen first in component A (the highest amplification component).

3.1.3. Implications for BELR Structure

Obtaining concrete constraints on the structure of the BELR will require detailed modeling and would greatly benefit from observations of additional microlensing events. Nevertheless, combining the data in hand with general arguments already permits some strong and valuable conclusions. First, unless

¹⁷ An isothermal ellipsoid plus shear lens model, which is simple but fits the data well, implies an amplification factor of 23 for component A. More complicated models yield a broad range of amplifications where the median is 18 but there is a long tail to amplifications of 100 or more. See Oguri et al. (2004) for modeling details.

the number of clouds is orders of magnitude smaller than required by other high-resolution Keck observations (Arav et al. 1998), the asymmetric nature of the microlensing (lensing of the blue wing only) rules out a spherically symmetric distribution of dynamically virialized, thermal line width clouds (Nemiroff 1988; Abajas et al. 2002; Lewis & Ibat 2004).

Pure radial outflow models can be ruled out because they would produce symmetric line profile changes with most of the variation in the line core (Nemiroff 1988). Pure radial inflow models cannot be fully excluded, but asymmetric microlensing would require the accretion disk to have a radial extent comparable to the radial extent of the BELR and to be optically thick (such that we do not see clouds at all velocities).

The asymmetry therefore seems to imply that a strong rotational component is needed in the high-ionization region of the BELR. Such a component could come in the form of a pure Keplerian disk or a rotating-disk wind (e.g., Murray & Chiang 1998; Elvis 2000). Microlensing of the part of the BELR that is rotating toward us would then easily explain the features that we observe. Popović et al. (2001) show how microlensing can affect the profiles of disk-based emission lines that are seen in quasars with double-peaked emission lines (e.g., Popović et al. 2003; Eracleous & Halpern 2003), although high-ionization emission lines like C IV and He II generally do not show the same double-peak emission-line structure as the Balmer lines in these objects and thus are likely to have a different origin.

The most robust statement we can make is that the observations confirm that the BELR has structure on the scale of the Einstein radius. Because we are sampling a region on the order of $\sim 1.4 \times 10^{16}$ cm, we effectively have a “telescope” with a resolution of $\sim 5 \times 10^{-7}$ arcseconds (given an angular diameter distance to the quasar of $\sim 5.4 \times 10^{27}$ cm). In other words, in SDSS J1004+4112, nature has provided us with an extremely powerful tool for the study of BELR structure.

3.1.4. Some Predictions

The microlensing hypothesis leads to several predictions that may guide further observations. First, the nature of the object(s) responsible for the microlensing is unknown. Two obvious possibilities are stars or MACHOs associated with a galaxy (presumably a cluster member) with a small projected impact parameters to component A, or stars or MACHOs in the intracluster medium. While the Subaru *i*-band image of the field (Fig. 3) suggests that there is indeed a galaxy near component A, the saturation of the quasar image makes PSF subtraction uncertain. Deep, high-resolution images, preferably in the near-IR, would better reveal whether this galaxy is real. If so, then the microlensing optical depth would be relatively high for component A and (perhaps quite) low for the other components, so further monitoring would probably reveal additional microlensing events in component A but not in the other components.

Alternatively, if the microlensing is caused by intracluster stars or MACHOs, then the microlensing optical depth for component A is probably fairly low, but it is likely to be similar for the other components. In this case, further monitoring could well reveal microlensing events in the other components, and the frequency of events would reveal the number density of intracluster objects.

If additional microlensing events are detected, it will be extremely interesting to track which lines are microlensed as a function of time. That would provide a unique and powerful

new probe of ionization stratification in the BELR. In addition, the velocity dependence of any enhancements of the BELR in future microlensing events will help to reveal the kinematic structure of the BELR.

3.2. Time-independent Emission-Line Differences

In addition to the time-dependent differences in the blue wings of the high-ionization emission lines, there are also subtle differences in the C IV emission line profiles between the components that persist over at least 322 days in the observed frame. In Figure 2 we have overplotted a Gaussian at the position of C IV emission to guide the eye and help illustrate these differences.

In particular, we note that there is a slight excess of high-velocity redshifted C IV emission in component B as compared with component A. This excess is best seen in the 2003 May 31 Keck spectra, where there is a kink in the profile of component B near 1560 Å that is not present in component A. In addition, in all observations of component B the falloff in the red wing toward 1600 Å is more gradual than in component A. We also see similar (but opposite) differences in the blue wing, with the most extreme blue wing flux falling off more gradually in component A than in component B. In other words, at all epochs the C IV emission line profile is somewhat blueward asymmetric in component A and somewhat redward asymmetric in component B.

The cause of these differences is unclear. Because the predicted A-B time delay is $\lesssim 30$ days, they are unlikely to be due to intrinsic variability (unless the time delays are grossly underestimated). Microlensing may also be the cause of these differences. One possibility is that microlensing is *de-amplifying* the red wing of component A and the blue wing of component B. Another possibility is that the mass scale is much larger than that of the blue-wing BELR microlensing discussed above (in order to make the variability timescale longer than 322 days in the observed frame). The responsible objects could perhaps be globular clusters or clumps of dark matter of mass $\sim 10^4$ – $10^8 M_\odot$, in which case the phenomenon would be termed millilensing (rather than microlensing) and could provide a unique probe of dark matter substructure of the type predicted in the cold dark matter paradigm (Metcalf & Madau 2001; Dalal & Kochanek 2002; Wisotzki et al. 2003; Metcalf et al. 2004).

One way to test the micro/millilensing hypotheses would be to normalize the spectra using narrow lines, since they should be insensitive to small-scale structure (Moustakas & Metcalf 2003). Any differences in the broad lines would then indicate micro/millilensing effects. This might be possible with either *J*-band IR spectra of [O III] $\lambda\lambda 4959, 5007$ or with the unusually strong (but not apparently microlensed) nitrogen lines seen in our optical spectra, since the nitrogen lines appear relatively narrow and may lack a broad component. As for distinguishing between the microlensing and millilensing hypotheses, our best ally is time. If the “time-independent” emission-line differences are due to millilensing, they should persist for a very long time, but if they are due to microlensing, they should change on a ~ 5 – 10 yr timescale.

4. CONCLUSIONS

We have presented seven epochs of spectroscopic data on the two brightest components of the wide-separation, quadruply imaged quasar SDSS J1004+4112. Although the simplest lensing scenarios predict that the four components should have identical spectra, the data reveal significant

differences in the emission-line profiles of the components. In particular, the C IV emission line profile in components A and B show both variable differences and differences that are constant over 322 observed-frame days. The He II and Si IV/O IV] lines in component A also show variability similar to that seen in the C IV line.

Because the predicted time delay between A and B is $\lesssim 30$ days, we argue that the differences are not due to intrinsic variability in the quasar coupled with a lensing time delay. Instead, we suggest that the variability in the blue wing of component A is best explained by microlensing of part of the broad emission line region, resolving BELR structure on the order of a few light days. This represents the first robust detection of BELR microlensing, with evidence based on multiple emission lines and involving observed variability. The nature of the time-independent differences is less clear, but they may also be the result of a lensing event. In any case, it is clear that continued spectroscopic monitoring of SDSS J1004+4112 should be carried out in an attempt to map the structure of its broad emission line region through additional microlensing events.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is [http://](http://www.sdss.org)

www.sdss.org. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, the Johns Hopkins University, Los Alamos National Laboratory, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, the University of Pittsburgh, Princeton University, the United States Naval Observatory, and the University of Washington.

Based on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium. Based on observations obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration, made possible by the generous financial support of the W. M. Keck Foundation. Based in part on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. G. T. R. was supported in part by NSF grant AST 03-07409 and HST grant HST-GO-09472.01-A. C. R. K. was supported by NASA through Hubble Fellowship grant HST-HF-01141.01-A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. D. P. S. was supported in part by NSF grant AST 03-07582. We thank Luka Popović, Rudy Schild, and an anonymous referee for helpful comments on this work.

REFERENCES

- Abajas, C., Mediavilla, E., Muñoz, J. A., Popović, L. Č., & Oscoz, A. 2002, *ApJ*, 576, 640
- Angonin, M.-C., Vanderriest, C., Remy, M., & Surdej, J. 1990, *A&A*, 233, L5
- Arav, N., Barlow, T. A., Laor, A., Sargent, W. L. W., & Blandford, R. D. 1998, *MNRAS*, 297, 990
- Baltz, E. A., Lauer, T. R., Zurek, D. R., Gondolo, P., Shara, M. M., Silk, J., & Zepf, S. E. 2004, *ApJ*, in press (astro-ph/0310845)
- Cao, L., Wei, J.-Y., & Hu, J.-Y. 1999, *A&AS*, 135, 243
- Chartas, G., Agol, E., Eracleous, M., Garmire, G., Bautz, M. W., & Morgan, N. D. 2002, *ApJ*, 568, 509
- Chartas, G., Eracleous, M., Agol, E., & Gallagher, S. C. 2004, *ApJ*, 606, 78
- Colley, W. N., & Schild, R. E. 2003, *ApJ*, 594, 97
- Dai, X., Chartas, G., Agol, E., Bautz, M. W., & Garmire, G. P. 2003, *ApJ*, 589, 100
- Dalal, N., & Kochanek, C. S. 2002, *ApJ*, 572, 25
- Elvis, M. 2000, *ApJ*, 545, 63
- Eracleous, M. 2004, in *ASP Conf. Ser. 311, AGN Physics with the Sloan Digital Sky Survey*, ed. G. T. Richards & P. B. Hall (San Francisco: ASP), 183
- Eracleous, M., & Halpern, J. P. 2003, *ApJ*, 599, 886
- Filippenko, A. V. 1989, *ApJ*, 338, L49
- Fitte, C., & Adam, G. 1994, *A&A*, 282, 11
- Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, *AJ*, 111, 1748
- Gómez-Álvarez, P., Mediavilla, Gradolph, E., Sánchez, S. F., Arribas, S., Wisotzki, L., Wambsganss, J., Lewis, G., & Muñoz, J. A. 2004, *Astron. Nachr.*, 325, 132
- Gunn, J. E., et al. 1998, *AJ*, 116, 3040
- Huchra, J., Gorenstein, M., Kent, S., Shapiro, I., Smith, G., Horine, E., & Perley, R. 1985, *AJ*, 90, 691
- Inada, N., et al. 2003, *Nature*, 426, 810
- Irwin, M. J., Webster, R. L., Hewett, P. C., Corrigan, R. T., & Jedrzejewski, R. I. 1989, *AJ*, 98, 1989
- Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, *ApJ*, 533, 631
- Kayser, R., Refsdal, S., & Stabell, R. 1986, *A&A*, 166, 36
- Kochanek, C. S. 2004, *ApJ*, 605, 58
- Lewis, G. F., & Ibata, R. A. 2004, *MNRAS*, 348, 24
- Lewis, G. F., & Irwin, M. J. 1995, *MNRAS*, 276, 103
- Lewis, G. F., Irwin, M. J., Hewett, P. C., & Foltz, C. B. 1998, *MNRAS*, 295, 573
- Metcalfe, R. B., & Madau, P. 2001, *ApJ*, 563, 9
- Metcalfe, R. B., Moustakas, L. A., Bunker, A. J., & Parry, I. R. 2004, *ApJ*, 607, 43
- Moustakas, L. A., & Metcalfe, R. B. 2003, *MNRAS*, 339, 607
- Murray, N., & Chiang, J. 1998, *ApJ*, 494, 125
- Nadeau, D., Racine, R., Doyon, R., & Arboit, G. 1999, *ApJ*, 527, 46
- Nemiroff, R. J. 1988, *ApJ*, 335, 593
- Oguri, M., et al. 2004, *ApJ*, 605, 78
- Oke, J. B., et al. 1995, *PASP*, 107, 375
- Peterson, B. M., & Wandel, A. 1999, *ApJ*, 521, L95
- Popović, L. Č., Mediavilla, E. G., Bon, E., Stanić, N., & Kubičela, A. 2003, *ApJ*, 599, 185
- Popović, L. Č., Mediavilla, E. G., & Muñoz, J. A. 2001, *A&A*, 378, 295
- Richards, G. T., et al. 2002, *AJ*, 123, 2945
- Schechter, P. L., & Wambsganss, J. 2002, *ApJ*, 580, 685
- Schechter, P. L., et al. 2003, *ApJ*, 584, 657
- Schneider, P., Ehlers, J., & Falco, E. E. 1992, *Gravitational Lenses* (Springer: Berlin)
- Schneider, P., & Wambsganss, J. 1990, *A&A*, 237, 42
- Strateva, I. V., et al. 2003, *AJ*, 126, 1720
- Totani, T. 2003, *ApJ*, 586, 735
- Wambsganss, J. 1992, *ApJ*, 386, 19
- Wambsganss, J., Paczynski, B., & Katz, N. 1990, *ApJ*, 352, 407
- Wandel, A., Peterson, B. M., & Malkan, M. A. 1999, *ApJ*, 526, 579
- Wisotzki, L., Becker, T., Christensen, L., Helms, A., Jahnke, K., Kelz, A., Roth, M. M., & Sanchez, S. F. 2003, *A&A*, 408, 455
- Woźniak, P. R., Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Soszyński, I., & Żebruń, K. 2000, *ApJ*, 540, L65
- Wucknitz, O., Wisotzki, L., Lopez, S., & Gregg, M. D. 2003, *A&A*, 405, 445
- York, D. G., et al. 2000, *AJ*, 120, 1579