THE REWARDS OF PATIENCE: AN 822 DAY TIME DELAY
IN THE GRAVITATIONAL LENS SDSS J1004+4112

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ABSTRACT

We present 107 new epochs of optical monitoring data for the four brightest images of the gravitational lens SDSS J1004+4112 observed between 2006 October and 2007 June. Combining this data with the previously obtained light curves, we determine the time delays between images A, B, and C. We confirm our previous measurement, that B leads A by \( \Delta \tau_{BA} = 40.6 \pm 1.8 \) days, and find that image C leads image A by \( \Delta \tau_{CA} = 821.6 \pm 2.1 \) days. The lower limit on the remaining delay is that image D lags image A by \( \Delta \tau_{AD} > 1250 \) days. Based on the microlensing of images A and B, we estimate that the accretion disk size at a rest wavelength of 2300 \( \AA \) is \( 10^{14.8 \pm 0.3} \) cm for a disk inclination of \( \cos \theta = \frac{1}{2} \), which is consistent with the microlensing disk size—black hole mass correlation function given our estimate of the black hole mass from the Mg II line width of \( M_{BH}/M_\odot = 8.4 \pm 0.2 \). The long delays allow us to fill in the seasonal gaps and assemble a continuous, densely sampled light curve spanning 5.7 yr whose variability implies a structure function with a logarithmic slope of \( \beta = 0.52 \pm 0.02 \). As C is the leading image, sharp features in the C light curve can be intensively studied 2.3 yr later in the A/B pair, potentially allowing detailed reverberation mapping studies of a quasar at minimal cost.

Subject headings: cosmology: observations — gravitational lensing — quasars: individual (SDSS J1004+4112)

Online material: machine-readable table

1. INTRODUCTION

The quasar SDSS J1004+4112 at \( z_s = 1.734 \) is split into five images by an intervening galaxy cluster at \( z_l = 0.68 \) (Inada et al. 2003, 2005; Oguri et al. 2004). With a maximum image separation of 14.62", it is a rare example of a quasar gravitationally lensed by a cluster (Wambsganss 2003; Inada et al. 2006). One of the most interesting applications of this system is to use the time delays between the lensed images to study the structure of the cluster. If we assume the Hubble constant is known, then the delays break the primary model degeneracy of lensing studies, the “mass sheet degeneracy” (Falco et al. 1985), as well as applies employing sources at different redshifts (see Sharon et al. 2005). The delay ratios constrain the structure even if the Hubble constant is unknown. After its discovery, several groups modeled the expected time delays in SDSS J1004+4112 and their dependence on the mean mass profile of the cluster (Kawano & Oguri 2006; Oguri et al. 2004; Williams & Saha 2004). When we measured the shortest delay in the system, between images A and B, we found a longer delay than predicted by the models (Fohlmeister et al. 2007, hereafter Paper I), where the discrepancy probably arose because the models included the cD galaxy and the cluster halo but neglected the significant perturbations from the member galaxies. As we measure the longer delays, where the cluster potential should be relatively more important than for the merging A/B image pair, we would not expect cluster substructures to play as important a role.

We also expect this lens to have a fairly short timescale for microlensing variability created by stars either in the intracluster medium or in galaxies near the images. The internal velocities of a cluster are much higher than in a galaxy (700 vs. 200 km s\(^{-1}\)), and SDSS J1004+4112’s position on the sky is almost orthogonal to the CMB dipole (Kogut et al. 1993), giving the observer a projected motion on the lens plane of almost 300 km s\(^{-1}\). We detected microlensing of the continuum emission in Paper I, and there is also evidence for microlensing of the C \( \nu \) broad line (Richards et al. 2004; Lamer et al. 2006; Gómez-Alvarez et al. 2006). Once we have measured the time delays we can remove the intrinsic quasar variability and use the microlensing variability to estimate the mean stellar mass and stellar surface density, the transverse velocities, and the structure of the quasar source (Gil-Merino et al. 2005; Mortonson et al. 2005; Pointdexter et al. 2008; Morgan et al. 2007).

Finally, we note that SDSS J1004+4112 could be an ideal laboratory for studying correlations in the intrinsic variability of quasars. With image C leading images A and B by 2.3 yr, sharp variations in image C can be used to plan intensive monitoring of images A and B to measure the response times as a function of wavelength (e.g., Kaspi et al. 2007), with the additional advantage that the delay between A and B provides redundancies that protect against weather, the Moon and the Sun. The long delays between the images also mean that seasonal gaps are completely filled, and we can examine the structure function of the variability with a densely-sampled, gap-free light curve (modulo corrections for microlensing). Such data generally do not exist, since most time variability data for quasars (other than nearby reverberation mapping targets; e.g., Peterson et al. 2004) have very sparse sampling (e.g., Hawkins [2007] on long timescales for a small number of objects, or Vandenberg [2004] on shorter timescales for many objects).

In Paper I we presented 3 yr of optical monitoring data for the four brightest images of SDSS J1004+4112 spanning 1000 days from 2003 December to 2006 June. The fifth quasar image, E, is too faint to be detected in our observations. We measured the time delay between the A and B image pair to be \( \Delta \tau_{BA} = 38.4 \pm 2.0 \) days. While larger separation lenses tend to have longer time delays, for these two images the propagation time difference is
small because they form a close image pair (3.8") created by the source lying close to a fold caustic. For the more widely separated C and D images we could only estimate lower limits on the delays of 560 and 800 days relative to images B and A. In this paper we present the 107 new optical monitoring epochs for the 2006–2007 season in § 2. When combined with our previous data we have light curves spanning 1250 days that allow us to measure the AC delay in § 3. In § 4 we use the microlensing variability of the A/B images to measure the size of the quasar accretion disk, and in § 5 we measure the structure function of the intrinsic variability. We discuss the future prospects for exploiting this system in § 6.

2. DATA

We monitored SDSS J1004+4112 in the r-band during the 2006–2007 season using the Fred Lawrence Whipple Observatory (FLWO) 1.2 m telescope on Mount Hopkins and the MDM 2.4 m Hiltner Telescope on Kitt Peak. The FLWO observations were obtained with Keplercam (0.672 pixels) and the MDM observations with RETROCAM (Morgan et al. 2005) (0.259 pixels). The data reduction was carried out as described in Paper I. We continued to use the same five stars to set the PSF model and the flux scale of each epoch and verified that these flux standards continue to show no variability. Table 1 presents the photometry for the four images in the 2006–2007 season.

In Figure 1 we present the resulting light curves for images A to D for the period from 2003 December to 2007 June. The average sampling rate during the 2006–2007 season is once every third day. The FLWO data are noisy, so for Figure 1 we show a running average of the data (one point every 5 days averaged over ±7 days) to emphasize the long-term trends.

During the fourth season, images A and B faded by approximately 0.4 mag, with a prominent feature near the middle of the season; image C was relatively constant; and image D brightened by about 0.4 mag. For the full four seasons, A and B have faded by approximately 1 mag, C has remained relatively constant, and D has brightened by about 1.5 mag.

3. THE TIME DELAY

For the determination of the time delay, we use the methods described in Paper I. Our first step with the new data was to re-measure the A/B delay. The fourth season shows a nice feature with maxima in images A and B near days 4120 and 4080, respectively, followed by a roughly 100 day decline to minima at 4220 (A) and 4180 (B) days. With the dispersion method (Pelt et al. 1994, 1996), we measure the delay between A and B to be \( \Delta T_{BA} = 40.1 \pm 3.5 \) days. For the Kochanek et al. 2006a polynomial method we used polynomial orders of \( N_{\text{src}} = 20, 40, 60, \) and 80 for the source and \( N_{\text{img}} = 1, 2, 3, \) and 4 for the microlensing variability, and derived the final estimate using the Bayesian weighting of these cases described in Pointdexter et al. (2008). We found delays of 40.6 ± 1.8, 40.1 ± 1.8, and 39.8 ± 1.8 (68% confidence regions) depending on whether we weighted the changes in the number of parameters using the Bayesian information criterion (which strongly penalizes extra parameters), the Akaike information criterion (which weakly penalizes extra parameters) or no penalty for extra parameters. These are consistent with our result from Paper I of \( \Delta T_{BA} = 38.4 \pm 2.0 \) days, but are somewhat more conservative in their treatment of the parameterization and the role of microlensing.

In Paper I we derived a lower limit on the BC delay of \( \Delta T_{CB} > 560 \) days and suggested, based on some similarities between the third season for A/B with the first season for C, that a delay of order 700 days was plausible but statistically too weak to claim as a measurement. We now see that the feature in the second season for image C strongly matches the feature we observe in the new season for A and B. Using the dispersion spectra method (Pelt et al. 1994, 1996), we find \( \Delta T_{CA} = 822 \pm 7 \) days and \( \Delta T_{CB} = 780 \pm 6 \) days, where the CA delay is slightly less accurate because the CA overlap is slightly less than the CB overlap due to the alignment of the light curves relative to the seasonal gaps. The three delays are mutually consistent since \( \Delta T_{CB} = \Delta T_{CA} - \Delta T_{BA} = 782 \pm 7 \) days. For the polynomial method analysis we simultaneously fit A, B, and C holding the A/B delay fixed to 40.6 days to find CA delays of 821.6 ± 2.1, 823.0 ± 2.1, and 820.2 ± 2.1 days for the three weighting methods, respectively. Image D should lag the other three images, and we see no feature in the light curve of image D that can be matched to the first season of images A/B. The lower limit on the time delay between images A and D is now \( \Delta T_{DA} > 1250 \text{ days} \) (3.4 yr).

We modeled the lens using the same approach as in Paper I, where we include the central cD galaxy, a NFW halo for the cluster dark matter and 12 pseudo–Jaffe models corresponding to

### TABLE 1

| HJD     | \( \chi^2/N_{\text{dof}} \) | Image A | Image B | Image C | Image D |
|---------|-------------------------------|----------|----------|----------|----------|
| 4019.006 | 1.15                          | 3.451 ± 0.027 | 3.880 ± 0.027 | 4.332 ± 0.027 | 4.323 ± 0.027 |
| 4029.001 | 1.99                          | 3.488 ± 0.027 | 3.952 ± 0.027 | 4.382 ± 0.027 | 4.347 ± 0.027 |
| 4031.006 | 1.46                          | 3.529 ± 0.027 | 3.985 ± 0.027 | 4.413 ± 0.027 | 4.361 ± 0.027 |
| 4035.026 | 0.99                          | 3.477 ± 0.027 | 4.024 ± 0.027 | 4.326 ± 0.027 | 4.395 ± 0.027 |
| 4035.980 | 2.20                          | 3.511 ± 0.027 | 3.997 ± 0.027 | 4.344 ± 0.027 | 4.362 ± 0.027 |
| 4039.016 | 2.02                          | 3.576 ± 0.027 | 4.061 ± 0.027 | 4.394 ± 0.027 | 4.434 ± 0.027 |
| 4043.955 | 0.86                          | 3.514 ± 0.027 | 3.924 ± 0.027 | 4.249 ± 0.027 | 4.297 ± 0.027 |
| 4044.949 | 0.95                          | 3.525 ± 0.027 | 3.930 ± 0.027 | 4.256 ± 0.027 | 4.318 ± 0.027 |
| 4045.966 | 0.77                          | 3.472 ± 0.027 | 3.985 ± 0.027 | 4.451 ± 0.040 | 4.274 ± 0.034 |
| 4046.966 | 1.03                          | 3.512 ± 0.027 | 3.916 ± 0.027 | 4.271 ± 0.027 | 4.285 ± 0.027 |
| 4047.004 | 0.47                          | 3.427 ± 0.103 | 3.915 ± 0.158 | 4.415 ± 0.252 | 4.625 ± 0.298 |
| 4048.968 | 1.34                          | 3.518 ± 0.027 | 3.924 ± 0.027 | 4.276 ± 0.027 | 4.337 ± 0.027 |
| 4050.008 | 0.97                          | 3.523 ± 0.027 | 3.943 ± 0.027 | 4.245 ± 0.027 | 4.322 ± 0.027 |
| 4054.008 | 0.59                          | 3.486 ± 0.027 | 3.877 ± 0.034 | 4.258 ± 0.049 | 4.344 ± 0.052 |

Notes.—The first gives the date of the observation relative to Heliocentric Julian Date (HJD) = 2,450,000. The \( \chi^2/N_{\text{dof}} \) column indicates how well our photometric model fit the imaging data. When \( \chi^2 > N_{\text{dof}} \) we rescale the photometric errors presented in this table by \( (\chi^2/N_{\text{dof}})^{1/2} \) before carrying out the time delay analysis to reduce the weight of images that were fit poorly. The image magnitudes are relative to the comparison stars (see text). The magnitudes enclosed in parentheses are not used in the time delay estimates. Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
cluster galaxies (we added an extra component at \((x, y) = (31.0'', 4.0'')\) relative to quasar image A in an effort to reduce the overall shear). The fits were carried out using \textit{lensmodel} (Keeton 2001), and while adequate they are not satisfactory, it is very difficult to find solutions with no additional quasar images created by the galaxies, and checking for the extra images makes the procedure extraordinarily slow. At present we lack the ability to model this system in detail (including uncertainties) at the precision of the constraints, while simplified models that ignore the galaxies are incapable of fitting the data at all. The model predicts an AD delay of order 2000 days (5.5 yr), which is consistent with our current lower bound.

4. MICROLENSING AND THE SIZE OF THE QUASAR ACCRETION DISK

The residuals of the A and B light curves (see Fig. 2) clearly indicate that microlensing is present. After correcting for the time delay, the mean magnitude differences between A and B for the four seasons are \(0.460 \pm 0.005, 0.283 \pm 0.007, 0.339 \pm 0.005\), and \(0.381 \pm 0.007\) mag. For the two seasons overlapping with C we find mean magnitude differences, seasonal gradients, and second derivatives of \(0.590 \pm 0.010\) mag, \(-0.04 \pm 0.02\) mag yr\(^{-1}\) and \(0.29 \pm 0.09\) mag yr\(^{-2}\) for C relative to A and \(0.368 \pm 0.005\) mag, \(0.05 \pm 0.01\) mag yr\(^{-1}\) and \(0.18 \pm 0.04\) mag yr\(^{-2}\) for...
FIG. 2.—Image A, B, and C light curves in their overlap region after shifting by the time delays. The data are binned in 1 week intervals with error bars derived by error propagation from the measurement errors (see Table 1). The lower box shows the residual magnitudes shifted by the offset between the images, revealing microlensing variability of order 0.15 mag. The light curve of image B was chosen to have constant flux because it has the most overlap with the other two images.

B relative to A. Figure 2 shows the superposition of the phased A, B, and C light curves and the differences between them that are the signature of microlensing.

We modeled the microlensing for images A/B using the Bayesian Monte Carlo method of Kochanek (2004). We used the microlensing parameters of our (adequate) lens model, with convergence $\kappa$ and shear $\gamma$ values of $\kappa = 0.48$ and $\gamma = 0.57$ for A and $\kappa = 0.47$ and $\gamma = 0.39$ for B. We allowed the surface density in stars $\kappa_s$ to vary from 10% to 100% of $\kappa$ in increments of 10%. We used a microlens mass function with $dn/dM \propto M^{-1.3}$ with a dynamic range in mass of a factor of 50 that approximates the Galactic disk mass function of Gould (2000). We generated 4096 x 4096 pixel magnification patterns with an outer scale of 20($R_\text{E}$), where $R_\text{E}$ is the Einstein radius at the mean stellar mass ($M$). We modeled the disk as a face-on, thin disk Shakura & Syunyaev (1973) neglecting the central temperature depression and relativistic effects. We measure the disk size $R_1$ as the point where the disk temperature matches the rest-frame energy of our monitoring band, $kT_\text{r} = hc/\lambda_0$, where $\lambda_0 \simeq 2300$ Å for the r-band at the source redshift (see Morgan et al. 2007). The half-light radius $R_{1/2} = 2.44R_1$ should be used to compare to any other disk model, since Mortonson et al. (2005) have shown that the half-light radius depends little on the surface brightness profile of the model. We made four realizations of each of the 10 microlensing models and drew $2 \times 10^5$ trial light curves for each of the 40 cases so that we would have a reasonable statistical sampling of light curves that fit the data well. We found that

$$R_{2300} = 10^{14.8 \pm 0.3} \frac{\text{cm}}{h_{70} \cos i}$$

for a disk inclination angle $i$, whether or not we use a prior on the mean microlens mass of $0.1 M_\odot < \langle M \rangle < 1 M_\odot$. We note in passing that the models favor higher rather than lower values of $\kappa_s$, suggesting that the microlensing is due to a satellite galaxy rather than intracluster stars.

From the Mg ii emission line width/black hole mass calibration of Kollmeier et al. (2006), the spectrum of image C from Richards et al. (2004), and a magnification-corrected Hubble Space Telescope $I$-band magnitude of $20.9 \pm 0.4$, we estimate a black hole mass of $\log M_{\text{BH}}/M_\odot = 8.4 \pm 0.2$. Figure 3 compares the disk size estimate to the characteristic scales of such a black hole.

5. THE STRUCTURE FUNCTION

The quasar structure function can be used as a tool to characterize quasar variability independent of short-timescale monitoring gaps and to compare with theoretical models of quasar variability (e.g., Kawaguchi et al. 1998). The structure function

$$S(\tau) = \sqrt{\frac{1}{N(\tau)} \sum_{i<j} \left( \frac{m(t_j) - m(t_i)}{\sigma_j - \sigma_i} \right)^2}$$

is the variability in the magnitude as a function of the time $\tau = t_j - t_i$ between measurements, where $m(t_i)$ is the measured magnitude at epoch $t_i$ with measurement uncertainty $\sigma_i$, and $N(\tau)$ is
assuming the \( S_{B/C} \) is the rest-frame time difference and \( \tau \) in the quasar rest frame. If we consider \( \tau \) is 0.7 mag for the D light curve. We measure the delay for image C for the first time, finding that it leads image A by B/C light curves we also computed the structure function after subtracting the estimated microlensing variability estimate found in the time delay analysis (see § 3). The three structure functions are shown in Figure 4. The bins were chosen to have equal logarithmic rest-frame time lag intervals and the uncertainties were determined by propagating the measurement uncertainty in the magnitude differences and the statistical error in the mean for the values in that bin.

The slopes of the structure function are mutually consistent, with \( \beta_{B/C} = 0.52 \pm 0.02 \), \( \beta_D = 0.55 \pm 0.03 \), and \( \beta_{B/C} = 0.54 \pm 0.02 \) after subtracting the estimated microlensing variability. Microlensing has little effect on the results because the source variability (\( \sim 0.7 \) mag) greatly exceeds the microlensing variability (\( \sim 0.15 \) mag). The amplitudes at 100 days are \( S_{100}(BC) = 0.19 \pm 0.05 \) mag for the BC light curve and \( S_{100}(D) = 0.30 \pm 0.06 \) mag for the D light curve.

Theoretical models of quasar variability involving a starburst scenario predict slopes of 0.74–0.90, whereas accretion disk instability models predict shallower slopes of 0.41–0.49 (Kawaguchi et al. 1998), as well as a flattening of the structure function after \( \sim 100 \) days in both cases. Our measurements are in disagreement with those predictions.

The structure function of SDSS 1004+4112 is steeper and shows a higher amplitude than the average quasar. For example, Vanden Berk et al. (2004) found \( \beta = 0.336 \pm 0.033 \) for a sample of 25000 quasars, de Vries et al. (2005) found \( \beta = 0.153 \pm 0.004 \) for about 40000 quasars, and Wilhite et al. (2007) found \( \beta = 0.486 \) for a sample of 8000 quasars. Individual quasars are known, however, to show a diversity of slopes. For example, Collier & Peterson (2001) measured UV slopes ranging from 0.7 to 1.5 for a sample of 15 nearby active galactic nuclei. For the same samples, the average amplitudes at 100 days were \( S_{100} \approx 0.11 \) (Vanden Berk et al. 2004), 0.23 (de Vries et al. 2005) and 0.121 mag (Wilhite et al. 2007). If the brightening of image D indicates that the quasar was fainter in the past (which need not be the case, depending on the absolute magnification of D), then the higher variability amplitude of the D light curve could be related to the anticorrelation between luminosity and variability found in the large surveys of quasar variability.

### 6. SUMMARY AND CONCLUSIONS

We present a fourth season of monitoring data for the four bright images of the five-image gravitational lens system SDSS J1004+4112. We confirm our previous estimate for the time delay between the merging A/B pair, finding that B leads A by 40.6 ± 1.8 days. We measure the delay for image C for the first time, finding that it leads image A by 821.6 ± 2.1 days (2.3 yr). We note that this is nearly twice the longest previously measured delay (the 417 day delay in Q0957+561, Schild & Thomson 1995; Kundic et al. 1997). We find a lower bound that D lags A by more than approximately 1250 days (3.4 yr). Our current mass model predicts that D lags A by approximately 2000 days (5.5 yr), which is consistent with the present limit. The fractional uncertainties in the AB delay are still dominated by sampling and microlensing, while the fractional uncertainties in the AC delay are dominated by cosmic variance due to density fluctuations along the line of sight rather than our measurement uncertainties of 0.3% (e.g., Barkana 1996).

A detailed model of this system, including the constraints from the multiply imaged, higher redshift arcs (Sharon et al. 2005), the X-ray measurements (Ota et al. 2006; Lamer et al. 2006) and a detailed understanding of the uncertainties will be a challenge. We lack a completely satisfactory model for the system at present, in the sense that the modeling process is extraordinarily slow due to the ability of the gravitational potentials associated with the cluster member galaxies to generate additional but undetected images of the quasar, making it impossible to carry out a reliable model survey. The record of models for this system is discouraging. As we noted in Paper I, all three model studies (Oguri et al. 2004; Williams & Saha 2004; Kawano & Oguri 2006) generically predicted shorter AB delays than the observed 40 days, and that this could be plausibly explained by the absence of substructure (i.e., galaxies) in the potential models. The longer AB-C and AB-D delays should be less sensitive to substructure. Oguri et al. (2004) do not include an estimate of the AB-C delays and have A-D delays consistent with our present limits. The range of B-C delays in Williams & Saha (2004) is consistent with our measurement of 780 days, but they predict AD delays shorter than our current lower bound of 1250 days. Kawano & Oguri (2006) predict a range for the longer delays over a broad range of mass distributions, none of which match our delays in detail. However, models with sufficiently long C-B delays generally have C-D delays long enough to agree with our present limits.

Based on our present mass model we used the microlensing between the A and B images to make an estimate of the size of the quasar accretion disk at 2300 Å in the quasar rest frame. If we convert this to the expected size at 2500 Å assuming the \( R_s \propto \lambda^{4/3} \) scaling for a thin disk and assume the mean disk inclination \( \cos (i) = 1/2 \), the scale on which the disk temperature matches the photon energy is \( R_{2500\AA} = 10^{15.6 \pm 0.3} \) cm. Comparisons to other
disk models should use the half-light radius, which is 2.44 times larger. Based on the quasar Mg ii emission line width we estimate that the black hole mass is $10^{8.4 \pm 0.2} M_\odot$. For this mass, the microlensing accretion disk size-black hole mass correlation found by Morgan et al. (2007) predicts that $R_{2500} = 10^{5.3} \text{ cm}$, which is in broad agreement with the measurement. Further observations, the inclusion of additional images, and monitoring in multiple bands should improve these measurements and potentially allow us to determine the mean surface density in stars near the images $\kappa_s$ and their average mass $\langle M \rangle$. Similarly, the ability to construct continuous light curves of the intrinsic variability and to use image C to provide early warning of sharp flux changes that can then be intensively monitored in images A and B may make this system a good candidate for applying reverberation mapping techniques to a massive, luminous quasar. At present, the structure function of this system indicates that the source is considerably more variable than the average quasar. This is promising for both improving the accuracy of the time delays and for using reverberation mapping techniques as an additional probe of the source structure.

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