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MEASURING THE SIZE OF QUASAR BROAD-LINE CLOUDS THROUGH TIME-DELAY LIGHT-CURVE ANOMALIES OF GRAVITATIONAL LENSES

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ABSTRACT

Intensive monitoring campaigns have recently attempted to measure the time delays between multiple images of gravitational lenses. Some of the resulting light curves show puzzling low-level, rapid variability that is unique to individual images, superposed on (and concurrent with) longer timescale intrinsic quasar variations that repeat in all images. We demonstrate that both the amplitude and variability timescale of the rapid light-curve anomalies are naturally explained by stellar microlensing of a smooth accretion disk that is occulted by optically thick broad-line clouds. This model also explains the observed correlation between microlensing and intrinsic variability. The rapid timescale is caused by the high velocities of the clouds ($\sim 5 \times 10^3 \text{ km s}^{-1}$), and the low-amplitude results from the large number of clouds covering the magnified or demagnified parts of the disk. The observed amplitudes of variations in specific lenses implies that the number of broad-line clouds that cover $\sim 10\%$ of the quasar sky is $\sim 10^5$ per $4\pi \text{ sr}$. This is comparable to the expected number of broad-line clouds in models where the clouds originate from bloated stars.

Subject headings: gravitational lensing — quasars: emission lines — quasars: general

1. INTRODUCTION

The use of time delays between the images produced by galaxy-scale gravitational lenses to measure the Hubble constant was proposed almost four decades ago (Refsdal 1964). With approximately 10 time delays now measured for different lenses (e.g., Kundic et al. 1997; Schechter et al. 1997; Burud et al. 2000), this method has recently become practical (see Kochanek 2002 for a recent summary and analysis). As part of the associated observational effort, Hjorth et al. (2002) and Burud (2002) have presented light curves with very well-determined time delays for the systems RX J0911+05 and SBS 1520+530.² In both systems the authors find evidence for short-term variability that is unique to individual images. The variability is observed on timescales of tens to hundreds of days, with an amplitude of up to a few percent, and appears to be associated with small intrinsic fluctuations. In both cases (Burud 2002; C. S. Kochanek 2002, private communication) the microlensing variability appears to be in the saddle point image (image of negative parity). Similar rapid, low-amplitude residual variability has previously been observed between the images of Q0957+561 (Schild 1996). If caused by microlensing within the lens galaxy, this short-term variability is puzzling because naively, the observed amplitudes require very small (nonstellar) microlens masses (Schild 1996) of $m \lesssim 10^{-4} M_\odot$ (see also Gould & Miralda-Escudé 1997). Having a dominant microlens population in the required mass range is ruled out by the work of Refsdal et al. (2000) and Wambsganss et al. (2000) on quasar microlensing in Q0957+561 and by Wyithe, Webster & Turner (2000a, 2000b) in Q2237+0305, as well as by Galactic microlensing experiments (e.g., Alcock et al. 2000). Another explanation was suggested by Gould & Miralda-Escudé (1997); in their model rapidly moving hot spots (or cold spots) on the disk

surface possess a high transverse velocity and lead to short timescale variability as the spots move across the stellar microlensing caustics. Since only a small fraction of the source area is magnified, the variability amplitude is small. By postulating the existence of spots with appropriate properties, one might avoid the need to invoke a population of planetary mass microlenses.

In this paper we offer a natural explanation for the observed properties of the short-term variability involving quasar phenomena identified through separate lines of inquiry. We start our discussion with a description of the standard quasar (§ 2) and microlensing (§ 3) models. In § 4 we explain how the rapid, low-amplitude microlensing observed by Hjorth et al. (2002) and Burud (2002) is naturally produced without postulating hypothetical components for either the quasar disk or the lens population. Our model includes typical stellar mass microlenses and a featureless accretion disk surrounded by a shell of optically thick broad-line clouds, which possess the high velocities and small source sizes necessary to explain the rapid, low-amplitude variability. In §§ 5.1 and 5.2 we compare this model against alternative explanations. Finally, we summarize our primary conclusions in § 6. Throughout the paper we assume a flat (filled beam) cosmology having density parameters of $\Omega_m = 0.3$ in matter, $\Omega_\Lambda = 0.7$ in a cosmological constant, and a Hubble constant $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. QUASAR MODEL

The UV-optical spectra of nearly all quasars show broad emission lines with Doppler widths of $\sim 5000 \text{ km s}^{-1}$. The emission is believed to originate from dense clouds having a small filling factor of $\sim 10^{-6}$, which are illuminated by a central ionizing continuum source (see, e.g., Netzer 1990 and references therein), for which we adopt the radial surface brightness profile due to a thermal accretion disk as computed by Agol & Krolik (1999). Two popular models containing discrete emitters were proposed for the origin of the

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² See also http://vela.astro.ulg.ac.be/themes/dataproc/deconv/theses/burud/ibthese_e.html.

broad-line emitters: (1) cool clouds confined within a hot medium (Krolik, McKee, & Tarter 1981) and (2) winds from giant stars that are bloated as a result of their exposure to the intense quasar radiation (Alexander & Netzer 1997 and references therein). In addition, models have been proposed where the broad lines are emitted from a space filling outflow (e.g., Murray & Chiang 1998). These models would not predict the microlensing effects outlined in this paper. The equivalent width of the lines indicates that $\sim 10\%$ of the continuum emission of the quasar is absorbed and reprocessed by the clouds. Hence, the fraction of sky covered by clouds when viewed from the central continuum source, is $F_c \sim 0.1$.

The velocity dispersion of the clouds can be inferred from the line widths, assuming a particular geometry. In this paper we adopt the simplest model, assuming that the velocity distribution of the occulting clouds is randomly oriented in a spherical shell of radius R and is induced by the gravitational force of the central black hole of mass M_{bh} (note that we neglect radiation pressure). The characteristic distance of the shell from the central source ($\sim 10^4$ Schwarzschild radii) is then larger by 3 orders of magnitude than the scale of the continuum emission region (see, e.g., Peterson 1997). From the virial theorem for the cloud distribution, we get

$$R = \frac{r_{\text{sch}}}{2f_g} \left(\frac{c}{\sigma_{\text{cl}}} \right)^2, \quad (1)$$

where σ_{cl} is the one-dimensional velocity dispersion of the broad lines in km s^{-1} , $r_{\text{sch}} = 2GM_{\text{bh}}/c^2$ is the Schwarzschild radius of the black hole, G is the gravitational constant, and c the speed of light. The constant f_g depends the geometry of the cloud velocity distribution; in our spherical shell (two-dimensional) geometry $f_g = 2$ (an isothermal sphere would be described by $f_g = 3$). Given a total number of clouds N_{cl} , the covering fraction is $F_c = N_{\text{cl}}\pi r_{\text{cl}}^2/4\pi R^2$, where r_{cl} is the physical radius of each cloud. Therefore

$$r_{\text{cl}} = R \sqrt{\frac{4F_c}{N_{\text{cl}}}}. \quad (2)$$

The number of clouds, which is important for our analysis, is the subject of some controversy. An upper limit for the largest number of individual clouds can be obtained from photoionization arguments, yielding $N_{\text{cl}} \lesssim 10^7 - N_{\text{cl}} \lesssim 10^8$ (Arav et al. 1998). In addition, a lower limit on the number of clouds $N_{\text{cl}} \lesssim 10^7 - N_{\text{cl}} \lesssim 10^8$, has been derived based on the smoothness of the emission lines of NGC 4151 (Arav et al. 1998) and 3C 273 (Dietrich et al. 1999), under the assumption that the clouds are confined with a thermal internal velocity dispersion of $\sim 10-20 \text{ km s}^{-1}$. However, the estimated number of clouds is expected to go down dramatically if this assumption is relaxed, bringing the required number to be as small as few times 10^5 for a velocity spread of $\sim 100 \text{ km s}^{-1}$ per cloud (H. Netzer 2002, private communication), as expected for the cometary tails of bloated stars. Hence, the observed smoothness of the emission lines does not rule out the bloated star model, which predicts the existence of 10^4-10^5 clouds per quasar. It was also suggested that the low-excitation lines on which the above analysis was based originate from the outer parts of the accretion disk, while the high-excitation lines are dominated by discrete emitters (see Dietrich et al. 1999 and references therein).

The microlensing variability phenomenon discussed below results from broad-line clouds that are optically thick in the UV ($\sim 2500 \text{ \AA}$) at the rest-frame wavelength corresponding (with cosmological redshift) to optical observations. Of course, the clouds do not need to be optically thick in the UV in order for them to emit the broad lines. However, the appearance of some low-ionization lines requires that part of the broad-line region be protected from photons at wavelengths longer than the Lyman limit (Ferland & Persson 1989), so that broad-line clouds may be optically thick all the way up to the Balmer edge ($\sim 3600 \text{ \AA}$). In addition to the broad emission lines, the clouds emit continuum UV radiation. Global energy balance requires that the sum of the fluxes contributed by all the clouds be smaller than $\sim 10\%$ of the flux emitted by the accretion disk (as this is the geometric fraction of the disk sky that is covered by the clouds). If the clouds are blackbody emitters, this implies a surface brightness temperature for the clouds of $\lesssim 5 \times 10^3 \text{ K}$. At this temperature, the surface brightness of the clouds in the UV is more than 2 orders of magnitude lower than that of the accretion disk out to the radius enclosing 95% of the disk flux. Even if the clouds have photoionization temperatures of $\sim 10^4 \text{ K}$ their surface brightness in the UV is more than an order of magnitude lower than that of the disk out to the radius enclosing 80% of the disk flux. We therefore assume, for simplicity, that the obscuring clouds are dark.

Based on the above considerations we discuss the microlensing implications for a lensed optical source modeled as an accretion disk surrounded by a large number of optically thick, dark spherical clouds. We note that the number of disk-transiting clouds on which we focus in this paper (we quote number per $4\pi \text{ sr}$) could in principle be significantly smaller than the total number of broad-line clouds. While we assume a covering fraction of $\sim 10\%$ in optically thick, dark clouds, the presence of additional very small, bright, or optically thin clouds, or of an additional broad-line-emitting outflow would not change our conclusions. In addition, there are several geometrical considerations. First, individual clouds on randomly oriented Keplerian orbits filling a spherical volume might have a distribution preferentially in the plane of the disk (Osterbrock 1993 cited in Dietrich et al. 1999). Second, if the cloud velocity distribution is dominated by an inflow or an outflow bulk velocity, then the number of transiting clouds would also be much smaller than the total (because the radial component of the velocity is much larger than the tangential component).

Throughout this paper we show numerical examples with typical parameter values of $M_{\text{bh}} = 5 \times 10^8 M_{\odot}$, $\sigma_{\text{cl}} = 5 \times 10^3 \text{ km s}^{-1}$, and $F_c = 0.1$ and assume a face-on disk profile observed in the R band. We show results as a function of the number of clouds, N_{cl} , which is the free parameter that is least constrained by existing observations of quasars.

3. MICROLENSING MODEL

Throughout most of this paper we consider a fiducial lensing scenario, comprising a lens galaxy at a redshift $z_d = 0.5$ and a source at $z_s = 1.5$. We assume typical microlensing parameters encountered just inside the Einstein radius of the lens galaxy, which is modeled as a spherical singular isothermal sphere. In particular, we adopt the likely values of $\kappa_* = 0.08$ and $\kappa_c = 0.46$ for the convergence in stars and smoothly distributed mass, respectively, and a

value of $\gamma = 0.54$ for the shear (see Wyithe & Turner 2002). The average magnification of the corresponding macro-image is -12.5 . The chosen image parameters correspond to a saddle point. Recently, Schechter & Wambsganss (2002) have pointed out that sources with radii much smaller than the microlens Einstein radius are subject to larger microlensing fluctuations, particularly in the presence of a significant component of smooth matter. Our choice is based on the fact that the observed fluctuations appear to be in images at saddle points. The magnification maps³ for the simulations in this paper were computed with the MICROLENS program kindly provided to us by Joachim Wambsganss.

4. VARIABILITY DUE TO OBSCURATION OF THE DISK BY BROAD-LINE CLOUDS

Monitoring data of the systems RX J0911+05 and SBS 1520+530 (Hjorth et al. 2002; Burud 2002) shows evidence for short-term variability that is unique to individual images. The variability is observed on timescales of tens to hundreds of days, with an amplitude of up to a few percent. Furthermore, the microlensing features appear to be associated with small intrinsic fluctuations. It is important to note that any microlensing scenario used to explain these observations must predict this correlation of intrinsic and microlensing fluctuations in addition to the timescales and amplitudes of the microlensing variability. In this section we

³ The average number of rays per pixel in our magnification maps is greater than $N_{\text{rays}} = 100$. Thus, the maps are computed to an accuracy better than $N_{\text{rays}}^{0.25}/N_{\text{rays}} \sim 3\%$ pixel⁻¹ and a significantly higher accuracy for high-magnification pixels. Note that the scaling is with $N_{\text{rays}}^{0.25}$ rather than the Poisson scaling of $N_{\text{rays}}^{0.5}$ because rays are placed on a regular grid in the image plane rather than being randomly distributed. Careful examination of “light curves” for individual clouds clearly demonstrates that the variability seen in Fig. 2 is not caused by simulation noise.

present a microlensing model that accounts for all three features.

4.1. Intrinsic and Microlensing Light Curves

Figure 1 shows the geometry of the system. The left-hand panel shows a portion of a magnification map computed for the aforementioned parameter values. Superposed on this map is a contour enclosing 95% of the *R*-band (observer frame) flux from the accretion disk source. This contour is displayed again on the right-hand panel of Figure 1, together with a random distribution of broad-line clouds, whose sizes were computed for $N_{\text{cl}} = 10^5$ (see eq. [2]). Since the velocities of the broad-line clouds are an order of magnitude larger than the projected transverse velocity expected for the lens galaxy, we assume the accretion disk to be stationary relative to the caustic network. The clouds obscure a fraction $F_c = 0.1$ of the disk surface. Since the disk surface brightness is a function of radius, the motion of the clouds across regions of varying surface brightness causes low-level variability of the total flux. Variability also results from the Poisson noise associated with the variance in the number of obscuring clouds. In the absence of microlensing, and assuming a stationary disk the intrinsic observed flux as a function of time, t , is

$$f_{\text{int}}(t) = \int_0^\infty r dr s_\nu(r) - \sum_{i=1}^{N_{\text{cl}}} \int_0^{r_{\text{cl}}} r dr \int_0^{2\pi} d\theta s_\nu \times \left(\left| \mathbf{r}_i \left(\frac{t}{1+z_s} \right) + \mathbf{r} \right| \right), \quad (3)$$

where $s_\nu(r)$ is the surface brightness of the disk at frequency ν and radius $r = |\mathbf{r}|$, and $\mathbf{r}_i = (r_i, \theta_i)$ are the time-dependent coordinates of the N_{cl} broad-line clouds. If the accretion disk is also subject to microlensing, then the microlensed surface brightness profile is the product of the position-dependent magnification $\mu(\mathbf{r})$ with the intrinsic accretion disk brightness $s_\nu(|\mathbf{r}|)$. Thus, in the presence of microlensing

FIG. 1.—Microlensing geometry. *Left*: Microlensing magnification map with the contour enclosing 95% of the flux from a face-on thermal accretion disk (Agol & Krolik 1999) around a $5 \times 10^8 M_\odot$ black hole. *Right*: Projection of a shell of 10^5 randomly distributed clouds assuming a covering factor of 10% and a velocity dispersion of 5000 km s^{-1} . The lens and source redshifts are $z_d = 0.5$ and $z_s = 1.5$. The microlens masses are $m = 0.1 M_\odot$.

the light curve is

$$f_{\text{ml}}(t) = \int_0^\infty r dr \int_0^{2\pi} d\theta \mu(r) s_\nu(|\mathbf{r}|) - \sum_{i=1}^{N_{\text{cl}}} \int_0^{r_{\text{cl}}} r dr \times \int_0^{2\pi} d\theta \mu \left[\mathbf{r}_i \left(\frac{t}{1+z_s} \right) + \mathbf{r} \right] s_\nu \left(\left| \mathbf{r} \left(\frac{t}{1+z_s} \right) + \mathbf{r} \right| \right). \quad (4)$$

The first term on the right-hand side of this equation (the magnified flux from the disk) is not a function of time since we have assumed a stationary disk. The variability in the continuum emission due to obscuration by broad-line clouds is very different from the variability in the line profiles due to microlensing of the broad-line emission itself (Schneider & Wambsganss 1990), but it is similar in spirit to the scenario outlined in Lewis & Belle (1998) describing microlensed induced spectral variability in broad absorption-line quasars.

In Figure 2 we show four sample light curves corresponding to $N_{\text{cl}} = 10^4, 10^5, 10^6$, and 10^7 , all with a duration of 2 yr. The light line shows the level of intrinsic variability $f_{\text{int}}(t)$, while the dark line shows variability including microlensing $f_{\text{ml}}(t)$. It is apparent that larger clouds produce variability of longer duration and larger amplitude. The amplitudes range from a few percent for the largest clouds under consideration down to hundredths of a percent for the smallest clouds (note that the scaling of the y-axis is different in each panel of Fig. 2). Similarly, the timescales for the variability range between tens and hundreds of days. The two curves show similar overall trends; however, the peaks and troughs in the microlensed light curve are more pronounced. The difference between the microlensed and intrinsic variability arise because the variation in effective surface brightness over the accretion disk surface is more

extreme in the microlensed case. Keeping in mind the simplicity of our model, the light curves computed using $N_{\text{cl}} \sim 10^5$ in Figure 2 show a striking qualitative resemblance to the light curves of SBS 1520+530 presented by Burud (2002). In particular the anomalous microlensing variability is superposed on, and concurrent with, intrinsic light-curve features.

The variability shown in Figure 2 (both f_{int} and f_{ml}) is superposed upon additional longer timescale intrinsic source variability (common to all of its images), which is observed in unlensed quasars (e.g., Webb & Malkan 2000). We have assumed a population of identical clouds. However for a real quasar we expect a spectrum of cloud sizes with a distribution $\phi(r_{\text{cl}})$, representing the number of clouds with radii between r_{cl} and $r_{\text{cl}} + \Delta r_{\text{cl}}$. Hence, the light curves reflect a superposition of the corresponding amplitudes and timescales due to this distribution. The total number of clouds is $N_{\text{cl}}^{\text{tot}} = \int_0^\infty dr_{\text{cl}} \phi(r_{\text{cl}})$. However, the effective number of clouds that contribute to the microlensing signal (N_{eff}) corresponds to an effective cloud radius $r_{\text{cl}}^{\text{eff}}$ calculated from the mean of the obscuration area weighted cloud-size distribution. For spherical clouds

$$N_{\text{eff}} \sim 4F_c \left(\frac{R}{r_{\text{cl}}^{\text{eff}}} \right)^2, \quad \text{where } (r_{\text{cl}}^{\text{eff}})^2 = \frac{\int_0^\infty dr_{\text{cl}} r_{\text{cl}}^4 \phi(r_{\text{cl}})}{\int_0^\infty dr_{\text{cl}} r_{\text{cl}}^2 \phi(r_{\text{cl}})}. \quad (5)$$

The values of N_{cl} quoted in this paper should be identified with N_{eff} .

While gravitational lensing of a point source is achromatic (in the limit of geometrical optics), the differential magnification of extended sources results in color-dependent variability. In the scenario described above, two different effects may be observed. First, if the effective size of the accretion disk is smaller at higher frequencies, then the

FIG. 2.—Sample light curves for a disk centered on the position shown in Fig. 1. Curves are shown assuming four different cloud sizes corresponding to a total number of clouds per 4π sr of $N_{\text{cl}} = 10^4, 10^5, 10^6$, and 10^7 . The light line shows the variability in the absence of microlensing, and the dark line shows the variability with microlensing. Note that the vertical axis has a different scale in each case. The lens and source redshifts are $z_d = 0.5$ and $z_s = 1.5$.

microlensing fluctuations in the continuum will be larger when observed at higher frequencies since a single cloud covers a larger fraction of the emission. In addition, the covering fraction F_c itself should be color dependent since the clouds are expected to be more extended at shorter wavelengths owing to higher opacity. Thus multicolor monitoring observations should yield additional diagnostics.

4.2. Variability Statistics

The light curves of Figure 2 demonstrate that bigger clouds produce variability of a longer duration and a larger amplitude. As can be seen from Figure 1, these light curves were computed (for the purpose of demonstration) using a favorable source location on the magnification map close to several caustics. In this section we present the characteristic timescales and variability amplitudes for 100 random accretion disk positions across the network of microlensing caustics. Since intrinsic variability will be present in all images of a multiply imaged quasar and only microlensing can produce the anomalous light-curve variability, we calculate variability statistics for the ratio, $f(t) = f_{\text{int}}(t)/f_{\text{ml}}(t)$ between the intrinsic and microlensed light curves at each source position. We calculate the autocorrelation function, $f_{\text{AC}}(\Delta t) = \text{sign}(f'_{\text{AC}}) \sqrt{|f'_{\text{AC}}|}$, where $f'_{\text{AC}} \equiv \langle (f(t) - \langle f \rangle)(f(t + \Delta t) - \langle f \rangle) \rangle$. Here, angular brackets denote averaging over long times. The characteristic variability amplitude is taken to be $\sigma = f_{\text{AC}}(0)$ (the light-curve variance),

and the correlation timescale Δt_{corr} is defined by the condition $f_{\text{AC}}(\Delta t_{\text{corr}})/f_{\text{AC}}(0) = 0.5$ for each source position. Figure 3 shows scatter plots of Δt_{corr} versus σ for $N_{\text{cl}} = 10^4, 10^5, 10^6$, and 10^7 . The aforementioned dependence of the timescale and variability amplitudes on N_{cl} are readily apparent in this plot. The upper panels of Figure 4 show one minus the single variable cumulative probabilities for σ and Δt_{corr} . Characteristic timescales of 50–100 days are consistent with all cloud sizes, while timescales below ~ 50 days are not consistent with $N_{\text{cl}} \lesssim 10^4$ and timescales above ~ 100 days are only consistent with $N_{\text{cl}} \lesssim 10^6$. Inspection of the top right-hand panel of Figure 4 shows an even stronger dependence on N_{cl} . In particular if $N_{\text{cl}} \sim 10^4$ – 10^5 , the variability amplitude is a few tenths of a percent to a few percent, while the variability amplitude is always below $\sigma \sim 0.2\%$ if $N_{\text{cl}} \gtrsim 10^6$.

As noted in § 3 the image parameters chosen correspond to a saddle point, which for small sources leads to larger microlensing fluctuations (Schechter & Wambsganss 2002). We have repeated the above calculation for the related minimum (positive parity) image ($\kappa_* = 0.07$, $\kappa_c = 0.39$, $\gamma = 0.46$, $\mu = +12.5$). We find that the resulting amplitude of microlensing due to obscuration of the disk by broad-line clouds is an order of magnitude lower for $N_{\text{cl}} \geq 10^5$, but equal for $N_{\text{cl}} = 10^4$ when compared with the saddle-point case. The lowered amplitude for $N_{\text{cl}} \geq 10^5$ results from the smaller microlensing fluctuations in image minima when compared to saddle points, while the lack of dependence on image parity for $N_{\text{cl}} = 10^4$ reflects the sensitivity of the effect

FIG. 3.—Scatter plots of the correlation timescale Δt_{corr} vs. the variance of the variability amplitude σ for different source positions on the magnification map. The light lines show the medians of both variables. The four panels correspond to $N_{\text{cl}} = 10^4, 10^5, 10^6$, and 10^7 . The lens and source redshifts are fixed at $z_d = 0.5$ and $z_s = 1.5$.

FIG. 4.—One minus the cumulative probabilities for the correlation timescale Δt_{corr} (left) and the variability variance σ (right) for the fiducial time-delay lens case (top; $z_d = 0.5$ and $z_s = 1.5$) and for a lensing configuration similar to Q2237+0305 (bottom; $z_d = 0.05$ and $z_s = 1.5$). Curves are shown for $N_{\text{cl}} = 10^4, 10^5, 10^6$, and 10^7 (top only).

described by Schechter & Wambsganss (2002) to finite source size.

Another heavily monitored gravitational lens is Q2237+0305 at an unusually low lens redshift of $z_d = 0.0394$ (Irwin et al. 1989; Corrigan et al 1991; Østensen et al. 1996; Wozniak et al. 2000a, 2000b). The lens was monitored not for the purpose of measuring time delays (for which its geometry is unsuited), but of observing quasar microlensing (for which it is the most favorable lens known). The variability record shows long-term, large-amplitude variation, but *no* variation at the percent level over timescales of tens of days. Thus if the model proposed in this paper is correct, it must not predict rapid, low-amplitude variability in Q2237+0305. To demonstrate the required consistency, we have repeated the calculation described above for a lens galaxy at $z_d = 0.05$ rather than $z_d = 0.5$ which closely mimics the Q2237+0305 geometry. The lower panel of Figure 4 shows one minus the single variable cumulative probabilities for σ and Δt_{corr} as before for $N_{\text{cl}} = 10^4, 10^5$, and 10^6 . The median variability for $N_{\text{cl}} = 10^4$ is around $\sigma \sim 1\%$ with a range of $0.1\% \lesssim \sigma \lesssim 5\%$. On the other hand, if $N \gtrsim 10^5$ the range is $0.01\% \lesssim \sigma \lesssim 0.5\%$, with a median of $\sigma \sim 0.1\%$. Thus we would not expect a previous detection of short-term anomalous variability in Q2237+0305 if $N_{\text{cl}} \gtrsim 10^5$. The timescales are comparable to those for the generic lens case, which is expected since the

timescale depends on velocities generated in the source plane rather than the lens plane.

The difference in the statistics of rapid, low-amplitude microlensing variability (due to obscuration of the continuum by broad-line clouds) between the typical lens geometry ($z_d \sim 0.5$) and the special case of a lens at very low redshift ($z_d \sim 0.05$) follows from the different size of the projected microlens Einstein radius. The broad-line cloud induced variability requires that a caustic lie across the accretion disk. In the typical lensing case ($z_d = 0.5$), the source is relatively large with respect to the caustic network, so that one or more caustics generally cross the source (see Fig. 1). In the low-redshift lens case ($z_d = 0.05$), caustic crossings are rare, and so are the broad-line microlensing events. Note that the value of $N_{\text{cl}} \sim 10^5$ bracketed by the nondetection at $z_d = 0.05$ and the detection at $z_d = 0.5$ corresponds to the expected number of broad-line clouds in the bloated star model (Alexander & Netzer 1997).

5. VIABILITY OF ALTERNATIVE EXPLANATIONS

Two alternative explanations for rapid, low-amplitude variability appear in the literature. We discuss these in turn and demonstrate their shortcomings in explaining the observations of RX J0911+05 and SBS 1520+530 (Hjorth et al. 2002; Burud (2002).

5.1. Variability Due to Disk Hot Spots

Gould & Miralda-Escudé (1997) (see also Rauch & Blandford 1991) suggested that the observed rapid, low-amplitude variability might result from hot spots on the surface of the disk. This scenario is similar to ours insofar as the short timescale results from the large orbital velocities in the source plane, while the low amplitude results from the fact that only a small fraction of the total flux is subjected to large-amplitude magnification by microlensing. The main differences from our model are that the hot spot velocities ($\sim 0.2c$) are larger than the cloud velocities because of their closer proximity to the black hole, and the amplitude of fluctuations is governed by the contrast between the surface brightness of the hot spots and the disk rather than that between the opaque clouds and the disk. In the following calculations we have assumed a confined hot spot. However other classes of “hot spots” will yield different microlensing statistics. These would include rapidly varying spiral structure and annular gaps in the disk, and hot spots at radii larger than those considered, which will have smaller velocities. These may have microlensing timescales more consistent with those observed than the example considered below.

We make the simple assumption of circular Keplerian rotation for the hot spots, and distribute a number N_{sp} of them at random within the contour containing 99% of the flux from the disk surface. We assume that the hot spots are long-lived for the purpose of the light-curve computation. This is equivalent to the computation of the statistics for the time averaged number of spots. We denote the radius of each spot by r_{sp} , and the ratio between the surface brightness of the spot and the disk (locally) by the contrast C . Hence, $C = 1$ if the spots have the same temperature as the disk, $C = 0$ if the spots have zero temperature and contribute no flux (equivalent to the obscuration case presented in the previous section), and $C > 1$ for spots that are hotter

than the disk. The microlensing light curve for a stationary disk with hot spots is

$$f_{\text{ml}}(t) = \int_0^\infty r dr \int_0^{2\pi} d\theta \mu(\mathbf{r}) s_\nu(|\mathbf{r}|) + (C - 1) \sum_{i=1}^{N_{\text{sp}}} \int_0^{r_{\text{sp}}} r dr \times \int_0^{2\pi} d\theta \mu \left[\mathbf{r}_i \left(\frac{t}{1+z_s} \right) + \mathbf{r} \right] s_\nu \left(\left| \mathbf{r}_i \left(\frac{t}{1+z_s} \right) + \mathbf{r} \right| \right), \quad (6)$$

where $\mathbf{r}_i = (r_i, \theta_i)$ are the time-dependent coordinates of the N_{sp} hot spots. This formulation does not result in intrinsic variability.

The parameters for this model are not constrained by observations, and we have computed statistics for six representative cases. We assume values for r_{sp} of 10^{14} cm and 5×10^{14} cm, with contrasts of $C = 50$ and $C = 2$, respectively, resulting in fluctuation amplitudes of $\sim 0.1\%$ – 1% . For each case we compute light curves for $N_{\text{sp}} = 1, 10$, and 100 . The corresponding fractions of disk covered by the spots are $F_{\text{sp}} = 0.0001, 0.001$, and 0.01 if $r_{\text{sp}} = 10^{14}$ cm and $F_{\text{sp}} = 0.0025, 0.025$, and 0.25 if $r_{\text{sp}} = 5 \times 10^{14}$ cm. The amplitude of the light-curve scales with $|1 + (C - 1)F_{\text{sp}}|$, and so the results in this section for the amplitude of the fluctuations can be easily generalized to other values of C .

Figure 5 shows sample light curves for these six cases. The signature of periodicity noted by Gould & Miralda-Escudé (1997) is apparent in the light curves with a single spot, although for $N_{\text{sp}} > 1$ the variability is due to the sum of many periodic light curves with a random phase and the periodicity is diluted. Figure 5 implies that the variability timescale is shorter than that generated by broad-line clouds. Furthermore, if only a few spots are present then the light curve resembles a classical microlensing light curve with M-shaped events, but with a reduced amplitude and timescale. Thus, small numbers of hot spots produce micro-

FIG. 5.—Sample light curves, assuming spot radii of $r_{\text{sp}} = 10^{14}$ cm (upper row) and $r_{\text{sp}} = 5 \times 10^{14}$ cm (lower row). In each case, light curves resulting from $N_{\text{sp}} = 1, 10$, and 100 are shown. The light line shows the lack of variability in the absence of microlensing, and the dark line shows the variability due to microlensing. Note that the vertical axis has a different scale in each case. The lens and source redshifts are $z_d = 0.5$ and $z_s = 1.5$. The contrast of individual spots in the upper and lower rows is $C = 50$ and $C = 2$, respectively.

FIG. 6.—Scatter plots of the correlation timescale Δt_{corr} vs. the variance of the variability amplitude σ for different source positions. The light lines show the medians of both variables. The upper and lower rows assume spot radii of $r_{\text{sp}} = 10^{14}$ cm and $r_{\text{sp}} = 5 \times 10^{14}$ cm. Plots for $N_{\text{sp}} = 1, 10$, and 100 are shown in each case. The contrast of individual spots in the upper and lower rows is $C = 50$ and $C = 2$, respectively.

lensing peaks that look qualitatively different from the troughs produced in the light curves by the broad-line clouds. Moreover, in our formulation, hot spots do not produce intrinsic variability, so that we do not expect microlensing peaks to be concurrent with intrinsic peaks as predicted by the broad-line cloud model and observed by Burud (2002). Microlensing of a hot spot should induce color variability resulting from magnification of a hotter (and therefore bluer) part of the source.

Figure 6 quantifies the variability statistics by showing scatter plots of Δt_{corr} versus σ for the six cases mentioned above. The variability amplitudes cannot be directly used to constrain N_{sp} or r_{sp} since it is governed by the contrast C . However, the timescales are much shorter than those due to the broad-line cloud absorption, with medians below 10–20 days in all cases except for a single large spot ($r_{\text{sp}} \sim 15r_{\text{sch}}$). Note that this timescale is nearly independent of the black hole mass; although a smaller M_{bh} lowers the orbital velocity at a fixed radius, the radius corresponding to a fixed level of disk emission is roughly proportional to M_{bh} . Overall, the variability timescales predicted by this model are shorter than those observed in RX J0911+05 and SBS 1520+530.

5.2. Microlensing by Very Small Masses

We also consider rapid low-amplitude microlensing variability due to a population of very low mass compact objects. In this scenario, small amplitude variability results from the source being large compared to the characteristic scale of the caustic network (or equivalently the microlens Einstein radius), while the rapid timescale results from the short crossing time of this network. We assume a featureless accretion disk without hot spots around a $5 \times 10^8 M_{\odot}$ black

hole that moves relative to the caustic network. The transverse velocity $\mathbf{v}_{\text{gal}}$ of the lens galaxy with respect to the observer-source line of sight is assumed to have a magnitude of 400 km s^{-1} . The light curve $f_{\text{ml}}(t)$ is

$$f_{\text{ml}}(t) = \int_0^\infty r dr \int_0^{2\pi} d\theta \mu \left[\mathbf{r}_0 + \mathbf{r} + (t - t_0) \frac{\mathbf{v}_{\text{gal}}}{1 + z_d} \frac{D_s}{D_d} \right] s_\nu(|\mathbf{r}|), \quad (7)$$

where $\mathbf{r}_0$ is the quasar position at time t_0 ; D_d and D_s are the angular diameter distances to the lens and source, which we again take to have redshifts $z_d = 0.5$ and $z_s = 1.5$. A sample magnification map for very low mass microlenses is shown in Figure 7. Superposed on this map are the contours enclosing 95% of the flux from a face-on thermal accretion disk assuming three different cases of microlens masses, namely, $m = 10^{-2}, 10^{-3}$, and $10^{-4} M_{\odot}$. The pair of circles in each case demonstrates how far the disk moves during 10 yr. Sample light curves are shown as the dark lines in the top panel of Figure 8. The light curves show two characteristic timescales: a long timescale governed by the caustic clustering length (see Fig. 7) as well as a shorter timescale.

In order to isolate the characteristic amplitude and timescales of the rapid variability, we performed the following procedure. For each light curve we find the correlation time, as before, and then smooth the light curve using the correlation time as the standard deviation of a Gaussian smoothing function. The resulting curves are shown by the light lines in the upper panels of Figure 8. The ratio between the two curves yields the rapid, low-amplitude variability. These are shown in the lower panels of Figure 8. We constructed autocorrelation functions for a hundred light curves in each case

FIG. 7.—Sample magnification map for very low mass microlenses. The contours enclosing 95% of the flux from a face-on thermal accretion disk (Agol & Krolik 1999) around a $5 \times 10^8 M_\odot$ black hole are shown for three microlens masses, namely, $m = 10^{-2}$, 10^{-3} , and $10^{-4} M_\odot$. The pair of circles in each case are shown to demonstrate how far the disk moves during 10 yr, assuming a transverse velocity for the lens galaxy of 400 km s^{-1} . The lens and source redshifts are $z_d = 0.5$ and $z_s = 1.5$.

and extracted the characteristic variability and amplitude as before. The results are shown in Figure 9. We find that the smallest masses under consideration can produce the required variability amplitudes of $\sim 1\%$. However the timescales are around 400 days, longer than those seen in RX J0911+05 and SBS 1520+530. Note that Δt_{corr} is proportional to the inverse of the transverse velocity assumed. The timescale is also dependent on the direction of the transverse velocity with respect to the microlensing shear. We have conservatively assumed that the direction to be parallel to the shear that results in the most rapid timescales. However a transverse velocity parallel to the shear can significantly increase Δt_{corr} (Wambsganss, Paczyński, & Katz 1990; Lewis & Irwin 1996) and make it even less compatible with the data. In addition to the relatively large timescale for the rapid component of variability, we note that the simulated light curves differ qualitatively from those observed. The observed light curves do not show long-term microlensing variability over the duration of the monitoring period, as is predicted by this model. Furthermore, since the microlensing variability must be uncorrelated between macroimages, there is no mechanism to explain the correlation between the intrinsic variability and the microlensing variability observed in the light curves of RX J0911+05 and SBS 1520+530.

To save this model, one might suppose that hot spots are present in addition to the very low mass microlenses. In this way, one might shorten the timescale predicted by the low-mass microlensing light curves using the large source plane velocities of the hot spots, while retaining the low amplitudes for the reasons discussed in § 5.1. However we argue that this scenario will also be inconsistent with the observa-

FIG. 8.—Sample light curves for a smooth accretion disk and very low mass microlenses. Curves are shown for the three microlens masses, $m = 10^{-2}$, 10^{-3} , and $10^{-4} M_\odot$. In the upper panels the dark lines show raw microlensing light curves, while the light lines show the light curves after being Gaussian-smoothed on the correlation timescale. In the lower panels, the curve shows the ratio between the raw and smoothed curves. The lens and source redshifts are $z_d = 0.5$ and $z_s = 1.5$, and the transverse velocity of the lens galaxy is 400 km s^{-1} .

FIG. 9.—Scatter plots of the correlation timescale Δt_{corr} vs. the variance of the variability amplitude σ for planetary-mass microlenses. The light lines show the medians of both variables. Plots are shown for microlens masses of $m = 10^{-2}$, 10^{-3} , and $10^{-4} M_{\odot}$.

tions. As can be seen from Figure 7, the short (~ 400 day) variability is superimposed on longer term variability that was removed in the above calculations of variability statistics. This long-term variability, which is due to the clustering of caustics on scales many Einstein radii in extent, will still be present following the addition of hot spots but is not seen in the light curves of RX J0911+05 and SBS 1520+530, which have durations of ~ 1000 – 1500 days. Thus predictions of microlensing variability due to very low mass microlenses differ qualitatively from observations, whether or not the disk has spots.

6. DISCUSSION

We have identified a simple explanation for the anomalous microlensing variability reported by Hjorth et al. (2002) and Burud (2002) in the systems RX J0911+05 and SBS 1520+530. We find that the obscuration of a differentially magnified (microlensed) accretion disk by optically thick broad-line clouds results in rapid variability owing to the high cloud velocities and in fluctuations with a low amplitude owing to the large number of clouds (and hence small level of Poisson fluctuations). The model predicts fluctuations with amplitudes (a few percent) and timescales (50–100 days), comparable to those observed. In addition, the model naturally explains the observed correlation between the intrinsic and microlensing features. The model does not require the inclusion of any hypothetical components.

It is in principle also possible to generate rapid, low-amplitude variability through microlensing of hot spots on the surface of an accretion disk (Gould & Miralda-Escudé 1997) or through very low mass microlenses. In the first case, our simulations show that the variability timescales are substantially shorter than those observed in RX J0911+05 and SBS 1520+530. Of the cases considered, the longer timescales are produced by a small number of relatively large spots ($r_{\text{sp}} \sim 10r_{\text{sch}}$). However, a small number of spots produces light curve shapes that differ qualitatively from those identified in the observations. In the second alternative model of planetary-mass microlenses, we find that the timescales are governed by the caustic clustering length and source crossing time rather than the crossing

time of the microlens Einstein radius. As a result, the predicted timescales are longer than those observed.

If our explanation for the nature of this unexpected microlensing signal is correct, it will be of great significance in constraining the properties of the broad-line region. Although the dimension of the broad-line region is measured by reverberation mapping and the covering factor is known to be $\sim 10\%$, there is currently little information regarding the number and hence the size, of individual broad-line clouds (see discussion in § 2). Our simple model suggests that a number $N_{\text{cl}} < 10^6$ of broad-line clouds that contribute a covering factor of $F_{\text{c}} \sim 0.1$ can explain the anomalous light curve features observed by Hjorth et al. (2002) and Burud (2002) in RX J0911+05 and SBS 1520+530. In addition, the lack of these features in Q2237+0305 suggests that $N_{\text{cl}} > 10^4$. Interestingly, these constraints bracket the predicted range for the number of clouds in the bloated star model (Alexander & Netzer 1997).

Our results provide a qualitative explanation for the rapid, low-amplitude microlensing variability recently observed in several gravitational lens systems. As more measurements of variability become available in the future for these and other lens system, it will become possible to refine our analysis by detailed modeling of individual systems. The submicroarcsecond resolution provided by the sensitivity of the rapid microlensing fluctuations to the number of discrete broad-line clouds, has the potential to place important constraints on models of the broad-line region.

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