MICROLENSING OF A RING MODEL FOR QUASAR STRUCTURE

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Received 2002 December 16; accepted 2003 April 22

ABSTRACT

Microlensing observations of QSO 0957+561A and QSO 0957+561B have consistently shown evidence for structure in the quasar that has not been evident in available microlensing models, where the luminous source has been consistently modeled as a single large, round structure. We show that the microlensing features can easily be reproduced by a luminous quasar model motivated by observations: a luminous inner accretion disk edge and outer ring-shaped structures where the emission lines form. Such a model can explain all of the features known from 24 years of QSO 0957+561 microlensing observations.

Key words: gravitational lensing — quasars: individual (QSO 0957+561)

1. INTRODUCTION

An early dream of the community studying microlensing of quasars was to actually learn something about the quasar’s structure (Chang & Refsdal 1979). At the time, the quasar was presumed to have an accretion disk, which should be luminous, and outer structure, perhaps a flock of clouds, where the emission lines formed, but not presumed to be a source of optical continuum.

With the discovery of the first time delay in QSO 0957+561 (Schild & Cholfin 1986), it was immediately evident that microlensing was observed (Grieger, Kayser, & Refsdal 1988) and that reasonable values of the quasar’s luminous structure were measured, based upon these models consisting of a simple filled circular source characterized by one parameter, the diameter.

However, the microlensing observations that soon followed immediately showed a problem with this oversimple model. The microlensing review of the first 10 years of data by Schild & Smith (1991) already indicated that “fine structure is also apparent.” This motivated Schild and colleagues to intensively monitor the system to determine an accurate time delay and to further define the fine structure in the microlensing.

By 1996, observations on 1000 nights were compiled by Schild & Thomson (1995) and analyzed by statistician D. J. Thomson (Thomson & Schild 1997; Schild & Thomson 1997), with several remarkable conclusions. The time delay was ill-defined even with vast amounts of high-quality data, and a rapid microlensing was usually present, with 1% amplitudes on a timescale of days. Structure in the autocorrelation plots of the two images taken individually indicated that the source quasar evidently had structure on size scales of 10 and 200 lt-days (observer’s clock), a factor of 10–100 larger than presumed accretion disk sizes. Analysis of brightness fluctuations from a historical record by Schild (1996) bolstered the case for large quasar structure, which was inferred to be dominated by “rings or clouds with a 10% filling factor.” He further inferred that “such structure may need to be taken into account to explain the observed high-frequency microlensing.”

By the year 2000, a new model of quasar structure was advanced by Elvis (2000) to explain the complex variety of emission- and absorption-line properties observed in quasars. This new unification model features two large ringlike structures that are actually hyperbolic in cross section. The structures contain outflows responsible for the blueshifted broad emission lines long known in quasar spectra, and different types of quasars were understood as resulting from different viewing angles of these structures. Because the sizes of these structures are comparable to the sizes already inferred by Schild (1996) for the continuum source, an empirical model of quasar structure now exists that is significantly different from the popular simple accretion disk model.

In addition to the outer structures identified by Elvis, there must also be a luminous inner edge of the accretion disk, as discussed by Colley et al. (2003). The size of this structure, about 10 lt-days (observer’s clock), has already been inferred by these authors, and it must somehow contribute to the total luminosity and structure.

It has long been known (Wills, Netzer, & Wills 1985) that quasar energy distributions are not well described by a simple thermal law, as is illustrated in the composite spectral energy distribution of Elvis et al. (1994). This has frequently been described as a broad “big blue bump” and a “small bump.” Different quasars seem to differ in the relative luminosities of these continuum sources. Thus the existence of discrete structures in a quasar has long been inferred observationally.

The purpose of the present report is to take this observational model seriously and examine how such a model will be microlensed, for comparison with microlensing observations already published. Microlensing calculations to date (Young 1981; Kayser, Refsdal, & Stabell 1986; Schmidt & Wambsganss 1998 and earlier references) have faced a vexing dilemma; for luminous sources modeled as a simple disk, small models that can produce the rapid brightness fluctuations observed produce large brightness fluctuations never observed in any quasar (lensed or not known as a gravitational lens system), whereas large models producing smaller brightness fluctuations cannot produce the rapid effects observed.

In the pages to follow, we will show that the empirical model based upon the Elvis (2000) model of quasar structure, the double components of the spectral energy distribution, and the autocorrelation peaks found in the brightness.
2. PARAMETER ESTIMATES FOR THE EMPirical QUASAR MODEL

According to the Elvis (2000) quasar unification model, most of the continuum and all the emission lines originate in large ringlike structures. A cut through the structure passing through the black hole produces conic sections of revolution as illustrated in Figures 3 and 4 of Elvis (2000). The radius of this structure is given as $10^{16}$ cm for a Seyfert galaxy such as NGC 5548. In our much larger radio source quasar, we presume that the structure scales approximately as the Schwarzschild radius of the black hole, which is a linear function of the mass. As a result, we would estimate a factor of 20 larger size scale for our QSO 0957+561 radio source quasar.

An observational estimate of this size comes directly from the autocorrelation analysis of the quasar brightness history. Thomson & Schild (1997; see also Schild 1996) found autocorrelation peaks in the quasar’s brightness record and interpreted these as indicative of structure on scales $2 \times 10^{17}$ cm. Note that these dimensions are a factor of 10–100 larger than quasar sizes ordinarily associated with quasar accretion disks (Schmidt & Wambsganss 1999; Refsdal et al. 2000). For our cosmological model, we adopt an Einstein–de Sitter universe with a Hubble constant of 60 km $s^{-1}$ Mpc$^{-1}$, and we adopt $D_s/D_d = 2$ to make our calculations applicable to an “average” lens system, where the actual ratio for QSO 0957+561 is 1.41 (the model is quite insensitive to this choice). For our physical quasar model, we have adopted a single ring of radius $2 \times 10^{17}$ cm and a radial thickness of $2 \times 10^{16}$ cm. The radius estimate follows from simplistic arguments attributing the observed lags to quasar luminous structures that probably reprocess radiations emitted near the black hole event horizon but are observed at Earth with a lag corresponding to the extra time needed to traverse the quasar structure region before being reemitted as ultraviolet radiation in our direction (the lag times are reported herein as measured in the observer’s frame). The radial thickness is determined from a Refsdal-Stabell (1991, 1993, 1997) argument, where the amplitudes of brightness fluctuations measured over the past 100 yr can be used to infer the total area of the light-emitting surface for large sources. While some small modifications to the theory might be required for ring-shaped sources rather than uniformly illuminated accretion disks, we believe that the Refsdal-Stabell theory provides a good starting point for our calculation. We will see that this estimate indeed reproduces the observed fluctuations on the relevant timescale of decades.

Thus we have simplified the somewhat complex outer structure of the Elvis (2000) model as a simple ring with a radius and radial thickness given above. There is also a small correction for the ellipticity of the observed ring, where our calculation assumes a round ring. It would be logical to assume that the quasar is seen inclined by approximately 45°, making a circular ring appear ellipsoidal in projection.

In addition to the large ring described above, there must be a smaller luminous ring at the inner edge of the accretion disk (facing the black hole). Justification for this structure and an estimate of its size have been given by Colley et al. (2003). The existence of complex quasar structure has long been inferred from observation of ultraviolet energy distributions of quasars; these have identified a power-law continuum and a “blue bump,” which we attribute to this small accretion disk ring. Thus we estimate the radius of this ring in QSO 0957+561 as $10^{16}$ cm (Colley et al. 2003). Our brightness measurements have been made with an $R$ filter having effective wavelength 6400 Å; for a redshift of $z = 1.41$, the proper wavelength becomes 2655 Å, where the amplitude of the blue bump is typically 20% of the total brightness. This is also compatible with the autocorrelation plot of the two quasar images (Fig. 3 of Schild 1996); here the autocorrelation peaks defining structures at 3, 50, 80, and 230 proper days are all of about the same amplitude, suggesting that they all contribute about equally to the luminosity. For the thickness of this ring, we will simply use the Schwarzschild diameter of the black hole as a best estimate, approximately $2 \times 10^{14}$ cm. Note that for a quasar seen at 45° inclination, the relevant thickness estimate is the greater of the true accretion disk thickness and the radial depth of the luminous structure into the accretion disk.

Thus we have come to a model of the luminous quasar structure that is dominated by two ring-shaped structures, the inner accretion disk edge and the outer surface where the emission lines originate. The radii, radial extents, and brightness ratio for these structures are summarized in § 5.

3. MICROLENSING OF THE LARGE OUTER STRUCTURE

In our modeling to follow, we consider the microlensing of the quasar’s inner and outer structures independently and then infer from the principle of superposition that the microlensing brightness curves would be the sum of the two components. For the large outer ring, we show in Figure 1 the microlensing expected. For a random distribution of uniform solar mass stars, a pattern of diamond-shaped caustics is presumed to cross in front of the quasar’s luminosity with a transverse pattern speed of 800 km s$^{-1}$. We have modeled the overall lens with parameters appropriate to the A quasar image; the shear is 0.2, and the total optical depth is 0.4, divided as stellar optical depth 0.04 and continuous optical depth (or planetary microlenses) 0.36. These parameters may be seen to be appropriate to many gravitational lenses, in the sense that they are about average for the approximately 70 lensed systems now known.

In Figure 1, we show the general view of the microlensing brightness pattern in relation to the ring-shaped luminous quasar source, presumed to be in relative motion. The locus of points for the center of the ring is the straight line, and the curve above shows the computed brightness (magnification) for the location of the ring center below. A timescale shown at the bottom is appropriate for our adopted transverse velocity of 800 km s$^{-1}$. The amplification scale on the left shows that relative to the unlensed quasar brightness, the observed image $A$ brightness is ordinarily about a factor of 3 greater. Our calculations show amplifications varying from 2.8 to 3.7, with an rms deviation from the mean value.
of 0.1, sampled on a timescale of 20 yr. Several M-shaped events are seen in Figure 1 at times 350, 420, and 830 yr.

These results agree well with the observations of Q0957+561 microlensing reported by Schild (1996). Brightness fluctuations sampled on timescales of decades were found to be 0.44 and 0.26 mag for images A and B, respectively. These estimates contain intrinsic quasar fluctuations, as well as microlensing fluctuations, and the true microlensing is presumed to be about the 0.1 mag rms value found in the model. It is not an accident that the modeled fluctuations match approximately the observations; the radial thickness (area) of the outer ring was computed to give the amplitude of fluctuations reported in Table 1 of Schild (1996) using the Refsdal-Stabell (1991, 1993, 1997) theory.

The M-shaped events on 25 yr timescales match almost exactly the event detected in the era 1980–1990 (Schild & Smith 1991; Refsdal et al. 2000) and even includes the small “dip” that may be seen at JD 2,450,000 in Figures 9 and 16 of Pelt et al. (1998). In this interpretation, the Q0957+561 system has passed about half-way through such an event, and in the coming decade should return to the upper plateau level before again dropping. These M-shaped events appear to be a characteristic feature of microlensing by a ring-shaped luminous structure at these low optical depths and were not anticipated in the analysis of the observed Q0957+561 microlensing by Refsdal et al. (2000). The observed event had an amplitude of 0.2 mag, whereas events from our present model are closer to 0.1 mag and have an elapsed time of 15 yr from onset to the central “dip.” Thus the observed microlens is indicated to be slightly below solar mass for our stated transverse velocity. The amplitude is in reasonable agreement for the small statistical sample available, especially since other events with the observed 0.2 mag rise are also found in our simulation.

It would be tempting to predict that the microlensing will now continue with a symmetric profile such that the coming 15 yr will be the reverse of the period 1981–1997. However, this is statistically disfavored, because the calculation presented here is for the low optical depth A image, and the event is probably a microlensing of the higher optical depth B image.

In principle, the outer ring could also produce fluctuations due to fine-scale structure in the “continuous opacity” component, which has an optical depth of 0.36. We

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Fig. 1.—Microlensing of the outer ring-shaped luminous quasar structure by identical randomly distributed solar-mass field stars. For each point along the line showing motion of the center of the quasar ring source past the high-amplification caustics, the amplification of the light by the field stars is shown as a dashed curve. For the low optical depth presumed for the luminous baryonic matter, 0.04, the diamond-shaped caustics produced by randomly distributed stars hardly overlap, and many M-shaped brightness profiles with 50 yr durations are predicted.
have modeled the continuous opacity as both a truly continuous opacity and as a population of planetary-mass microlenses of $10^{-5} M_\odot$. We find that the planetary-mass microlensing by the outer ring would produce fluctuations of only 0.001 mag, which presently would be unmeasurable among the several larger effects predicted.

4. MICROLENSING OF THE INNER LUMINOUS STRUCTURE

The microlensing of the inner accretion disk edge is expected to produce larger amplitude and faster microlensing effects, but their amplitudes will be diluted by the nearly constant outer ring emission, which we have shown to be nearly constant on year and subyear timescales. We show in Figure 2 the microlensing effects expected when the luminous inner ring crosses the diamond caustic pattern of a solar-mass microlens, with the continuous opacity again modeled as planetary mass microlenses randomly distributed. Here we find an excitingly new pattern that is relevant to the published brightness curves. Numerous sharply peaked brightness profiles are predicted that have amplitudes of approximately 30% and durations of approximately half a year. Numerous sharp peaks of this description have been found in the Q0957+561 brightness record, illustrated as Figure 2 in Schild (1996). The typical amplitudes of the events from observations, 0.05 mag, are about appropriate for cusp profiles with peaks of 30% but diluted by the nearly constant outer ring luminosity, which is 80% of the total. Such brightness peaks are presumably responsible for the broad 3.5 cycle yr$^{-1}$ maximum in the Fourier power spectrum of the microlensing (Fig. 4 of Schild 1996). A detailed profile of one of these peaked brightness features is illustrated as Figure 5 of Schild (1996).

Also seen in the Schild (1996, Fig. 5) profile is a continuous pattern of fine structure having an amplitude of only 0.01 mag and a timescale of only 10 days. Our model reproduces these fine features if the accretion disk thickness parameter is taken to be $2 \times 10^{14}$ cm, which is slightly smaller than we originally estimated from the black hole Schwarzschild diameter. We are not concerned about issues of the stability of such fine structure, because this illuminated region is presumably part of a larger accretion disk structure that has already been extensively described in the literature and is presumed stable.

We illustrate in Figure 3 a synthesized profile from our Figure 2 brightness curve that shows how the profiles can be easily matched to the observations. Although the exact locations of the fine structure do not match, because they are generated by random microlensing mass distributions, the amplitudes and widths of the features match quite well. The widths of the features were estimated from observations to be typically 10 days, and our calculation without parameter fitting gives widths of nearly 30 days. We presume that adjustment of the transverse velocity and thickness of the inner ring will eventually produce closer agreement.

Figure 3 also shows that the fine structure originates in the planetary mass microlenses. In Figure 3, the thin curve shows the microlensing pattern for an optical depth of 0.36 as planetary-mass microlenses, and the heavy curve is for an equivalent optical depth of smoothly distributed dark matter. We see from this figure that the fine-structure pattern (thin curve) disappears when the planetary-mass microlenses are removed.

To emphasize the similarity between the observed and modeled profile, we show them side by side in Figure 4. Here we see that the general shape and structure are very similar. The exact locations of the fine structures do not align in the

![Fig. 2.—Microlensing of the inner ring-shaped luminous quasar structure. As the ring and amplification pattern cross each other, for each center of the ring on the straight line, the amplification is shown above as a dashed curve. This curve has more structural detail because of the smaller diameter and thickness of the inner ring. The magnification pattern is calculated for a 0.1 $M_\odot$ star and for a random distribution of $10^{-5} M_\odot$ missing mass particles constituting 90% of the baryonic mass.](image-url)
Fig. 3.—Details of the expected brightness fluctuations as the inner ring passes the magnification pattern produced by stars and planetary mass dark matter objects. In the main plot, the amplification relative to no diamond-shaped caustic is plotted as a function of time in years. The heavy curve shows the amplification if the baryonic dark matter is distributed in a smooth sheet, and the light curve shows the effects of the equivalent amount in planetary mass objects. In the inset, a magnified view of the peak at 7 yr is shown with the timescale expanded and the planetary mass case vertically shifted slightly. The expected brightness is shown in magnitudes to permit easy comparison with the observational result, Fig. 5 of Schild (1996), for our adopted 1:4 ratio of inner ring to outer ring brightness.

Fig. 4.—Comparison of the modeled microlensing profile and published observations. In the left panel, we repeat the curve plotted as an inset to Fig. 3 but here with magnitude and timescales shown to permit immediate comparison with observations. Thus dates and magnitudes are shown for arbitrary zero points. The heavy solid line shows the computed profile for continuously distributed dark matter, and the lighter line shows the effects of planetary mass dark matter objects. The right panel is a repeat of data published as Fig. 5 of Schild (1996) with observation dates and observed magnitudes shown. The shaded interval is a 1σ error interval for the 90 nightly average data points on which the profile is based. Interference between the printer’s lithographic dot pattern and the original dot pattern corrupted this error zone shading in the original publication. The heavy solid line is a simple Lorentzian profile fitted to the data, and the dashed line shows a cubic fit to the residuals.
modeled profile because they result from randomly distributed planetary mass microlenses. The duration time of the observed profile is a factor of 5 shorter than in the model profile, suggesting that the width of the inner ring has been modeled too large, but this thickness is one of the least constrained parameters in the model. For a statistically preferred quasar inclination of approximately 45°, the thickness parameter for the side of the inner ring closest to Earth is probably different than for the far side; the latter is surely lensed by the black hole.

It is also worth noting in Figures 3 and 4 that the fine-structure pattern seems to have about equal numbers and amplitudes of positive and negative peaks, with a small bias toward more positive events. Our small optical depth of 0.36 may be insufficient to produce exactly equal positive and negative microlensing structure, which is a well-known feature of microlensing when the optical depth is near unity (Schneider, Ehlers, & Falco 1992, p. 343) and which is very difficult to contrive if structure is caused by bright points (Gould & Miralda-Escudé 1997) or dark clouds (Wyithe & Loeb 2002; Schechter et al. 2003) in the quasar accretion disk.

To understand what is happening, it is useful to again examine Figure 2. When the inner luminous ring passes behind the magnification pattern for the planetary mass microlenses far away from a diamond caustic, fluctuations of only 0.01 mag are produced, but because these are swamped by the larger and nearly constant luminosity of the outer ring, they would be observed at an amplitude 5–10 times smaller. However, as the luminous ring passes behind the diamond caustic, the stronger peaked profiles formed by the planetary-mass microlenses in the strong shear of the solar-mass microlens produces the stronger rapid fluctuations.

The existence of microlensing fluctuations of such short duration and low amplitude is still controversial because of a fundamental conundrum in the observational program; to recognize such fluctuations, the time delay must be known within a fraction of a day, but because of the microlensing, it is extremely difficult to determine such an accurate time delay. This conundrum has now been broken by the Quasar Observing Consortium Around The Clock monitoring program (Colley et al. 2002, 2003), wherein 12 observatories around the globe continuously monitored the Q0957+561 system for 10 days and produced a time delay accurate to a tenth of a day. This delay has now been used to show a microlensing event in previously published data having a statistical certainty exceeding 99.9% and an amplitude of 1% on a timescale of half a day (Colley & Schild 2003). The published data may be seen in Figure 7 of Colley & Schild (2000), where the significance of the event was noted but time delay uncertainty at the time precluded statistical certainty.

The observed Colley & Schild (2003) 12 hr event implies even sharper quasar structure or, less plausibly, a substantially larger transverse velocity than modeled here. Detection of the longer 30 day events modeled here will be difficult because data of accuracy better than 1% over observing campaigns of weeks to months will be required; such observations would be of the utmost importance for the detection and study of the baryonic dark matter.

Another important aspect of these model calculations in agreement with the observed Schild (1996, Fig. 5) profile is the asymmetry. After the peak of the profile is past, the observed profile asymptotically approaches a brightness level that is significantly higher than the level of the approach side. It may be seen that this is a simple result of the significant quasar luminosity that has passed to the region behind the diamond caustic, which has a substantial magnification. Note that this asymmetry allows us to catalog the comings and goings of such crossings; we can predict that after a few years time, there should have been a second peak followed by a return to a lower level. Similar effects have been predicted also for solid accretion disks passing behind diamond-shaped microlensing caustic patterns, as first demonstrated by Young (1981) and as described and explained by Kayser et al. (1986).

5. CONCLUSIONS AND DISCUSSION

The principal result of our modeling is that a double-ring quasar luminous structure can produce all of the Q0957+561 microlensing effects recorded in observations to date. Most important is the conclusion that the microlensing peaks with 5% amplitude and 100 day timescale are easily predicted. The signature of a population of planetary-mass microlenses would be fluctuations is the brightness with weekly duration and equal positive and negative amplitudes of 1%.

A devil’s advocate would note that our more complex model has five adjustable parameters and can of course explain any observation. The parameters describing our double ring model are

1. The radius of the large ring, $2 \times 10^{17}$ cm;
2. The radial thickness of the large ring, $2 \times 10^{16}$ cm;
3. The radius of the small ring, $1 \times 10^{16}$ cm;
4. The thickness of the small ring, $2 \times 10^{14}$ cm; and
5. The brightness ratio of the two rings, 4:1.

We note, however, that these parameters are not arbitrarily adjustable and have been in fact inferred from published astronomical data and analysis.

With the adoption of the double-ring quasar structure model, our calculations appear to successfully model 10 aspects of the Q0957+561 brightness history, including

1. 2. The history of brightness fluctuations on timescales of 20–100 years—the model produces fluctuations of the (1) timescale and (2) amplitudes of the observed fluctuations;
3. 4. The existence of brightness cusps with (3) 5% amplitude and (4) 100 day duration;
5. The asymmetry of the above profiles;
6. The 10 day (30 day) timescale of the fine brightness fluctuations;
7. The 1% amplitudes of the fine brightness fluctuations;
8. Both positive and negative events in the fine structure;
9. The peaks observed in the autocorrelation estimates for the observed brightness fluctuations; and
10. The structure in the quasar’s ultraviolet energy distribution.

It will obviously be of interest to undertake further modeling of this kind to understand the sensitivity of the model to the details of the estimated model parameters. Thus far, these parameters have been derived from observational constraints, and many are interrelated; for example, adjusting the brightness ratio of the two rings causes changes in the brightness effects of both rings, but this ratio is not
highly adjustable because it must also be compatible with the observed nature of the spectroscopically measured ultraviolet quasar continuum.

In a sense, it will be noticed that the model seems robust in that it can produce 10 measured structure parameters, with only five available parameters. Because the Q0957+561A image analyzed here is fairly typical of lensed quasar images, the model calculations should be approximately applicable to many such systems.

We admit that we have been somewhat loose in claiming agreement between models and observations, even though disagreements of a factor of 2 or so may sometimes be found. We find this of little concern thus far, because the model is clearly oversimplified in many subtler respects. For an inclined quasar, the far side of the inner ring must suffer relativistic effects as the radiation passes the black hole and is lensed. Moreover, the structures we model as round rings are in reality ellipses for any reasonable quasar inclination, and as we describe the radial thicknesses of the rings they must also have some thickness in the $z$ (polar) direction. We presume that these effects introduce errors of approximately a factor of the square root of 2.

The authors thank Anatoly Minakov and Victoria Tsvetkova for helpful discussions and a sustained interest in our work. V. V. is especially grateful to James Bush and Kim Morla (Pontificia Universidad Católica del Perú, Lima) for their valuable financial support, which has made the simulation possible. Helpful discussions with Martin Elvis are appreciated and acknowledged.

REFERENCES

Schechter, P. L., et al. 2003, ApJ, 584, 657
Schild, R., & Thomson, D. J. 1995, AJ, 109, 1970
———. 1997, AJ, 113, 130
Schild, R. E. 1996, ApJ, 464, 125
Schild, R. E., & Choflin, B. 1986, ApJ, 300, 209
Schild, R. E., & Smith, R. C. 1991, AJ, 101, 813
Schmidt, R., & Wamburgans, J. 1998, A&A, 335, 379
Schneider, P., Ehlers, J., & Falco, E. E. 1992, Gravitational Lenses (New York: Springer)
Thomson, D. J., & Schild, R. 1997, in Applications of Time Series in Astronomy and Meteorology, ed. T. Subba Rao, M. B. Priestley, & O. Lessi (New York: Chapman & Hall), 187
Wills, B. J., Netzer, H., & Wills, D. 1985, ApJ, 288, 94
Wyithe, J. S. B., & Loeb, A. 2002, ApJ, 577, 615
Young, P. 1981, ApJ, 244, 756