EVIDENCE FOR A SOURCE SIZE OF LESS THAN 2000 AU IN QUASAR 2237+0305

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ABSTRACT

Recently, the OGLE team has reported a clear quasar microlensing signal in Q2237+0305. We have analyzed the microlensing event of “image C” by using their finely sampled light curves. From the light-curve fitting, we can unambiguously set the source size of $\leq 0.98$ Einstein ring radius as a conservative limit. This limit corresponds to 2000 AU, if we adopt the $M_{\text{gas}} \sim 0.1 M_\odot$ value obtained by a recent statistical study of the mean mass of the lens object. This is clear evidence for the existence of an accretion disk in the central region of the quasar.

Subject headings: accretion, accretion disks — galaxies: active — gravitational lensing — quasars: individuals (Q2237+0305)

1. INTRODUCTION

It is widely believed that the central engine driving the activity of quasars and active galactic nuclei (AGNs) is an accretion disk surrounding a $10^8$–$10^9 M_\odot$ supermassive black hole (SMBH). To find direct evidence for this general belief is one of the most exciting projects in the current research in astronomy and astrophysics, but unfortunately, the expected angular size of accretion disks is too small ($\leq 1 \mu$as) to resolve directly and spatially by using the present observational instruments. For this reason, the SMBH hypothesis remains unproven in the study of quasars and AGNs, and it is not expected to be proved any time soon in the near future.

However, “quasar microlensing” may be the key to proving this hypothesis. Following the first report of a detection of quasar microlensing in Q2237+0305 (the “Einstein Cross” or “Huchra’s lens”) by Irwin et al. (1989) and the subsequent extensive theoretical works (e.g., Wambsganss 1990), many researchers focused on this interesting subject and presented many meaningful results.

Roughly speaking, there are two different approaches to probing the structure of the central region of quasars. One is the statistical approach, which is the analysis of long-term monitoring data (obtained by, e.g., Östensen et al. 1996) that are expected to contain many microlensing events. Recently, Wyithe, Webster, & Turner (1999, 2000a, 2000b) performed a thorough statistical study; they compare real and mock observational results and constrain the transverse velocities of the lens, the mean mass of the lens, the source size, and so on. Another approach is to focus on a single high-magnification event (HME), on the basis of reasonable assumptions and/or some statistical features, and constrain the source size or structure (e.g., Shalyapin 2001; Wyithe et al. 2000d and references therein).

Thus, in this Letter, we take the latter approach and perform a light-curve fitting for the accurately and densely observed microlensing event, which the OGLE team had recently detected in Q2237+0305 (Woźniak et al. 2000a, 2000b), to put a limit on the microlensed source size. In § 2, we briefly present our method for fitting an observed light curve; results and discussions are presented in § 3.

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by only one parameter, $k$, and four representative FC cases for an angle range of the caustic curve (see Chang & Refsdal 1984), and the FCs appear to break down. However, if this assumption holds (e.g., $\kappa \sim \kappa$), we are able to characterize the features of the FC and CC by only one parameter, $\theta$.

In the case of the Chang-Refsdal lens, two different types of CCs will be formed at four or six angular positions of the closed caustic curve (see Chang & Refsdal 1984), and the FCs appear to be connecting these CCs. Thus, we consider two CC cases and four representative FC cases for an angle range of $\theta = 0 \sim \pi/2$ because of its symmetry. Moreover, we only consider the circular shape source with a top-hat brightness profile; i.e., we neglect the effect of the inclination angle brightness profile. Therefore, magnification $\mathcal{M}$ at any given source position ($x$ or $y$) is obtained by the integration of $\mu$ on the circular disk with radius $R$, assuming a top-hat brightness profile. This is a fairly simple treatment, because the shape of the microlensing light curve depends on the source brightness profile (e.g., Yonehara et al. 1999). However, the resultant source size can be regarded as an effective (equivalent) source size, and we use the top-hat brightness profile for its convenience for numerical integrations (with a 1000 mesh number in this study).

To include here the magnification caused by macrolensing and another caustic for microlensing, we add the constant magnification $M_0$ plus the gradual change of the magnification $M_{\text{grad}}$ to the total magnification. The latter mimics the magnification changes for the ensemble of other microlenses, and this gradual change makes the fits better (J. S. B. Wyithe & E. L. Turner 2000, private communication). Furthermore, the intrinsic variability of this quasar may be a long duration with a small amplitude (Wyithe et al. 2000c), and this term may also mimic the intrinsic variabilities of the quasar.

In addition, we should evaluate the apparent magnitude of the quasar without any microlensing and macrolensing, i.e., the intrinsic magnitude $m_0$. It is quite difficult because quasars have intrinsic variabilities and also because the observed magnitude of Q2237$+0305$ is affected by small-amplitude and/or long-timescale microlensing. Fortunately, from the monitoring data by Østensen et al. (1996) and the OGLE team, the observed magnitude of image C is roughly constant at $\sim 18.6$ mag long before the recent HME. We thus take this as the magnitude of the quasar without any microlensing. Moreover, by using the previously applied values of $\kappa$ and $\gamma$, we can evaluate the macrolensing magnification of image C, and the intrinsic magnitude is estimated to be $m_0 = 18.6 - 2.5 \log [(1 - \kappa)^2 - \gamma^2] \sim 19.6$.

Finally, by assuming that the source trajectory is straight and by determining the source velocity on the source-plane time, $v = (v_x, v_y)$, when the source crosses a caustic (the FC case) or the $x$-axis (the CC case), $t_m$, the expected microlensing light curve for any given parameter is obtained from $m(t) = m_0 - 2.5 \log [M + M_{\text{grad}}] + 5M(t)$ (for the CC case and the FC-gazing case, the impact parameter $d$ is also required).

To obtain the best-fit light curve and its parameter, we minimize the $\chi^2$ value between the observed light curve $m_{\text{obs}}(t)$ and the mock light curve for a given parameter $m(t)$ for each caustic case (FC and CC) by using one of the downhill simplex methods, i.e., the so-called “AMOEBA” routine (Press et al. 1992). Nonetheless, the caustic case has a kind of singularity, and the fitting methods that include singularities do not work so well. For this reason, we subdivide each caustic case into a considerable path case (depicted in Fig. 1) and perform a light-curve fitting for every possible case. After the best-fit parameters are obtained, we compare the reduced $\chi^2$ for all the possible cases for FC and CC, and we determine the best-fit (smallest $\chi^2$) parameters for each FC and CC case.

In this light-curve fitting, we only took into account the data points around the peak of image C (JD $= 2,450,000 = 1289.905 - 1529.531$; the total number of used data points is 83). Of course, we can also take into account the data points before and after the peak, but in those epochs, the distance between the source and the caustic could be larger than that in the peak region. Thus, it is unclear whether or not the approximation for magnification is reasonable before and after the peak. And so, we have restricted ourselves to the data points around the peak.

3. RESULTS AND DISCUSSIONS

Our resultant best-fit parameters for all the cases that we have considered are summarized in Table 1. The resultant path of the source, the best-fit light curve, and the source-size dependence of the reduced $\chi^2$ are also shown in Figures 2 and 3 (the degree of freedom [dof] is $83 - 6 = 77$ for the FC and $83 - 7 = 76$ for the CC). In the case of an infinitely small source size (i.e., a point source), the expected light curves for the microlensing event are quite different from case to case; i.e., a light curve for the FC case and that for the CC case are clearly different, the differences between the light curves of fold 1 and fold 2 (Fig. 1) are also evident, and so on. But, as you can easily see in Table 1 and Figures 1–3, the fitting for all cases works well (the best-fit reduced $\chi^2$ is $\sim 1$). This is due to the finite-size source effect, and we can manage to reproduce the observed feature for every considerable case.

We also performed a Monte Carlo simulation for every case in order to estimate the confidence regions of the best-fit parameters by using the following procedures: (1) By supposing that the best-fit parameter is a real parameter, we calculate an ideal light curve without any errors. (2) By adding random errors to the magnitude corresponding to the observational error dispersion and by sampling this light curve at the times corresponding to the actually observed times, we obtain a mock light curve. (3) By using this mock light curve, we again perform a light-curve fitting for all considerable cases (at the FC

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**Fig. 1.** Schematic view of a possible HME. All six cases reproduce the observed, fairly symmetric HME event. Two are FC cases, and four are CC cases.
and CC cases indicated before; see also Fig. 1) and obtain a set of the best-fit parameters for the mock light curve.

By iterating procedures 2 and 3 in this study 100 times and by summarizing the best-fit values for mock light curves, we can evaluate the confidence regions. To evaluate the 90% confidence regions from the Monte Carlo results, we calculate the confidence regions. To evaluate the 90% confidence regions from the Monte Carlo results, we pick up 90% parameter sets that have a smaller total \( \chi^2 \). Finally, from these selected parameter sets, we can obtain the maximum and minimum values of the parameters, and we define the range between these maximum and minimum values as the 90% confidence regions.

In Figures 2 and 3, we also present a histogram for the \( \chi^2 \) differences between the “mock” light curves and the best-fit light curve, and for the ideal \( \chi^2 \) distribution curves for corresponding degrees of freedom (6 dof for the FC and 7 dof for the CC). These two exhibit similar distributions, and our confidence region estimate seems to be reasonable.

For every case, if the source size is larger than the best-fit value, expected magnification will be suppressed, the light curve will become shallow, and the goodness of fit is reduced. On the other hand, if the source is smaller than the best-fit value, the expected magnification will be enhanced, the light curve will become sharp, and the goodness of fit will be reduced too. These are qualitative reasons why the source size is limited to a somewhat small range.

Considering all our fitting results, at least we can say that the source size of Q2237+0305 should be \( \approx 0.98 \sigma_s \) (more than 90% confidence level). This upper limit is given in the case of the FC (fold 3 in Table 1), while another case suggests a much

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**TABLE 1**

| Parameters     | Folds | Cusps |
|----------------|-------|-------|
| Angle          | 0.00  | 0.50  |
| Best fit       | FC1   | FC1   |
| \( R \times 10^{-3} \) | 1.78±0.19 | 2.42±0.21 |
| \( t_i \times 10^{-3} \) | 0.30±0.06 | 0.43±0.05 |
| \( T_a \)       | 1348±2  | 1351±2  |
| \( d \times 10^{-3} \) | 9.05±0.37 | 9.23±0.31 |
| \( M_e \times 10^{-3} \) | -3.05±0.99 | -3.15±1.09 |
| \( \chi^2 \)    | 1.46  | 1.49  |

**Note.**—All the length scales and timescales are normalized by and 1 day, respectively. The unit of velocity is \( \sigma_s \) divided by a day, \( \sigma_s \) corresponds to . The upper and lower values denoted beside the best-fit parameters show a 90% confidence level (see the text).

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**Fig. 2.**—Fitting results in an FC case (fold 3). Upper left-hand panel: Best-fit source path (dashed line) relative to the caustic (solid line). Upper right-hand panel: Observed flux (error bar) and best-fit light curve (solid line). Lower left-hand panel: Total \( \chi^2 \) value with respect to source size (solid line) and result of Monte Carlo simulation (histogram). Lower right-hand panel: Distribution of \( \chi^2 \) with 6 dof (solid line) and distribution of \( \chi^2 \) difference between the mock light curve and the best-fit light curve (histogram). All of the length scales are normalized by \( \sigma_s \). Kinks in the source-size dependence of the total \( \chi^2 \) value (lower left-hand panel) are caused by changes from a best-fit subdivided case to another subdivided case; e.g., at a source size of \( \approx 0.6 \), the best-fit subdivided case changes from FC1 to FC2.

**Fig. 3.**—Same as Fig. 2, but for the CC case (cusp 1). The degree of freedom for the lower right-hand panel is 7 in this case. Kinks in the source-size dependence of the total \( \chi^2 \) value (lower left-hand panel) appear for the same reason as in Fig. 2.
smaller source size. Thus, this limit is a fairly conservative upper limit for the source. Since $r_\text{q}$ of quasar microlensing is typically $\approx 1$ $\mu$as, our result indicates the existence of a submicroradian source in the quasar!

To obtain the actual size, we have to calculate $r_\text{q}$ for relevant parameters. If we assume 1.0 $M_\odot$ as the mass of the lens object $M_\text{lens}$ and a Hubble constant $H_0 = 76$ km s$^{-1}$ Mpc$^{-1}$ (Kundic et al. 1997), $r_\text{q}$ will correspond to 10$^{17}$ cm. This value depends strongly on $H_0$ ($r_\text{q} \propto H_0^{-1/2}$) and the lens mass ($r_\text{q} \propto M_\text{lens}^{-1/3}$) rather than the cosmological parameters in this case (an $\sim 15%$ uncertainty covers roughly all the reasonable range). And finally, we get $10^{17}$ cm $\approx 7 \times 10^3$ AU as the resultant upper limit to the source size. This value is consistent with the result of the statistical research performed by Wyithe et al. (2000b). Moreover, for the $\sim 0.1$ $M_\odot$ lens object case suggested by Wyithe et al. (2000a) as a mean lens mass, the size will be reduced by some factor and become $\sim 2 \times 10^4$ AU! Alternatively, the lens object may be a stellar object, and so there is an upper mass limit that exists stably. Even if we adopt this upper limit of $\sim 100$ $M_\odot$ for the lens mass, the size will be $\sim 0.3$ pc, at most. Therefore, our result strongly supports the existence of an accretion disk in a quasar and that an accretion disk smaller than this size is a fairly dominant source of radiation from the quasar, at least in the $V$ band at the observer frame. Additionally, the resultant effective transverse velocity on the source plane is $\approx 10^4$ km s$^{-1}$ and is also consistent with the value presented by Wyithe et al. (1999).

In contrast, if we assume that the accretion disk is the type described by the standard accretion disk model (Shakura & Sunyaev 1973), we can also estimate the effective source size from its luminosity. The magnitude of this quasar in the absence of a macro lensing effect is easily converted into flux $f_\nu$ (Woźniak et al. 2000a). If we denote the absorption as $A_\nu$ magnitude and adopt the luminosity distance $d_L$ for the quasar, the luminosity $L$ of the quasar at this observed wave band is estimated to be $L \approx \nu (f_\nu \times 10^{3.44}) 4\pi d_L^2 \times 3.7 \times 10^2$ ergs s$^{-1}$. Furthermore, the radiation process of the standard accretion disk is a blackbody radiation process, and the effective temperature $T_{\text{eff}}$ of the accretion disk at this wave band corresponds to $\sim 2.5 \times 10^4$ K. On the other hand, we can relate the effective temperature, luminosity, and radius to the central black hole mass and accretion rate,

$$T_{\text{eff}} \approx \left( \frac{3}{4\pi \sigma} \right)^{1/4} L^{1/4} r^{-1/2}, \quad (2)$$

where $\sigma$ is the Thomson-scattering cross section. Consequently, we are able to estimate the effective source size, which is $r \approx 2.0 \times 10^{4+0.24}$ cm. There is an uncertainty in $A_\nu$, but this is consistent with our results and strongly indicates the existence of an accretion disk. We should pay attention and not insist that the existing source should be a standard-type accretion disk (other accretion disk models may be also consistent with our results). Rauch & Blandford (1991) reported that the accretion disk in Q2237+0305 is nonthermal or optically thin. But there are some ambiguities in this work (e.g., absorption, lens mass), and it is quite difficult to support or oppose the report from our results. To specify disk models, we have to perform more extensive monitorings and/or analyze the multiband microlensing light curves in order to compare the resultant source sizes.

The performed fitting procedures do work, but, strictly speaking, all our best-fit reduced $\chi^2$ are somewhat larger than 1. This means that the goodness of fit of our results is not extremely good and, probably, that there may be some systematic errors that we did not take into account. In this work, we neglect the detailed feature of the source, the magnification patterns, and the intrinsic variabilities of the quasar. However, if such effects really exist, the shape of the light curve will be systematically altered, and the best-fit reduced $\chi^2$ may be increased by these effects. There are difficulties to be taken into account for all of the above possibilities in our procedure, but that will be done in the future.

In future work, we should further develop the quasar microlensing technique in two statistical ways. One way is to study the statistical properties of the magnification near the FC and CC. Although the statistical features have already been studied by many researchers (e.g., Wambsganss & Kundic 1995), their effects, such as the lens object clustering that affects the properties of magnification in the vicinity of the caustic, are not well understood. The other way is to continue monitoring this kind of quasar and to sample similar microlensing events more and more. Such an analysis may be able to reduce the ambiguities arising because of an unknown lens mass and/or different features of caustic networks, etc.

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