OGLE-2009-BLG-023/MOA-2009-BLG-028: Characterization of a Binary Microlensing Event Based on Survey Data

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ABSTRACT
We report the result of the analysis of the light curve of a caustic-crossing binary-lens microlensing event OGLE-2009-BLG-023/MOA-2009-BLG-028. Even though the event was observed solely by survey experiments, we could uniquely determine the mass of the lens and distance to it by simultaneously measuring the Einstein radius and lens parallax. From this, we find that the lens system is composed of M-type dwarfs with masses \((0.50 \pm 0.07) M_\odot\) and \((0.15 \pm 0.02) M_\odot\), located in the Galactic disk with a distance of \(\sim 1.8\) kpc toward the Galactic bulge direction. The event demonstrates that physical lens parameters of binary-lens events can be routinely determined from future high-cadence lensing surveys and thus microlensing can provide a new way to study Galactic binaries.

Key words: gravitational lensing: micro – binaries: general

1 INTRODUCTION
Microlensing occurs when a foreground star (lens) is closely aligned to a background star (source) and the light from the source
is refracted by the gravity of the lens. The phenomenon causes splits and distortions of the background stellar image. For source stars in the Galaxy, the separation between the split images is of an order of milli-arcsec and thus cannot be directly observed. However, the phenomenon can be observed through the brightness change of the source star caused by the change of the relative lens-source separation (Paczynski 1986). Currently, two groups (OGLE: Udalski et al. 2003; MOA: Bond et al. 2002) are conducting survey observations to detect microlensing events by observing stars located toward the Galactic bulge direction. From these surveys, more than 500 events are being detected every year.

For most cases of Galactic microlensing events where source stars are lensed by a single foreground star, the lensing light curve is represented by

\[ A(t) = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}}, \quad u(t) = \left[ \frac{t - t_0}{t_E} \right]^2 + u_0^2 \]  

(1)

Here \( u \) represents the lens-source separation normalized by the Einstein radius \( \theta_E \), \( t_E \) is the time required for the source to transit the Einstein radius (Einstein time scale), \( t_0 \) is the time of the closest lens-source approach, and \( u_0 \) is the lens-source separation at that moment. Among the lensing parameters of \( t_E, t_0 \) and \( t_0 \) characterizing lensing light curves, only the Einstein time scale provides information about the lens because it is related to the physical parameters of the lens mass \( M \), relative lens-source parallax \( \pi_{\text{col}} \), and proper motion \( \mu \) by

\[ t_E = \frac{\theta_E}{\mu}, \quad \theta_E = (\kappa M \pi_{\text{col}})^{1/2}, \]  

(2)

where \( \kappa = 4G/(e^2A)U \) and \( D_L \) and \( D_S \) represent the distances to the lens and source star, respectively. However, the time scale results from the combination of the underlying physical lens parameters. As a result, it is difficult to uniquely determine the individual lens parameters from the time scale alone.

The degeneracy of the lens parameters can be partly lifted by measuring either a proper motion or a lens parallax, and can be completely broken by measuring both. The proper motion is related to the Einstein radius and the time scale by \( \mu = \theta_E/t_E \) and thus measuring \( \mu \) is equivalent to measuring \( \theta_E \). Einstein radii are generally measured from the deviation of the light curve from that of a point-source event caused by the finite-source effect (Nemiroff & Wickramasinghe 1994; Witt & Mao 1994; Gould 1994). The microlens parallax is defined by the ratio of the Earth’s orbit to the Einstein radius projected on the observer plane, \( \pi_E \), i.e.,

\[ \pi_E = \frac{AU}{\tilde{r}_E}, \]  

(3)

Lens parallaxes are generally measured by analyzing the deviation of the light curve caused by the change of the observer’s position over the course of the event due to the orbital motion of the Earth around the Sun (Refsdal 1964; Gould 1992; Smith et al. 2003). As a result, parallaxes are usually measured for events with long time scales that are comparable to a significant portion of the Earth’s orbital period, i.e. 1 yr. If both Einstein radius and lens parallax are measured, the mass and the distance to the lens are uniquely determined by

\[ M = \frac{\theta_E}{\kappa \pi_E} \quad D_L = \frac{AU}{\pi_E \theta_E + \pi_S}, \]  

(4)

respectively. Here \( \pi_S = AU/D_S \) represents the parallax of the source star.

A fraction of lensing events are produced by lenses composed of binary masses (Mao & Paczyński 1991). These binary-lens events provide a good chance to determine the physical parameters of lenses. The first reason for this is that most binary-lens events are detected through the channel of caustic crossings. The magnification gradient in the region around the caustic is so steep that finite-source effect is always manifested in the light curves of caustic-crossing events. If the caustic-crossing part of the light curve is resolved, then, it is possible to measure the Einstein radius. Second, the average mass of binary lenses is heavier than that of single lenses and thus the time scales of binary events tend to be longer than those of single-lens events. This implies that the chance to measure lens parallaxes is higher.

Despite these advantages, mass measurements of binary lenses by measuring both \( \theta_E \) and \( \pi_E \) were possible only for a handful number of events. These events include EROS-2000-BLG-5 (Alcock et al. 2001; An et al. 2001; Gould et al. 2004), OGLE-2002-BLG-069 (Kubas et al. 2005), OGLE-2005-BLG-071 (Udalski et al. 2005; Dong et al. 2009), OGLE-2005-BLG-153 (Hwang et al. 2010b), OGLE-2006-BLG-109 (Gaudi et al. 2008; Bennett et al. 2010), MOA-2007-BLG-192 (Bennett et al. 2008), MOA-2009-BLG-016 (Hwang et al. 2010a), and OGLE-2009-BLG-092/MOA-2009-BLG-137 ( Ryu et al. 2010). Among these events, three (OGLE-2005-BLG-071, OGLE-2006-BLG-109, MOA-2007-BLG-192) are planetary events for which intensive follow-up observations were conducted during the events. Unfortunately, follow-up observations are not being conducted for general binary events due to the limited observational resource.

However, the situation is rapidly changing with the instrumental upgrade of the survey experiments. The second phase of the MOA survey experiment started in 2006 by replacing its old 0.6 m telescope with a new 1.8 m telescope equipped with a camera of 2.2 deg\(^2\) field of view. In 2010, the OGLE group started its fourth phase survey observations with a new camera of 1.4 deg\(^2\) field of view that is 3.5 times wider than that of the camera used in the third phase experiment. With the improved photometric precision combined with the increased monitoring cadence provided by the upgraded instrument, the survey experiments detect much more events. For example, the MOA group detected 563 events in 2009 season compared to 56 events in 2005. In addition, it became possible to constrain lenses based on the data obtained from survey observations alone for an increasing number of events.

In this paper, we present the result of the analysis of a caustic-crossing binary-lens microlensing event OGLE-2009-BLG-023/MOA-2009-BLG-028. This event demonstrates that physical parameters of binary lenses can be constrained based on the data obtained from survey observations. We provide the physical parameters of the lens system. We also discuss the use of future microlensing surveys in the studies of Galactic binaries.

## 2 OBSERVATION

Figure 1 shows the light curve of the event OGLE-2009-BLG-023/MOA-2009-BLG-028. As evidenced by the two strong perturbations at HJD ∼ 2454905 and 2454920 and the characteristic “U”-shape trough region between them, the event is a typical caustic-crossing binary-lens event. The brightening of the source star was noticed in the early 2009 bulge season by both OGLE and MOA survey experiments using the 1.3 m Warsaw telescope of Las Campanas Observatory in Chile and the 1.8 m of Mt. John Observatory in New Zealand, respectively. The perturbation produced by the first caustic crossing was detected on March 12 by both survey...
Figure 1. Light curve of the microlensing event OGLE-2009-BLG-023/MOA-2009-BLG-028. Also presented are the model curves for the best-fit solutions with and without the parallax effect. We note that the MOA data except the caustic-induced perturbation part (2454900 ≤ HJD ≤ 2454920) are binned for a clear view. The zoomed view of the caustic-induced part of the light curve is presented in Fig. 4.

experiments. The time gap during 2454780 ≤ HJD ≤ 2454860 corresponds to the period during which the bulge could not be seen. We note that OGLE observation was stopped on HJD ∼ 2454960 for the upgrade of the camera. In addition, no follow-up observations of the event was conducted. Nevertheless, the light curve of the event was well covered during the whole 2009 bulge season.

For the analysis of the light curve, we use 1058 $I$-band and 15 $V$-band OGLE images taken during 2453417 ≤ HJD ≤ 2454955 and 2453470 ≤ HJD ≤ 2454951, respectively. The MOA data is composed of 1298 $R$-band images taken during 2454495 ≤ HJD ≤ 2455134. The photometry was processed by the individual groups using their own software.

3 MODELING

Light curves of binary-lensing events result from a complex phenomenology and thus exhibit an astonishing diversity (Schneider & Weiss 1986). As a result, modeling light curves is a difficult task. One important difficulty arises due to the large number of parameters to be included in modeling. These parameters are needed to describe various features of the light curve. To describe light curves of standard single-lens events, a set of three parameters of $t_E$, $t_0$, and $u_0$ are needed. To describe the deviation caused by the lens binarity, an additional set of three binary parameters is needed. These binary parameters include the mass ratio between the lens components, $q$, the projected binary separation in units of the Einstein radius, $s$, and the angle of the source trajectory with respect to the binary axis, $\alpha$. Since OGLE-2009-BLG-023/MOA-2009-BLG-028 is a caustic-crossing binary event, an additional parameter of the normalized source radius, $\rho_\star \equiv \theta_\star / \theta_E$, is needed to account for the finite-source effect. Here $\theta_\star$ represents the angular radius of the source star. In addition, the event lasted throughout the whole 2009 bulge season and thus it is needed to check the possibility of deviations induced by the parallax effect. To incorporate the parallax effect, it is required to include two parallax parameters $\pi_{E,N}$ and $\pi_{E,E}$, which are the components of the microlens-parallax vector $\pi_E$ projected on the sky in the north and east celestial coordinates, respectively, where the direction of the parallax vector is that of the lens-source relative motion in the frame of the Earth at the peak of the event. Due to the sheer size of the parameter space, brute-force searches for solutions are very difficult and extremely time-consuming.

The second important difficulty in modeling binary-lensing light curves is caused by the complexity of $\chi^2$ surface. This complexity implies that even if a solution that apparently describes the observed light curve is found, it is difficult to be sure that all possi-
urable minima have been investigated (Dominik 1999b). As a result, a simple downhill approach to search for solutions cannot be used.

For efficient modeling but avoiding the difficulties mentioned above, we use a hybrid approach of parameter searches. In this approach, grid searches are conducted over the space of a subset of parameters and the remaining parameters are searched for by letting them vary so that they result in minimum \( \chi^2 \) at each set of the grid parameters. We choose \( s, q, \) and \( \alpha \) as the grid parameters because they are related to the light curve features in a complex way such that a small change in the values of the parameters can lead to dramatic changes in the resulting light curve. On the other hand, the other parameters are more directly related to the light curve features and thus they can be searched for by using a downhill approach. For the \( \chi^2 \) minimization in the downhill approach, we use a Markov Chain Monte Carlo method. Once the \( \chi^2 \) minima of the individual grid points are determined, the best-fit model is obtained by comparing their \( \chi^2 \) values. We investigate the degeneracy of solutions by probing local minima that appear in the space of the grid parameters.

The last major difficulty in binary-lensing modeling arises due to the fact that the modeling requires large computations. Finding the best-fit parameters and evaluating their uncertainties requires generating a large number of trial model light curves. The problem is that most binary-lensing events exhibit deviations induced by the finite-source effect and calculating finite-source magnifications requires intensive computations. Formally, the magnification of a finite source can be calculated by integrating the point-source magnifications of the elements of the the source star over its surface. However, this approach is impractical due to the divergent nature of the magnification near the caustic and the large amount of computation time required for precision calculation. Although there exist semi-analytic approximations (Schneider & Weiss 1984), it is not precise enough to describe the caustic-crossing feature of lensing light curves. Therefore, an efficient method of finite-magnification calculation is important for binary-lensing modeling.

For the finite-source magnification calculation, we use a modified version of the ray-shooting method. In the usual ray-shooting method, one shoots a large number of uniformly spaced rays in the image plane, and determine which ones land on the surface of the source using the lens equation. Then, the magnification corresponding to a source position is calculated as the ratio between the number density of rays on the image plane to that of rays on the source surface (Kasner et al. 1986; Wambsganss et al. 1990). Based on this basic scheme, we minimize the computation time by using the following methods.

(i) Magnification map making
Instead of calculating the magnifications corresponding to the individual source positions, we construct magnification maps of the region encompassing perturbation regions (Dong et al. 2008). The main advantage of this method is that once a map for a fixed \((s,q)\) parameter set is constructed, one can reuse it for the calculations of many light curves resulting from different combinations of other parameters instead of re-shooting rays all over again.

(ii) Minimization of ray-shooting region
We further reduce the calculation time by minimizing the area of the ray-shooting region. We set the regions of ray shooting in the image plane only for which rays arrive in the region around caustics on the source plane where the finite-source is important. For example, if the perturbation occurs near the peak of a high-magnification map, the perturbation is localized in the central region around the binary lens components, where a small caustic is located. This region in the source plane corresponds to the annulus around the Einstein ring in the image plane (Griest & Safaszadeh 1998; Dong et al. 2008). Then, by shooting rays only in the localized region in the image plane, we minimize the number of rays needed for finite-source magnification calculations and thus reduce the calculation time. In Appendix A, we describe how the region of ray-shooting is set.

(iii) Semi-analytic approximation
Finally, we further speed up computations by limiting numerical computation of finite-source magnifications only when the source is located very close to the caustic and using simple semi-analytic hexadecapole approximations (Gould A. 2008; Pejcha & Heyrovsky 2009) in the vicinity of the caustic. For this, we divide the source plane into small grids and then register the individual grids by different levels depending on the distance from the caustic. Based on the levels, we apply different levels of approximations for the magnification calculations.

4 BEST-FIT MODEL
From modeling, it is found that OGLE-2009-BLG-023/MOA-2009-BLG-028 is produced by the crossings of a Galactic bulge F-type main-sequence source star over the caustic produced by a disk binary lens composed of M-type main-sequence stars. The determined values of the normalized star-planet separation and planet/star mass ratio are

\[
s = 1.65 \pm 0.02, \quad q = 0.30 \pm 0.01,
\]

respectively. In Table 1 we present the lensing parameters determined from modeling. The model light curve is presented in Figure 1. Figure 2 shows the geometry of the lens system under the best-fit model, where the two dots represent the locations of the lens components, the closed figure composed of concave curves represents the caustic. The coordinates \((\xi, \eta)\) are centered at the primary lens and the abscissa is aligned with the binary axis. The line with an arrow represents the source trajectory. Note that the source trajectory is curved due to the parallax effect. All lengths are normalized by the Einstein radius corresponding to the total mass of the binary.

![Figure 2: Geometry of the lens system for the best-fit parallax model.](image-url)

The two dots represent the locations of the binary lens components and the closed figure composed of concave curves represents the caustic. The coordinates \((\xi, \eta)\) are centered at the primary lens and the abscissa is aligned with the binary axis. The line with an arrow represents the source trajectory. Note that the source trajectory is curved due to the parallax effect. All lengths are normalized by the Einstein radius corresponding to the total mass of the binary.

\[\chi^2 = 1.0\]
Table 1. Fit Parameters. HJD$^\prime = \text{HJD} - 2450000$.

| no parallax | parallax ($u_0 > 0$) | parallax ($u_0 < 0$) |
|-------------|----------------------|----------------------|
| $\chi^2$/dof | 4067.18/2365         | 2371.12/2363         | 2370.08/2363         |
| $s$         | 1.860±0.015          | 1.705±0.020          | 1.645±0.022          |
| $q$         | 0.260±0.004          | 0.304±0.008          | 0.295±0.012          |
| $\alpha$ (deg) | 106.87±0.15     | 102.50±0.29          | -102.34±0.40         |
| $t_0$ (HJD$^\prime$) | 4915.48±0.06 | 4913.72±0.10         | 4913.85±0.19         |
| $u_0$       | 0.094±0.003          | 0.116±0.004          | -0.120±0.033         |
| $t_E$ (days) | 153.56±2.622         | 100.87±2.315         | 92.49±2.61           |
| $\rho_\star$ | $(2.9±0.3) \times 10^{-4}$ | $(8.4±0.6) \times 10^{-4}$ | $(9.5±0.7) \times 10^{-4}$ |
| $\pi_{E,N}$ | -0.081±0.015         | -0.120±0.033         |                           |
| $\pi_{E,E}$ | -0.231±0.008         | 0.252±0.111          |                           |

Figure 3. Upper panel: Contour of $\chi^2$ in the parameter space of $(\pi_{E,E}, \pi_{E,N})$, which are the components of the lens-parallax vector $\pi_E$ projected in the sky in the north and east celestial coordinates, respectively. Lower panel: Contours of $\chi^2$ in the parameter space of the normalized source radius $\rho_\star$ and the Einstein time scale $t_E$.

4.1 Lens Parallax

Light curves of long time-scale events are susceptible to the parallax effect. The time scale of the event OGLE-2009-BLG-023/MOA-2009-BLG-028 is $t_E \sim 100$ days, which comprises nearly 1/3 of the orbital period of the Earth. We, therefore, search for solutions considering the parallax effect. From this, we find that the parallax model provides a significantly better fit with $\Delta \chi^2 = 1697$. The determined values of the parallax parameters are

$$
\pi_{E,N} = -0.12 \pm 0.03, \quad \pi_{E,E} = 0.25 \pm 0.01.
$$

The upper panel of Figure 3 shows the scatter plot of $\chi^2$ in the parameter space of $(\pi_{E,E}, \pi_{E,N})$. The contours are elongated along the $\pi_{E,N}$ axis because the apparent motion of the Sun at $t_0$ projected onto the sky is perpendicular to the $\pi_{E,N}$ axis.

It is known that the orbital motion of a binary source can give rise to distortions of lensing light curves (‘xallarap’ effect) that are similar to those induced by the parallax effect (Smith et al. 2003). We check this possibility by conducting xallarap modeling under the assumption that the binary source is in a circular orbit. From this, we find that the improvement of the fit of the xallarap model from that of the parallax model is merely $\Delta \chi^2 \sim 2.4$, which is much smaller than the improvement by the parallax effect $\Delta \chi^2 \sim 1700$. In addition, the minimum $\chi^2$ occurs at an orbital period of $P \sim 1$ yr, which corresponds to the orbital period of the Earth around the Sun. Both facts support the parallax interpretation of the light curve deviation.
Table 2. Physical Parameters

|                      | parallax (\(u_0 > 0\)) | parallax (\(u_0 < 0\)) |
|----------------------|-------------------------|-------------------------|
| \(\theta_E\) (mas)   | 1.583±0.191             | 1.475±0.187             |
| \(\mu\) (mas yr\(^{-1}\)) | 5.727±0.692             | 5.822±0.738             |
| \(D_L\) (kpc)       | 1.933±0.203             | 1.845±0.214             |
| \(M_1\) (\(M_\odot\)) | 0.608±0.077             | 0.500±0.071             |
| \(M_2\) (\(M_\odot\)) | 0.185±0.023             | 0.148±0.021             |

4.2 Einstein Radius

The Einstein radius is measured from the normalized source radius \(\rho_s\) combined with the information about the angular source radius \(\theta_s\) by

\[
\theta_E = \frac{\theta_s}{\rho_s}.
\]

(7)

The normalized source radius is measured with a moderate uncertainty from the analysis of the light curve during the caustic crossings. In the lower panel of Figure 5, we present the enlargement of the caustic-crossing part of the light curve. From the figure, it is found that a single OGLE data point taken during the time when the source is on the fold caustic (at HJD ~ 4903.78) and multiple MOA data points taken at the time when the source is about to leave the caustic (during 4904.05 ≤ HJD ≤ 4904.20) provide constraints on \(\rho_s\). The measured value of the normalized source radius is

\[
\rho_s = (9.5 \pm 0.7) \times 10^{-4}.
\]

(8)

Considering that the normalized source radius of a main-sequence source star \(\rho_s \sim (O)10^{-3}\) for typical lensing events caused by low-mass lens stars located half way between the source and observer, the measured value of \(\rho_s\) is substantially small. This means that the Einstein radius is big, suggesting that either the lens is heavy or it is located close to the observer. The lower panel of Figure 5 shows the \(\chi^2\) distribution in the parameter space of \(\rho_s\) and \(t_E\).

The angular source radius is determined from the information of the de-reddened color of the source star [Yoo et al. 2004]. We determine the color by using the centroid of clump giant stars in the color-magnitude diagram as a reference position [Stanek et al. 1994, 1997] under the assumption that the source star and clump giants experience the same amount of extinction. The offset between the source and clump centroid is measured in the instrumental color-magnitude diagram that is constructed by using the OGLE \(V\) and \(J\) band images taken toward the bulge field where the source is located (Figure 5). Then, the angular source size is determined by first transforming from \((V-I)_0\) to \((V-K)_0\) using the color-color relation of [Bessel & Brett 1998] and then applying the relation between \((V-K)_0\) and the angular stellar radius of [Kervella et al. 2004]. For the best-fit model, we find that the de-reddened magnitude and color of the source star are \(I_0 = 16.7\) and \((V-I)_0 = 0.67\), respectively, implying that the source is an F-type main-sequence star with an angular radius of

\[
\theta_s = (1.40 \pm 0.15) \mu\text{as}.
\]

(9)

Here we adopt an average distance to clump giants toward the field of 7.7 kpc estimated based on the Galactic mass distribution model of [Han & Gould 2003]. The uncertainty of \(\theta_s\) is determined from the combination of the uncertainty of the distance to the source and an additional 7% intrinsic error in the conversion process from the measured color to the source radius.

With the measured values of the normalized and angular source radii, the Einstein radius is determined as

\[
\theta_E = (1.48 \pm 0.19) \mu\text{as}.
\]

(10)

This corresponds to the relative lens-source proper motion of

\[
\mu = \frac{\theta_E}{t_E} = (5.82 \pm 0.74) \text{mas yr}^{-1}.
\]

(11)

4.3 Physical Parameters

With the measured Einstein radius and parallax, the mass and distance to the lens are determined from the relations in equation (4).

\(M = (0.65 \pm 0.09) \, \text{\(M_\odot\)}\)

(12)

and

\(D_L = (1.8 \pm 0.2) \, \text{kpc}\),

(13)

respectively. With the determined mass ratio, it is found that the masses of the individual lens components are \(M_1 = (0.50 \pm 0.07) \, \text{\(M_\odot\)}\) and \(M_2 = (0.15 \pm 0.02) \, \text{\(M_\odot\)}\), respectively. Therefore, the lens is composed of an early and a late M-type main-sequence stars located in the Galactic disk. The model with \(u_0 > 0\) yields
the distance and mass of the lens slightly bigger than those of the model with \( u_0 < 0 \) (see Table 2).

5 DISCUSSION AND CONCLUSION

We analyzed the light curve of the long time-scale, caustic-crossing, binary-lens event OGLE-2009-BLG-023/MOA-2009-BLG-028. Despite that the event was observed solely by survey experiments, we could uniquely determine the mass of the lens and distance to it by simultaneously measuring the Einstein radius and lens parallax. It was turned out that the event was produced by the crossings of a Galactic bulge F-type main-sequence source star over the caustic produced by a disk binary lens composed of M-type main-sequence stars. The event demonstrates that the physical parameters of binary lenses can be uniquely determined from data obtained by survey observations.

Microlensing can potentially probe the distributions of binaries as functions of mass ratio and separation, that can provide important observational constraints on theories of star formation (Gould 2001). Especially, microlensing is sensitive to low-mass companions that are difficult to be detected by other methods and thus it is possible to make complete distributions down to lower mass limit of binary companions. Due to this importance, there have been several systematic searches for binary lenses (Alcock et al. 2000; Jaroszyński 2002, Jaroszyński et al. 2004, 2005, 2006, Skowron et al. 2007). However, the samples of binaries acquired from previous surveys were not adequate enough to strongly constrain the binary distributions. One important reason for this is the difficulty in estimating the detection efficiency of binary-lens events. Most binary-lens events are detected through the channel of caustic-crossing events where caustic crossings were accidently discovered by the sudden rise of the source star flux. Due to this haphazard nature of binary-lens events, it is difficult to estimate the detection efficiency that is essential for the statistical studies of binaries. In addition, the physical quantities of lenses for most of binary-lens events could not be determined, making detailed studies of binaries difficult.

However, the situation will be different with the advent of new-generation experiments. As mentioned, the recent upgrades of the OGLE and MOA experiments already significantly increased the observational cadence of the surveys. In addition to these experiments, there is a planned experiment that can increase the cadence even higher. Korea Microlensing Telescope Network (KMTNet) is an approved project that will employ three telescopes, each of which will have a 1.6 m aperture and 4 deg\(^2\) field of view. They will be located in three different continents of South America (Chile, Africa (South Africa), and Australia for continuous observations of microlensing events. The expected cadence of the experiment is 6 hr\(^{-1}\). Considering that the typical time scale of caustic crossings is several hours for events involved with main-sequence stars and extends to \( \geq 10 \) hrs for events associated with giant source stars, the cadence of the survey is high enough to resolve caustic crossings of most events, enabling measurements of Einstein radii. For a significant fraction of these events, it will be possible to additionally measure lens parallaxes, enabling to completely determine the physical parameters of binary lenses. Furthermore, the uniform coverage of events will make it easier to estimate the detection efficiency of binary-lens events, enabling statistical analysis of binary distributions possible. Therefore, future lens surveys can provide a new way to study Galactic binary stars.

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APPENDIX A: REGION OF RAYSHOOTING

We determine the range of rayshooting as follows. For sources close to a fold caustic, the point-source magnification is represented by

\[ A_p = A_0 + \frac{(d/u_\perp)^{-1/2}}{2} \Theta(d), \]

where \( d \) is the perpendicular distance to the caustic with \( d > 0 \) for sources interior to the caustic, \( u_\perp \) represents the characteristic strength of the local caustic, \( \Theta(x) \) is the Heaviside step function, and \( A_0 \) represents the total magnification of the slowly varying images (Schneider & Weiss 1986; Gaudi & Petters 2002). Then, under the approximation that the magnification variation of the slowly varying images is negligible, the point-source approximation can be used for magnifications in the region outside the caustic with \( |d| > \rho_\star \). Inside the caustic, the finite-source magnification, \( A_f \), is expressed as

\[ A_f \propto \rho_\star^{-2} \int_{-\rho_\star}^{\rho_\star} \left( \frac{\rho_\star^2 - r^2}{d + r} \right)^{1/2} dr = d^{-1/2} f(d/\rho_\star). \]

Then, the fractional deviation from the point-source magnification is

\[ \epsilon = \frac{A_f - A_p}{A_p} = \epsilon(d/\rho_\star), \]

implying that the fraction deviation depends only on the ratio \( d/\rho_\star \). We find that the deviation are 2%, 1%, and 0.5% for the distances from the caustic of \( d = 2.3\rho_\star, 3.1\rho_\star, \) and \( 4.3\rho_\star \), respectively, implying that the deviation decreases rapidly with the increase of \( d/\rho_\star \). To be conservative, we set the range of rayshooting as \( d < 2\rho_\star \) inside and \( d < 5\rho_\star \) outside the caustic, respectively.