OGLE-2017-BLG-0039: Microlensing Event with Light from a Lens Identified from Mass Measurement

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Abstract

We present an analysis of the caustic-crossing binary microlensing event OGLE-2017-BLG-0039. Thanks to the very long duration of the event, with a time scale $t_{\text{eq}} \sim 130$ days, the microlens parallax is measured precisely despite its low value of $\pi_{\text{e}} \sim 0.06$. Analysis of the well-resolved caustic crossings during the source star’s entrance and exit of the caustic yields an angular Einstein radius of $\theta_{\text{E}} \sim 0.6$ mas. The measured $\pi_{\text{e}}$ and $\theta_{\text{E}}$ indicate that the lens is a binary composed of two stars with masses $\sim 1.0 M_{\odot}$ and $\sim 0.15 M_{\odot}$, and is located at a distance of $\sim 6$ kpc. From the color and brightness of the lens estimated from its determined mass and distance, it is expected that $\sim 2/3$ of the $I$-band blended flux comes from the lens. The event is a rare case of a bright lens event for which high-resolution follow-up observations can confirm its nature.

Key words: binaries: general – gravitational lensing: micro

1. Introduction

It is believed that most microlensing events detected toward the Galactic bulge field are produced by stars (Han & Gould 2003). For stellar lens events, the observed light comes from the lens as well as from the source star. However, lenses in
most cases are much fainter than the source stars being monitored, and thus it is difficult to detect the light from them. In some rare cases for which the lenses are bright, light from them can be detected. However, even in such cases, it is still difficult to attribute the excess flux to the lens because this may come from nearby stars blended in the image of the source or possibly from its companion if the source is a binary.

There have been several methods proposed to identify light from lenses. The most explicit method is to resolve the lens from the source or other blended stars from high-resolution follow-up observations. For typical lensing events, the relative lens–source proper motions is \( \mu \sim 5 \text{ mas yr}^{-1} \). This means that one has to wait \( \sim 10-20 \text{ yr} \) for direct lens imaging until the lens is separated enough from the source even using the currently available instruments with the highest resolution (Han & Chang 2003).\(^{30}\) As a result, the method has been applied to only three lensing events: MACHO-LMC-5 (Alcock et al. 2001), MACHO-95-BLG-37 (Kozłowski et al. 2007), and OGLE-2005-BLG-169 (Batista et al. 2015; Bennett et al. 2015).

A bright lens can also be identified from astrometric observations of lensing events. When a source star is gravitationally lensed, the centroid of the source star image is displaced from the position of the unlensed source star (Hogg et al. 1995; Miyamoto & Yoshii 1995; Boden et al. 1998; Paczyński 1998). Due to the relative lens–source motion, the position of the image centroid traces out an elliptical trajectory whose size and shape are determined by the angular Einstein radius and the impact parameter of the lens event (Walker 1995; Jeong et al. 1999). If an event is produced by a bright lens, the astrometric shift is affected by the light from the lens and one can identify the bright lens from the deviation (Han & Jeong 1999).

Lensing-induced astrometric shifts produced by nearby stars have been measured, e.g., Stein 2051 B (Sahu et al. 2017) and Proxima Centauri (Zurlo et al. 2018). For general lensing events, however, it is currently difficult to measure image motions due to the required high accuracy of order \( 10 \mu \text{as} \).

In some limited cases, a bright lens can also be identified from analysis of the lensing light curve obtained from photometric observations. This photometric identification is possible for events where the mass \( M \) and distance \( D_L \) to the lens are determined. With the determined \( M \) and \( D_L \), one can predict the color and brightness of the lens. If these are close to those of the blend, then it is likely that the flux from the lens comprises an important portion of the total blended flux. Due to the bright nature of the lens, it will be visible in high-resolution images obtained from space-based or ground-based adaptive optic (AO) observations, as additional light that is blended with the source image (Bennett et al. 2007). Then, one can identify the lens by comparing the excess flux with the prediction from lens modeling. Bright lenses have been identified by space-based follow-up observations using the Hubble Space Telescope for the first two planetary microlensing events OGLE-2003-BLG-235 (Bond et al. 2004) and OGLE-2005-BLG-071 (Udalski et al. 2005) by Bennett et al. (2006) and Dong et al. (2009), respectively. For OGLE-2006-BLG-109 (Gaudi et al. 2008; Bennett et al. 2010) and OGLE-2012-BLG-0026 (Han et al. 2013), for which multiple microlensing planetary systems were found, the light from the lenses was confirmed by Keck AO follow-up observations conducted by Bennett et al. (2010) and Beaulieu et al. (2016), respectively.

For various reasons, long-timescale binary-lens events are ideal targets for applying the photometric method of bright lens identification. First, the chance to determine the lens mass and distance is high for these events. For the determination of \( M \) and \( D_L \), it is required to measure both the microlens parallax \( \pi_E \) and the angular Einstein radius \( \theta_E \), which are related to \( M \) and \( D_L \) by (Gould 2000)

\[
M = \frac{\theta_E}{\kappa \pi_E} \tag{1}
\]

and

\[
D_L = \frac{\text{au}}{\pi_E \theta_0 + \pi_S}. \tag{2}
\]

Here \( \kappa = 4G/(c^2 \text{au}) \), \( \pi_S = \text{au}/D_S \) is the parallax of the source star, and \( D_S \) denotes the distance to the source. We note that \( \pi_S \) is known for events detected toward the Galactic bulge because source stars are located there and thus \( D_S \) is known. The angular Einstein radius is measured from the deviation in lensing light curves due to finite-source effects. For single-lens events, finite-source effects can be detected only for very rare events in which the lens passes over the surface of the source star (e.g., Choi et al. 2012), and thus the chance to measure \( \theta_E \) is low.\(^{31}\) For binary-lens events, in contrast, the chance to measure \( \theta_E \) is high because these events usually accompany caustic-crossing features in lensing light curves from which one can measure \( \theta_E \). The chance to measure \( \pi_S \) is also high for these events due to their long timescales. As an event timescale approaches or exceeds the orbital period of the Earth, i.e., \( 1 \text{ yr} \), the relative lens–source motion deviates from rectilinear due to the acceleration of the observer’s motion caused by the Earth’s orbital motion. The deviation in the relative lens–source motion results in lensing light curve deviations from which one can measure the microlens parallax (Gould 1992). Being able to measure both \( \theta_E \) and \( \pi_S \), the chance to measure the physical lens parameters \( M \) and \( D_L \) is high for long-timescale binary-lens events. Also, the chance for these events to be produced by bright lenses is higher. This is because the event timescale is proportional to the square root of the lens mass, i.e., \( \theta_E \propto \sqrt{M} \), and thus the lens mass tends to be heavier and brighter than for general events due to their long timescales. As the lens becomes brighter, the fraction of the lens flux in the total blended flux increases, making it easier to identify.

In this work, we present an analysis of the binary-lens event OGLE-2017-BLG-0039. The event has a very long timescale with well-resolved caustic-crossing features in the light curve.

\(^{30}\) With adaptive optics observations using the Extremely Large Telescope, which is planned to begin operation in 2024, the waiting time will be reduced to a few years, and direct lens imaging will become routine.

\(^{31}\) We note that, although rare, source-passing single-lens events are important because they provide a channel to measure the masses of single-mass objects. In addition to \( \theta_E \) from finite-source effects, the lens masses in two cases of extremely high-magnification events (Gould et al. 2009; Yee et al. 2009) are determined by “terrestrial parallax” measurement of \( \pi_S \) (Gould 1997). The chance to measure \( \pi_S \) is becoming higher as more events are simultaneously observed from the ground and from a space-based satellite in a heliocentric orbit such as Spitzer (Refsdal 1966; Gould 1994). Events with measured lens masses from Spitzer observations include OGLE-2015-BLG-1268, OGLE-2015-BLG-0763 (Zhu et al. 2016), OGLE-2017-BLG-0896 (Shvartzvald et al. 2018), OGLE-2017-BLG-1186, OGLE-2017-BLG-0722, OGLE-2017-BLG-1161, OGLE-2017-BLG-1254 (W. Zhang et al. 2018, in preparation), OGLE-2015-BLG-1482 (Chung et al. 2017), and OGLE-2016-BLG-1045 (Shin et al. 2018).
From determination of the lens mass and distance by simultaneously measuring both $\varphi_E$ and $\theta_E$, we check the lens origin of the blended light.

2. Observations

The microlensing event OGLE-2017-BLG-0039 occurred on a star located toward the Galactic bulge field. The coordinates of the source star are (R.A., decl.)$_{2000}$ = (18:01:47.95, $-27:20:34.7$), which corresponds to the Galactic coordinates $(l, b) = (3^\circ18, -2^\circ27)$. The apparent baseline brightness before lensing magnification was $I_{\text{base}} \sim 19.1$.

The lensing-induced brightening of the source star was found and alerted by the early warning system of the Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 2015) survey on 2017 February 14 (HJD = HJD $- 24,500,000 \sim 7798$). The OGLE survey was conducted using the 1.3 m Warsaw Telescope located at the Las Campanas Observatory in Chile. The event was in the OGLE BLG511.23 field, toward which observations were carried out three to ten times per night. Images were taken primarily in the $I$ band, and V-band images were occasionally obtained for the color measurement of the source star. Photometry of the images was extracted using the OGLE difference-imaging pipeline (Udalski 2003).

The event was also in fields observed by the Microlensing Observations in Astrophysics (MOA; Bond et al. 2001) and the Korea Microlensing Telescope Network (KMTNet; Kim et al. 2016) surveys. MOA observations were conducted in a customized $R$-band using the 1.8 m telescope of the Mt. John University Observatory in New Zealand. The event was dubbed MOA-2017-BLG-080 in the list of MOA transient events. About 10 images were taken each night from the MOA survey. KMTNet observations of the event were conducted using three identical 1.6 m telescopes that are globally distributed at the Cerro Tololo Inter-American Observatory, Chile (KMTC), the South African Astronomical Observatory (KMTS), and the Siding Spring Observatory, in Australia (KMTC). Most KMTNet data were taken in the $I$ band, and some $V$-band images were acquired for the source color measurement. The event is in the KMTNet BLG03 field for which observations were conducted at a cadence of two per hour. Most of the BLG03 field is additionally covered by the BLG43 field with a slight offset in order to cover the gaps between CCD chips as well as to increase the rate of observation. The event happens to be just outside the BLG43 field, and thus no data are obtained from the BLG43 field. Photometry of the MOA and KMTNet data was conducted using the software packages customized by the individual groups based on the difference imaging method: Bond et al. (2001) and Albdrow (2017) for the MOA and KMTNet surveys, respectively.

Figure 1 shows the light curve of OGLE-2017-BLG-0039. It shows that the lensing magnification was in progress from the second half of the 2016 season and lasted throughout the 2017 season. The event could not be observed during a roughly three month period when the Sun passed the bulge field. The event was found in the early 2017 season when the source was brightened by $\sim 0.7$ mag. On 2017 March 12, the source became brighter by $\sim 2$ mag within $\lesssim 0.5$ day. Such a sudden brightening occurs when a source passes over the caustic formed by a binary lens. The binary-lens interpretation became more plausible as the light curve exhibited a “U”-shaped feature after the caustic-crossing spike. Because caustics of a binary lens form closed curves, caustic crossings occur in pairs. On 2017 March 21 (HJD $\sim 7833$), V. Bozza circulated a model based on the binary-lens interpretation and predicted that another caustic crossing would occur on HJD $\sim 7842$. The second crossing occurred at about the anticipated time. Bozza circulated another model based on additional data after the second caustic crossing. After completing the crossings, the event gradually returned to its baseline.

Two factors make the event scientifically important. The first is that the duration of the event is very long. The lensing-induced magnification of the source flux started in the 2016 season and lasted throughout the 2017 season. Due to the long duration, the chance to measure the microlens parallax was high. The second factor is that both of the crossings, when the source entered and exited the caustic, were densely and continuously covered from the combined observations using the globally distributed telescopes. In Figure 2, we present a zoom of the light curve during the caustic entrance (left panels) and exit (right panels). Analysis of the caustic-crossing parts of the light curve enables one to measure the angular Einstein radius. Being able to measure both $\varphi_E$ and $\theta_E$, one can uniquely determine the mass and distance to the lens. This also enables one to check the lens origin of the blended flux.

In Table 1, we list details of the data used in the analysis. The coverage column indicates the time range, and $N_{\text{data}}$ represents the number of data points in the individual data sets. For the OGLE data set, we use nine years of data from 2010 to 2018 for the secure measurement of the baseline magnitude. Although the event was observed by the KMTNet survey since its commencement in 2015, the system was under development during the 2015 season. We therefore used KMTNet data that were acquired since the 2016 season, after the system was stabilized. For the MOA data, photometric uncertainties of the data near the baseline were considerable, but the data densely covered the caustic exit. We therefore used partial MOA data around the caustic-crossing features obtained during $7800 \lesssim \text{HJD} \lesssim 7860$.

3. Analysis

Considering the caustic-crossing features, we model the observed light curve based on the binary-lens interpretation. We begin modeling under the assumption that the relative lens-
source motion is rectilinear although it is expected that it would be non-rectilinear due to the long duration of the event. Under this assumption, a lensing light curve is described by seven principal parameters. Four of these describe the lens—the lens position, we use the center of mass of the binary— including the projected binary separation normalized to the angular Einstein radius, i.e., ρ = θₐ/θₑ. 

In the preliminary modeling, we conduct a grid search for the binary-lens parameters s and q while other parameters are sought using a downhill approach. For this approach, we use the Markov chain Monte Carlo (MCMC) method. From this preliminary search, we find two candidate solutions with (s, q)_{close} ≈ (0.84, 0.13) and (s, q)_{wide} ≈ (1.61, 0.20). We designate the individual solutions as “close” and “wide” based on the fact that the projected binary separation is less (s < 1) and greater (s > 1) than the angular Einstein radius, respectively.

Although the solutions found from the preliminary modeling describe the overall light curve, they leave subtle long-term residuals from the models. It is known that long-term deviations are caused by two major higher-order effects. The first is the microlens-parallax effect caused by the orbital motion of the Earth (Gould 1992). The other is caused by the orbital motion of the lens, lens-orbital effects (Dominik 1998; Ioka et al. 1999). We therefore check whether the fit improves with consideration of these higher-order effects.

Consideration of the microlens-parallax effect requires one to include two additional lensing parameters of θₑ and μₑ. They represent the north and east components of the microlens-parallax vector, μₑ, projected onto the sky along the north and east equatorial coordinates, respectively. The magnitude of the microlens-parallax vector is e = (θₑ + θₑ)²/2 and is directed toward that of the relative lens—source proper motion vector μ, i.e., e = e(μ/μ). Consideration of the lens-orbital effect also requires additional parameters. Under the approximation that the change of the lens position is small, the effect is described by the parameters ds/dt and dμ/dt, which represent the rates of change in the projected binary separation and the source trajectory angle, respectively.

In Table 2, we list the results of the additional modeling considering higher-order effects. We compare the goodness of the fit for the individual models in terms of χ² values. The “static” model denotes the solution obtained under the assumption of the rectilinear relative lens—source motion. In the “orbit” and “parallax” models, we separately consider the microlens-parallax and the lens-orbital effects, respectively. In the “orbit+parallax” model, we simultaneously consider both higher-order effects. For microlensing solutions obtained considering the microlens-parallax effects, it is known

| Data set  | Coverage (HJD′) | Ndata |
|-----------|-----------------|-------|
| OGLE      | 5376–8236       | 5751  |
| KMTNet    | 7444–8220       | 2237  |
| KMTA      | 7439–8216       | 2842  |
| KMTS      | 7441–8216       | 3739  |
| MOA       | 7800–7860       | 268   |

Note. HJD′ = HJD − 2450000.
that there may exist a pair of degenerate solutions with \( u_0 > 0 \) and \( u_0 < 0 \) due to the mirror symmetry of the source trajectories with respect to the binary axis between the two degenerate solutions: ecliptic degeneracy (Smith et al. 2003; Skowron et al. 2011). We therefore check the ecliptic degeneracy whenever parallax effects are considered in modeling. The lensing parameters of the pair of solutions caused by the ecliptic degeneracy are roughly in the relation
\[
(u_0, \alpha, \pi_E, \dot{\alpha}) \rightarrow -(u_0, \alpha, \pi_E, \dot{\alpha}/d\theta).
\]

From the comparison of \( \chi^2 \) values between the close and wide binary solutions, it is found that the former is preferred over the latter by \( \Delta \chi^2 \sim 123 \). This is statistically significant enough to resolve the degeneracy between the two solutions.

We find that consideration of higher-order effects significantly improves the fit; they improve it by \( \Delta \chi^2 \sim 726 \) for the close-binary solution, which provides the best fit. For the pair of solutions resulting from the ecliptic degeneracy, it is found that the degeneracy is moderately severe with \( \Delta \chi^2 \sim 6.4 \), and the \( u_0 > 0 \) solution is preferred over the \( u_0 < 0 \) solution.

In order to better show the region of fit improvement by the higher-order effects, in Figure 3, we present the cumulative distribution of \( \Delta \chi^2 \), where \( \Delta \chi^2 \) represents the difference in \( \chi^2 \) between the static and orbit+parallax (\( u_0 > 0 \)) models. It shows that the fit improvement occurs throughout the event.

In Table 3, we list the lensing parameters determined from modeling. Although the close/wide degeneracy is clearly resolved, we present the parameters of the wide-binary solution for readers who may wish to reproduce the result. In Figure 4, we also present the lens-system configuration in which the source trajectory (curve with an arrow) with respect to the binary lens components (marked by \( M_1 \) and \( M_2 \)) and the caustic (cuspy closed figure) is shown. According to the best-fit model (close \( u_0 > 0 \) solution), it is found that the lensing event is produced by a binary with \( (s, q) \sim (0.85, 0.15) \). Due to the proximity of the binary separation to the angular Einstein radius, the caustics form a single closed curve composed of six folds. Due to the relatively low mass ratio, \( q \sim 0.15 \), the caustic is tilted toward higher-mass lens component, i.e., \( M_1 \), with a protruding cusp pointing toward the lower-mass lens component, \( M_2 \). The source passes through the protruding cusp region of the caustic, producing the two observed spikes when it enters and exits the caustic. The source trajectory is curved by the higher-order effects, especially by the lens-orbital effect.

The change rate of the source trajectory angle is \( |d\alpha/d\theta| \sim 1.22 \text{ rad yr}^{-1} \sim 70^\circ \text{ yr}^{-1} \).

We note that the microlens-parallax parameters are well determined despite their small values. Figure 5 shows the distribution of points in the MCMC chain on the \( \pi_{\text{E},N}-\pi_{\text{E},E} \) parameter plane. It shows that, despite the small magnitude of the parallax, it is possible to resolve the degeneracy between the two solutions resulting from the ecliptic degeneracy, it is found that the lensing event is produced by a binary with \( (s, q) \sim (0.85, 0.15) \). Due to the proximity of the binary separation to the angular Einstein radius, the caustics form a single closed curve composed of six folds. Due to the relatively low mass ratio, \( q \sim 0.15 \), the caustic is tilted toward higher-mass lens component, i.e., \( M_1 \), with a protruding cusp pointing toward the lower-mass lens component, \( M_2 \). The source passes through the protruding cusp region of the caustic, producing the two observed spikes when it enters and exits the caustic. The source trajectory is curved by the higher-order effects, especially by the lens-orbital effect.

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| Model       | \( \chi^2 \) Close | \( \chi^2 \) Wide |
|-------------|-------------------|-------------------|
| Static      | 16081.8           | 15634.0           |
| Orbit       | 15476.8           | 15565.7           |
| Parallax    | (\( u_0 > 0 \))   | 15886.7           | 15565.6           |
|             | (\( u_0 < 0 \))   | 15862.8           | 15575.4           |
| Orbit+parallax | (\( u_0 > 0 \)) | 15355.8           | 15479.2           |
|             | (\( u_0 < 0 \))   | 15362.2           | 15463.4           |

Figure 3. Cumulative distribution of \( \Delta \chi^2 \) between the models with and without consideration of the microlens-parallax and lens-orbital effects. The light curve in the upper panel is presented to show the region of fit improvement.

\[ \pi_E = (\pi_{\text{E},N}^2 + \pi_{\text{E},E}^2)^{1/2} \sim 0.06, \] the microlens parallax is precisely measured to be clearly distinguished from a zero-parallax model. This is possible mainly due to the long timescale of the event, which is measured to be \( t_E \sim 130 \text{ days} \).

4. Physical Lens Parameters

4.1. Angular Einstein Radius

In addition to the microlens parallax, one needs to measure the angular Einstein radius for the unique determinations of the lens mass and distance. The angular Einstein radius is measured from the normalized source radius by

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

The normalized radius is precisely determined from modeling. Then, one needs to measure \( \theta_s \) to determine \( \theta_E \).

We measure the angular source radius from the de-reddened color \((V-I)_0\) and magnitude \( I_0 \). In Figure 6, we mark the position of the source in the color–magnitude diagram (CMD) constructed based on the pyDIA photometry of the KMTC data set. To obtain \((V-I)_0\) and \( I_0 \), we calibrate the instrumental color and magnitude using the centroid of red giant clump (RGC), for which its de-reddened color and magnitude \((V-I, I)_{\text{RGC}} = (1.06, 14.29)\) (Bensby et al. 2011; Nataf et al. 2013) are known, as a reference (Yoo et al. 2004). The locations of the source and RGC centroid in the instrumental CMD are \((V-I, I)_{\text{S}} = (1.17, 17.25)\) and \((V-I, I)_{\text{RGC}} = (1.59, 13.76)\), respectively. Then, the de-reddened color and magnitude of the source are estimated from the offsets in color \( \Delta(V-I) = (V-I)_0 - (V-I)_{\text{RGC}} \) and magnitude \( \Delta I = I_0 - I_{\text{RGC}} \) with respect to the RGC centroid by \( (V-I, I)_{\text{S}} = [(V-I)_0 + \Delta(V-I), I_0 + \Delta I] = (0.65 \pm 0.02, 17.78 \pm 0.01) \). The estimated de-reddened color and magnitude indicate that the source is likely to be a metal-poor turnoff star. The measured
V–I color is converted into V–K color using the color–color relation of Bessell & Brett (1988) and the angular source radius is estimated using the relation between V–K and the surface brightness of Kervella et al. (2004). The measured angular source radius is $\theta_s = 1.04 \pm 0.08 \mu$ as.

In Table 4, we list the measured angular Einstein radius. We also present the relative lens–source proper motions in the geocentric, $\mu_{\text{geo}}$, and heliocentric frames, $\mu_{\text{helio}}$. The geocentric proper motion vector is determined from the measured angular Einstein radius, event timescale, and microlens parallax vector $\pi_{\text{E}} = (\pi_{\text{E,N}}, \pi_{\text{E,E}})$ by

$$\mu_{\text{geo}} = \frac{\theta E}{t_{\text{E}}} \frac{\pi_{\text{E,N}}}{\pi_{\text{E,E}}}.$$  

The heliocentric proper motion is computed by

$$\mu_{\text{helio}} = \mu_{\text{geo}} + v_{\odot,\perp} \pi_{\text{red}} / a_u,$$

where $v_{\odot,\perp}$ represents the velocity of the Earth motion projected on the sky at $t_0$ and $\pi_{\text{red}} = \pi_{\odot} - \pi_E = au(D_E^{-1} - D_S^{-1})$ is the relative lens–source parallax (Gould 2004; Dong et al. 2009). The angle $\phi$ represents the orientation angle of $\mu_{\text{helio}}$ as measured from the north. It is found that the measured Einstein radius of $\theta_E \approx 0.6$ mas is close to that of a typical lensing event. However, the measured relative lens–source proper motion, $\mu_{\text{geo}} \approx 1.7$ mas yr$^{-1}$, is substantially slower than the typical value of $\sim 5$ mas yr$^{-1}$. This indicates that the long timescale of the event is mainly caused by the slow relative lens–source motion. From simulation of Galactic lensing events, Han et al. (2018) pointed out that majority of long-timescale events

![Figure 4](image1.png)

**Figure 4.** Configuration of the lens system. The curve with an arrow represents the source trajectory. The closed curve composed of six folds represents the caustic. The small filled dots marked by $M_1$ and $M_2$ represent the positions of the binary-lens components. All lengths are scaled to the angular Einstein radius corresponding to the total mass of the lens. Due to the orbital motion of the lens, the positions of the lens components and the caustic shape vary in time. We mark the positions at HJD$' = 7824.8$ and 7841.9, which correspond to the times of source star’s caustic entrance and exit, respectively.

![Figure 5](image2.png)

**Figure 5.** $\Delta\chi^2$ map of MCMC points in the $\pi_{\text{E,N}}$–$\pi_{\text{E,E}}$ parameter plane for the best-fit solution ("orbit+parallax" solution with $u_0 > 0$). The color coding represents the points of the MCMC chain within 1σ (red), 2σ (yellow), 3σ (green), 4σ (cyan), and 5σ (blue). The inset shows the zoom of the MCMC-point distribution.
are caused by slow relative lens-source proper motion arising due to the chance alignment of the lens and source motions. In this sense, OGLE-2017-BLG-0039 is a typical long-timescale event.

4.2. Mass and Distance

We estimate the mass and distance to the lens using Equations (1) and (2) and list them in Table 5. Also listed are the projected separation \( a_\perp = sD_L \theta_E \) and the projected kinetic-to-potential-energy ratio \((\text{KE}/\text{PE})_\perp\). This ratio is computed based on the projected binary separation \( a_\perp \), lens mass \( M = M_1 + M_2 \), and the lensing parameters \( s \), \( ds/dt \), and \( d\alpha/dt \) by

\[
(\text{KE}/\text{PE})_\perp = \frac{(a_\perp/au)^3}{8\pi^2(M/M_\odot)} \left[ \left( \frac{1}{s \ \text{yr}^{-1}} \right)^2 + \left( \frac{d\alpha/dt}{\text{yr}^{-1}} \right)^2 \right].
\]

The ratio should be less than unity for the lens system to be a gravitationally bound system. It is found that the measured ratios for both the \( u_0 > 0 \) and \( u_0 < 0 \) solutions satisfy this condition. Furthermore, the estimated kinetic-to-potential-energy ratio is within the expected range \( 0.2 \lesssim \text{KE}/\text{PE} \lesssim 0.5 \) for binaries with moderate orbital eccentricity that are not viewed at unusual angles, e.g., a wide binary in an edge-on orbit.

According to the best-fit solution, the estimated masses of the primary, \( M_1 \sim 1.0 \, M_\odot \), and the companion, \( M_2 \sim 0.15 \, M_\odot \), of the lens correspond to the masses of early G-type and late M-type dwarfs, respectively. The estimated distance to the lens is \( D_L \sim 6.0 \, \text{kpc} \).

4.3. Flux from the Lens

The estimated mass of the primary lens, \( M_1 \sim 1.0 \, M_\odot \), is substantially heavier than those of the most common lens population of M dwarfs. If the lens is a star, then, its flux will contribute to the blended flux.

In Figure 6, we mark the position of the primary lens, which dominates the flux from the binary lens, in the instrumental CMD expected from the determined lens mass and distance. Here we assume that the primary lens is a main-sequence star and the ranges of color and magnitude are estimated based on the uncertainty of the estimated lens mass. Because the estimated distance to the lens, \( D_L \sim 6 \, \text{kpc} \), indicates that the lens is likely to be located behind most obscuring dust in the disk, it experiences extinction and reddening similar to those of the source star. Under this assumption, we estimate the lens position in the CMD by

\[
(V-I)_L = (V-I)_0 - ([V-I]_\text{RGC}) - (V-I)_0.\text{RGC}],
\]

where \((V-I)_\text{RGC} = (1.59, 13.76)\) represent the apparent color and magnitude of the RGC centroid in the instrumental CMD and \((V-I)_0.\text{RGC} = (1.06, 14.29)\) represent the de-reddened values. The color \((V-I)_0 \sim 0.68\) represents the intrinsic color corresponding to the estimated lens mass (Allen 1976). The de-reddened lens magnitude is estimated by

\[
I_{0,\text{L}} = [M_V - (V-I)_0,\text{L}] + 5 \log(D_L/\text{pc}) - 5,
\]

where \(M_V \sim 4.7\) is the absolute V-band magnitude of a main-sequence star with a mass corresponding to the lens mass (Allen 1976). The estimated color and magnitude of the lens in the instrumental CMD are \((V-I)_0 = (1.21^{+0.07}_{-0.06}, 17.37^{+0.54}_{-0.73})\). Also marked in the CMD is the location of the blend (square dot) which has color and brightness of \((V-I)_0 = (1.44, 16.93)\). It is found that the position of the lens in the CMD is close to that of the blend.

The proximity of the lens position to that of the blend in the CMD indicates that the flux from the lens comprises a significant fraction of the blended flux. From the comparison of the I-band magnitudes of the lens and blend, it is found that the lens is \( \Delta I \sim 0.44 \) magnitude fainter than the total blended flux.

### Table 4

**Angular Einstein Radius and the Relative Lens–Source Proper Motion**

| Parameter          | Value   |
|--------------------|---------|
| \( \theta_E \) (mas) | 0.59 ± 0.04 |
| \( \mu_{\text{geo}} \) (mas yr\(^{-1}\)) | 1.67 ± 0.12 |
| \( \mu_{\text{helio}} \) (mas yr\(^{-1}\)) | 1.64 ± 0.12 |
| \( \phi \) | 142° (35°) |

*Note.* The orientation angle values of the heliocentric proper motion, \( \phi \), in and out of the parenthesis are for the \( u_0 > 0 \) and \( u_0 < 0 \) solutions, respectively.

### Table 5

**Physical Lens Parameters**

| Parameter | \( u_0 > 0 \) | \( u_0 < 0 \) |
|-----------|---------------|---------------|
| \( M_1 \) (\( M_\odot \)) | 1.03 ± 0.15 | 1.03 ± 0.15 |
| \( M_2 \) (\( M_\odot \)) | 0.15 ± 0.02 | 0.15 ± 0.02 |
| \( D_L \) (kpc) | 5.99 ± 0.77 | 5.94 ± 0.76 |
| \( a_\perp \) (au) | 3.00 ± 0.39 | 2.99 ± 0.38 |
| \((\text{KE}/\text{PE})_\perp\) | 0.49 ± 0.02 | 0.49 ± 0.02 |
flux. Because the flux from the lens contributes to the blended flux, this means that the lens comprises \( \sim 2/3 \) of the I-band blended flux, although this fraction is somewhat uncertain due to the uncertainty of the lens brightness. The lens is bluer than the blend by \( \Delta (V-I) \sim 0.23 \). This indicates the possibility that there exists another blended star that is redder than the lens. An alternative explanation of the slight differences in color and brightness between the lens and blend is that the lens is a "turnoff star" rather than a main-sequence star. Since a turnoff star has evolved off the main sequence, it is slightly redder and brighter than a main-sequence star with a similar mass.

In order to check the two possible explanations for the slight differences in the color and brightness between the lens and blend, we measure the "astrometric offset" between the source and baseline object using the OGLE images. If there exists another blend, the position of the baseline object, which corresponds to the centroid of the combined image of the blend and source, will be slightly different from the position when the source is magnified, and thus there will be an astrometric offset. If the "turnoff star" explanation is correct, on the other hand, there will be no measurable astrometric offset. From this measurement, we find that the image centroid where the source was magnified is shifted from the baseline object by \( \sim 0.26 \pm 0.07 \) pixels, which corresponds to \( \sim 65 \pm 17 \) mas. This supports the explanation that there is another blend.

5. Conclusion

We analyzed the binary-lensing event OGLE-2017-BLG-0039. The long duration of the event enabled us to precisely measure the microlens parallax despite its small value. In addition, analysis of the well resolved caustic crossings during the source star’s entrance and exit of the caustic allowed us to measure the angular Einstein radius. From the combination of \( \theta_E \) and \( \theta_E^{\prime} \), we measured the mass and distance to the lens and found that it was a binary composed of an early G and a late M dwarf located at a distance \( \sim 6 \) kpc. From the location of the lens in the CMD, it was found that the flux from it comprised \( \sim 2/3 \) of the blended light. Therefore, the event was a rare case of a bright lens event for which follow-up spectroscopic observations could confirm its nature.

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