REANALYSIS OF THE GRAVITATIONAL MICROLENSING EVENT MACHO-97-BLG-41 BASED ON COMBINED DATA

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ABSTRACT

MACHO-97-BLG-41 is a gravitational microlensing event produced by a lens composed of multiple masses detected by the first-generation lensing experiment. For the event, there exist two different interpretations of the lens from independent analyses based on two different data sets: one interpreted the event as produced by a circumbinary planetary system while the other explained the light curve with only a binary system by introducing orbital motion of the lens. According to the former interpretation, the lens would not only be the first planet detected via microlensing but also the first circumbinary planet ever detected. To resolve the issue using state-of-the-art analysis methods, we reanalyze the event based on the combined data used separately by the previous analyses. By considering various higher-order effects, we find that the orbiting binary-lens model provides a better fit than the circumbinary planet model with $\Delta \chi^2 \sim 166$. The result signifies the importance of even and dense coverage of lensing light curves in the interpretation of events.

Key words: binaries: general – gravitational lensing: micro – planetary systems

Online-only material: color figures

1. INTRODUCTION

The past two decades have witnessed tremendous progress in gravitational microlensing experiments. On the observational side, improvement in both hardware and software has contributed to the great increase in the detection rate of lensing events from tens of events per year at the early stage of the experiments to thousands per year at the current stage. In addition, photometry based on difference imaging substantially improved the quality of photometry.

Along with the observational progress, there also has been advances on the analysis side. A good example is the analysis of light curves of lensing events produced by multiple masses. The light curve of a single-lens event is described by a simple analytic equation with a small number of parameters and the lensing magnification varies smoothly with respect to the lensing parameters. As a result, observed light curves can be easily modeled by a simple $\chi^2$ minimization method. However, when events are produced by multiple masses, modeling light curves becomes very complex not only because of the increased number of lensing parameters but also because of the non-linear variation of lensing magnification with respect to the parameters. The non-linearity of lensing magnifications is caused by the formation of caustics that denote positions on the source plane where the lensing magnification of a point source diverges. Caustics cause difficulties in lens modeling in two ways. First, they make it difficult to use a simple linearized $\chi^2$ minimization method in modeling light curves because of the complexity of the parameter space caused by the singularity. Second, magnification computations for source positions on a caustic are numerically intensive. As a result, modeling a multiple lens event was a daunting task during the early stages of lensing experiments. However, with the introduction of efficient non-linear modeling methods such as the Markov Chain Monte Carlo algorithm, combined with advances in computer technology such as computer clusters or graphic processing units, precise and fast modeling became possible and now it is routine to model light curves in real time as lensing events progress (Dong et al. 2006; Cassan 2008; Kains et al. 2009; Bennett 2010; Ryu et al. 2010; Bozza et al. 2012). Furthermore, current modeling takes into account various subtle higher-order effects.

In this Letter, we reanalyze the lensing event MACHO-97-BLG-41 that is a multiple-lens event detected by the first-generation lensing experiment Massive Compact Halo Objects (MACHO; Alcock et al. 1993). For the event, there exist two different interpretations. Based mainly on the data obtained from the MACHO experiment, Bennett et al. (1999) interpreted the event as produced by a circumbinary planetary system where a planet was orbiting a stellar binary. On the other hand, Albrow et al. (2000), from independent analysis based on a different data set obtained by the Probing Lensing Anomalies NETwork (PLANET; Albrow et al. 1998) group, arrived at a different interpretation that the light curve could be explained without the introduction of a planet but rather by considering the orbital motion of the binary lens. According to the interpretation of Bennett et al. (1999), the lowest-mass component of the triple-mass lens would be not only the first planet detected via microlensing but also the first circumbinary planet ever detected. Despite the importance of the event, the issue of its correct interpretation remains unresolved. Therefore, we revisit MACHO-97-BLG-41, applying state-of-the-art analysis methods to the combined data used separately by Bennett et al. (1999) and Albrow et al. (2000).

2. DATA

The data used for our analysis come broadly from two streams. The first stream comes from MACHO survey observations plus the Global Microlensing Alert Network (Alcock et al. 1997) and Microlensing Planet Search (Rhie et al. 1999) follow-up observations. We refer to this data set as the “MACHO data.” The other stream comes from observations conducted by
Figure 1. Light curve of MACHO-97-BLG-41 based on the combined MACHO plus PLANET data sets. Also presented is the best-fit model curve from our analysis. The two insets in the upper panel show the enlarged view of the two caustic-involved features at HJD′ ∼ 619 and 654. The lower three panels show the residual from the orbiting binary, triple, and static binary-lens models.

(A color version of this figure is available in the online journal.)

Table 1

| MACHO Data | PLANET Data |
|------------|-------------|
| Observatory | Number | Observatory | Number |
| MSO 1.3 m (R) | 711 | SAAO 1.0 m (I) | 97 |
| MSO 1.3 m (R) | 772 | SAAO 1.0 m (I) | 14 |
| MSO 1.9 m (R) | 16 | ESO/Dutch 0.9 m (I) | 58 |
| Wise 1.0 m (R) | 17 | ESO/Dutch 0.9 m (V) | 18 |
| CTIO 0.9 m (R) | 35 | Canopus 1.0 m (I) | 95 |
| CTIO 0.9 m (V) | 14 | Canopus 1.0 m (V) | 14 |
| Perth 0.6 m (I) | 26 |

Notes. MSO: Mount Stromlo Observatory; CTIO: Cerro Tololo Inter-American Observatory; SAAO: South African Astronomical Observatory; ESO: European Southern Observatory.

3. ANALYSIS

3.1. Standard Binary-lens Model

To describe the observed light curve of the event, we begin with a standard binary-lens model. In this model, the light curve is described by seven lensing parameters. Among them, three
parameters describe the geometry of the lens–source approach:
the time of the closest lens–source approach, \( t_0 \), the separation
between the lens and the source at the moment of the closest
approach, \( u_0 \) (impact parameter), and the duration required for
the source to cross the radius of the Einstein ring, \( t_E \) (Einstein
timescale). The Einstein ring denotes the image of a point
source when the lens and source are exactly aligned and its
radius, \( \theta_E \), is commonly used as a length scale in describing
lensing phenomenon. The impact parameter is expressed in \( \theta_E \).
Another three parameters are needed to describe the binarity of
the lens: the projected separation \( s \) and the mass ratio \( q \) between
the binary-lens components, and the angle between the source
trajectory and the binary axis \( \alpha \) (source trajectory angle). The
binary separation \( s \) is also expressed in units of \( \theta_E \). The two
peaks of the light curve of MACHO-97-BLG-41 are likely to be
features involved with caustic crossings or approaches during
which finite-source effect becomes important (Dominik 1995;
Gaudi & Gould 1999; Gaudi & Petters 2002). To account for
this effect, an additional parameter, the normalized source radius \( \rho_s = \theta_s/\theta_E \) is needed, where \( \theta_s \) is the angular source radius. In
our standard binary-lens modeling, we additionally consider the
limb-darkening variation of the source star surface brightness by
introducing linear-limb-darkening coefficients, \( \gamma_l \). The surface
brightness profile is modeled as \( S_\lambda = S_\lambda^0 (1 - \gamma_l \cos \phi/2) \),
where \( \lambda \) denotes the observed passband and \( \phi \) is the angle
between the normal to the surface of the source and the line of
sight toward the source (Albrow et al. 1999). Based on the source
type (subgiant) determined by the spectroscopic observation
conducted by Lennon et al. (1997), we adopt coefficients from
Claret (2000). The adopted values are \( \Gamma_R = \Gamma_B = 0.793 \), \( \Gamma_V = 0.666 \),
\( \Gamma_R = 0.575 \), and \( \Gamma_I = 0.479 \) for data sets acquired with
a standard filter system. For the MSO 1.3 m data, which used a
non-standard filter system, we adopt \( \langle \Gamma_R + \Gamma_I \rangle / 2 \) for the B-band
data and \( \langle \Gamma_R + \Gamma_I \rangle / 2 \) for the R-band data.

Although the two sets of solutions presented by Bennett et al.
(1999) and Albrow et al. (2000) already exist, we separately
search for solutions in the vast parameter space encompassing
wide ranges of binary separations and mass ratios in order to
check the possible existence of other solutions. From this, we
find a unique solution with \( \chi^2 \sim 0.49 \) and \( q \sim 0.48 \). See Table 1
for the complete solution of the model. We note that the solution
is basically consistent with the results of Bennett et al. (1999)
and Albrow et al. (2000) in the interpretation of the main part
of the light curve including the peak at HJD’ \( \sim 654 \). At the bottom
panel of Figure 1, we present the residual of the standard binary
model. It is found that there exist some significant residuals for
the standard model. This is also consistent with the previous
analyses that a basic binary model is not adequate to precisely
describe the light curve.

3.2. Higher-order Effects

The existence of residuals in the fit of the standard binary-lens
model suggests the need for considering higher-order effects.
We consider the following effects.

First, we consider the effect of the motion of an observer
cau sed by the orbital motion of the Earth around the Sun. This
“parallax” effect causes the source trajectory to deviate from
rectilinear, resulting in long-term deviations in lensing light
curves (Gould 1992). The event MACHO 97-BLG-41 lasted
\( \sim 100 \) days, which is an important portion of the Earth’s orbital
period, i.e., 1 yr, and thus the parallax effect can be important.
To describe the parallax effect, we add two more lensing
parameters: \( \pi_{E,N} \) and \( \pi_{E,E} \). They denote the two components of
the lens parallax vector \( \pi_E \) projected onto the sky along the north
and east equatorial coordinates, respectively. The direction of
the lens parallax vector corresponds to the relative lens–source
proper motion seen from the Earth at a certain time and its
magnitude is the ratio of the relative lens–source parallax,
\( \pi_{rel} = AL(D_s^{-1} - D_E^{-1}) \), to the angular Einstein radius, i.e.,
\( \pi_E = \pi_{rel}/\theta_E \) (Gould 2004). In our modeling, we use \( t_0 \) for
the reference time of the lens parallax measurement (Gould 2004).

Second, the orbital motion of a binary lens can also cause the
source trajectory to deviate from rectilinear (Dominik 1998).
The orbital motion causes further deviations in lensing light
curves by deforming the caustic over the course of the event.
The “lens orbital” effect can be important for long timescale
events produced by close binary-lens events for which the event
duration comprises an important portion of the orbital period
of the lens system (Shin et al. 2013). For modest orbital effects, the
lens orbital motion can be described by two parameters: \( ds/dt \)
and \( d\pi/dt \). These parameters represent the rate of change of the
binary separation and the source trajectory angle, respectively
(Albrow et al. 2000).

Third, we also check the possible existence of a third body
in the lens system. Introducing an additional lens component
requires three additional lensing parameters including the nor-
malized projected separation, \( s_2 \), and the mass ratio, \( q_2 \), between
the primary and the third body, and the position angle of the
third body with respect to the line connecting the primary and
secondary of the lens, \( \psi \).

3.3. Result

We test models considering various combinations of the
higher-order effects. In Table 2, we list the goodness of the
fits and the best-fit parameters for the individual tested models.
From the comparison of the models, we find the following
results.

First, we confirm the result of Albrow et al. (2000) that the
consideration of the orbital effect substantially improves the fit.
We find that the improvement is \( \Delta \chi^2 \sim 441 \) compared to the
static binary model. When we additionally consider the parallax
effect, the improvement of the fit, \( \Delta \chi^2 \sim 2.7 \), is very meager.
This implies that between the two effects, the orbital motion of
the lens is the dominant higher-order effect in explaining the
residual from the standard model. In Figure 1, we present the
model light curve on the top of the observed light curve and
the residual of the model. In Figure 2, we also present the
geometry of the lens system.

Second, we find that the existence of a third body does not
provide a fully acceptable fit. Our best-fit solution of three-body
lens modeling is consistent with the solution of Bennett et al.
(1999) in the sense that the third body is a circumbinary planet
with a small mass ratio. See Table 2 for the best-fit parameters
and Figure 2 for the lens system geometry. With the introduction
of a planetary third body, the fit does improve from the standard
binary model with \( \Delta \chi^2 \sim 270 \). The additional consideration
of the parallax effect further improves the fit with \( \Delta \chi^2 \sim 9 \), but it is still substantially poorer than the orbiting binary-lens
model with \( \Delta \chi^2 \sim 166 \). From the comparison of the residual
(see Figure 1), it is found that the triple lens model cannot
precisely describe the light curve during and before the first
peak, \( 595 \leq \text{HJD}' \leq 625 \).

The key PLANET data that exclude the triple lens are from
SAAO. Their smooth “parabolic” decline signals a caustic
exit along the axis of cusp. This is compatible with the
triangular caustic generated by the close binary, but not with the
Figure 2. Geometry of the lens system for the best-fit binary (upper panels) and triple (lower panels) lens solutions. In each panel, the closed cuspy figures represent caustics and the curve with an arrow is the source trajectory. The filled circles are the locations of the lens components and the dotted circle is the Einstein ring centered at the barycenter of the lens. The right panels show the enlarged view of the corresponding shaded regions in the left panels. For the binary model, caustics and lens positions vary in time due to the orbital motion. We present two sets of caustics at HJD′ = 619 and 654. The coordinates are corotating with the binary axis so that the binary axis aligns with the abscissa. All lengths are scaled by the Einstein radius θE.

(A color version of this figure is available in the online journal.)

Table 2

| Parameter | Standard | Binary Lens | Triple Lens |
|-----------|----------|-------------|-------------|
| $\chi^2$/dof | 2355.8/1915 | 1915.1/1913 | 1912.4/1911 |
| $t_0$ (HJD′) | 653.519 ± 0.004 | 653.426 ± 0.007 | 653.388 ± 0.008 |
| $u_0$ (10$^{-2}$) | 8.123 ± 0.024 | 7.303 ± 0.074 | 7.284 ± 0.056 |
| $t_0$ (days) | 20.26 ± 0.016 | 25.95 ± 0.213 | 25.40 ± 0.150 |
| $s_1$ | 0.494 ± 0.0003 | 0.481 ± 0.002 | 0.480 ± 0.002 |
| $q_1$ | 0.481 ± 0.003 | 0.342 ± 0.005 | 0.326 ± 0.005 |
| $\alpha$ | 1.211 ± 0.003 | 1.179 ± 0.003 | 1.156 ± 0.005 |
| $s_2$ | 1.900 ± 0.007 | 1.900 ± 0.007 | 1.875 ± 0.008 |
| $q_2$ (10$^{-3}$) | 5.149 ± 0.160 | 5.149 ± 0.160 | 4.644 ± 0.180 |
| $\psi$ | 1.872 ± 0.003 | 1.872 ± 0.003 | 1.858 ± 0.008 |
| $r_{\star} (10^{-3})$ | 7.36 ± 0.09 | 7.36 ± 0.09 | 7.35 ± 0.01 |
| $\sigma_E$ | 0.72 ± 0.050 | 0.67 ± 0.050 | 0.34 ± 0.08 |
| $\sigma_E$ | 0.95 ± 0.037 | 0.30 ± 0.16 | 0.34 ± 0.08 |
quadrilateral caustic induced by the putative planet. In particular, the near-symmetric shape of the quadrilateral caustic implies that a cusp-axis trajectory would have a near-symmetric excess flux in the approach to the first peak as after its exit, which is not seen in the pre-peak MSO data.

4. CONCLUSION

We have conducted a reanalysis of the event MACHO-97-BLG-41 for which there exist two different interpretations. From the analysis considering various higher-order effects based on the combined data sets used separately by the previous analyses, we find that the dominant effect for the deviation from the standard binary-lens model is the orbital motion of the binary lens.

The result signifies the importance of even and dense coverage of lensing light curves for correct interpretation of gravitational lenses. For MACHO-97-BLG-41, the difference between the two previous interpretations partially stems from the poor coverage of the first peak that is important in the interpretation. Although a strategy based on survey plus follow-up observations can densely cover anomalies occurring at an expected time (e.g., peak of a high-magnification event) or long-lasting anomalies, it would be difficult to densely cover short-lasting anomalies arising abruptly at an unexpected moment. Since the first-generation lensing experiments, there has been great progress in survey experiments. The cadence of survey observations has increased from $\sim 1$ to $2 \text{ day}^{-1}$ to several dozens a day for the current lensing experiments (OGLE: Udalski 2003; MOA: Bond et al. 2001; Sumi et al. 2003; Wise: Shvartzvald & Maoz 2012). Furthermore, a new survey based on a network of multiple telescopes (KMTNet; Korea Microlensing Telescope Network) equipped with large format cameras is planned to achieve a cadence of more than $100 \text{ day}^{-1}$. With improved coverage, the characterization of microlenses by future surveys will be more accurate.

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