

# INTERPRETATION OF A SHORT-TERM ANOMALY IN THE GRAVITATIONAL MICROLENSING EVENT MOA-2012-BLG-486

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### ABSTRACT

A planetary microlensing signal is generally characterized by a short-term perturbation to the standard single lensing light curve. A subset of binary-source events can produce perturbations that mimic planetary signals, thereby introducing an ambiguity between the planetary and binary-source interpretations. In this paper, we present analysis of the microlensing event MOA-2012-BLG-486, for which the light curve exhibits a short-lived perturbation. Routine modeling not considering data taken in different passbands yields a best-fit planetary model that is slightly preferred over the best-fit binary-source model. However, when allowed for a change in the color during the perturbation, we find that the binary-source model yields a significantly better fit and thus the degeneracy is clearly resolved. This event not only signifies the importance of considering various interpretations of short-term anomalies, but also demonstrates the importance of multi-band data for checking the possibility of false-positive planetary signals.

*Subject headings:* gravitational lensing – binaries: general – planetary systems

### 1. INTRODUCTION

Microlensing is one of the major methods of detecting and characterizing extrasolar planets. The method is important for the comprehensive understanding of planet formation because it is sensitive to planets that are difficult for other methods to detect, especially planets near and beyond the snow line (Sumi et al. 2011; Cassan et al. 2012; Gaudi 2012).

It is known that such short-term perturbations in microlensing light curves can be caused by scenarios other than planetary companions. In particular, some subset of nearly equal-mass binary lenses can exhibit perturbations with similar magnitudes and durations as those caused by very low mass ratio companions (Albrow et al. 2002; Han & Gaudi 2008). Another example is when the lens is an isolated star, but the source is itself a binary with a large flux ratio. In this case, if the lens passes close to both members of the binary source, the light curve can appear as a normal single lens curve, superposed with a short duration perturbation that results when the lens passes close to the fainter source (Gaudi 1998; Gaudi & Han 2004). Gaudi (1998) pointed out that the frequency of planetary-like perturbations produced by binary-source events can be as high as planet-induced perturbations. Therefore, the analysis of a short-term signal in a lensing light curve requires careful examination considering all possible interpretations.

In this paper, we present our analysis of MOA-2012-BLG-486. The light curve of the event exhibits a short-term perturbation. In § 2, we describe the observation of the event. In § 3, we describe the analyses conducted to examine the nature of the perturbation and present results. We summarize and conclude in § 4.

### 2. OBSERVATIONS AND DATA

The microlensing event MOA-2012-BLG-486 occurred on a star in the Galactic bulge field at the equatorial and Galactic coordinates (RA, DEC)<sub>J2000.0</sub> = (18<sup>h</sup>01<sup>m</sup>08<sup>s</sup>.82, −33°13′06″.1) and (*l*, *b*)<sub>J2000.0</sub> = (357.99°, −5.03°), respectively. It was discovered by the Microlensing Observations in Astrophysics (MOA; Bond et al. 2001; Sumi et al. 2003) survey during the 2012 observing season. From the preliminary analysis of the event based on the rising part of the light curve, it was found that the event would reach a high magnification. Since such a high-magnification event is very sensitive to a planet (Griest & Safizadeh 1998), an alert was issued for intensive follow-up observations. Based on the alert, the event was

additionally observed by other groups including Microlensing Follow-Up Network ( $\mu$ FUN; Gould et al. 2006), Probing Lensing Anomalies NETWORK (PLANET; Beaulieu et al. 2006), and RoboNet (Tsapras et al. 2009). In Table 1, we list the survey and follow-up groups along with the telescopes used for the observations. We note that although most data were taken in *I* band, some data sets were obtained in other bands. Real-time modeling played an important role in the acquisition of the color data that ultimately allowed us to distinguish between binary-lens and binary-source models. The CTIO *VIH* points over the first peak were taken as part of normal  $\mu$ FUN observing strategy (possible high-magnification event). But the later observations, which measured the colors of the second peak were taken in direct response to circulation of two models (binary-lens and binary-source), in a specific effort to distinguish them. The event did not return to its baseline brightness until the end of the 2012 bulge season. For secure measurement of the baseline, the event was additionally observed in 2013 season.

Figure 1 shows the light curve of MOA-2012-BLG-486. It is characterized by a short-term anomaly at HJD' = HJD − 2450000  $\sim$  6137. Apart from the anomaly, the overall light curve is well described by the standard form of a single-lens event. Since the characteristics of the light curve strongly indicate the possible existence of a planetary companion, we conduct a detailed analysis of the event.

For the data sets used in the analysis, initial reductions were conducted using photometry codes developed by the individual groups. For some data sets, we conducted additional reduction to improve photometry using a pipeline based on difference image analysis (Bond et al. 2001; Albrow et al. 2009). Nevertheless, the photometric accuracy is limited because there exists a bright star close to the source. When this occurs, the photometric measurements are often correlated with the seeing. To minimize the seeing effect, we use data taken with seeing less than 3 arc-seconds. We normalize the photometry uncertainties of different data sets by first adding a quadratic term so that the cumulative distribution of  $\chi^2$  ordered by magnification is approximately linear and subsequently rescaling the errors so that  $\chi^2$  per degree of freedom ( $\chi^2/\text{dof}$ ) for each data set becomes unity (Bachelet et al. 2012; Miyake et al. 2012).

### 3. MODELING

TABLE 1  
TELESCOPES

| group     | telescope                                                          | passband |
|-----------|--------------------------------------------------------------------|----------|
| MOA       | 1.8m Mt. John Observatory, New Zealand                             | MOA-Red  |
| $\mu$ FUN | 1.3m SMARTS, Cerro Tololo Inter-American Observatory (CTIO), Chile | V, I, H  |
| $\mu$ FUN | 0.6m Observatorio do Pico dos Dias (OPD), Brazil                   | I        |
| PLANET    | 1.0m South African Astronomical Observatory (SAAO), South Africa   | I        |
| RoboNet   | 2.0m Faulkes North Telescope (FTN), Hawaii, USA                    | I        |
| RoboNet   | 2.0m Faulkes South Telescope (FTS), Australia                      | I        |

NOTE. — MOA-Red band is a custom wide band where the band width roughly corresponds to the sum of R and I bands.

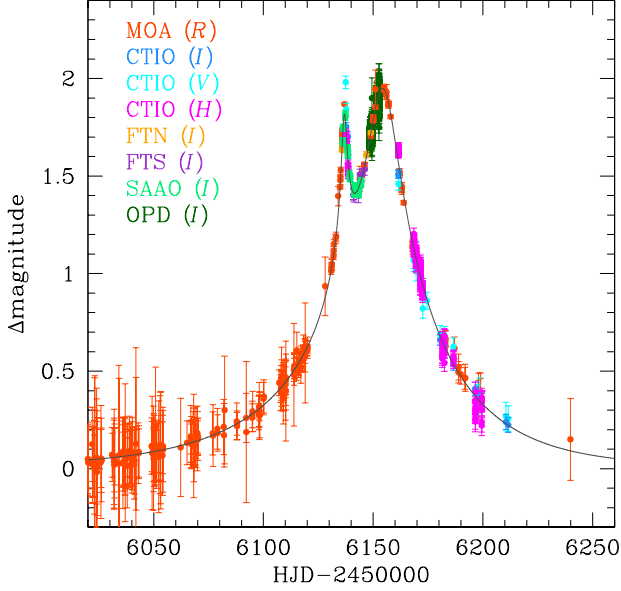


FIG. 1.— Light curve of MOA-2012-BLG-486. The presented model curve is based on the single-band binary-source model. The notation in the parenthesis after the legend of each observatory denotes the passband of observation.

Knowing that a short-term perturbation in a lensing light curve can be produced either by a binary (including planetary) companion to the lens or a binary companion to the source, we conduct both binary-lens and binary-source modeling of the light curve. Due to their physical natures, the two types of modeling require widely different parameterization.

Binary lens modeling requires 7 basic parameters. Among them, three parameters are needed to describe the lens-source approach, including the time of the closest lens-source approach,  $t_0$ , the lens-source separation at that moment,  $u_0$  (impact parameter), and the time scale required for the source to cross the Einstein radius of the lens,  $t_E$  (Einstein time scale). The Einstein ring represents the image of the source for the case of exact lens-source alignment and its radius  $\theta_E$  (Einstein radius) is commonly used as a length scale in lensing phenomena. We note that the lens-source impact parameter  $u_0$  is normalized by  $\theta_E$ . Three additional parameters are needed to characterize the star-planet system, including the projected separation,  $s$  (normalized by  $\theta_E$ ), the mass ratio,  $q$ , and the source trajectory angle with respect to the binary axis,  $\alpha$ . A planetary perturbation usually occurs when the source encounters a caustic, and so finite-source effects become important. To account for these effects, one needs the additional parameter  $\rho_* = \theta_*/\theta_E$  (normalized source radius), where  $\theta_*$  represents the angular radius of the source star.

The lensing magnification of a binary-source event corresponds to the flux-weighted mean of the single-lens mag-

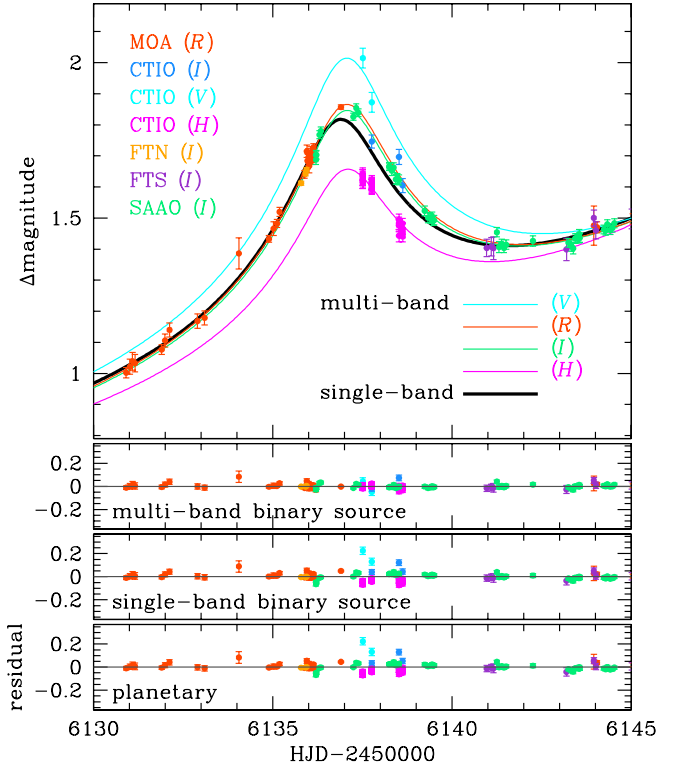


FIG. 2.— Zoom of the perturbation region of the light curve of MOA-2012-BLG-486. The thick solid black curve is the best-fit model obtained from single-band binary-source modeling, while thin curves with various colors are model curves considering color effects. The 3 bottom panels show the residuals from the three sets of modeling.

nifications associated with the individual source stars, i.e.  $A = (A_1 F_{S,1} + A_2 F_{S,2}) / (F_{S,1} + F_{S,2})$  (Griest & Hu 1992). Here  $F_{S,i}$  and  $A_i$  ( $i = 1, 2$ ) represent the flux and magnification for each source star. To describe the lens approach to the individual source stars, one needs pairs of the impact parameters ( $u_{0,1}$  and  $u_{0,2}$ ) and times of closest approach ( $t_{0,1}$  and  $t_{0,2}$ ). Furthermore, an additional parameter is needed to specify the flux ratio between the source stars,  $q_F = F_{S,2}/F_{S,1}$ . In our modeling, we set  $F_{S,1} > F_{S,2}$  and thus  $q_F < 1.0$ .

Besides the basic parameters, it is often needed to consider higher-order effects to precisely describe lensing light curves. The event MOA-2012-BLG-486 lasted for two observing seasons. For such a long time-scale event, the positional change of an observer caused by the Earth's orbital motion around the Sun might cause a deviation in the lensing light curve due to the deviation of the apparent lens-source motion from a rectilinear trajectory (Gould 1992). Considering this parallax effect requires two additional lensing parameters  $\pi_{E,N}$  and  $\pi_{E,E}$ , which are the components of the lens parallax vector  $\pi_E$  projected on the sky along the north and east equatorial axes,

TABLE 2  
LENSING PARAMETERS

| parameters             | planetary          | binary source      |                    |
|------------------------|--------------------|--------------------|--------------------|
|                        |                    | single band        | multi bands        |
| $\chi^2/\text{dof}$    | 2828.8/2184        | 2855.7/2187        | 2165.3/2184        |
| $t_{0,1}$ (HJD')       | $6149.33 \pm 0.24$ | $6154.43 \pm 0.02$ | $6154.24 \pm 0.03$ |
| $t_{0,2}$ (HJD')       | —                  | $6137.19 \pm 0.05$ | $6137.20 \pm 0.05$ |
| $u_{0,1}$              | $0.059 \pm 0.002$  | $0.099 \pm 0.004$  | $0.077 \pm 0.003$  |
| $u_{0,2}$              | —                  | $0.024 \pm 0.003$  | $0.027 \pm 0.002$  |
| $t_E$ (days)           | $92.8 \pm 2.2$     | $66.4 \pm 1.9$     | $78.1 \pm 2.8$     |
| $s$                    | $1.65 \pm 0.01$    | —                  | —                  |
| $q$                    | $0.029 \pm 0.001$  | —                  | —                  |
| $\alpha$               | $2.789 \pm 0.006$  | —                  | —                  |
| $\rho_*$ ( $10^{-3}$ ) | $0.5 \pm 0.3$      | —                  | —                  |
| $\pi_{E,N}$            | $-0.51 \pm 0.04$   | $-0.18 \pm 0.11$   | $-0.37 \pm 0.09$   |
| $\pi_{E,E}$            | $0.11 \pm 0.03$    | $0.17 \pm 0.03$    | $0.08 \pm 0.02$    |
| $ds/dt$                | $-1.62 \pm 0.28$   | —                  | —                  |
| $d\alpha/dt$           | $-0.46 \pm 0.13$   | —                  | —                  |
| $q_F$                  | —                  | $0.097 \pm 0.002$  | —                  |
| $q_{F,V}$              | —                  | —                  | $0.163 \pm 0.007$  |
| $q_{F,R}$              | —                  | —                  | $0.125 \pm 0.003$  |
| $q_{F,I}$              | —                  | —                  | $0.118 \pm 0.003$  |
| $q_{F,H}$              | —                  | —                  | $0.081 \pm 0.002$  |

NOTE. — HJD' = HJD - 2450000.

respectively. For the binary-lens case, the positional change of the lens caused by the orbital motion can also induce long-term deviations in lensing light curves. To first order approximation, the lens orbital effect is described by the two parameters  $ds/dt$  and  $d\alpha/dt$  that represent the change rates of the normalized binary separation and source trajectory angle, respectively (Albrow et al. 2000; An et al. 2002).

For both binary-lens and binary-source models, we look for best-fit sets of lensing parameters by running a Markov Chain Monte Carlo search of parameter space. In the initial binary-source modeling, we model the light curve with a single flux ratio (single-band model). In Table 2, we list the best-fit parameters for the individual models. We find that the overall shape and the short-term feature of the light curve can be described by both planetary and binary-source models with similar values of  $\chi^2$ :  $\chi^2 = 2828.8$  for the planetary model and  $\chi^2 = 2855.7$  for the binary-source model (single band). However, there exist some residuals from the models, especially in the region of the short-term anomaly as shown in the lower panels of Figure 2. Although consideration of parallax and orbital (for the planetary model) effects somewhat improves the fits of both models, they contribute to the fits of the overall shape of the light curve, not to the anomaly feature. This indicates the need to consider another higher-order effect.

Color change can occur for a binary-source event. This color change occurs because the stars comprising a binary source have, in general, different colors and thus the colors measured at the moments of the lens' approaches close to the individual source stars can be different. From the initial single-band binary-source modeling, the measured flux ratio between the two source stars,  $q_F \sim 0.1$ , is small. This implies that the types of the source stars are likely to be very different and thus color effects would be pronounced during the perturbation. To check whether the color effect can explain the residual in the anomaly, we conduct additional binary-source modeling. For this, we specify flux ratios for the individual passbands of the data covering the anomaly, including  $V$  (CTIO),  $R$  (MOA),  $I$  (CTIO, FTN, FTS, SAAO), and  $H$  (CTIO) band.

In Figure 2, we present the light curves in the region of

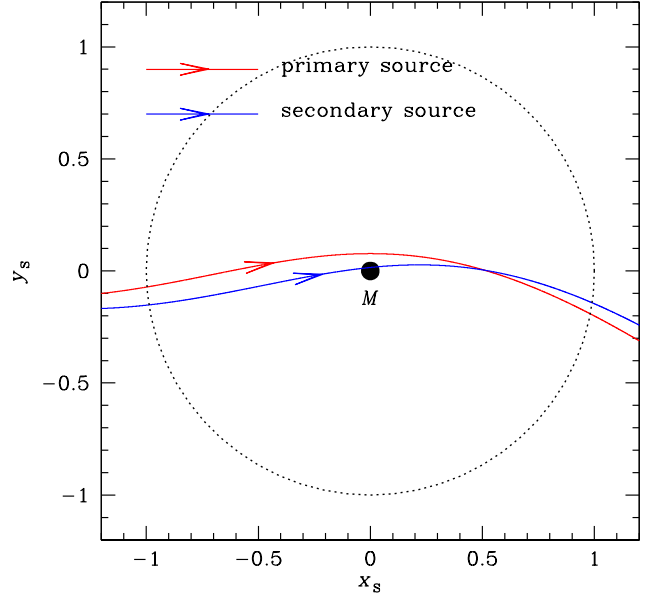


FIG. 3.— Geometry of the lens system for the binary-source model. The lens is positioned at the origin (marked by  $M$ ) and the dotted circle is the Einstein ring. The 2 curves with arrows represent the trajectories of the two source stars. Lengths are scaled by the Einstein radius.

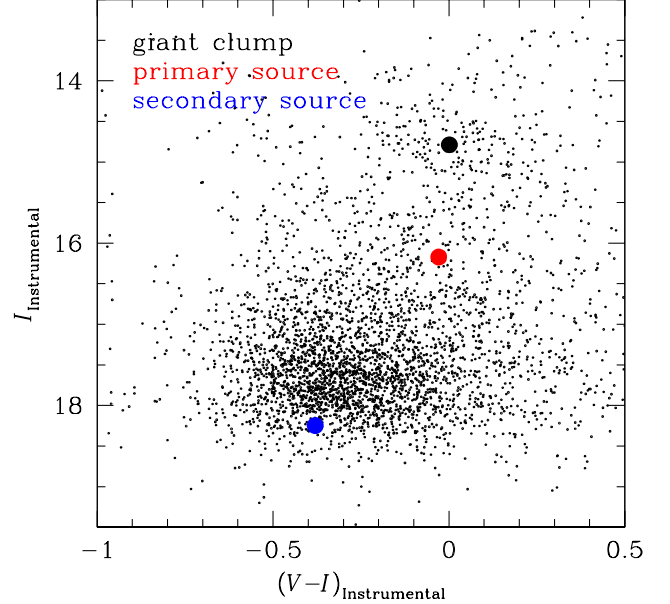


FIG. 4.— Positions of the components stars of the binary source in the color-magnitude diagram.

the anomaly resulting from modeling considering the color effect (multi-band binary-source model). We note that since lensing magnifications depend on the observed passband, 4 model light curves corresponding to the individual passbands are presented. The measured flux ratio of each passband between the binary source stars is listed in Table 2. We find that the model considering the color effect significantly improves the fit with  $\Delta\chi^2 = 690.4$  compared to the single-band binary-source model. Furthermore, the multi-band binary-source model is better than the planetary model by  $\Delta\chi^2 = 663.5$ . The improvement of the fit can be visually seen from the residuals presented in Figure 2. The superiority of the fit compared to the planetary model combined with the obvious color ef-

fect strongly supports the binary-source interpretation of the anomaly.

In Figure 3, we present the trajectories of the individual source stars with respect to the lens for the best-fit binary-source model. The fact that the event is brighter in shorter wavelength passbands during the anomaly indicates that the faint source component (secondary) is bluer than the bright component (primary). We choose the color of each source trajectory in order to reflect the color of each star. According to the model, the faint blue star approached very close to the lens, producing a short-term anomaly, and then the bright red star followed. The flux ratio between source stars is small, ranging from 0.08 ( $H$  band) to 0.16 ( $V$  band). As a result, the light curve is dominated by the light from the bright source star except for the short term of the lens' approach to the faint source star. We note that the trajectories are curved due to parallax effects.

In Figure 4, we present the locations of the binary source components in the color-magnitude diagram. Based on the source flux measured from modeling combined with the reference position of the centroid of clump giants with the known de-reddened magnitude at the Galactic distance  $I_0 = 14.54$  (Nataf et al. 2013) and color  $(V - I)_0 = 1.06$  (Bensby et al. 2011), we determine the de-reddened magnitude and color of the individual source stars as  $(I, V - I)_0 = (15.93, 1.03)$  for the primary and  $(18.25, 0.68)$  for the secondary. These correspond to a K-type giant and a turn-off star for the primary and secondary, respectively.

We check the possibility of the limb-darkening surface brightness variation of the source star as a cause of the color variation. From additional modeling, we find that  $\chi^2$  improvement by the limb-darkening effect is negligible and thus exclude the possibility.

#### 4. CONCLUSION

We analyzed the microlensing event MOA-2012-BLG-486 where the light curve exhibited a short-term perturbation indicating the possible existence of a planetary companion to the lens. By conducting detailed modeling of the light curve considering both planetary and binary-source interpretations, we found that the perturbation was better explained by the

binary-source model. The degeneracy between the planetary and binary-source interpretations was clearly resolved via the color effect that occurred during the anomaly thanks to the multi-band data obtained during the anomaly. The event not only signifies the importance of considering various interpretations of short-term anomalies but also demonstrates the importance of multi-band data for checking the possibility of false-positive planetary signals.

Our ability to distinguish between the planetary and binary-source solutions rested critically on  $VIH$  photometry. However, while such dense multi-band photometry is routine for follow-up observations from  $\mu$ FUN SMARTS CTIO, microlens survey observations are typically taken overwhelmingly in one band. With the advent of second generation surveys, a large fraction of microlensing planets are being detected from survey-only data, and this will be increasingly true in the future. Hence, the protocols for these surveys should be carefully evaluated to make sure that color coverage is adequate to distinguish binary-source events from planetary events.

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