OGLE-2012-BLG-0724LB: A SATURN-MASS PLANET AROUND AN M DWARF

Y. HIRAO\(^1,16\), A. UDALSKI\(^2,17\), T. SUMI\(^1,16\), D. P. BENNETT\(^3,4,16\), I. A. BOND\(^5,16\), N. RATTENBURY\(^6,16\), D. SUZUKI\(^3,4,16\), N. KOSHIKI\(^1,16\), and F. ABE\(^7\), Y. ASAKURA\(^7\), A. BHATTACHARYYA\(^7\), M. FREEMAN\(^5\), A. FUKUI\(^8\), Y. ITO\(^7\), M. C. A. LI\(^5\), C. H. LING\(^5\), K. MASUDA\(^7\), Y. MATSUBARA\(^7\), T. MATSUO\(^1\), Y. MURAKI\(^7\), M. NAGAKANE\(^1\), K. OHNISHI\(^9\), H. OYOKAWA\(^7\), T. SAITO\(^10\), A. SHARAN\(^5\), H. SHIBAI\(^1\), D. J. SULLIVAN\(^11\), P. J. TRISTRAM\(^12\), A. YONEHARA\(^13\)

(THE OGLE COLLABORATION)

AND

R. POLESKI\(^14\), J. SKOWRON\(^2\), P. MRÓZ\(^2\), M. K. SZYMANSKI\(^2\), S. KOZŁOWSKI\(^2\), P. PIETRUKOWICZ\(^2\), I. SOSZYŃSKI\(^2\), L. WYRZYKOWSKI\(^2\), and K. ULACZYK\(^15\)

(THE MOA COLLABORATION)

1 Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan
2 Warsaw University Observatory, Al. Ujazdowski 4, 00-478 Warszawa, Poland
3 Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA
4 Laboratory for Exoplanets and Stellar Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
5 Institute of Information and Mathematical Sciences, Massey University, Private Bag 102-904, North Shore Mail Centre, Auckland, New Zealand
6 Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand
7 Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan
8 Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, 3037-5 Honjo, Kamogata, Asakusa, Okayama 719-0232, Japan
9 Nagano National College of Technology, Nagano 381-8550, Japan
10 Tokyo Metropolitan College of Aeronautics, Tokyo 116-8523, Japan
11 School of Chemical and Physical Sciences, Victoria University, Wellington, New Zealand
12 Mt. John University Observatory, P.O. Box 56, Lake Tekapo 8770, New Zealand
13 Department of Physics, Faculty of Science, Kyoto Sangyo University, Kyoto 603-8555, Japan
14 Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA
15 Department of Physics, University of Warwick, Gibbet Hill Rd., Coventry, CV4 7AL, UK

Received 2016 February 1; revised 2016 April 8; accepted 2016 April 18; published 2016 June 21

ABSTRACT

We report the discovery of a planet by the microlensing method, OGLE-2012-BLG-0724Lb. Although the duration of the planetary signal for this event was one of the shortest seen for a planetary event, the anomaly was well covered thanks to high-cadence observations taken by the survey groups OGLE and MOA. By analyzing the light curve, this planetary system is found to have a mass ratio \(q = (1.58 \pm 0.15) \times 10^{-3}\). By conducting a Bayesian analysis, we estimate that the host star is an M dwarf with a mass of \(M_\star = 0.29^{+0.33}_{-0.16} M_\odot\) located at \(D_L = 6.7^{+1.1}_{-1.2}\) kpc away from the Earth and the companion’s mass is \(m_p = 0.47^{+0.54}_{-0.26} M_{\text{Jup}}\). The projected planet–host separation is \(a_p = 1.6^{+0.4}_{-0.3}\) AU. Because the lens–source relative proper motion is relatively high, future high-resolution images would detect the lens host star and determine the lens properties uniquely. This system is likely a Saturn-mass exoplanet around an M dwarf, and such systems are commonly detected by gravitational microlensing. This adds another example of a possible pileup of sub-Jupiters or more massive planets are unlikely to form around M dwarfs, supporting the prediction by core accretion models and transit methods. The planet abundances estimated by microlensing are complementary to other methods (Bennett & Rhie 1996). Sumi et al. (2010) constructed the planet mass function beyond the snow line and found that Neptune-mass planets are \(\sim 3\) times more common than Jupiter-mass planets based on 10 microlensing planets. Gould et al. (2010) estimated the planet abundance beyond the snow line based on six events and found that they are 7 times more likely than that at close orbits of 1 AU. Cassan et al. (2012) used 6 yr of PLANET collaboration data to constrain the cool planetary mass function for masses \(5 M_\oplus \sim 10 M_{\text{Jup}}\) and separation 0.5–10 AU, including constraints obtained by the two previous works by Sumi et al. (2010) and Gould et al. (2010), and found that there is one planet per star in the Galaxy. Clanton & Gaudi (2014) found that the planet abundances estimated by microlensing are consistent with those found by radial velocity. Recently, Shvartzvald et al. (2015) estimated planet abundance and mass

1. INTRODUCTION

Since the first discovery of exoplanets (Mayor & Queloz 1995), about 1900 exoplanets have been found to date. They include a wide variety of planetary systems such as hot Jupiters, eccentric planets, etc. But a comprehensive planetary formation model that explains all these planet types has not yet been established.

Most exoplanets have been found by the radial velocity (Butler et al. 2006) and transit (Borucki et al. 2011) methods. These methods are sensitive to low-mass planets orbiting less than 1 AU from the host star. In contrast, gravitational microlensing is sensitive to planets orbiting at a few AU away from the host stars down to Earth mass, which is
function based on nine events and found that 55% of stars host a planet beyond the snow line and Neptune-mass planets are ~10 times more common than Jupiter-mass planets. Suzuki et al. (2016) found a break and possible peak in the exoplanet mass ratio function at $q \sim 10^{-3}$ and found 0.75 planets per star at $q > 5 \times 10^{-5}$ and 1.12 planets per star for $q > 0$. However, the numbers of planets used in these analyses were small. Thus, discovering more statistics for microlensing planets is important for improving our statistical estimates of planet abundances.

In microlensing, we can measure the planet/host mass ratio $q$ and their separation $s$ in units of Einstein radii. The mass and the distance can be measured when we detect the microlensing parallax effect or detect the lens directly together with an angular Einstein radius, $\theta_E$, obtained from the finite-source effect. Also, there are other effects that can help break the degeneracy, such as astrometric microlensing (Gould & Yee 2014) and interferometry (Cassan & Ranc 2016). Recently, follow-up observations by Spitzer helped resolve the degeneracy by detecting parallax effects (Udalski et al. 2015b; Zhu et al. 2015). Further, space-based parallax observations of microlensing events by the Kepler telescope (K2C9) are planned in 2016 (Gould & Horne 2013). But we need to wait for results from the WFIRST satellite, for large number statistics. Until then, we need to collect as many ground-based microlensing events as possible, including events without parallax measurements. In such an analysis, a careful treatment of events with a weak signal or with a degeneracy between parameters is important.

In this paper, we report the analysis of a microlensing event OGLE-2012-BLG-0724, which has a relatively weak planetary signal and degenerate solutions. We describe the observation of this event in Section 2. Section 3 explains our data reduction procedure. Section 4 discusses the modeling of the light curve and the comparison with other models. Section 5 discusses the likelihood analysis. Finally, we discuss the results of this work in Section 6.

2. OBSERVATION

The Microlensing Observations in Astrophysics MOA collaboration conducts a high-cadence microlensing survey observation program toward the Galactic bulge at Mount John in New Zealand (Bond et al. 2001; Sumi et al. 2003). The second phase of MOA uses the 1.8 m MOA-II telescope equipped with a very wide field of view (FOV; 2.2 deg$^2$) MOA-cam3 CCD camera (Sako et al. 2008). The MOA-II observing strategy is that six fields (~13 deg$^2$) with the highest lensing rate are observed with a 15-minute cadence, while the six next best fields are observed with a 47-minute cadence, and eight additional fields are observed with a 95-minute cadence. The MOA-II observations are carried out in the custom MOA-Red wide-band filter, which corresponds to the sum of the standard Cousins $R$ and $I$ bands. MOA issues ~600 alerts of microlensing events in real time each year.\(^{18}\) The 61 cm B&C telescope at the same site is used for follow-up observations with standard $I$- and $V$-band filters.

The Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 2015a) conducts a microlensing survey with the 1.3 m Warsaw telescope at the Las Campanas Observatory in Chile. The fourth phase of OGLE, OGLE-IV, started its high-cadence survey observations in 2010 with a 1.4 deg$^2$ FOV mosaic CCD camera. OGLE-IV observes the Galactic bulge fields with cadences ranging from one observation every 20 minutes for three central fields to less than one observation every night for the outer bulge fields. Most observations are taken in the standard Kron-Cousin $I$ band with occasional observations in the Johnson $V$ band. OGLE-IV issues alerts for ~2000 microlensing events in real time each year.\(^{19}\)

The gravitational microlensing event OGLE-2012-BLG-0724 was first found and alerted by OGLE on 2012 May 22 (HJD$^\prime = \text{HJD} - 245,000 \sim 6069.60$) at (R.A., decl.) (J2000) = (17h55m52s39, $-29^\circ49\arcmin06\arcsec7$) or $(l, b) = (0^\circ385, -2^\circ371)$ in Galactic coordinates. MOA independently detected and alerted the same event on the next day (HJD$^\prime = 6071.02$) as MOA-2012-BLG-323. The light curves are shown in Figure 1. Because the magnification of this event was predicted to be very high, ~100, which is sensitive to planets (Gould & Loeb 1992; Rattenbury et al. 2002), this event was alerted as a high-magnification event. During the event, the small deviation from the point-source point-lens model fit was detected in the MOA-II data in real time. So follow-up observations were started using the B&C telescope immediately and increased the observation cadence. The data covered both the caustic entry and exit, but the photometry accuracy at the caustic exit was a little worse due to a thin cloud. Because the duration of the anomaly was short, about 6 hr, and the peak magnitude of $I_{\text{peak}} = 16.5$ was too faint for small telescopes, only the B&C telescope could conduct follow-up observations of the anomaly.

3. DATA REDUCTION

The MOA-Red-band and B&C $I$- and $V$-band data were reduced by the MOA Difference Image Analysis (DIA) pipeline (Bond et al. 2001). The OGLE $V$- and $I$-band data were reduced by the OGLE DIA photometry pipeline (Udalski et al. 2015a). Systematic photometry trends in the MOA data with seeing and differential refraction measured in years other than 2012 were linearly subtracted from all the MOA photometry data.

It is known that the nominal errors from the photometric pipeline are underestimated for the stellar dense fields like ours. We renormalized the error bars of each data set by using the following standard formula:

$$\sigma_i' = k \sqrt{\sigma_{i}^2 + \epsilon_{\text{min}}^2},$$

where $\sigma_i$ is the original error of the $i$th data point in magnitudes, and $k$ and $\epsilon_{\text{min}}$ are the renormalizing parameters (Yee et al. 2012). The cumulative $\chi^2$ distribution from the tentative best-fit model, which is sorted by their magnification of the model at each data point, is supposed to be a straight line if the data are normal distribution. Thus, $\epsilon_{\text{min}}$ is chosen to make this cumulative $\chi^2$ distribution a straight line. Then $k$ is chosen so that each data set gives $\chi^2/\text{dof} = 1$. The results are shown in Table 1.

4. LIGHT-CURVE MODELING

For a binary lens model, fitting parameters are the time of closest approach to the lens masses, $t_0$, $f_0$, and $u_0$ are the

\(^{18}\) \url{https://it019909.massey.ac.nz/ moa/}

\(^{19}\) \url{http://ogle.astrouw.edu.pl/ogle4/ews/ews.html}
Einstein radius crossing time and the impact parameter in units of the angular Einstein radius \( q \). \( q \) is the planet/host mass ratio, \( s \) is the planet–star separation in Einstein radius units, and \( \alpha \) is the angle of the source trajectory relative to the binary lens axis. When we take account of the finite-source effect and the parallax effect, the angular radius of the source star in units of \( q \), \( \rho \), and the east and north components of the microlensing parallax vector, \( \rho_{E} \) and \( \rho_{E,N} \), are added for each case. The modeling light curve can be given by

\[
F(t) = A(t)F_s + F_b
\]

where \( F(t) \) is the flux at time \( t \), \( A(t) \) is a magnification of the source star at \( t \), and \( F_s \) and \( F_b \) are baseline fluxes from the source and blend stars, respectively.

### 4.1. Limb Darkening

In this event, the caustic entry and exit were observed. This allows an estimate of the finite-source star parameter, \( \rho \equiv \theta_s/\theta_E \). To get \( \rho \) properly, we have to apply limb darkening in the finite-source calculation. We adopt a linear limb-darkening surface brightness, \( S_\lambda(\vartheta) \), given by

\[
S_\lambda(\vartheta) = S_\lambda(0)[1 - u_\lambda(1 - \cos(\vartheta))] \tag{3}
\]

where \( \vartheta \) is the angle between the normal to the stellar surface and the line of sight, and \( u_\lambda \) is a limb-darkening coefficient in each filter. The effective temperature calculated from the source color discussed in Section 5 is \( T_{\text{eff}} \sim 4930 \text{ K} \) (González Hernández & Bonifacio 2009). Assuming \( T_{\text{eff}} = 5000 \text{ K} \), surface gravity \( \log g = 4.5 \text{ cm s}^{-2} \), and metallicity \( \log[M/H] = 0 \), the limb-darkening coefficients selected from Claret (2000) are \( u_I = 0.5880 \), \( u_V = 0.7592 \), and \( u_{\text{red}} = 0.6809 \) for each filter.

### 4.2. Best-fit Model

We search for the best-fit model over a wide range of values of microlensing parameters by using the Markov Chain Monte Carlo (MCMC) algorithm (Verde et al. 2003) and the image-
centered ray-shooting method (Bennett & Rhie 1996; Bennett 2010). To find the global best model, we first conduct a grid search by fixing three parameters, \( q \), \( s \), and \( \alpha \), at 20,000 different grid points with other parameters free. Next, by using the best 100 smallest \( \chi^2 \) models as initial parameters, we search for the best-fit model by refining all parameters.

The best-fit light curve and the parameters are shown in Figure 1 and Table 2. The \( \Delta \chi^2 \) of these models compared to the PSPL and FSPL (finite-source point-lens) are about 373 and 210, respectively, so the planetary signal is detected confidently. As is often the case for high-magnification events, there are two degenerate solutions with a separation of \( s = 1/\sigma \) that can explain the light curve, which is known as the “close–wide” degeneracy. We call the models with \( s < 1 \) and \( s > 1 \) the close and wide models, respectively. The other parameters are almost the same. These solutions are equally preferred with \( \Delta \chi^2 \) of 0.2. The overall shapes of the caustics of these two models are different, but the central parts where the source crosses are very similar; see Figure 2. Thus, we cannot distinguish between the models.

4.3. Parallax Model

Microlensing parallax is an effect where the orbital motion of the Earth causes the apparent lens–source relative motion to deviate from a constant velocity. This can be described by the microlensing parallax vector \( \mathbf{p}_E = (\pi_E, \pi_E) \), whose direction is the direction of the lens–source relative motion projected on the sky and its amplitude, \( \pi_E = \pi_0 / D_E \), is the inverse of the Einstein radius, projected to the observer plane.

If the parallax effect and finite-source effect are measured in a gravitational microlensing event, we can calculate the lens properties uniquely by assuming the distance to the source star, \( D_s \), as \( M_L = \theta_E / (\kappa \pi_E) \) and \( D_\pi = \pi_0 / \theta_E + \pi_E \), where \( \kappa = 4G/c^2AU = 8.144 \text{ mas } M_\odot \) and \( \pi_0 = \text{AU/D}_s \) (Gould 2000).

We searched for the best model with the parallax effect and found a model with an improvement in \( \chi^2 \) of \( \Delta \chi^2 = \chi_{\text{stat}}^2 - \chi_{\text{para}}^2 \sim 47 \). However, the values of the parallax parameters are \( \pi_{E,E} = 1.53 \pm 0.18 \) and \( \pi_{E,N} = -8.00 \pm 0.63 \), which are much larger than typical values, i.e., unity or less. If they were real, then the lens host star would be close to three Jupiter masses. Figure 3 shows the difference in the cumulative \( \chi^2 \) between the static model and the model with the parallax effect. The \( \Delta \chi^2 \) of MOA-Red and OGLE-I are \( \Delta \chi^2_{\text{MOA-Red}} \sim 35 \) and \( \Delta \chi^2_{\text{OGLE-I}} \sim 12 \), respectively. The largest improvement in \( \chi^2 \) due to parallax comes from very low level continuous deviations around HJD’ \( \sim 6000 \), which is far from the main magnified part of the event. This period corresponds to the beginning of the observation season, and the GB fields were observed at low altitudes. It is known that the light curves taken at high airmass are affected by the systematics due to the basic parameters of the static model, at both the beginning and the end of the season as shown in the bottom panel of Figure 3. For this reason, we regard this parallax signal as not real, but due to residual systematics that could not be corrected by the detrending process applied to the light curve. Therefore, we decided not to include the parallax effects in the following analysis.

4.4. Search for Degenerate Solution

In the initial grid search for best-fitting models, we found some local minima with stellar binary mass ratios. To check the uniqueness of the best planetary model, we inspected the models with the mass ratio \( q \) in the range of \( -5 < \log q < 0 \) carefully. Figure 4 shows \( q \) versus \( \Delta \chi^2 \). We found two local minima around \( q \sim 4 \times 10^{-5} \) and \( \sim 1 \), which are the planetary mass ratio and binary mass ratio, respectively. But the \( \Delta \chi^2 \) compared from the best-fit models are about 91 and 100, respectively, so we conclude that the best models are superior by about 9\( \sigma \) and 10\( \sigma \).

5. Lens Property

The lens physical parameters cannot be derived directly because a credible parallax effect is not measured in this event. Only the angular Einstein radius \( \theta_E = \theta_\star / \rho \) can be measured from the finite-source effect, where \( \theta_\star \) is the angular source star radius.

Figure 5 shows the OGLE instrumental \((V - I, I)\) color–magnitude diagram (CMD) within \( 2\' \) around the source star. The centroid of red clump giants (RCGs), \((V - I, I)_{\text{RCG}} = (2.31, 15.88) \pm (0.01, 0.02)\), and the best-fit source color and magnitude, \((V - I, I)_{\text{S}} = (2.231, 21.89) \pm (0.002, 0.07)\), are shown as filled red and blue circles, respectively. In Figure 5, we also show the stars in Baade’s window observed by the Hubble Space Telescope (HST; Holtzman et al. 1998), which are corrected for the extinction and reddening by the RCG position in the HST CMD, \((V - I, I)_{\text{RCG,HST}} = (1.62, 15.15)\) (Bennett et al. 2008). They are plotted as green dots in Figure 5. We find out that the best-fit source color and magnitude are consistent with bulge main-sequence stars. Assuming that the source suffers the same dust extinction and reddening as the RCGs and using the expected extinction-free RCG centroid \((V - I, I)_{\text{RCG,0}} = (1.06, 14.42) \pm (0.06, 0.04)\) at this position (Bensy et al. 2013; Natof et al. 2013), we estimated the extinction-free color and magnitude of the source as \((V - I, I)_{\text{S,0}} = (0.98, 20.43) \pm (0.06, 0.09)\). We also independently derived the source color and magnitude from the MOA-Red and MOA-V bands, which are transformed to standard \( I \) and \( V \) bands, and the CMD within \( 2\' \) around the source star in the MOA reference image, and we confirmed the

| Parameter | Close | Wide |
|-----------|-------|------|
| \( \rho \) (days) | 13.3556 | 13.4935 |
| \( \omega_0 \) (10\(^{-3}\)) | 0.8479 | 0.8639 |
| \( q \) (10\(^{-3}\)) | 1.5848 | 1.5935 |
| \( \alpha \) (radian) | 0.9195 | 1.0990 |
| \( \epsilon \) (mas) | 0.0053 | 0.0063 |
| \( \chi^2 \) | 35752.40 | 35752.60 |
| dof | 35788 | 35788 |
above results. We adopt the color from the OGLE data as it is more accurate.

The angular source radius $q_*$ is calculated by using the observed $(V-I)_{SD}$ and the relation between the limb-darkened stellar angular diameter, $q_{LD}$, $(V-I)$, and $I$ from Boyajian et al. (2014) and Fukui et al. (2015),

$$\log \theta_{LD} = 0.5014 + 0.4197(V - I) - 0.2I.$$  \hspace{1cm} (4)

This gives $\theta_\epsilon = \theta_{LD}/2 = 0.336 \pm 0.025 \mu\text{as}$, whose error includes the $\sigma_{(V-I)}$, $\sigma_I$, and the 2% uncertainty in Equation (4).
We derived the angular Einstein radius $\theta_E$ and the geocentric lens–source relative proper motion $\mu_{\text{geo}}$ for close and wide models as follows:

$$\theta_E = \frac{\theta_0}{\rho} = 0.239 \pm 0.028 \text{ mas (close)}$$

$$= 0.242 \pm 0.029 \text{ mas (wide)},$$

$$\mu_{\text{geo}} = \frac{\theta_E}{t_E} = 6.52 \pm 0.87 \text{ mas yr}^{-1} \text{ (close)}$$

$$= 6.55 \pm 0.90 \text{ mas yr}^{-1} \text{ (wide)}.$$

We conduct a Bayesian analysis to get the probability distribution of the lens properties (Beaulieu et al. 2006; Gould 2006; Bennett et al. 2008). We calculate the likelihood by using the Galactic model (Han & Gould 2003) and the observed $t_E$ and $\theta_E$. We also used the dereddened blending flux, which includes the lens and unrelated stars derived from the OGLE-I and OGLE-V light curves as the upper limit for the lens brightness,

$$I_0 = 18.54 \pm 0.05,$$

$$V_0 = 18.39 \pm 0.08.$$  

Because the $\chi^2$ and physical parameters of close and wide models are similar, we combined the probability distribution of these models by weighting the probability distribution of the wide model by $e^{-\Delta \chi^2/2}$, where $\Delta \chi^2 = \chi^2_{\text{wide}} - \chi^2_{\text{close}} \sim 0.20$. Figures 6 and 7 show the probability distribution of the lens properties derived from the Bayesian analysis. According to the results, the lens host star is an M dwarf with a mass of $M_\star = 0.29^{+0.33}_{-0.16} M_\odot$ and its distance is $D_\odot = 6.7^{+1.1}_{-1.2} \text{ kpc}$ away from Earth, and the mass of the planet is $m_p = 0.47^{+0.54}_{-0.26} M_{\text{Jup}}$ and the projected separation is $a_p = 1.6^{+0.4}_{-0.3} \text{ AU}$. If we assume a circular and randomly oriented orbit for the planet, the three-
dimensional semimajor axis is expected to be $a = 2.0^{+1.0}_{-0.5}$ AU. The probability distribution of $I$, $V$, and $H$-band magnitudes of the lens star with the extinction is shown in Figure 7. The extinction for the lens is assumed to be the same as that for the source because the lens is predicted to be near the Galactic bulge. The $H$-band magnitude of the source with the extinction is calculated to be $H_S = 20.52 \pm 0.12$ from the extinction-free $(I - H)$ color of the source estimated from $(V - I)$ color using the stellar color–color relation (Kenyon & Hartmann 1995) and the $H$-band extinction $A_H$ estimated from $A_I$ and $A_V$ using the extinction law by Cardelli et al. (1989). The lens is predicted to be fainter than the source by $\sim 3$ mag in the $I$ band, $\sim 5$ mag in the $V$ band, and $\sim 2$ mag in the $H$ band, respectively. Thus, it is not easy to detect the lens flux by future high-resolution follow-up observations.

6. DISCUSSION AND CONCLUSION

Originally, OGLE-2012-BLG-0724Lb was thought to comprise a binary star lens system. In this work, we concluded that OGLE-2012-BLG-0724Lb is a Saturn-mass planet orbiting around an M dwarf. This system is of a type typically found by gravitational microlensing. Recently, Fukui et al. (2015) found a possible pileup of sub-Jupiters ($0.2 < m_{\text{Jup}}/M_\text{Jup} < 1$) in contrast to a lack of Jupiters ($\sim 1 - 2 M_\text{Jup}$) around M dwarfs, suggesting that Jupiter-mass planets are rarely formed around M dwarfs, as predicted by core accretion models (e.g., Ida & Lin 2005). OGLE-2012-BLG-0724Lb belongs to the sub-Jupiter class, supporting the above idea. However, the statistical error of the abundance of these planets is still large. A larger sample will give us a better understanding of the planetary formation mechanisms.

In statistical analysis leading to estimates of planet abundances, we need to beware of events that have degenerate solutions. For example, OGLE-2008-BLG-355Lb was originally published as a stellar binary, but the reanalysis of Koshimoto et al. (2014) concluded that it was a planet. In such cases, we need to investigate the wide range of parameters so as not to be fooled by local minima. Event OGLE-2012-BLG-0724 has a relatively short timescale, the anomaly lasted for only 6 hr, and it was not very bright even at the high-magnification peak, which was difficult for follow-up observations by small telescopes. We could figure out the planetary nature and its superiority over the binary solution thanks to the high-cadence observations by OGLE and MOA.

The recent high-cadence survey observations by medium-aperture telescopes equipped with a wide FOV camera as used by the MOA, OGLE, and KMTNet groups are going to detect many planetary events without dense follow-up observations. But if we seek more rare events like an Earth-mass planetary event, the sampling during short anomalies will be limited and we will face similar marginal conclusions. This is also true at the boundary of detection limits even for the future space-based observations by WFIRST (Spergel et al. 2013) and Euclid (Penny et al. 2013). This work is a test case for analysis efforts in such marginal events.

We could not measure the mass of the system because microlensing parallax was not detected. We can measure the lens properties if we can directly resolve the lens flux in high-resolution follow-up observations by $HST$ or large ground-based telescopes, such as Keck, VLT, and Subaru (Bennett et al. 2006, 2015; Batista et al. 2015). The unrelated blending stars can usually be separated from the source and high-resolution follow-up observations. The lens–source relative proper motion is $\mu_{\text{geo}} = 6.52 \pm 0.87$ mas yr$^{-1}$. This implies that the source and lens will be separated by $\sim 1$ $HST$ pixel ($\sim 39.12 \pm 5.22$ mas) by 2018. But in the $I$ band, the median lens magnitude is predicted to be very faint compared to the source magnitude by $\sim 3$ mag (see Figure 7), and this makes it difficult to observe the lens star. From Figure 7, we see that the $H$-band magnitude of the median prediction for the lens and source differs by $\sim 2$ mag. The lens is likely to be too faint to be detected until the lens and source are resolved. The future high-resolution images by $HST$, JWST, or ground-based telescopes using adaptive optics such as Thirty Meter Telescope (TMT) which is currently under construction in more than 10 yr after peak magnification, which is in 2022, may detect the lens host star and determine the lens properties uniquely.

However, if the lens and source have different colors, the apparent centroid shift of the lens plus source differs from images in different filter bands. In OGLE-2003-BLG-235, the color-dependent centroid offset was detected at the level of 0.6 mas by $HST$ (Bennett et al. 2006). In OGLE-2012-BLG-0724, we expect to detect the color-dependent centroid shift of $dx = 1.0$ mas in $dt = 4$ yr after the peak magnification from the relation $dx = dt \times (f_{I} - f_{V}) \times \mu_{\text{geo}}$. Here $\mu_{\text{geo}} = 6.52$ mas yr$^{-1}$ and the fraction of the lens–source flux that is due to the lens, $f_{\text{lens}} = 0.05$ and $f_{V} = 0.01$ in the $I$ and $V$ band, respectively. Thus, the follow-up observations in different filter bands by $HST$ in 2016 can detect the lens flux and determine the lens properties.

T.S. acknowledges the financial support from the JSPS, JSPS23103002, JSPS24253004, and JSPS26247023. The MOA project is supported by grants JSPS25103508 and 23340064. The OGLE project has received funding from the National Science Centre, Poland, grant MAESTRO 2014/14/A/ST9/00121 to A.U. The OGLE Team thanks Profs. M. Kubiak and G. Pietrzyński, former members of the OGLE team, for their contribution to the collection of the OGLE photometric data over the past years. D.P.B. acknowledges support from NSF grants AST-1009621 and AST-1211875, as well as NASA grants NNX12AF54G and NNX13AF64G. Work by I.A.B. was supported by the Marsden Fund of the Royal Society of New Zealand, contract no. MAU1104. N.J.R. is a Royal Society of New Zealand Rutherford Discovery Fellow. A.S., M.L., and M.D. acknowledge support from the Royal Society of New Zealand. A.S. is a University of Auckland Doctoral Scholar. N.K. is supported by Grant-in-Aid for JSPS Fellows.

REFERENCES

Batista, V., Beaulieu, J.-P., Bennett, D. P., et al. 2015, ApJ, 808, 170
Beaulieu, J.-P., Bennett, D. P., Fouqué, P., et al. 2006, Natur, 439, 437
Bennett, D. P. 2010, ApJ, 716, 1408
Bennett, D. P., Anderson, J., & Bond, I. A. 2006, ApJ, 647, L171
Bennett, D. P., Bhattacharya, A., Anderson, J., et al. 2015, ApJ, 808, 169
Bennett, D. P., Bond, I. A., Udalski, A., et al. 2008, ApJ, 684, 663
Bennett, D. P., & Rhie, S. H. 1996, ApJ, 472, 660
Bensby, T., Yee, J. C., Felting, S., et al. 2013, A&A, 549, A147
Bond, I. A., Abe, F., Dodd, R. J., et al. 2001, MNARS, 327, 868
Borucki, W. J., Koch, D. G., Basri, G., et al. 2011, ApJ, 736, 19
Boyajian, T. S., von Braun, K. 2014, AJ, 147, 47
Butler, R. P., Wright, J. T., Marcy, G. W., et al. 2006, ApJ, 646, 505
Cardelli, J. A., Clayton, G. C., & Mathis, J. A. 1989, ApJ, 345, 245C
Cassan, A., Kubas, D., Beaulieu, J. P., et al. 2012, Natur, 481, 167
Cassan, A., & Ranc, C. 2016, MNARS, 458, 2074
Clanton, C., & Gaudi, B. S. 2014, ApJ, 791, 90
Claret, A. 2000, A&A, 363, 1081
Fukui, A., Gould, A., Sumi, T., et al. 2015, ApJ, 809, 74
González Hernández, J. I., & Bonifacio, P. 2009, A&A, 497, 497
Gould, A. 2000, ApJ, 5442, 785
Gould, A., Dong, S., Gaudi, B. S., et al. 2010, ApJ, 720, 1073
Gould, A., & Horne, K. 2013, ApJL, 779, L28
Gould, A., & Loeb, A. 1992, ApJ, 396, 104
Gould, A., Udalski, A., An, D., et al. 2006, ApJL, 644, L37
Gould, A., & Yee, J. C. 2014, ApJL, 784, 64
Han, C., & Gould, A. 2003, ApJ, 592, 172
Holtzman, J. A., Watson, A. M., Baum, W. A., et al. 1998, AJ, 115, 1946
Ida, S., & Lin, D. N. C. 2005, ApJ, 625, 1045
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Koshimoto, N., Udalski, A., Sumi, T., et al. 2014, ApJ, 788, 128
Mayor, M., & Queloz, D. 1995, Natur, 378, 355
Nataf, D. M., Gould, A., Fouqué, P., et al. 2013, ApJ, 769, 88
Penny, M. T., Kerins, E., Rattenbury, N., et al. 2013, MNRAS, 434, 2
Rattenbury, N. J., Bond, I. A., Skuljan, J., et al. 2002, MNRAS, 335, 159
Sako, T., Sekiguchi, T., Sasaki, M., et al. 2008, ExA, 22, 51
Shvartzvald, D., Maoz, D., Udalski, A., et al. 2015, MNRAS, 457, 4089
Spergel, D., Gehrels, N., Breckinridge, J., et al. 2013, arXiv:1305.5422
Sumi, T., Abe, F., Bond, I. A., et al. 2003, ApJ, 591, 204
Sumi, T., Bennett, D. P., Bond, I. A., et al. 2010, ApJ, 710, 1641
Suzuki, D., Bennett, D. P., Sumi, T., et al. 2016, ApJ, submitted
Udalski, A., Szymański, M. K., & Szymański, G. 2015a, AcA, 65, 1
Udalski, A., Yee, J. C., & Gould. A. 2015b, ApJ, 799, 237
Verde, L., Peiris, H. V., & Spergel, D. N. 2003, ApJS, 148, 195
Yee, J. C., Shvartzvald, Y., Gal-Yam, A., et al. 2012, ApJ, 775, 102
Zhu, W., Udalski, A., Gould, A., et al. 2015, ApJ, 805, 8