SUPER-MASSIVE PLANETS AROUND LATE-TYPE STARS—THE CASE OF OGLE-2012-BLG-0406Lb

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Abstract

Super-Jupiter-mass planets should form only beyond the snow line of host stars. However, the core accretion theory of planetary formation does not predict super-Jupiters forming around low-mass hosts. We present a discovery of a 3.9 ± 1.2 MJup mass planet orbiting the 0.59 ± 0.17 MJ⊙ star using the gravitational microlensing method. During the event, the projected separation of the planet and the star is 3.9 ± 1.0 AU, i.e., the planet is significantly further from the host star than the snow line. This is the fourth such planet discovered using the microlensing technique and challenges the core accretion theory.

Key words: gravitational lensing: microlensing: planetary systems—planets and satellites: formation

Online-only material: color figures

1. INTRODUCTION

There are two main theories of planetary formation: core accretion and gravitational instability. The first one does not predict planets to be formed much beyond the snow line (the ring in protoplanetary disks where the temperature is below the sublimation temperature of ice). One of the tests for these theories is the observational census of super-Jupiter mass planets around low-mass stars, i.e., M dwarfs (Laughlin et al. 2004). Kennedy & Kenyon (2008) predicted that the probability that a 0.6 MJ⊙ star has at least one giant planet is 2%. The slope α of the planetary mass function (dN/d ln M ∼ M^α) is −0.31 ± 0.2 according to Cumming et al. (2008), for other estimates, see, e.g., Cassan et al. (2012). For super-Jupiters, the planetary mass function should be even steeper because their mass is close to the total mass of the disk. We may expect that the probability that a 0.6 MJ⊙ star has a 2–4 MJup mass object is ≈1% or even smaller. Thus, detection of a super-Jupiter beyond the snow line of a late-type star challenges the core-accretion theory.

It is hard to discover super-Jupiters around low-mass stars using either radial velocities or transit methods if the planetary orbit is beyond the snow line. For a 0.5 MJ⊙ star, the snow line is located at about 1.3 AU. If the planet is twice as far out, then its orbital period is 5.9 yr and the radial velocity amplitude is 25(Mp/MJup) m s−1, where Mp is the mass of the planet. Although the amplitude is large, the long orbital period of the planet makes detection difficult. None of the radial velocity detected planets is a super-Jupiter beyond the snow line on a list of known planets around M dwarfs presented by Bonfils et al. (2013). Though, close to this part of the parameter space there are planets GJ 317b and GJ 676Ab. Among the planetary transit candidates with more than one transit announced by the Kepler mission, the longest orbital periods are around 500 days (Borucki et al. 2011; Batalha et al. 2013), i.e., much shorter than the expected 5.9 yr. Moreover, the probability of the proper orbit alignment is very low; hence, it is very difficult for transit surveys to find planets with 5.9 yr periods if they exist. Also high spatial resolution imaging is not an efficient way of finding such planets, as they are too close to the parent star. Thus, gravitational microlensing seems to be the most efficient method in discovering super-Jupiter planets around dwarf stars (Gaudi 2012). The relatively large mass ratio q makes both central and planetary caustics large, as their size is proportional to q and q^{1/2}, respectively (Gould & Loeb 1992; Griest & Safizadeh 1998; Chung et al. 2005; Han 2006). This makes discovering such planets more feasible because the probability that the background source would pass close enough to the caustic is higher.

In fact, microlensing has already been successful in discovering massive planets around M dwarfs. Dong et al. (2009b) analyzed all available data, including the Hubble Space Telescope images, to constrain the parameters of OGLE-2005-BLG-071Lb, which was discovered by Udalski et al. (2005). Dong et al. (2009b) concluded that the 3.8 ± 0.4 MJup mass planet orbits an M = 0.46 ± 0.04 MJ⊙ star and lies at projected separation of 3.6 ± 0.2 AU. Batista et al. (2011) analyzed the MOA-2009-BLG-387 event. The projected separation of the planet and the star was comparable to the size of the Einstein ring, which resulted in a very large resonant caustic. This allowed a very precise measurement of the mass ratio q = 0.0132 ± 0.003 with most probable planet and host masses of 2.6 MJup and 0.19 MJ⊙, respectively. The estimated projected separation is 1.8 AU. There are two more microlensing planets that were claimed to be super-Jupiters orbiting low-mass stars beyond the snow-line based on Bayesian analysis, not the direct measurement of lens mass from microlensing model: OGLE-2003-BLG-235Lb (Bond et al. 2004; Bennett et al. 2006) and MOA-2011-BLG-293Lb (Yee et al. 2012). Both events were observed with high spatial resolution, and these observations neglected the results of Bayesian analysis in the latter case (Batista et al. 2014). We note that Street et al. (2013) found a planetary mass object MOA-2010-BLG-073Lb (11 MJup) orbiting an M-dwarf beyond the snow line, but they concluded that it is most likely an extremely low-mass product of star formation.

The observing strategy that resulted in almost all of the microlensing planets discovered so far involved survey and follow-
up groups. Survey groups conduct observations with 1 m class telescopes and large CCD cameras. Microlensing Observations in Astrophysics (MOA-II) is using an 80 megapixel camera with 2.2 deg$^2$ field of view. The camera used during the fourth phase of the Optical Gravitational Lensing Experiment (OGLE-IV) contains 256 megapixel and gives 1.4 deg$^2$ field of view. The search for microlensing events is performed by survey groups on a daily basis, and all the events found are presented to the astronomical community. Then, the follow-up groups, which have access to a large number of different class telescopes widely spread in geographic coordinates, observe the events that are likely to be highly magnified (thus more sensitive to planets) or already show anomalies deviating from the standard microlensing light curve. Until now, only two secure planets were announced using survey-only data (OGLE-2003-BLG-235Lb/MAO-2003-BLG-53, and MOA-2007-BLG-192Lb; Bond et al. 2004; Bennett et al. 2008, respectively) and both of them used MOA and OGLE data. Bennett et al. (2012) analyzed the microlensing event MOA-bin-1 using only MOA data and concluded that the lensing star hosts a planet. However, this case lacks the strong lensing signal of the host star. Thus, the host lensing parameters and the fact that the event was caused by microlensing do not rely on the data other than the anomaly. We note that sources other than planets can cause anomalies in microlensing events (see, e.g., Gould et al. 2013 for MOA-2010-BLG-523). Yee et al. (2012) showed that the planet MOA-2011-BLG-293Lb would have been discovered in survey-only data if photometry from OGLE-IV, MOA-II, and the Wise Observatory were routinely combined and analyzed jointly for all microlensing events. However, this still has not been implemented. The currently operating and future surveys have greatly increased the number of events discovered; hence, the follow-up groups are unable to cover all the ongoing events. Also, the cadence of survey observations increased. The consequence of these factors is an increase in the number of planetary detections in survey-only data. At this point, the questions about the reliability of detections and the accuracy of parameters found in survey-only data arises (Yee et al. 2012).

Here we present the detection of a planetary system in the microlensing event OGLE-2012-BLG-0406. We use the data collected by the OGLE survey only. The planet turned out to be a super-Jupiter orbiting a star that is an M or K dwarf. The projected separation places the planet well beyond the snow line of the host star, making it the fourth such object discovered via microlensing.

2. OBSERVATIONS

The observations were collected using the 1.3 m Warsaw Telescope situated in the Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institute for Science. The telescope is equipped with a 32 CCD chip mosaic camera, which gives 1.4 deg$^2$ field of view. The pixel size is 15 μm, corresponding to 0.26 on the sky. The observations were conducted using the $I$-band filter. A few $V$-band observations of different fields are taken each night. They do not constrain the microlensing model and are used only to assess the color of the source star.

The microlensing event OGLE-2012-BLG-0406 was found at equatorial coordinates of 17:53:18.17 − 30:28:16.2 (l = −0°46, b = −2°22) by the Early Warning System (Udalski 2003). The event was found in the OGLE-IV field that is monitored with a typical cadence of 55 minutes. The photometry for nights at HJD′ = HJD − 2450000 of 6108 and 6109 showed a significant disagreement with a previously fitted standard Paczyński (1986) light curve. Then the observations of the field were suspended because of proximity of the Moon. The microlensing community was alerted on HJD′ = 6110.8099 that the event was showing an anomaly by V. Bozza, who browsed the OGLE Early Warning System alert Web site, which presents updated OGLE photometry. The alert prompted the follow-up groups to collect additional measurements, which are not analyzed here. It is worth noting here that OGLE-IV microlensing strategy in the high cadence fields is to conduct well-defined automated experiment with minimum human intervention; thus, the OGLE-IV by definition does not distribute anomaly alerts.

The OGLE observations returned at HJD′ = 6113.52784 and showed the star brightened by 0.3 mag. The following images revealed it was also fading. This made it obvious that the additional peak in the light curve occurred when the Moon was passing close to the event. Further observations were carried out with the standard cadence except that one additional measurement was taken at HJD′ = 6113.85679, i.e., 25 minutes after the previous one, to secure additional data point of the setting lens before reaching the OGLE high air mass limit. This does not significantly affect the microlensing model fitted and thus the analysis can be treated as based on survey-only data. We note that observations of this event were also taken by follow-up groups during the Moon gap in the OGLE data, and these can be used to verify our results. After the Moon gap, the anomaly lasted for 10 days, including one more peak centered on HJD′ = 6120.9.

The main peak of the event occurred at $t_0 = 6141.5$. It was just after the Moon passed close to the OGLE-2012-BLG-0406. Unfortunately, a suspicious linear small scale trend is present in our photometry during the four nights starting at HJD′ = 6140. Larger scatter during that time is also present in photometry of nearby red clump stars and in some cases, linear trends with 2σ significance are seen. High sky background or poor seeing conditions (above 1′′) clearly affected at least 9 out of 21 epochs collected at that time (including all on HJD′ = 6142 and 6143). It is worth noting that 1′′5 away from the source star, there is another star that is 1 mag brighter than the event in the baseline and was 0.3 mag brighter than the event during the main peak. This neighbor star most likely affected the event photometry, especially during poor seeing conditions. As these factors caused not only larger scatter of points but also an apparent linear trend, we decided to skip these data in our primary fitting procedure and check their influence separately. During a $2\sigma_c = 128.7$ day period centered on $t_0$, 528 $I$-band data points were collected ($t_E$ is Einstein crossing time, $t_0$ is the time of closest approach). The sky area where the event is located was also observed during the third phase of the OGLE project. Altogether, more than 4300 epochs were collected since 2001, and no other variability was seen except the analyzed event.

The light curve of the event is presented in Figure 1 with the baseline $I = 16.459$ mag and $V = 19.268$ mag. The uncertainties of photometry were scaled as is typically done in the analysis of microlensing events: $\sigma_{\text{new}} = 1.5\sqrt{\sigma_{\text{old}}^2 + (4 \text{ mmag})^2}$ (see, e.g., Skowron et al. 2011). We transformed photometry to the standard system using Szymański et al. (2011) photometric maps.

3. MICROLENSING MODEL

The light curve clearly shows anomalies and cannot be fitted with the standard point source-point lens Paczyński light curve ($\Delta \chi^2 \approx 10000$). The rough estimates of the event properties
can be found using analytical approximations presented by Han (2006; see Appendix). We start our search with a static binary-lens model and run it on a wide grid of \(q, s_0\) and \(\alpha_0\) parameters (planet–host mass ratio and separation, and the source trajectory angle, respectively). The limb-darkening coefficient \(u_I = 0.450, \Gamma_I = 0.353\) was assumed. We try to fit models in which the source passes the lensing star on the same side as the planetary caustic as well as the opposite side. Only the former models resulted in acceptable fits. After the first well-fitting models were found, the microlensing parallax \(\pi, \pi_E\) and lens orbital motion \(\gamma_\parallel, \gamma_\perp\) were taken into account in subsequent modeling. We check models with both positive and negative values of the impact parameter \(u_0\) to examine a well-known degeneracy (Smith et al. 2003; see Skowron et al. 2011 for detailed description of standard microlensing parameters). The source was passing the caustic for a much shorter time than the orbital period of the system, thus the lens orbital motion is approximated by two components of instantaneous velocity. The magnification is calculated using the hexadecapole approximation (Gould 2008; Pejcha & Heyrovský 2009) except the points with the highest magnification. These are four points with HJD in the range of 6113.56501–6113.68359. For those, we use the “mapmaking” method (Dong et al. 2006, 2009a). We further enhanced the mapmaking procedure by calculating point source magnifications for all the images that are outside the map. This allows us to make the map smaller and for calculations to be more accurate. The map is placed around the planet because it caused the anomaly and has a radius of \(\theta_E^{1/2}\). Mapmaking implicitly assumes \(\gamma_\parallel = (ds/dt)/s_0 = 0\); thus, we constructed the map at HJD = 6113.5846. We have checked that ignoring \(ds/dt\) during the 0.12 day time interval affects the calculated magnifications at a level that is much smaller than the photometric errors.

The parameters of the best-fitting models are presented in Table 1. The quantity \(\rho\) is the source size relative to Einstein ring radius and \(f_b/f_s\) denotes blend to source flux ratio. The model with both the binary motion and the microlensing parallax gives the smallest \(\chi^2\). It has \(u_0 > 0\) and the solution with \(u_0 < 0\) is worse by \(\Delta \chi^2 = 13.6\). We report parameters of both models. The positive/negative \(u_0\) ambiguity is not fully removed; thus, we present analyses of both cases. For the best-fitting model
without lens orbital motion as well as the one without parallax, we present the $u_0 > 0$ solution only, consistent with the lowest $\chi^2$ model. In these cases, the positive/negative $u_0$ degeneracy is very severe (maximum $\Delta \chi^2 = 2.4$). Significant negative blending (Park et al. 2004) suggests that the last three models presented are not correct solutions, i.e., neglecting parallax or lens orbital motion results in wrong parameter estimates. The parameters were fitted using Monte Carlo Markov Chains. We checked how inclusion of data collected during four nights around $t_0$ influences the parameters fitted. The 21 additional points increased $\chi^2$ by 25.1. The largest change in values of parameters fitted was only $0.33\sigma$ in case of $t_E$.

Table 1 reveals that there is a degeneracy between $\pi_{E,N}$ (which is a proxy for the component of $\pi_E$ perpendicular to the direction of the projected Sun’s acceleration) and $y_\perp$. This degeneracy is well known (Skowron et al. 2011; Batista et al. 2011). There is also a suggestion that the analyzed event is subject to degeneracy between $\pi_{E,E}$ and $y_\parallel$, which was presented by Park et al. (2013).

The reason for the second degeneracy is not well understood.

The model that includes both the microlensing parallax and orbital motion of the lens gives $\chi^2$ smaller by 24.5 than any other model. This shows that the effects of the lens orbital motion are significant, yet not strong enough to warrant a full Keplerian orbital analysis. In order to use information that comes with a detection of an orbital motion, we put arbitrary priors on the ratio between projected kinetic and potential energy:

$$\frac{E_{\perp,\text{kin}}}{E_{\perp,\text{pot}}} = \frac{(\gamma s_0 D_\gamma) \theta_E^2}{2GM/r_\perp},$$

(1)

where $D_\gamma$ is lens distance, $\theta_E$ is the angular Einstein radius (see next section), and $r_\perp$ is projected star–planet separation. The priors$^7$ are presented in Figure 2. The ratio $E_{\perp,\text{kin}}/E_{\perp,\text{pot}}$ must be smaller than unity so that the solution is bound. Values close

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Table 1

| Quantity | Unit | Parallax and Orbital Motion | Parallax and Orbital Motion with Priors | Parallax and Orbital Motion ($u_0 < 0$) | Orbital Motion Only | Parallax Only | Oritel Motion and No Orbital Motion |
|----------|------|-----------------------------|----------------------------------------|-----------------------------------------|-------------------|-------------|----------------------------------|
| $\chi^2$ |      | 1651.96                     | 1665.56                                | 1676.42                                 | 1701.95          | 1712.83     |                                  |
| dof      |      | 1652                        | 1652                                   | 1650                                    | 1650             | 1648        |                                  |
| $f_s/f_s$|      | 0.039                       | 0.035                                  | 0.006                                   | -0.028           | -0.072      | -0.069               |
| $t_0$ - 6141 | day | 0.548                       | 0.565                                  | 0.583                                   | 0.676            | 0.736       | 0.593               |
| $\pi_0$  | $r_E$| 0.5065                      | 0.5072                                 | -0.5169                                 | 0.5257           | 0.5441      | 0.5425            |
| $t_E$    | day  | 64.33                       | 64.28                                  | 61.94                                   | 63.79            | 62.25       | 62.63              |
| $\rho$   |      | 0.49                        | 0.44                                   | 0.81                                    | 0.54             | 0.27        | 0.16               |
| $\pi_{E,N}$ |      | -0.118                      | -0.118                                 | 0.232                                   | ...              | -0.026      | ...                |
| $\pi_{E,E}$ |      | 0.046                       | 0.046                                  | 0.020                                   | ...              | 0.029       | ...                |
| $\pi_{E,E}$ |      | 0.0100                      | 0.0100                                 | 0.0009                                  | 0.0074           | 0.0097      | 0.0098            |
| $q$      | $10^{-3}$ | 6.26                        | 6.01                                   | 5.40                                    | 4.17             | 5.85        | 5.78               |
| $\delta$ |      | 0.78                        | 0.41                                   | 0.64                                    | 0.53             | 0.10        | 0.08               |
| $s_0$    | $r_E$| 1.3134                      | 1.3157                                 | 1.3289                                  | 1.3453           | 1.3514      | 1.3500            |
| $\sigma_0$ |      | 47.98                       | 48.01                                  | -47.40                                  | 49.29            | 49.35       | 49.58              |
| $y_{\parallel}$ | yr^{-1} | -0.46                      | -0.42                                  | -0.22                                   | 0.06             | ...         | ...                |
| $y_\perp$ | rad yr^{-1} | 0.57                        | 0.42                                   | 0.29                                    | -0.90            | ...         | ...                |

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Figure 2. Priors constraining the projected energy ratio $E_{\perp,\text{kin}}/E_{\perp,\text{pot}}$.

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$^7$ The priors are defined as $f(E_{\perp,\text{kin}}/E_{\perp,\text{pot}}) = x = \arctan((10 - 10x)/12$ for $x \geq 0.4$. For $x \leq 0.25$, we assumed $f(x) = 2x \chi$ and $\beta = 0.2$. For $0.25 < x < 0.4$, the third order polynomial is used that at 0.25 and 0.4 has values and first derivatives equal to values of corresponding functions defined above.
to unity are obviously disfavored. We also disfavored small values of $E_{\perp,\text{kin}}/E_{\perp,\text{pot}}$ because they would correspond to the planet lying close to the lens–observer line, which should be a small part of the planetary orbit. We note that for a flat distribution in the logarithm of the semimajor axis (Opik’s Law) and circular orbits, the distribution of projected energy ratio is $2\beta E_{\perp,\text{kin}}/E_{\perp,\text{pot}}$, where $\beta$ is the exponent of the semimajor axis distribution. This defines our prior for small values of $E_{\perp,\text{kin}}/E_{\perp,\text{pot}}$. Comparison of the third and fourth columns of Table 1 reveals that parameter estimates are consistent and the priors did not significantly affect the precision of most of the parameters. The exceptions are the mass ratio and parameters of the lens orbital motion. Analysis of additional data for this system should allow one to determine whether such priors provide more accurate parameter values.

The trajectory of the source relative to the caustics and lensing system is presented in Figure 3. Because of the nonzero $\gamma_{\perp}$, the caustics and the planet are plotted for three selected moments in time.

In Figure 4, we present the predicted brightness variations for the best-fitting models with $u_0 > 0$ (gray thick line) and $u_0 < 0$ (dotted line). We also present four randomly chosen models with $\Delta \chi^2 = 9$ to illustrate the uncertainties in our model. In order to present which part of the predicted light curve is well constrained, we present the first observing night after the peak using points. The last measurement before the peak was taken at HJD' = 6109.87.

4. PHYSICAL PROPERTIES

In order to constrain the physical properties of the system, one must first estimate the angular Einstein radius $\theta_E$. We do this with the standard microlensing technique (Yoo et al. 2004). The position of the source star and the blended object on the color–magnitude diagram is presented in Figure 5. The position of the source star is consistent with the bulge red clump. This figure also presents the brightness and color of the blended light. There is one star of $I$-band brightness between 19.5 and 20.5 mag every 3 arcsec$^2$ in the Galactic bulge (Holtzman et al. 1998). Because of high stellar density and large uncertainty in blending flux, we cannot unambiguously attribute the blending flux to the lens.

The intrinsic color $(V - I)_{\text{RC,0}} = 1.06$ mag and brightness $(I_{\text{RC,0}} = 14.47$ mag) of the red clump were taken from Bensby et al. (2011) and Nataf et al. (2013), respectively. By combining these with the measured color and brightness of the red clump in the vicinity of the event, we obtained the reddening and extinction of $E(V - I) = 1.70$ mag and $A_I = 1.96$ mag. The de-reddened color and brightness of the source star were measured using the microlensing model: $(V - I)_0 = 1.12$ mag and $I_0 = 15.66$ mag. Using the relations by Bessell & Brett (1988), we obtain the source color $(V - K)_0 = 2.60$ mag, which correlates well with the source size.
Figure 5. Color–magnitude diagram for stars within 1.5 of the event. The green circle shows the position of the source star as derived from the microlensing model, while the red circle presents the total light observed at the baseline. The magenta triangle presents position of the blend.

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

Table 2

| Parameter | Unit | $u_0 > 0$ Solution | $u_0 < 0$ Solution |
|-----------|------|-------------------|-------------------|
| $\theta_E$ | mas | 0.57 ± 0.07 | 0.68 ± 0.09 |
| $M$ | $M_\odot$ | 0.59 ± 0.17 | 0.48 ± 0.20 |
| $M_p$ | $M_\text{Jup}$ | 3.8 ± 1.2 | 2.6 ± 1.2 |
| $D_L$ | kpc | 5.1 ± 0.4 | 3.6 ± 1.3 |
| $\mu_{\text{geo}}$ | mas yr$^{-1}$ | 3.2 ± 0.4 | 3.9 ± 0.6 |
| $r_\perp$ | AU | 3.8 ± 0.6 | 3.2 ± 1.2 |
| $E_{\perp,\text{kin}}/E_{\perp,\text{pot}}$ | | 0.67 | 0.15 |

Note. The $u_0 > 0$ solution is favored (Table 1).

(Kervella et al. 2004). The measured angular size of the source is $\theta_s = 6.3 \pm 0.3$ mas. The source size relative to Einstein ring radius $\rho = \theta_s/\theta_E = 0.0109 \pm 0.0012$ from the $u_0 > 0$ model implies $\theta_E = \theta_s/\rho = 0.57 \pm 0.07$ mas.

The value of $\theta_E$ allows the estimation of parameters of the lens in physical units. As there remained little ambiguity between the $u_0 > 0$ and $u_0 < 0$ models, we present the physical parameters of the lens for both solutions in Table 2. We assume the source parallax $\pi_s = 0.125$ mas since the source is a bulge red clump star (Figure 5). The geocentric proper motion of the lens is $\mu_{\text{geo}} = \theta_E/t_E = 3.3 \pm 0.4$ mas yr$^{-1}$. The lens proper motion is consistent with the estimated distance. The proper motion corrected to the heliocentric frame is $\mu_{\text{helio}} = [3.2 \pm 1.0, 1.6 \pm 0.4]$ mas yr$^{-1}$ (North, East). If the next class of adaptive optics systems are built, they should be able to resolve the lens and the source in 10 yr.

The mass of the lens is (Gould 2000)

$$M = \frac{\theta_E}{\kappa \pi_E}; \quad \kappa = \frac{4G}{c^2} \approx 8.1 \text{ mas}/M_\odot.$$  \hspace{1cm} (2)

The probability distribution of the host mass is shown in Figure 6 for both the $u_0 > 0$ and $u_0 < 0$ solutions. The boundary mass of M/K dwarfs of $\approx 0.6 M_\odot$ is close to the peak of distribution for the $u_0 > 0$ solution. We conclude that the star is either a K or M dwarf. The long tail of the mass distribution is caused by the fact that $\pi_E$ is detected at only 5$\sigma$ and 3$\sigma$ for $u_0 > 0$ and $u_0 < 0$, respectively. The priors on the projected energy ratio did not significantly affect the lens mass estimate. The values of kinetic-to-potential projected energy ratio (Batista et al. 2011) are consistent with a bound system.

The values of all the quantities presented in this section, together with $M_p$, $D_L$ and $r_\perp$, are given in Table 2. Since the positive/negative $u_0$ degeneracy is not fully removed, we present results for both solutions.

5. DISCUSSION AND SUMMARY

We presented the microlensing detection of a super-Jupiter orbiting a low-mass star. The lens mass can be used to estimate how far from the star the snow line lies. It is approximately $2.7 M_\odot$ ($M/M_\odot = 1.6$ AU), which is significantly smaller than the derived projected separation of $3.8 \pm 0.6$ AU. We note that OGLE-2012-BLG-0406Lb is the fourth super-Jupiter orbiting a low-mass star beyond the snow line discovered by the microlensing method. The existence of such objects is a challenge for the core accretion theory of planetary formation and, to our knowledge, has not been addressed. For a recent review on the core accretion theory, see Zhou et al. (2012).

Single telescope data were used to discover OGLE-2012-BLG-0406Lb, what makes this planet unique among microlensing discoveries with well-characterized host lensing and planetary anomaly. We note that the unfortunate Moon proximity to the event has not occurred during the cusp crossing, the parameters of the lensing system would probably be derived more accurately. All the fitted model parameters can be verified by incorporating data from other ground-based telescopes and the EPOXI spacecraft, which also observed the event.

The presence of the planet caused two well-separated anomalies, each lasting a few days. One may ask why more such detections were not claimed before as microlensing surveys had...
a cadence of one day a decade ago. It should be noted that even though such a cadence should be enough to detect anomalies caused by similar planets in other events, it is not enough to give a high level of confidence. Only recently microlensing surveys achieved cadences of 15–60 minutes over many square degrees in the Galactic bulge, which allows reliable detections of such planets. Microlensing planetary discoveries benefit most from the follow-up observations only if the central or resonant caustic is causing the anomaly (Griest & Safizadeh 1998), as was the case for OGLE-2005-BLG-071 (Dong et al. 2009b) and MOA-2011-BLG-387 (Batista et al. 2011). In the event analyzed here, the planetary caustic is causing the anomaly in the light curve. In such events, the anomaly is well separated from the lensing star, thus the magnification of the event before and after the caustic approach is rather low and the approach may be long before or after the closest approach to the lensing star. Follow-up groups typically do not densely monitor such events (Gould et al. 2010). Unlike planetary events with central-caustic perturbation, planetary-caustic events do not suffer from ambiguity in planet–star separation due to the discrete close–wide degeneracy. Thus, the planet sample discovered from planetary caustics may provide cleaner statistics in orbital separation distribution than those found in high-magnification events. The OGLE-IV survey discovers around 2000 microlensing events every year, and independent from the follow-up observations, it alone will potentially provide a powerful probe on the distribution of super-Jupiters orbiting low-mass stars beyond the snow line. The evidence for the existence of such planets is growing and puts a severe challenge for the core accretion theory of planetary formation.

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APPENDIX
M ICROLENSING MODEL PARAMETERS FROM ANALYTICAL APPROXIMATION

The idea that the observed characteristics of the planetary microlensing event give estimates of lens parameters was presented some time ago (Gould & Loeb 1992; Gauid & Gould 1997). Here we present an example of such calculations, which yield basic point-lens \((u_0, t_0)\) and static binary-lens parameters \((\alpha_0, s_0, q)\). The rectilinear motion of the source and absence of blending are assumed. The geometry of the source trajectory compared to the planetary caustic and the lens is presented in Figure 7.

The brightness difference between the baseline and the time when the source is closest to the lens is 0.78 mag. Thus, the maximum magnification \(A_{\text{max}} = 2.05\). It is related to the minimum impact parameter \(u_0\) via the Paczyński (1986) formula:

\[
A_{\text{max}} = \frac{u_0^2 + 2}{u_0\sqrt{u_0^2 + 4}}. \tag{A1}
\]

Inverting this relation yields \(u_0 = 0.539\). Equation (A1) can be used to estimate the magnification, and thus the brightness, of the event at epochs \(t_0 - t_0^c\) and \(t_0 + t_0^c\) where \(t_0 = 6143.4\). The result is 16.09 mag. We can find the epochs in Figure 1 when this brightness was observed. Half of the time interval between these two epochs gives \(t_0^c = 62.5\) days. We note that the values of \(u_0\) and \(t_0^c\) critically depend on the assumption that the blending can be neglected.

Figure 1 can be used to find the epoch when the source approached the first \((t_1 = 6112.4\) days) and the second cusp \((t_2 = 6120.9\) days). This allows one to determine the distance of the source from the lens at these two epochs in the units of \(\theta_E\):

\[
u(t) = \sqrt{(t - t_0)^2 + u_0^2} = \sqrt{(t - t_0)^2 + u_0^2}. \tag{A2}
\]

It results in \(u(t_1) = 0.73\) and \(u(t_2) = 0.65\). This, in turn, can be used to find the value of \(\alpha = \arcsin(u_0/u(t_1)) = 47^\circ.4\). However, small changes in the value of \(\alpha\) can result in significant changes in the light curve shape and this value should be treated with caution.

The light curve of OGLE-2012-BLG-0406 showed two anomalies, and we assume that each of them corresponded to the source passing exactly through the cusp. Figure 3 can be used to validate this assumption in the fitted model. During the second anomaly, the distance between the source and the cusp was significant, but we are not able to make better analytical approximations near cusps (Pejcha & Heyrovský 2009).

The value of \(s_0\) can be found by calculating the distance between the lens and the position of the second cusp projected onto the binary axis (point \(X\) in Figure 7). Basic geometry gives a value of 0.61. It is equal to \(s_0 - 1/s_0\), thus \(s_0 = 1.35\). The distance between the projected position of the second cusp and the first cusp is \(2\sqrt{\bar{q}}/(s\sqrt{s^2 - 1})\) (Han 2006), and in the analyzed case equals 0.126. Thus, the mass ratio is 0.0059.
The values found using this analytical approximation are close to the results presented in Table 1, especially when compared to the model without microlensing parallax and orbital motion. In the case of events perturbed by the cusps of planetary caustics, such calculations should be useful for starting values in model fitting.

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