TRIPLE MICROLENS OGLE-2008-BLG-092L: BINARY STELLAR SYSTEM WITH A CIRCUMPRIMARY URANUS-TYPE PLANET

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ABSTRACT

We present the gravitational microlensing discovery of a 4 $M_{Uranus}$ planet that orbits a 0.7 $M_\odot$ star at $\approx$18 AU. This is the first known analog of Uranus. Similar planets, i.e., cold ice giants, are inaccessable to either radial velocity or transit methods because of the long orbital periods, while low reflected light prevents direct imaging. We discuss how similar planets may contaminate the sample of the very short microlensing events that are interpreted as free-floating planets with an estimated rate of 1.8 per main-sequence star. Moreover, the host star has a nearby stellar (or brown dwarf) companion. The projected separation of the planet is only about three times smaller than that of the companion star, suggesting significant dynamical interactions.

Key words: binaries: general – gravitational lensing: micro – planets and satellites: detection – planets and satellites: dynamical evolution and stability

Online-only material: color figures

1. INTRODUCTION

The solar system planets are divided into three groups: small rocky planets, massive gas giants, and intermediate mass ice giants. These groups differ not only in mass but also in location of their orbits. The orbits of all rocky planets lie within the snow line, i.e., a boundary beyond which ices can condense, resulting in much more efficient planetary formation. The snow line lies at 2 AU in the solar system and increases with stellar mass (Kennedy & Kenyon 2008). Beyond the snow line, all planets have masses larger than the limit for runaway accretion, which is $\approx$10 $M_\oplus$. Gas giants have the highest masses and their orbits are only a small factor larger than the snow line distance (1.9 for Jupiter and 3.5 for Saturn). By contrast, the ice giants have smaller masses, but still above 10 $M_\oplus$, and lie significantly farther away—Uranus is 7 times farther than the snow line distance and Neptune is 11 times farther.

In contrast to other solar system planets, ice giants could not have formed close to their present location. The lifetime and the density of a protoplanetary disk were not large enough for planetesimal growth to accrete sufficient mass for in situ formation (Pollack et al. 1996). The models that assume the formation of Uranus and Neptune close to Jupiter and Saturn not only predict currently observed orbital separations, but are also consistent with the observed properties of the Kuiper Belt (Thommes et al. 1999, 2002) and require that Jupiter and Saturn have crossed the 2:1 mean motion resonance (Tsiganis et al. 2005). The solid-to-gas ratio puts additional constraints on Uranus and Neptune formation (Goldreich et al. 2004; Helled & Bodenheimer 2014).

The process of planetary formation cannot be well understood without studies of planets similar to those in the solar system. The Kepler satellite has revealed extrasolar analogs of rocky planets (Borucki et al. 2012; Quintana et al. 2014). Objects with masses comparable to Jupiter and Saturn have been discovered using radial velocities and some of these have orbits larger than the snow line of the parent stars (Butler et al. 2006). Gravitational microlensing also detects analogs of Jupiter and Saturn (e.g., Bond et al. 2004; Gaudi et al. 2008). However, both transit and radial velocity methods fail when analogs of Uranus and Neptune are searched for (Kane 2011), and no such object is known. The orbital periods of these planets are longer than the human lifetime. Thus, methods that depend on periodic phenomena like the change in the host radial velocity or a transit in front of the star would require extremely long experiments in order to find such planets. On the other hand, direct imaging is capable of discovering planets that are far away from the hosts and does not require data taken over a whole orbital period for clear planet detection. Nonetheless, the planets that are directly observed are much more massive and hotter objects that inhabit young systems and thus are different from Uranus and Neptune. Thus, the only method that can discover analogs of Uranus and Neptune is gravitational microlensing (see review by Gaudi 2012). Instead of looking for periodic phenomena, microlensing uses light from a fortuitously aligned background source to obtain a snapshot of a planetary system’s gravitational potential. This allows planets to be discovered irrespective of their orbital periods.

Here, we report the microlensing discovery of the first planet that has mass and orbital separation similar to Uranus and thus likely shares a similar origin. The microlensing event OGLE-2008-BLG-092L showed a separate lensing signal from each of the lens components. The large time difference between the planet and host microlensing subevents indicates that the projected separation is about five times larger than the Einstein radius $\theta_E$, which sets the angular scale of the event. For typical disk lenses, the Einstein radius corresponds to
\[ r_E = D_L/D_S \approx 3 \text{AU}, \] where \( D_L \) is the distance to the lens. This means that the planetary orbit is very wide. We confirm the large value of projected separation by detailed modeling of the event. This raises a question of planet formation. A third microlensing subevent observed on the same source revealed the presence of the stellar companion to the planet host.

In the next section, we present observations of the event. Very simple yet complete microlensing and physical parameters are presented in Section 3.1 in a form that is accessible for broad readership. More detailed analysis is presented in Sections 3.2 and 4. In Section 5, we discuss planetary properties and formation, as well as the prospects for finding similar planets in the future, compare the planetary anomaly in this event to free-floating planets, and remark on the long-term stability of the system. We conclude in Section 6.

2. OBSERVATIONS

The Optical Gravitational Lensing Experiment (OGLE) discovered a microlensing event on HJD' = HJD \(- 2450000 = 4542.103\) at R.A.: 17h47m29.42, Decl. \(-34^\circ 43' 35.6'' (l \approx -4^\circ 75, b \approx -3^\circ 34)\) based on an approximately two day long planetary anomaly. Although only four epochs were collected during this time, the anomaly led to the announcement of the event OGLE-2008-BLG-092 by the OGLE Early Warning System (Udalski 2003). Following this initial bump, a standard microlensing was observed with relatively low magnification and a timescale slightly longer than is typical, see Figure 1. At this point, the possibility that the lens could be composed of a star with a distant planet was recognized, but could not be verified based on the existing data.

The data were collected by the third phase of OGLE project (OGLE-III), which used the 1.3 m Warsaw Telescope situated in the Las Campanas Observatory, Chile. The telescope was equipped with an eight chip CCD camera. The pixel scale was 0.26 and the total field of view was 36' x 36'. For details of the instrumentation setup, see Udalski (2003). In 2009, OGLE-III ended and the camera was replaced by a four times larger instrument, and the fourth phase of the survey (OGLE-IV) started. The new camera had the same pixel size of 15 \(\mu\)m and the same pixel scale. Its 32 k x 2k pixel CCD chips gave a total field of view of 1.4 deg\(^2\). As before, the I-band filter was used for most observations. The photometry was performed using Difference Image Analysis (Alard & Lupton 1998; Alard 2000; Woźniak 2000). The observations resumed in 2010. The same year, one more microlensing event at the position of OGLE-2008-BLG-092 was observed. Its presence was not recognized at that time because OGLE online data reduction and microlensing alerts started a year later. The last subevent had a larger amplitude than the previous one. It was found that the event was not significantly blended, which turns out to be crucial in ruling out multi-source models, as we show below. This established clearly that the 2008 subevents were caused by a lens composed of a star with a distant planet. The 2010 subevent revealed a companion to the 2008 lens that is either a low mass star or a brown dwarf. Thanks to the weakness of the interactions of the three masses composing the lens system, all important properties of the lens system can be derived based on simple light curve inspection. This is in contrast to previously analyzed triple lens microlensing events, i.e., OGLE-2006-BLG-109 (Gaudi et al. 2008; Bennett et al. 2010), OGLE-2012-BLG-0026 (Han et al. 2013), and OGLE-2013-BLG-0341 (Gould et al. 2014). The configuration of the lens in this system is one of the simplest that is possible for a triple lenses, i.e., each lens component produces a separate microlensing subevent.

OGLE-2008-BLG-092 was discovered on a relatively bright star of \(t = 13.9\) mag. Very few microlensing events have been observed on such bright stars (Wyrzykowski et al. 2014). The source star was also observed in the first two phases of the OGLE project (Udalski et al. 1992, 1997). The pixel scales of those observations were 0.44 and 0.417, respectively. The reference images constructed using the best-quality frames have seeing FWHM of 1'12 and 1'14, respectively, and correspond to 16 and 11 years before the event, respectively. Inspection of these reference images does not reveal elongated profile of the source star that would constrain the models if the lens were a nearby fast-moving object (see Section 3.2). The OGLE-II time series photometry did not reveal any brightness changes. In the OGLE-I data, the source star is slightly overexposed.

This analysis is based on the 2007-2009 OGLE-III data and the first two seasons of OGLE-IV data. The online OGLE-III photometry that facilitated the real-time detection of microlensing events was re-reduced to correct for a low-level systematic noise. The 2009 data end in May when the OGLE-III camera was dismounted. The error bars for all photometric points were set to the dispersion of the baseline data (OGLE-III: 4.7 mmag, OGLE-IV: 6.8 mmag). This is justified because the event was not blended and not highly magnified. The final data set consisted of 354 OGLE-III and 383 OGLE-IV photometric points. The OGLE-III data were transformed to the standard system as described by Udalski et al. (2008) and Szymański et al. (2011). The zero point of the OGLE-IV photometry was transformed in a similar manner. No significant dependence of the correction on the \((V-I)\) color was found, while the dispersion of the brightness differences of nearby stars was 0.013 mag. The baseline brightness of this event is 0.02 mag brighter than in the OGLE-III, i.e., 1.7\(\sigma\).

3. MICROLENSING MODEL

3.1. Basic Model

In strong contrast to all previous triple and the majority of binary microlensing events, the essential physics of this event can be completely understood by decomposing it into three independent point-lens events. We begin by adopting this approach not only for its didactic value but also because of its important implications for the question of free-floating planets (Sumi et al. 2011).

The flux changes \(F(t)\) in point-source/point-lens microlensing are described by five parameters, \((t_0, u_0, \theta_E, f_s, f_b)\),

\[
F(t) = f_s A(t) + f_b; \quad A(t) = \frac{u^2 + 2}{u \sqrt{u^2 + 4}},
\]

\[
u(t) = \sqrt{\frac{(t - t_0)}{\theta_E}} + u_0^2. \tag{1}
\]

These are, respectively, the time of the closest approach, the impact parameter in units of the Einstein radius \(\theta_E\), the Einstein radius crossing time, the source flux, and the unmagnified (or blended) flux within the aperture.

Light curves of the form of Equation (1) fully describe both stellar subevents. However, the planetary lens transits the source, meaning that the point-source formula (1) must be convolved with the source profile in that case. This introduces an
The parameters of a separate fit for each subevent are shown in Table 1. Note that we have allowed \( f_b \) as a free parameter for the final subevent (due to the secondary star in OGLE-IV data), but have imposed \( f_0 = 0 \) in the remaining two (OGLE-III data) subevents.

Setting \( f_0 \) at zero is appropriate under the assumption that the source is the same for all three subevents. In principle, one must consider that one or both of the OGLE-III subevents results from lensing of a faint source that is blended with the principal, very bright source. However, given that less than 10% of the light comes from sources other than the one that was lensed in the OGLE-IV subevent, this implies that \( f_0/f_s \gg 1 \) for either of the other subevents (if it is not due to the same bright source). Imposing this constraint leads to unacceptably bad fits for both subevents. Note that Jaroszyński et al. (2010) found an acceptable binary-source fit to two OGLE-III subevents before the OGLE-IV subevent was discovered.

The Einstein timescales \( t_{E,i} \) (index \( i \) numbers consecutive subevents) are related to the masses \( M_i \) by

\[
t_E = \frac{\theta_E}{\mu}; \quad \theta_E = \sqrt{\kappa \pi_{\text{rel}}}; \quad \kappa \equiv \frac{4G}{c^2 \text{AU}} = 8.1 \text{ mas} \frac{M_i}{M_\odot},
\]

where \( \mu \) and \( \pi_{\text{rel}} \) are the lens-source relative proper motion and parallax, respectively. Because the internal motions of the system are much smaller than the system motion across the line of sight, we approximate \( \mu \) as the same for all subevents. Then the mass ratios between lenses generating subevents are \( q_{i,j} \equiv M_i/M_j = (t_{E,i}/t_{E,j})^2 \). We then find ratios \( q_{1,2} = 2.66 \times 10^{-4} \) and \( q_{3,2} = 0.22 \). Similarly, the separation in units of \( \theta_{E,2} \) (i.e., primary) can be estimated from \( s_{1,2} \equiv |t_{0,2} - t_{0,1}|/t_{E,1} \), yielding \( s_{1,2} \approx 5 \) and \( s_{3,2} \approx 17 \). Even \( \theta_{E,2} \) can be estimated once \( \theta_E \approx 14.25 \mu\text{as} \) has been evaluated (see below) from \( \theta_{E,2} = (\theta_E/\rho_1)(t_{E,2}/t_{E,1}) = 0.33 \text{ mas} \). This then gives an angular scale to the system and the basis to estimate the lens masses and distance (see Section 4). The planet–host separation is \( s_{1,2} \approx 1.6 \text{ mas} \), which for lenses lying in the Galactic bulge corresponds to about 15 AU (projected). In the same manner, the projected separation of the primary and the secondary stars is 48 AU. The assumption of bulge lens (as opposed to disk lens) gives also the primary mass of about 0.7 \( M_\odot \), with an upper limit \( M < 1.2 M_\odot \), regardless of lens location.

The geometry of this system is illustrated in Figure 2. In the interest of maximum precision, we carry out more rigorous calculations in the next section, but these confirm the very simple arguments outlined here.

### 3.2. Detailed Model

Binary lenses have three parameters beyond those of the single lenses: projected separation \( s_{1,2} \), mass ratio \( q_{1,2} \), and \( \alpha_{1,2} \)—the angle of the lens–source relative motion with respect to the binary axis. One can find more accurate than above (but still approximate) values of these parameters and \( \rho \) by using simple geometry, scaling to appropriate \( \theta_E \), and correcting \( s_{1,2} \rightarrow s_{1,2} - 1/s_{1,2} \) (Han 2006). These are compared to the

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### Table 1

| Quantity | Unit | Planetary Subevent | Primary Subevent | Secondary Subevent |
|----------|------|-------------------|-----------------|-------------------|
| \( t_0 \) | days | 4541.208(29) | 4727.39(47) | 5579.57(46) |
| \( u_0 \) |      | 1.51(20) | 1.5502(65) | 0.523(25) |
| \( \theta_E \) | days | 0.629(58) | 38.56(49) | 17.94(52) |
| \( \rho \) |      | 2.66(13) | 0\( ^d \) | 0\( ^d \) |
| \( f_b/f_s \) |      | 0\( ^d \) | 0\( ^d \) | 0.016(73) |
| \( \chi^2/\text{dof} \) |      | 372.0/349 | 368.6/343 | 427.2/378 |

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Notes.

\(^a\) The fit is based on OGLE-III data with primary lensing signal subtracted.

\(^b\) Seven OGLE-III epochs closest to planetary anomaly were removed before this fit was performed.

\(^c\) Data do not constrain value of \( \rho \).

\(^d\) Value fixed based on secondary subevent results.

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Figure 1. Light curve of OGLE-2008-BLG-092 microlensing event. Models fitted to OGLE-III (Section 3.2) and OGLE-IV (Section 3.1) photometry are presented by lines. The bottom panel shows the models residuals. The inset shows the planetary subevent. The OGLE-IV baseline flux was aligned to the OGLE-III for plotting.

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

\[ \rho 

\]
results of the final modeling in Table 2. One finds very good agreement especially in the case of $s_{1,2}$. For final solution, the magnification during the planetary subevent was evaluated using the “mapmaking” method (Dong et al. 2006) with modifications (Dong et al. 2009; Poleski et al. 2014). The magnification for other epochs was calculated by hexadecapole approximation (Pejcha & Heyrovský 2009; Gould 2008). Note that OGLE-IV data (Table 1) to obtain parameters of the triple lens. There are three additional parameters that must be estimated: $q_3,2$—secondary to primary mass ratio, $s_{3,2}$—primary–secondary projected separation (in units of primary $\theta_0$), and $\phi_{2,3}$—the angle between the secondary and the planet as viewed from the primary. We checked that at $s_{3,2} \approx 17$ the perturbations caused by the presence of one of the stars on the microlensing signal of the other one are much smaller than the photometric errors. The Einstein timescale is proportional to the square root of the lens mass, thus $q_3,2$ is the squared ratio of primary and secondary $\theta_0$ and equals 0.216(12). The values of $s_{3,2}$ and $\phi_{2,3}$ are calculated using simple geometry and noting that the caustics of both stars are $s_{3,2} = 1/s_{3,2}$ apart. The source could have passed the stellar caustics on the same or opposite sides but the data do not constrain this. If they were passed on the same side (as illustrated in Figure 2), we obtain $s_{3,2} = 16.99(38)$ and $\phi_{2,3} = 157:59(35)$. The opposite situation

| Quantity | Unit | Value | Uncertainty | Approximated$^a$ |
|----------|------|-------|-------------|-----------------|
| $i_0$    | days | 4727.374 | 0.047       |                 |
| $u_0$    |      | 1.545 | 0.043       |                 |
| $i_E$    | days | 38.64 | 0.88        |                 |
| $\rho$   |      | 0.0414 | 0.0025 | 0.0434         |
| $\alpha_{1,2}$ | deg | 17.99 | 0.30 | 18.06          |
| $s_{1,2}$ |      | 5.26  | 0.11 | 5.27           |
| $q_{1,2}$ | $10^{-4}$ | 2.41 | 0.45 | 2.66           |
| $f_b/f_s$ |      | 0.011 | 0.071       |                 |
| $\chi^2$/dof |      | 371.5/346 |        |                 |

Notes.

$^a$ These values were estimated based on single lens fits to the three subevents (see Section 3.2).

$^b$ Assumes $f_b/f_s = 0.000 \pm 0.073$ (see Section 3.2).
leads to a very similar value of $s_{3,2} = 17.03(38)$ and slightly smaller $\phi_{3,3} = 155\!.95(36)$.

In order to investigate the self-consistency of the triple-lens model, we checked how the presence of the secondary affects the position of the planetary caustic that is the only caustic that was approached closely. We fixed the mass ratios as well as the positions of the primary and the secondary and tried to find the position of the planet that gives the same position and size of the planetary caustic, as we have in the double-lens model. It was enough to change the planet position by as little as 0.01 to match the caustics. This is much less than the 0.11 uncertainty of $s_{3,2}$. Therefore, we conclude that our approach to the triple-lens modeling is valid and available data do not require more complicated methods.

The models presented above neglected the microlensing parallax ($\pi_E$) effect. We tried to incorporate $\pi_E$ in the single-lens models fitted to the OGLE-IV data but the short event timescale renders the parallax effect too weak to measure. The $\Delta \chi^2 = 9$ limit is $\pi_E < 3.6$ for negative $u_0$ and $\pi_E < 3.1$ for positive $u_0$. The low magnification of the primary event in the OGLE-III data also does not allow $\pi_E$ to be measured. For similar reasons, the effect of the lens rotation was ignored.

There is one more possibility that one should consider. While three separate subevents were observed and these had to be caused by three different lenses, this does not necessarily imply that these three objects are bound. The secondary subevent could have been caused by a star that is unrelated to the planet–host system. Such an unrelated lens can give rise to microlensing of a given source with probability similar to the planet–host system. Such an unrelated lens can give rise to the microlensing event only if the secondary subevent happening within two years before or after the main event, the probability is about $4 \times 10^{-5}$. On the other hand, the frequency of binary systems with separations equal or smaller than the deprojected separation of OGLE-2008-BLG-092L is on order of 40% (Duquennoy & Mayor 1991). However, the putative companion gives rise to the microlensing event only if the source trajectory passes close enough, i.e., $u_{0,3} < 1$. In the case of OGLE-2008-BLG-092L, the source had to enter or exit (factor of two) the circle of circumference $2\pi s_{3,2}\theta_E$ within an arc of length $2\theta_E$. Thus the probability that the secondary is detected is

$$4\theta_E / (2\pi s_{3,2}\theta_E) \approx 0.02.$$ 

In this sample of binary system must have smaller separations than considered above, which leads to higher probability of detecting the secondary, which we assume here to be 0.04. Finally, $0.4 \times 0.04 = 0.016$ is 400 times larger than $4 \times 10^{-5}$, which makes unbound lens scenario highly unlikely.

4. PHYSICAL PROPERTIES

4.1. Source Star Properties

The first step required to translate microlensing parameters to physical parameters is estimating the angular source radius ($\theta_s$). The source has observed $I$-band brightness of 13.90 mag and $(V-I)$ color of 1.88 mag and almost all stars at this part of the color–magnitude diagram (Figure 3) are located in the bulge. The red clump intrinsic $(V-I)$ color is 1.06 mag (Bensby et al. 2011) and $I = -4.75$ implies dereddened $I$-band brightness of 14.61 mag (Nataf et al. 2013). The source reddening corrected $V$-band brightness of 14.23 mag and $(V-I)$ color of 1.28 mag. The corresponding $(V-K)$ color is 2.88 mag (Bessell & Brett 1988). The color–surface brightness relation (Kervella et al. 2004) leads to $\theta_s = 14.25(60)$ $\mu$as. The Einstein ring radius is

$$\theta_E = \theta_s / \rho = 0.344(20) \mathrm{mas}.$$ 

This results in

$$\mu = \theta_E / t_E = 3.25(22) \mathrm{mas \ yr}^{-1}.$$ 

The baseline flux comes almost entirely from the source. Thus, we can use eight years of the OGLE-III monitoring to measure the source proper motion. Its value relative to the local red clump stars is $\mu_{\alpha,\cos\delta} = 0.25(31) \mathrm{mas \ yr}^{-1}$ and $\mu_{\alpha,\delta} = 1.17(31) \mathrm{mas \ yr}^{-1}$. This corresponds to $\mu_{\alpha,\cos\delta} = 1.13(31) \mathrm{mas \ yr}^{-1}$ and $\mu_{\alpha,\delta} = 0.39(31) \mathrm{mas \ yr}^{-1}$ in Galactic coordinates.

4.2. Lens System Properties

The lens parallax and mass are (Gould 2000):

$$\pi_t = \pi_{\text{rel}} + \pi_t, \quad \pi_{\text{rel}} = \pi_E \theta_E$$

$$M = \frac{\theta_E}{\kappa \pi_E},$$

where $M$ is the primary mass (because $\theta_E$ corresponds to primary lens). Both the source position in the color–magnitude diagram and proper motion are consistent with a bulge location. For some previously published planets, the value of $\pi_t$ was found from the microlensing model fit. Despite three subevents observed, one of them having an Einstein timescale longer than a month, we were not able to make a meaningful measurement of $\pi_E$. The limits on $\pi_E$ from OGLE-IV data translate to uninteresting limits on lens mass $M > 0.012 M_\odot$ and distance $D_l > 0.75 \mathrm{kpc}$.

Instead of finding $\pi_E$ and calculating $D_l$ and $M$ from this, we constrain $D_l$ and $D_s$ using the indirect evidence based on $\theta_E$ and $\mu$. The value of $\mu = 3.2 \mathrm{mas \ yr}^{-1}$ is comparable to the dispersion of the proper motions in the Galactic bulge in one direction (Vieira et al. 2007). This strongly suggests
that the source and the lens are relatively close to each other, i.e., the lens lies in the bulge or close to its edge. We do not know the orientation of \( \mu \) relative to the source proper motion \( \mu_s = 1.2 \text{ mas yr}^{-1} \) but even in the most unfavorable case, the bulge lens hypothesis is preferred over a disk lens because the typical proper motions of disk stars are 6.5 mas yr\(^{-1}\).

Noting that the lens is in the bulge, we can put the upper limit on the lens mass. The problem of the bulge highest-mass main-sequence (MS) stars was not investigated previously from observers’ point of view. There are no direct mass measurements for bulge MS stars. Masses can be estimated based on the high-resolution and high signal-to-noise spectra, but these require extremely long observations even at the largest existing telescopes for bulge MS targets. This can be overcome by observing the high-magnification microlensing events with the MS sources close to the peak. Bensby et al. (2013) presented the most recent analysis of spectra from the ongoing project aimed at systematic spectroscopic observations of the microlensing events with subgiant or MS sources. In Figure 4, we present the histogram of derived masses. We see that most of the values are close to 1 \( M_\odot \) and the highest measured masses are around 1.3 \( M_\odot \). This distribution is significantly affected by the selection bias, as lower mass stars are too faint to be observed. Taking into account measurement errors in spectroscopically derived masses and the fact that these can be both subgiant and MS stars, we estimate that the bulge MS stars have masses below 1.2 \( M_\odot \) or probably even below 1.1 \( M_\odot \). The former limit corresponds to a planet mass \( q_{1,2} M \) close to that of Saturn.

The distances to the source and the lens were estimated using a simulation of microlensing events. Only the events with both sources and lenses in the bulge were simulated. The density of stars was modeled according to (Nataf et al. 2013) results at the vicinity of the event, i.e., with mean distance of 8.86 kpc and Gaussian distribution of distance modulus with a dispersion of 0.263 mag. The probability of observing microlensing event depends not only on the density of stars but also on the size of the \( \theta_E \), thus the simulated events were additionally weighted by \( \sqrt{1/D_1 - 1/D_2} \). We rejected the events that resulted in lens masses above 1.2 \( M_\odot \). Integrating the lens and source distances in the rest of the simulated events leads to \( D_1 = 8.1 \text{kpc} \) and \( D_2 = 9.7 \text{kpc} \).

The Einstein radius in physical units is then \( D_1 \theta_E = 2.8 \text{AU} \). The projected separation of the planet is 15 AU, while the secondary is at the projected separation of 48 AU. These values can be de-projected by multiplying by \( \sqrt{3/2} \), which yields 18 AU and 58 AU, respectively. The adopted distances \( (D_1, D_2) = (8.1, 9.7) \text{kpc} \) yield \( \pi_{\text{rel}} = 20 \text{mas} \) and therefore \( M = \theta_E^2 / k \pi_{\text{rel}} = 0.71 M_\odot \). This gives the planetary mass of \( q_{1,2} M = 3.3 M_{\text{Neptune}} = 3.9 M_{\text{Uranus}} \). The mass of the secondary is \( q_{3,2} M = 0.15 M_\odot \).

5. DISCUSSION

5.1. Planet Properties and Formation

The ratio of the de-projected separation to the snow line distance is

\[
\frac{\sqrt{3/2} \theta_E D_1}{2.7 \left( \frac{M_*}{M_\odot} \right) \text{AU}} = 56 \times \left( 1 - \frac{D_1}{D_2} \right).
\]

For the inferred distances \( D_1 = 8.1 \text{kpc} \) and \( D_2 = 9.7 \text{kpc} \), this ratio is about 9, making OGLE-2008-BLG-092LAb the first extrasolar analog of Uranus. The above ratio would be closer to values found in solar system gas giants as opposed to ice giants if \( D_1 / D_2 > 0.91 \). This condition is almost equivalent to already excluded values of \( M > 1.2 M_\odot \). The simulation of bulge–bulge events presented above indicates the probability of \( D_1 / D_2 > 0.91 \) is marginal.

Uranus and Neptune formed closer to the Sun and migrated outward because of the interaction with Jupiter and Saturn. The key factors that led to this conclusion were planetary masses and separations. If the properties of OGLE-2008-BLG-092LAb are taken at face value and combined with a host mass that is smaller than the Sun, they suggest in situ planet formation is not possible. However, the density of the protoplanetary nebula of OGLE-2008-BLG-092LA could be higher than the solar one. This would lead not only to formation of OGLE-2008-BLG-092LAb, but also other massive planets in this system. The sensitivity for detecting such additional planets was very low, thus we cannot rule out the hypothesis of much denser protoplanetary nebula.

The planet could be also formed closer to the host and migrated outward. In a hierarchical triple system, the Lidov–Kozai effect (Lidov 1962; Fabrycky & Tremaine 2007) changes the eccentricity of the inner orbit in an oscillatory way. For a short period of time, the eccentricity of the inner binary is very large, resulting in short pericenter distance. During the pericenter passage, the tidal forces can only shrink the orbit, not expand it. Alternatively, the system may contain more planets whose role might then have been similar to Jupiter and Saturn in the solar system. It is also possible that the planetary orbit has significant eccentricity. This would affect the relation between the semi-major axis and observed projected separation, leading to a semi-major axis that is overestimated. With more examples of similar planets observed in the future, a more definitive answer to the question of their origin could be derived.

5.2. Prospects for Detecting Similar Planets

Detecting cold ice giants that, like Uranus and Neptune, are many AU away from their hosts is extremely difficult for techniques other than microlensing. In the case of the radial
velocity method, a very long survey would be required to accomplish this. Currently, the longest period transiting planet is Kepler-421b with a period of nearly two years (Kipping et al. 2014). This period is still about 40 times shorter than required to find a Uranus analog. There are a few candidates for longer orbital periods found by the Kepler satellite (Burke et al. 2014). For some stars, even the longest observing campaigns conducted reveal only one transit. Although the orbital period cannot be estimated based on photometry alone, combining transit timing with radial velocity measurements may constrain the orbital period (Yee & Gaudi 2008). Such a combination of transit and radial velocity methods is still limited by the low probability that a planet on a very wide orbit transits in front of the host star. Ice giants orbiting nearby stars can have angular separations larger than the resolution achieved by direct imaging. However, the problem lies in detecting the light from the planet, which cannot be done by any of the instruments that are currently working or planned for the near future.

We showed above that microlensing is capable of discovering planets on very wide orbits. There are a few different channels that can lead to microlensing planet discoveries. First, the source may approach very close to the lens. This gives rise to very large magnification and the event is sensitive to even small perturbations in the magnification pattern caused by the presence of the lens companions (Griest & Safizadeh 1998). Such close proximity can be predicted while the event is ongoing, and intensified observations lead to greater sensitivity for planets (e.g., Udalski et al. 2005; Gould et al. 2010). This channel led to most of the planets published to date (Zhu et al. 2014), but its sensitivity drops for planets with large s. The size of central caustic is \( w = \frac{(4 g)}{(is - s^{-1})^2} \) (Chung et al. 2005) and for OGLE-2008-BLG-092, it would result in \( w = 3.8 \times 10^{-5} \) if the secondary star were not present. Such small caustics cannot be detected by current microlensing experiments because the signal is smeared by the much larger source (Chung et al. 2005).

Second, the planet can be revealed if the source approaches a resonant caustic, which is large and forms if \( s \approx 1 \). This requires that the Einstein ring has a size larger than 10 AU, which is highly unlikely. Third, the source may approach the planetary caustic that is located close to the planet (Mao & Paczynski 1991; Gould & Loeb 1992; Di Stefano & Scalzo 1999). Such approaches are unpredictable and well separated in time from the host lensing event. Follow-up photometry can be obtained after the anomaly is detected or by routine monitoring of many events after the peak, which is not done currently. This shows that the microlensing surveys that cover significant part of the bulge with high cadence are the only efficient way to investigate the population of extrasolar ice giants.

There are further obstacles to detecting microlensing planets at large separations. The typical microlensing event has \( t_E \approx 25 \) days, which means that a significant number of planetary caustic approaches are a few months before or after the main peak. They may be unobservable because of the conjunction of the Sun and the bulge. They may also happen when the Sun is relatively close to the bulge so that 24 hour per day observations are not possible. We showed that even a few years ago, the OGLE survey had cadence good enough to identify such an anomaly. At present, the OGLE-IV survey has sufficient cadence to observe events similar to OGLE-2008-BLG-092 in \( 26 \) deg\(^2\) of bulge. The survey observing strategy is well defined, therefore, a larger sample of similar planetary caustic approaches would allow one to estimate the frequency of such planets.

5.3. Planetary Anomaly and Free-floating Planets

One of the important outcomes of the microlensing experiments was the detection of an excess of the events with very short \( t_F \) of one to two days (Sumi et al. 2011). Since \( t_F \) is proportional to the square root of the lens mass, these events should be produced by planetary mass objects. Sumi et al. (2011) presented 10 events with very short \( t_F \) and no signs of other lenses and therefore interpreted them as free-floating planets with abundance of \( 1.8^{+0.7}_{-0.5} \) per MS star. There are other possible interpretations of these events. Some of them may involve bound planets on very wide orbits, for which the presence of the host was not revealed based on either additional bump in photometry (Han et al. 2005) or distortion of planetary event (Ryu et al. 2013).

Based on the direct imaging upper limits on the abundance of Jupiter-mass planets on 10–250 AU wide orbits ( Lafrenière et al. 2007), Sumi et al. (2011) estimated that no more than 25% of detected short events are caused by bound planets. However, we find a significant observational bias in detecting the stellar hosts for these planets. Even if the microlensing planet is bound, the signal from the host may be too weak to be measured. In the case of OGLE-2008-BLG-092, even a 1% signal would be revealed because the source is very bright. This corresponds to \( u_{0.2} < 3.5 \) for host lensing. For source trajectories crossing the planetary caustic with randomly selected angle relative to the planet–host axis, the probability that the source would make a closer approach to the host is 0.49. For 10% magnification \( u_{0.2} < 1.7 \), the corresponding probability is 0.21. These numbers ignore the lack of data due to seasonal gaps. It is harder to detect host subevent if the photometric accuracy is lower. The source stars in Sumi et al. (2011) sample were at least 3.5 mag fainter than OGLE-2008-BLG-092S and 1% signals could be easily missed.

We note that the events similar to OGLE-2008-BLG-092 but with fainter sources (i.e., smaller \( p \)) and different \( t_{1,2} \) would not pass the selection criteria used by Sumi et al. (2011). One of their requirements was \( u_0 < 1 \) and we measured \( u_{0.1} = 1.51(20) \) in single-lens approximation.

Sumi et al. (2011) presented also 2\( \sigma \) detection limits for hosts of each presented planet based on the light curve distortions. Only 2 out of 10 cases are inconsistent with a planet that is similar to OGLE-2008-BLG-092Lab, i.e., with \( s = 5.26 \). These are MOA-ip-1 and MOA-ip-10. The third case (MOA-ip-7) is marginally consistent \((s > 5.2)\). We note that there are two other events that showed separate subevents by planetary microlensing. First, Skowron et al. (2009) analyzed the event OGLE-2002-BLG-045. The best-fitting model was a binary lens with \( s = 4.0 \) and \( q = 0.008 \). However, the analyzed data were very limited. Even though the mass ratio was found to be in the planetary regime, this event is not considered a secure planet detection. Second, Bennett et al. (2012) presented event MOAbin-1 that is best fitted by a planet with \( s = 2.10 \) and \( q = 0.0049 \). In this case, the host lensing signal was not detected, but the evidence for its presence is a distortion of the planetary anomaly.

5.4. Long-term Stability of the System

We have discovered a relatively compact triple system and thus its long-term dynamical stability should be investigated. Holman & Wiegert (1999) investigated the conditions under which a massless planet orbiting one component of a stellar binary is a stable configuration. The initial planetary orbit was assumed to be circular, prograde, and coplanar with the stellar binary. A wide range of stellar binary eccentricities \((e)\) was
tested. Based on results of Holman & Wiegert (1999) and \(q_{3,2}\) in OGLE-2008-BLG-092L, we obtain the following stability criterion (\(a_c\)—critical planet semi-major axis, \(a_b\)—stellar binary semi-major axis):

\[
\frac{a_c}{a_b} = 0.397(7) - 0.527(36)e + 0.115(43)e^2,
\]

where the quoted uncertainties take into account the uncertainty of \(q_{3,2}\) as well as those from the formula in Holman & Wiegert (1999). We have measured \(s_{1,2}/s_{3,2} = 0.3096(95)\), thus the system is stable if the measured projected separation ratio represents the semi-major axis ratio and the stellar orbit is circular. However, we must note that \(s_{1,2}\) and \(s_{3,2}\) correspond to two different epochs. The planetary orbit remains stable for binary eccentricities up to 0.17. If the stellar binary is at its apoapastron, then the planetary orbit is stable for \(e < 0.11\).

6. SUMMARY

The microlensing event OGLE-2008-BLG-092 showed three separate subevents that reveal a wide stellar binary system with a planet orbiting the primary star. The planet turns out to be the first extrasolar analog of Uranus, i.e., a cold ice giant that orbits the parent star at a distance many times larger than the snow line distance. The planet likely also shares a similar origin with solar system ice giants. This discovery opens a new part of the planet properties’ parameter space. We also showed that no method other than microlensing can be used to find such planets. Among different scenarios that lead to microlensing planet detection, only the approach to the planetary caustic gives a high chance for detecting planets on wide orbits. The contribution of bound planets to the very short events sample gives a high chance for detecting planets on wide orbits. The detection of the bump due to a putative host can be hindered by gaps in the data and lower photometric accuracy for fainter sources. These should be considered together with constraints from the anomaly distortions to find unbiased abundances of both free-floating and bound planets.

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