OGLE-2018-BLG-1428Lb: a Jupiter-mass planet beyond the snow line of a dwarf star

Yun Hak Kim,1,2 Sun-Ju Chung,1,2* Andrej Udalski,3 Andrew Gould,4,5 Michael D. Alibrow,6 Youn Kil Jung,1 Kyu-Ha Hwang,1 Cheongho Han,7 Yoon-Hyun Ryu,1 In-Gu Shin,1 Yossi Shvartzvald,8 Jennifer C. Yee,9 Weicheng Zang,10 Sang-Mok Cha,1,11 Dong-Jin Kim,1 Hyoun-Woo Kim,1,12 Seung-Lee Kim,1 Dong-Joo Lee,1 Yongseok Lee,1,11 Byeong-Gon Park,1 Richard W. Pogge,4 (KMTNet Collaboration), Przemek Mróz,3,13 Radek Poleski,4 Marcin Wrona,3 Patryk Iwanek,3 Michał K. Szymański3, Jan Skowron3, Igor Soszyński,3 Szymon Kozłowski,3 Paweł Pietrukowicz,3 Krzysztof Ulaczyk3,14 and Krzysztof Rybicki3

(The OGLE collaboration)

1Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-Gu, Daejeon 34055, Republic of Korea
2University of Science and Technology, Korea, (UST), 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea
3Warsaw University Observatory, Al. Ujazdowskie 4, PL-00-478 Warsaw, Poland
4Department of Astronomy, Ohio State University, 140 W. 18th Avenue, Columbus, OH 43210, USA
5Max-Planck-Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany
6Department of Physics and Astronomy, University of Canterbury, Private Bag 4800 Christchurch, New Zealand
7Department of Physics, Chungbuk National University, Cheongju 361-763, Republic of Korea
8Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel
9Center for Astrophysics 1 Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
10Department of Astronomy and Tsinghua Center for Astrophysics, Tsinghua University, Beijing 100084, China
11School of Space Research, Kyung Hee University, Giheung-gu, Yongin, Gyeonggi-do 17104, Republic of Korea
12Department of Astronomy, Chungbuk National University, Cheongju 361-763, Republic of Korea
13Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
14Department of Physics, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL, UK

Accepted 2021 February 19. Received 2021 February 17; in original form 2020 August 17

ABSTRACT

We present the analysis of the microlensing event OGLE-2018-BLG-1428, which has a short-duration (~1 d) caustic-crossing anomaly. The event was caused by a planetary lens system with planet/host mass ratio \( q = 1.7 \times 10^{-3} \). Because of the detection of the caustic-crossing anomaly, the finite source effect was well measured, but the microlens parallax was not constrained due to the relatively short time-scale \( t_c = 24 \) d. From a Bayesian analysis, we find that the host star is a dwarf star \( M_{\text{host}} = 0.43^{+0.32}_{-0.22} \ M_\odot \) at a distance \( D_L = 6.22^{+1.03}_{-1.51} \) kpc and the planet is a Jovian-mass planet \( M_p = 0.77^{+0.77}_{-0.53} \ M_J \) with a projected separation \( a_\perp = 3.30^{+0.59}_{-0.83} \) au. The planet orbits beyond the snow line of the host star. Considering the relative lens-source proper motion \( \mu_{\text{rel}} = 5.58 \pm 0.38 \) mas yr\(^{-1}\), the lens can be resolved by adaptive optics with a 30 m telescope in the future.

Key words: gravitational lensing: micro–planets and satellites: detection.

1 INTRODUCTION

The core accretion model proposes that gas giant planets originated beyond the snow line of their host stars, such as Jupiter and Saturn in the Solar system (Mizuno 1980; Pollack et al. 1996; Inaba, Wetherill & Ikoma 2003). This model predicts that it takes ~3 Myr to form gas giant planets at 5 au around Sun-like stars, while for low-mass stars it does not seem to be able to form such planets because the lifetime of the proto-planetary disc for low-mass stars is not long enough to form such giant planets (Ida & Lin 2004; Laughlin, Bodenheimer & Adams 2004; Boss 2006). For example, the formation time of gas giant planets for a 0.4 \( M_\odot \) dwarf is \( \gtrsim 10 \) Myr, whereas its disc lifetime is \(< 10 \) Myr (Boss 2006). On the other hand, the disc instability model is thought to be more likely to form gas giants around beyond the snow line of M dwarfs (Boss 2006). Actual detections of Jupiter-mass planets orbiting low-mass stars (Boss 2006 and references therein) are consistent with the disc instability model. Hence, these two planet formation models may actually complement one another, although this remains uncertain.

Currently, the majority of host stars with exoplanets are Sun-like stars, and their planets are mostly located inside the snow line. Those planets have been mostly discovered by the radial velocity and transit methods. However, most of stars in the Galaxy are low-mass stars with low-mass planets. The core accretion model predicts that it takes ~3 Myr to form gas giant planets at 5 au around Sun-like stars, while for low-mass stars it does not seem to be able to form such planets because the lifetime of the proto-planetary disc for low-mass stars is not long enough to form such giant planets (Ida & Lin 2004; Laughlin, Bodenheimer & Adams 2004; Boss 2006). For example, the formation time of gas giant planets for a 0.4 \( M_\odot \) dwarf is \( \gtrsim 10 \) Myr, whereas its disc lifetime is \(< 10 \) Myr (Boss 2006). On the other hand, the disc instability model is thought to be more likely to form gas giants around beyond the snow line of M dwarfs (Boss 2006). Actual detections of Jupiter-mass planets orbiting low-mass stars (Boss 2006 and references therein) are consistent with the disc instability model. Hence, these two planet formation models may actually complement one another, although this remains uncertain.
M dwarf stars, which are difficult to observe with the two methods. On the other hand, the microlensing method typically detects low-mass M dwarfs hosting planets located beyond the snow line. This is because the microlensing depends only the mass of objects, not the light. Therefore, microlensing provides very important samples to constrain planet formation models including the core-accretion and gravitational instability models.

However, a majority of masses of microlensing planets were not directly measured but estimated from a Bayesian analysis, which assumes that the planet-hosting probability is independent of the host star mass (Bhattacharya et al. 2020; Vandorou et al. 2020). The lens masses estimated from the Bayesian analysis can be confirmed from high-resolution follow-up observations. This is because the lens and source stars are typically separated each other within ~10 yr after the peak time of event, thus making it possible to discriminate the two stars. Until now, the masses of 18 planetary lens systems (e.g. Bennett et al. 2006, 2015; Batista et al. 2015; Fukui et al. 2015; Bhattacharya et al. 2020; Vandorou et al. 2020) have been measured from high-resolution follow-up observations with Keck, VLT, Subaru, or HST.

In addition, the masses of lens systems can be directly measured from the measurement of two parameters of angular Einstein radius ($\theta_E$) and microlens parallax ($\pi_\ell$). However, it is usually hard to measure the two parameters. This is because $\theta_E$ can be measured from events with high-magnification or caustic-crossing features, while $\pi_\ell$ can be measured from the detection of the distortions induced by the orbital motion of the Earth on a standard microlensing light curve (Gould 1992). In general, the measurement of the microlens parallax is limited to events with long time-scale $t_0 \gsim 60$ d or large $\pi_\ell$ to detect the light-curve distortion induced by the orbital motion of the Earth. This means that for short time-scale events induced by low-mass objects (e.g. M dwarfs or brown dwarfs), it is difficult to measure the microlens parallax. The microlensing parallax measurement was first reported in 1995 (Alcock et al. 1995), and it was due to a long time-scale of the event, $t_0 = 110$ d. For the measurement of the microlens parallax for all events, a simultaneous observation of an event is required from the Earth and a satellite (Refsdal 1966; Gould 1994). Then, the microlens parallax is measured from the difference in the light curves as seen from the two observatories (Refsdal 1966; Gould 1994). Over 900 events so far have been detected from ground-based observations and the Spitzer satellite, which is for studying the Galactic distribution of planets (Zhu et al. 2017 and the references therein). Also, the Nancy Grace Roman (Roman, formerly WFIRST) satellite will be launched in near future (Spergel et al. 2015). With this satellite, it is expected to detect ~1400 bound exoplanets (Penny et al. 2019) and ~250 free-floating planets (Johnson et al. 2020).

Hence, the masses of over 1000 planetary systems can be measured from the Roman together with ground-based observations, such as the Korea Microlensing Telescope Network (KMTNet; Kim et al. 2016). However, we note that the main mass measurement method for the Roman Galactic Exoplanet Survey will be the detection of the exoplanet host stars in the Roman imaging data. The microlensing parallax between the Earth and Roman will be difficult to measure for most events for two reasons. First, most events detected by Roman will be too faint to observe from the ground, particularly with small telescopes. Secondly, for events without caustic-crossings, the separation between the Earth and Roman’s orbit at L2 will not be large enough to reveal a microlensing parallax measurement. Fortunately, for events with caustic-crossings the Earth-L2 separation yields a useful microlensing parallax measurement as Wyzykowski et al. (2020) demonstrate. Moreover, for events with anomalies due to terrestrial planets, the microlens parallax may be measurable even in the absence of caustic-crossing features (Gould, Gaudi & Han 2003).

Recently, planetary systems composed of low-mass dwarfs and a giant planet beyond the snow line of the dwarfs have been routinely detected from the KMTNet microlensing survey, even though most of masses of the host stars were estimated from a Bayesian analysis. OGLE-2018-BLG-1428 is one such planetary system. In this paper, we present the analysis of the planetary event OGLE-2018-BLG-1428, which has a short-duration caustic-crossing anomaly. Although the finite source effect was measured from the caustic-crossing feature, the microlens parallax was not measured. Therefore, the physical parameters of the lens system are estimated from a Bayesian analysis.

### 2 OBSERVATION

The planetary lensing event OGLE-2018-BLG-1428 is located at equatorial coordinates (RA, dec.)$_{2000} = (17:42:11.69, -26:08:16.4)$, corresponding to the Galactic coordinates ($l$, $b$) = (1.99, 2.11). The event was first alerted at 2018 August 6 by the Optical Gravitational lensing Experiment (OGLE; Udalski, Szymański & Szymański 2015). OGLE uses 1.3 m Warsaw telescope with 1.4 deg$^2$ field of view (FOV) at the La Campanas Observatory in Chile. The event lies in the OGLE-IV field BLC5652 with a low cadence of $\Gamma \simeq 0.01 - 0.1 h^{-1}$. In addition, the event is very near the edge of the OGLE chip and therefore has many missing data points due to small pointing variations. In spite of this fact, OGLE alerted it at HJD = 2450000 (HJD') = 8337.32, just before the peak. However, due to the sparseness of the data points, the short-duration (~1 d) caustic-crossing anomaly was not covered.

In 2018, KMTNet started to run its own alert system, but only for the northern bulge fields (Kim et al. 2018). From the KMTNet alert system, OGLE-2018-BLG-1428 was independently announced at HJD' = 8337.68, and it was designated as KMT-2018-BLG-0423. KMTNet uses three identical telescopes with 4 deg$^2$ FOV, which are individually located at CTIO in Chile (KMTC), SAAO in South Africa (KMTS), and SSO in Australia (KMTA). The event lies in the KMT field BLG18 with cadence of $\Gamma \simeq 1 h^{-1}$. With this cadence, the anomaly was well covered by KMTNet. While most of KMTNet data were taken in the $I$ band, some of them were taken in the $V$ band in order to characterize the source star. However, we found that the extinction toward the event, $A_I = 3.07$, is high, and thus it is difficult to use the $V$-band data to constrain the source colour. To estimate the source colour ($I - H$), we used the $H$-band data of the VVV microlensing survey (Navarro, Minniti & Contreras-Ramos 2017, 2018), which will be described in Section 4. The KMTNet data were reduced by pySIS based on difference image analysis (Tomayn & Crotts 1996; Alard & Lupton 1998; Alblok et al. 2009).

### 3 LIGHT-CURVE ANALYSIS

#### 3.1 Standard model

OGLE-2018-BLG-1428 is a binary lensing event with a clear caustic-crossing anomaly, which lasts ~1 d. In order to describe a standard binary lensing event, seven lensing parameters are needed. They include three single lensing parameters ($t_0$, $\omega_0$, $\theta_E$), three binary lensing parameters ($s$, $q$, $\alpha$), and the source radius normalized to the angular Einstein radius of the lens $\theta_E$ ($\rho = \theta_0 / \theta_E$). Here, $t_0$ is the
Figure 1. Light curve of the best-fitting lensing model. The right inset shows the source trajectory crossing the planetary caustic.

peak time of the event, $u_0$ is the separation (in units of $\theta_E$) between the lens and the source at $t_0$, $t_E$ is the crossing time of the Einstein radius, $s$ is the star–planet separation in units of $\theta_E$, $q$ is the planet–star mass ratio, and $\alpha$ is the angle between the source trajectory and the binary axis. In the binary lensing modelling process, the observed fluxes of each observatory at a given time $t$ are modelled as $F_i(t) = A_i(t)f_{s,i} + f_{b,i}$, where $A_i$ is the magnification at the $i$th observatory and $f_{s,i}$ and $f_{b,i}$ are the source and the blended fluxes at the $i$th observatory, respectively. The $(f_{s,i}, f_{b,i})$ are obtained from a linear fit.

In order to find the best-fitting solution, we conduct a grid search over $(s, q, \alpha)$, which have the ranges of $-1 \leq \log s \leq 1$, $-4 \leq \log q < 0$, and $0 \leq \alpha < 2\pi$, respectively. During the grid search, the $(s, q)$ are fixed, and the other parameters ($t_0, u_0, t_E, \alpha, \rho$) are allowed to vary in a Markov Chain Monte Carlo chain. From the grid search, we find three local solutions including binary and planetary lens models with $(s, q, \alpha) = (1.29, 0.0095, 1.74), (0.85, 0.0126, 1.82), \text{and } (1.35, 0.0015, 1.74)$. We then conduct additional modelling in which the local solutions are set to the initial values and all parameters are allowed to vary. As a result, we find that the best-fitting solution of the event is the planetary lens model with $(s, q) = (1.42, 0.0017)$, not the binary lens model. The planetary lens model is favoured by $\Delta \chi^2 = 493$ relative to the binary lens model. In this case, there is no $s$↔$1/s$ degeneracy. Fig. 1 shows the light curve of the best-fitting planetary lens model. The best-fitting lensing parameters are listed in Table 1.

Because the source crosses the caustic, we should consider the limb darkening of the finite source star in the modelling. Considering the source type (discussed in Section 4), we assume that the source has solar metallicity, effective temperature $T_{\text{eff}} = 4750$K, surface gravity $\log g \approx 3.0$, and microturbulent velocity $v_t = 2.0 \text{ km s}^{-1}$. We thus adopt the limb-darkening coefficient $\Gamma_1 = 0.51$ (Claret 2000) and use equation (7) of Chung et al. (2019) for the source brightness profile.

### 3.2 Investigation of microlens parallax

Because the event time-scale of $t_E = 24$ d is relatively short and the source is relatively faint ($I_s = 19$), we do not expect to be able to measure the parallax. However, we attempt to do so for completeness. The orbital motion of the lens system can mimic the microlens parallax signal (Batista et al. 2011, Skowron et al. 2011). We thus model the event adding both the microlens parallax and lens orbital motion. The microlens parallax is described by

Table 1. Best-fitting lensing parameters.

| Parameter | Value |
|-----------|-------|
| $\chi^2$/dof | 2902.14/2927 |
| $t_0$ (HJD) | 8339.6157 ± 0.0950 |
| $u_0$ | 0.7002 ± 0.0030 |
| $t_E$ (d) | 24.4448 ± 0.1858 |
| $s$ | 1.4233 ± 0.0019 |
| $q$ ($10^{-3}$) | 1.7144 ± 0.0553 |
| $\alpha$ (rad) | 1.7271 ± 0.0052 |
| $\rho$ | 0.0073 ± 0.0002 |
| $f_{s,\text{kmt}}$ | 0.4480 ± 0.0022 |
| $f_{b,\text{kmt}}$ | 0.4855 ± 0.0021 |
| $f_{s,\text{ogle}}$ | 0.3901 ± 0.0028 |
| $f_{b,\text{ogle}}$ | 0.0088 ± 0.0028 |

Note. HJD’ = HJD - 2450000.
For example, the parallax values of (\( \pi \)) are broad, allowing for a wide range of parallax values. However, this does not mean the parallax has to be large. The contours are broad, allowing for a wide range of parallax values. Thus, they are likely due to correlated noise rather than a real signal.

In order to identify the source of the \( \chi^2 \) improvement and check for systematics, we build the cumulative distribution of \( \Delta \chi^2 \) between the two models as a function of time. As shown in Fig. 2, the \( \chi^2 \) improvement comes from KMTC and KMTS (especially the former), while there is essentially no improvement for OGLE and KMTA. We thus check the systematics of KMT data by binning them to 1 per day. These investigations show that the \( \Delta \chi^2 \) improvement primarily comes from structures in the KMTC and KMTS data that are not seen in KMTA or OGLE. Thus, they are likely due to correlated noise rather than a real signal.

Hence, we conduct the parallax+orbital remodelling with partial data sets for KMTC and KMTS and full data sets for KMTA and OGLE. We restrict KMTC and KMTS data to data taken over the anomaly, i.e. in the range 8330.0 < HJD' < 8342. The result shows that the \( \Delta \chi^2 \) between the standard and the parallax+orbital models is 16. No orbital motion, \( (d\pi/dt, \sigma_{\pi}/dt) = (0, 0) \) is within 3\( \sigma \) of the best-fitting values, meaning these parameters are not significantly detected. By contrast, \( (\pi_{E,N}, \pi_{E,E}) = (0.4, -0.2) \) are compatible with the data at \( \Delta \chi^2 = 6 \) (see Fig. 3). Since these values are not unreasonable, the parallax could be real.

### 3.3 Xallarap effect

However, the parallax-like effects could be due to xallarap (source orbital motion). We thus check the xallarap model. Fig. 4 shows the \( \chi^2 \) distribution for the best-fitting xallarap solutions as a function of a fixed binary source orbital period \( P \). The red dot is the \( \chi^2 \) of the best-fitting parallax+orbital model.

Of a fixed binary source orbital period \( P \). If the estimated parallax is real, the best-fitting xallarap solution should appear at \( P = 1.0 \) yr because the parallax is caused by the orbital motion of the Earth. As shown in Fig. 4, the best-fitting xallarap solution is at \( P = 0.2 \) yr, not \( P = 1.0 \) yr, but several other solutions including \( P = 1.0 \) yr have \( \chi^2 \) near the best solution. The \( \Delta \chi^2 \) between the best-fitting parallax and xallarap solutions is \( \Delta \chi^2 = 34 \). This suggests that the parallax solution is wrong and the large (and so, suspicious) parallax value is actually due to xallarap effects or systematics in the data.

We first check that all xallarap solutions are physically reasonable. For each xallarap solution, we have two key parameters: the orbital period of binary source motion \( P \) and the counterpart of the parallax \( \xi_E \). The \( \xi_E \) is defined as \( \xi_E = \alpha_s/r_E \), where \( \alpha_s \) is the semimajor axis of the source and \( r_E \) is the Einstein radius projected to the source plane. Thus, the source semimajor axis is

\[
\alpha_s = \xi_E r_E \quad \text{and} \quad \frac{r_E}{\text{AU}} = \theta_E D_S.
\]

As discussed in Section 4, the source is a G-type giant in the bulge, \( \theta_E = 0.377 \) mas, and we assume \( D_S = 8.0 \) kpc. The source mass is thus \( \sim 1 M_\odot \), and then \( r_E = 3.02 \) au.
According to Kepler’s third law,
\[
\frac{M_{\text{tot}}}{M_{\odot}} \left( \frac{P}{\text{yr}} \right)^3 = \left( \frac{a_{\text{tot}}}{\text{au}} \right)^3,
\]
where \(M_{\text{tot}} = M_s + M_{\text{comp}}\) and \(a_{\text{tot}}/a_t = M_{\text{comp}}/M_{\text{tot}}\). Here, \(M_s\) and \(M_{\text{comp}}\) are the masses of the source and the source companion, respectively. We can parametrize equation (2) by \(Q = M_{\text{comp}}/M_s\). Equation (2) then becomes
\[
(1 + Q)^2 = \frac{M_s}{M_{\odot}} \left( \frac{P}{\text{yr}} \right)^2 \frac{a_t^3}{a^3}.
\]
Using the estimated \(a_t\), it is
\[
(1 + Q)^2 = 0.036 \left( \frac{P}{\text{yr}} \right)^2 \frac{\xi_{\text{E}}^3}{\xi_{\text{E}}^3}.
\]
We solve this cubic equation for \(Q\). Then if \(0.1 < Q < 1.0\), the solution is ‘physically reasonable’. That is, the companion will be a ‘typical main-sequence star’.

The results for each \(P\) and \(\xi_{\text{E}}\) are \(Q = 2.1, 10.1, 33.7, 2309.1, 5051.8, 30294.9, 53230.2, 497978.1, \) and 14568063 for \(P = 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.6, \) and 2.0, respectively. This means that the companion would be a very massive black hole. Since the parallax measurement is unreliable, we perform a Bayesian analysis to estimate physical parameters of the lens system, i.e. the source and source companion.

4 ANGULAR SOURCE RADIUS

KMTNet data were taken in the \(I\)- and \(V\)-bands in order to measure the instrumental source colour. Usually, the source colour \((V - I)\) is measured from the linear regression of the \(V\) on \(I\) flux. However, because there is only one \(V\) point that is sufficiently magnified to give a significant signal due to high extinction \(A_V = 3.07\), we cannot measure a reliable \((V - I)\).

In order to determine a reliable source colour, we use the VVV \(H\)-band catalogue. Because the source is bright and the best-fitting model shows negligible blending \((f_t \gg f_b)\), we can attempt to measure the offset between the baseline object and the clump in the instrumental colour–magnitude diagram (CMD). Here, we assume the baseline object corresponds to the source star due to negligible blending.

Fig. 5 shows the calibrated \((I - H, I)\) and \((V - I, I)\) CMDs. The CMDS have been calibrated by first applying the OGLE-IV calibration constants to the OGLE-IV data and then transforming the instrumental KMTNet pyDIA data to the calibrated OGLE-IV system, in which the KMT data are already matched to the VVV stars before the calibration. From the \((I - H, I)\) CMD, we find that \((I - H, I_\text{rel}) = (3.68, 17.55)\) and \((I - H, I_\text{cl}) = (3.52, 18.97)\), thus \(\Delta(I - H) = -0.15\). Using Bessel & Brett (1988), we find that this corresponds to \(\Delta(V - I) = -0.11\). From the \((V - I, I)\) CMD, we find that \((V - I, I_\text{rel}) = (3.63, 17.57)\) and \((V - I, I_\text{cl}) = (3.37, 18.97)\), thus \(\Delta(V - I) = -0.26\). Note that this baseline measurement derives from a stacking of several dozen images and is more reliable than the regression method, which relies on a single magnified \(V\) point. We finally adopt that \(\Delta(V - I) = -0.19\) by taking the average of these two values. The instrumental source magnitude is \(I = 18.87\) from the best-fitting model, and the magnitude and flux of the calibrated source is \(I = 18.99\) and \(f_t = 0.4017\). The source angular radius \(\theta_e\) is estimated from the intrinsic colour and magnitude of the source, in which are determined from
\[
(V - I, I)_0 = (V - I, I)_\text{cl} + \Delta(V - I, I). \tag{5}
\]
With the measured \(\Delta(V - I) = -0.19, I = 18.99\), and \((V - I, I)_\text{cl} = (1.06, 14.37)\), we find that \((V - I, I_0) = (0.87, 15.76)\), indicating that the source is a G-type giant. We then estimate the source angular radius by using the VIK colour–colour relation of Bessel & Brett (1988) and the colour–surface brightness relation of Kervella et al. (2004). From this, it is found that \(\theta_e = 2.717 \pm 0.164\) mas. With the \(\theta_e\) and \(\rho\), the Einstein angular radius of the lens is determined by
\[
\theta_{\text{E}} = \theta_e/\rho = 0.373 \pm 0.026 \text{ mas} \tag{6}
\]
and the relative lens-source proper motion is
\[
\mu_{\text{rel}} = \theta_{\text{E}}/t_{\text{E}} = 5.58 \pm 0.38 \text{ mas yr}^{-1}. \tag{7}
\]

5 LENS PROPERTIES

Because the parallax measurement is unreliable, we perform a Bayesian analysis to estimate physical properties of the lens, i.e. the mass and distance. The Bayesian analysis implicitly assumes that all stars have an equal probability to host a planet of the measured mass ratio. The Bayesian analysis is carried out with the same procedures as Jung et al. (2018) did, but we use a new Galactic model based on more recent data and scientific understanding. The new Galactic model includes the bulge mean velocity and dispersions taken from Gaia, disc density profile, and disc velocity dispersion from the Robin-based model in Bennett et al. (2014), while the bulge mean velocity is generally zero and the bulge density profile is the same as the one in Jung et al. (2018). However, we know the proper motion of the source \((\mu_t, \mu_\epsilon) = (-2.607 \pm 2.371, -3.014 \pm 1.751)\) from
The lens distribution in Fig. 6 shows that the lens is a K or a G dwarf. The physical parameters of the lens system are located in the disc and bulge with equal probability. This is consistent with the relative proper motion of 5.6 mas yr$^{-1}$

Considering the brightness of the giant source star with $K = 14.7$, the lens star is $\sim 240$ times fainter than the source. This high contrast between the source and the lens makes it difficult to resolve the two stars by follow-up observations. However, for both MOA-2007-BLG-400 (Bhattacharya et al. 2020) and MOA-2013-BLG-220 (Vandorou et al. 2020), the lens mass measured from Keck is much closer to the $2\sigma$ upper limit from the Bayesian analysis than the median. Thus, considering the $2\sigma$ upper limit of the lens brightness, the lens with $K = 17.1$ is 9 times fainter than the source. Recently, Bhattacharya et al. (2020) reported that lens star with $K = 18.9$, which is $\sim 10$ times fainter than the source and is $\sim 50$ mas away from the source, can be detected at a separation of 0.53 full width at half-maximum with Keck. For this event, because the proper motion is 5.6 mas yr$^{-1}$, the lens will be separated from the source by 56 mas in 2028. Hence, it seems plausible that a lens at $K \sim 17$ would be detectable by Keck, while for a lens at $K < 21$ it would be hard to detect with Keck. If the lens is a very faint star at $K < 21$, the lens can be resolved by a 30 m telescope equipped with a state-of-the-art laser guide star adaptive optics system, even though the contrast between source and lens is high. Such a measurement can resolve the nature of the lens and confirm the results of the Bayesian analysis.

### 6 SUMMARY

We analysed the event OGLE-2018-BLG-1428 with a caustic-crossing feature. From the Bayesian analysis, it is found that the lens is a star $M_L = 0.43^{+0.33}_{-0.22}$ $M_{\odot}$ hosting a sub Jupiter-mass planet $M_p = 0.77^{+0.77}_{-0.53}$ $M_J$ at a distance $D_L = 6.22^{+1.03}_{-1.51}$ kpc, and the projected separation between the star and the planet is $3.30^{+0.59}_{-0.83}$ AU, suggesting that the planet orbits beyond the snow line of the host. The lens distance distribution and the proper motion $\mu_{ref} = 5.6$ mas yr$^{-1}$ indicate that the lens is located in the disc and bulge with equal probability. The lens can be resolved by adaptive optics of a 30 m telescope in the future.

### ACKNOWLEDGEMENTS

Work by Y. H. Kim and S-J Chung was supported by the KASI (Korea Astronomy and Space Science Institute) grant 2021-1-830-08. Work by AG was supported by JPL grant 1500811. Work by CH was supported by the grant of National Research Foundation of Korea (2019R1A2C2085965 and 2020R1A4A2002885). The OGLE project has received funding from the National Science Centre, Poland, grant MAESTRO 2014/14/A/ST9/00121 to A.U. This research has used the KMTNet system operated by the KASI, and the data were obtained at three sites of CTIO in Chile, SAAO in South Africa, and SSO in Australia.

### DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

### REFERENCES

Alard C., Lupton R. H., 1998, ApJ, 503, 325
Albrow M. D. et al., 2009, MNRAS, 397, 2099
Alcock C. et al., 1995, ApJ, 454, L125
Alcock C. et al., 1997, ApJ, 486, 697
Alcock C. et al., 2001, Nature, 414, 617
Batista V. et al., 2011, A&A, 529, A102
Batista V. et al., 2015, ApJ, 808, 170

Batista V. et al., 2015, ApJ, 808, 170

**Table 2.** Physical lens parameters.

| Parameter | $M_{host}$ ($M_\odot$) | $M_p$ ($M_J$) | $D_L$ (kpc) | $\alpha_L$ (au) | $\theta_E$ | $\mu_{ref}$ (mas yr$^{-1}$) |
|-----------|-----------------|----------------|-------------|-----------------|-----------|-----------------|
|           | $0.43^{+0.33}_{-0.22}$ | $0.77^{+0.77}_{-0.53}$ | $6.22^{+1.03}_{-1.51}$ | $3.30^{+0.59}_{-0.83}$ | $0.373 \pm 0.026$ | $5.58 \pm 0.38$ |

**Gaia**, even though its error is big. We thus use the proper motion value as the mean velocity of the source for bulge–bulge events.

In addition, we should consider the extinction at a given distance for the lens brightness. For the extinction to the lens $A_I$, we use the following equation (Batista et al. 2015; Bennett et al. 2015):

$$A_{I,I} = \frac{1 - e^{-|D_L/(h_{dust}\sin b)|}}{1 - e^{-|D_L/(h_{dust}\sin b)|}} A_{I,S},$$

(8)

where the index $i$ denotes the passband: $V$, $I$, or $K$, and the dust scale height is $h_{dust} = 120$ pc. Here, we adopt the extinction to the source of $A_{V,S} = 2.98$ and $A_{K,S} = 0.35$ from the VVV/KMTC CMD analysis and VIK colour–colour relation of Bessell & Brett (1988), which were discussed in Section 4.

In Fig. 6 shows the results of the Bayesian analysis. From this, we find that the lens is a sub Jupiter-mass planet $M_p = 0.77^{+0.77}_{-0.53}$ $M_J$ orbiting a star $M_L = 0.43^{+0.33}_{-0.22}$ $M_\odot$ at a distance $D_L = 6.22^{+1.03}_{-1.51}$ kpc, and the projected star–planet separation is $3.30^{+0.59}_{-0.83}$ au. This indicates that OGLE-2018-BLG-1428L is likely to be an M dwarf star hosting a sub Jupiter-mass planet beyond the snow line based on $a_{snow} = 2.7 (M/M_\odot)$; Kennedy & Kenyon 2008). However, it could be also a K or a G dwarf. The physical parameters of the lens system are listed in Table 2. The lens distribution in Fig. 6 shows that the lens is located in the disc and bulge with equal probability. This is consistent with the relative proper motion of 5.6 mas yr$^{-1}$.

Fig. 6 also shows the Bayesian distributions for the brightness of host star. The distributions show that if the host star is a main-sequence star, its brightness is $I_L = 25.3^{+0.9}_{-2.4}$ and $K_L = 20.7^{+0.7}_{-1.8}$.
