OGLE-2018-BLG-1185b: A Low-Mass Microlensing Planet Orbiting a Low-Mass Dwarf

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We report the analysis of planetary microlensing event OGLE-2018-BLG-1185, which was observed by a large number of ground-based telescopes and by the Spitzer Space Telescope. The ground-based light curve indicates a low planet-host star mass ratio of \( q = (6.9 \pm 0.2) \times 10^{-5} \), which is near the peak of the wide-orbit exoplanet mass-ratio distribution. We estimate the host star and planet masses with a Bayesian analysis using the measured angular Einstein radius under the assumption that stars of all masses have an equal probability to host this planet. The flux variation observed by Spitzer was marginal, but still places a constraint on the microlens parallax. Imposing a conservative constraint that this flux variation should be \( \Delta f_{\text{Spz}} < 4 \) instrumental flux units indicates a host mass of \( M_{\text{host}} = 0.37^{+0.35}_{-0.21} M_\odot \) and a planet mass of \( m_p = 8.4^{+7.9}_{-4.7} M_\oplus \). A Bayesian analysis including the full parallax constraint from Spitzer suggests smaller host star and planet masses of \( M_{\text{host}} = 0.091^{+0.064}_{-0.018} M_\odot \) and \( m_p = 2.1^{+1.5}_{-0.4} M_\oplus \), respectively. Future high-resolution imaging observations with HST or ELTs could distinguish between these two scenarios and help to reveal the planetary system properties in more detail.
1. INTRODUCTION

The gravitational microlensing method has a unique sensitivity to low-mass planets (Bennett & Rhie 1996) beyond the snow line of the host star (Gould & Loeb 1992), where the core accretion theory predicts that planet formation is most efficient (Lissauer 1993; Pollack et al. 1996). The Microlensing Observations in Astrophysics (MOA; Bond et al. 2001; Sumi et al. 2003) collaboration presented the most complete statistical analysis of planets found by microlensing to date and the best measurement of the planet distribution beyond the snow line in Suzuki et al. (2016). They found that the mass-ratio distribution from the 2007–2012 MOA-II microlensing survey combined with earlier samples (Gould et al. 2010; Cassan et al. 2012) is well fitted by a broken power-law model.

Their result shows the mass-ratio distribution peaks at \( q_{br} = (6.7^{+9.0}_{-1.8}) \times 10^{-5} \) with power-law slopes of \( n = -0.85^{+0.12}_{-0.13} \) and \( p = 2.6^{+1.2}_{-2.1} \) above and below \( q_{br} \), respectively. This result is consistent with previous microlensing analyses which suggest that Neptune mass-ratio planets are more common than larger gas giants (Gould et al. 2006; Sumi et al. 2010) and further indicates that Neptune mass-ratio planets are, in fact, the most common type of planet (large or small) in wide orbits.

Additionally, Suzuki et al. (2018) reveals a disagreement between the measured mass ratio distribution in Suzuki et al. (2016) and the predictions of the runaway gas accretion scenario (Ida & Lin 2004), which is part of the standard core accretion theory. Population synthesis models based on core accretion, including runaway gas accretion, predict too few planets in the mass range of approximately \( 20-80M_{\oplus} \) compared to those inferred from microlensing observations. Similar tension is indicated by ALMA observations. Nayakshin et al. (2019) compared wide orbit (9–99 au) planet candidates with masses of \( 0.01M_{\text{jup}} \) to a few \( M_{\text{jup}} \) suggested by ALMA proto-planetary disk observations to a population synthesis prediction from the runaway gas accretion scenario. They found that the scenario predicts fewer sub-Jovian planets than those inferred from the ALMA observation. 3D hydrodynamical simulations of proto-planetary disks do not support the runaway gas accretion scenario either (Lambrechts et al. 2019).

The peak position of the mass-ratio function and its slope at small mass ratios are uncertain due to the lack of planets with mass ratios of \( q < 5.8 \times 10^{-5} \) in the Suzuki et al. (2016) sample. Udalski et al. (2018) and Jung et al. (2019b) used samples of published planets to refine the estimates of the peak and the low mass-ratio slope of the mass-ratio function. Udalski et al. (2018) confirmed the turnover shown in Suzuki et al. (2016) and obtained the slope index on the low-mass regime, \( p \sim 0.73 \), using seven published planets with \( q < 1 \times 10^{-4} \). Jung et al. (2019b) found \( q_{br} \sim 0.55 \times 10^{-4} \) using 15 published planets with low mass ratio \( (q < 3 \times 10^{-4}) \). The Jung et al. (2019b) study was subject to “publication bias”. That is, the planets were not part of a well-defined statistical sample. Instead, these planets were selected for publication for reasons that are not well characterized. Nevertheless, the authors make the case that this publication bias should not be large enough to invalidate their results. By contrast, the Udalski et al. (2018) study only made the implicit assumption that all

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1 These values are the median and 68% confidence level by the Markov Chain Monte Carlo analysis with the thirty planet sample, which are given in Table 5 of Suzuki et al. (2016). So the 1σ range of the mass-ratio distribution peaks is roughly \( q_{br} \sim (0.5–2) \times 10^{-4} \). At the same time, they also show that the best fitting parameters are \( q_{br} = 1.65 \times 10^{-4} \) with power-law slopes of \( n = -0.92 \) and \( p = 0.47 \) in Table 4 of Suzuki et al. (2016).
planets with \( q < 1 \times 10^{-4} \) (and greater than that of the actual published planet) would have been published. If this is true (which is very likely), the study is not subject to publication bias.

A more definitive improvement of the Suzuki et al. (2016) mass-ratio function can be obtained with an extension of the MOA-II statistical sample to include additional microlensing seasons (Suzuki et al., in preparation). The low mass-ratio planet analyzed in this paper, OGLE-2018-BLG-1185Lb, will be part of that extended sample, and it will contribute to an improved characterization of the low end of the wide orbit exoplanet mass-ratio function.

The statistical analysis of the wide-orbit planet population can also be improved by including information on the lens physical parameters, such as the lens mass, \( M_L \), and the distance to the lens star, \( D_L \). While the lens planet-host mass ratios, \( q \), are usually well constrained from the light-curve modeling, we need at least two mass-distance relations in order to derive \( M_L \) and \( D_L \) directly. There are three observables that can yield mass-distance relations: finite source effects, microlens parallax effects, and direct detection of the lens flux.

In recent years, lens flux detection by high-resolution imaging follow-up observations (such as by the Hubble Space Telescope (HST) or Keck) has been done for several microlens planetary systems after the lens and the source are separated enough to be detected (Bennett et al. 2006, 2007, 2015, 2020; Batista et al. 2014, 2015; Bhattacharya et al. 2017, 2018; Koshimoto et al. 2017; Vandorou et al. 2020). However, the required separation for resolving the lens and source depends on their relative brightnesses, and even if they are comparable in brightness, it typically takes a few years for them to separate sufficiently.

If both the Einstein radius \( \theta_E \) from the finite source effect and the microlens parallax \( \pi_E \) from the parallax effect are measured, we can derive two mass-distance relations as follows,

\[
M_L = \frac{c^2}{4G} \theta_E^2 \frac{D_S D_L}{D_S - D_L} = \frac{c^2}{4G} \frac{\text{au}}{\pi_E^2} \frac{D_S - D_L}{D_S D_L},
\]

where \( D_S \) is the distance to the source (Gould 1992, 2000). Finite source effects are detected in most planetary-lens events through the observation of a caustic crossing or a close approach to a caustic cusp, thus enabling the measurement of \( \theta_E \).

The most common method for measuring the microlens parallax has been via the effects of the motion of the observer, which is called the “orbital parallax effect.” In order to detect the orbital parallax, the ratio of \( t_E \) (typically \( t_E \) is \( \sim 30 \) days) to Earth’s orbital period (365 days) should be significant. Thus, we only measure the orbital parallax effect for microlensing events with long durations and/or with relatively nearby lens systems, yielding mass measurements in less than half of published microlensing planetary systems.

The most effective method for routinely obtaining a microlens parallax measurement is via the “satellite parallax effect” (Refsdal 1966), which is caused by the separation between two observers. Because the typical Einstein radius projected onto the observer plane, \( \tilde{r}_E \), is about 10 au, the satellite parallax effect can be measured for a wide range of microlenses provided the separation between Earth and the satellite is about 1 au (as was the case for Spitzer).

For the purpose of measuring the Galactic distribution of planets and making mass measurements through the satellite parallax effect, the Spitzer microlensing campaign was carried out from 2014–2019 (Gould, & Yee 2013; Gould et al. 2014, 2015a,b, 2016, 2018). During the six-year program, close to 1000 microlensing events were simultaneously observed from the ground and by Spitzer,
and there are 11 published\textsuperscript{2} planets with satellite parallax measurements from \textit{Spitzer}: OGLE-2014-BLG-0124Lb (Udalski et al. 2015b), OGLE-2015-BLG-0966Lb (Street et al. 2016), OGLE-2016-BLG-1067Lb (Calchi Novati et al. 2019), OGLE-2016-BLG-1195Lb (Shvartzvald et al. 2017), OGLE-2016-BLG-1190Lb (Ryu et al. 2018), OGLE-2017-BLG-1140Lb (Calchi Novati et al. 2018), TCP J05074264+2447555 (Nucita et al. 2018; Fukui et al. 2019; Zang et al. 2020b), OGLE-2018-BLG-0596Lb (Jung et al. 2019a), KMT-2018-BLG-0029Lb (Gould et al. 2020), OGLE-2017-BLG-0406Lb (Hirao et al. 2020), and OGLE-2018-BLG-0799Lb (Zang et al. 2020c). Comparing the planet frequency in the disk to that in the bulge could probe the effects of the different environments on the planet formation process.

Obvious correlated noise in the \textit{Spitzer} photometry was first noted by Poleski et al. (2016) and Zhu et al. (2017), but those works did not expect the systematic errors would have a significant effect on the parallax measurements. Indeed, two comparisons of small, heterogeneous samples of published \textit{Spitzer} microlensing events confirmed this expectation (Shan et al. 2019; Zang et al. 2020a). However, a larger study (Koshimoto & Bennett 2020) of the 50-event statistical sample of Zhu et al. (2017) indicated a conflict between the \textit{Spitzer} microlensing parallax measurements and Galactic models. They suggested that this conflict was probably caused by systematic errors in the \textit{Spitzer} photometry. Based, in part, on the Koshimoto & Bennett (2020) analysis, the \textit{Spitzer} microlensing team has made a greater effort to understand these systematic errors, including obtaining baseline data in 2019 for many of the earlier planetary events. These additional baseline data proved very useful in characterizing systematics in the \textit{Spitzer} photometry for three previously published events (Gould et al. 2020; Hirao et al. 2020; Zang et al. 2020c). Those analyses show that systematics in the \textit{Spitzer} photometry can be present at the level of 1–2 instrumental flux units, so observed signals in the \textit{Spitzer} photometry on those scales should be interpreted with caution.

In this paper, we present the analysis of planetary microlensing event OGLE-2018-BLG-1185, which was simultaneously observed by many ground-based telescopes and by the \textit{Spitzer} Space Telescope. From the ground-based light-curve analysis, the planet-host star mass ratio turns out to be very low, \(q \sim 6.9 \times 10^{-5}\), which is thought to be near the peak of the wide-orbit exoplanet mass-ratio distribution in Suzuki et al. (2016), Udalski et al. (2018), and Jung et al. (2019b). Section 2 explains the observations and the data reductions. Our ground-based light-curve modeling method and results are shown in Section 3. In Section 4, we derive the angular Einstein radius from the source magnitude and color and the finite source effect in order to constrain the physical parameters of the planetary system. In Section 5, we estimate the physical properties such as the host star and planet masses based on the ground-based light curve alone by performing a Bayesian analysis using the measured angular Einstein radius under the assumption that stars of all masses have an equal probability to host this planet. We present our parallax analysis including the \textit{Spitzer} data in Section 6. Finally, we discuss the analysis and summarize our conclusions in Section 7.

\section{Observations and Data Reductions}

\subsection{Ground-based Survey Observations}

\footnote{In addition Yee et al. (2021) have submitted a paper on OGLE-2019-BLG-0960.}
The microlensing event OGLE-2018-BLG-1185 was first discovered on 2018 July 7 (HJD′ = HJD − 2450000 ∼ 8306), at the J2000 equatorial coordinates (RA, Dec) = (17h 59m 10.26s, −27° 50′ 06″.3) corresponding to Galactic coordinates (l, b) = (2.465°, −2.004°) by the Optical Gravitational Lensing Experiment (OGLE; Udalski 2003) collaboration. The OGLE collaboration conducts a microlensing survey using the 1.3m Warsaw telescope with a 1.4 deg² field-of-view (FOV) CCD camera at Las Campanas Observatory in Chile and distributes alerts of the discovery of the microlensing events by the OGLE-IV Early Warning System (Udalski et al. 1994; Udalski 2003). The event is located in the OGLE-IV field BLG 504, which is observed with a cadence of one observation per hour.

The event was also discovered independently on 2018 July 9 by the MOA collaboration and identified as MOA-2018-BLG-228 by the MOA alert system (Bond et al. 2001). The MOA collaboration conducts a microlensing exoplanet survey toward the Galactic bulge using the 1.8m MOA-II telescope with a 2.2 deg² wide FOV CCD-camera, MOA-cam3 (Sako et al. 2008) at the University of Canterbury’s Mt. John Observatory in New Zealand. The MOA survey uses a custom wide-band filter referred to as R_{MOA}, corresponding to the sum of the Cousins R- and I-bands and also uses a Johnson V-band filter. The event is located in the MOA field gb10, which is observed at a high cadence of one observation every 15 minutes.

The Korea Microlensing Telescope Network (KMTNet; Kim et al. 2016) collaboration conducts a microlensing survey using three 1.6m telescopes each with a 4.0 deg² FOV CCD camera. The telescopes are located at Cerro Tololo Interamerican Observatory in Chile (KMTTC), South African Astronomical Observatory in South Africa (KMTS), and Siding Spring Observatory in Australia (KMTA). This event is located in an overlapping region between two fields (KMTNet BLG03 and BLG43) and was identified by the KMTNet EventFinder (Kim et al. 2018) as KMT-2018-BLG-1024.

2.2. Spitzer Observations

In order to construct statistical samples from the Spitzer microlensing campaign, Yee et al. (2015) established detailed protocols for the selection and observational cadence of Spitzer microlensing targets. On 2018 July 8 (HJD′ ∼ 8308.25), OGLE-2018-BLG-1185 was selected as a “Subjective, Immediate” (SI) target to be observed with the “objective” cadence by the Spitzer microlensing team. The selection as SI meant that this event was observed even though it never met the objective criteria established in Yee et al. (2015). The Spitzer Space Telescope began to observe this event on 2018 July 14 (HJD′ ∼ 8313.83), which was three days after the peak observed from the ground-based telescopes. The “objective” cadence resulted in approximately one observation per day for the remainder of the observing window (27 days total). These observations were taken with the IRAC camera in the 3.6 μm (L) band.

2.3. Ground-based Follow-up Observations

After the event was selected for Spitzer observations, some ground-based follow-up observations were conducted. Microlensing Network for the Detection of Small Terrestrial Exoplanets (MiND-STEp) used the 1.54m Danish Telescope at La Silla Observatory in Chile and the 0.6m telescope at Salerno University Observatory in Italy. The Microlensing Follow Up Network (μFUN) used the 1.3m SMARTS telescope at CTIO in Chile. Las Cumbres Observatory (LCO; Brown et al. 2013) used the 1.0m telescopes at CTIO in Chile, at SSO in Australia, and at SAAO in South Africa, as a part of LCO-Spitzer program. The ROME/REA team (Tsapras et al. 2019) also used the 1.0m
LCO robotic telescopes at CTIO in Chile, at SSO in Australia, and at SAAO in South Africa. A summary of observations from each telescope is given in Table 1.

2.4. Data Reduction

The OGLE, MOA, and KMTNet data were reduced using the OGLE Difference Image Analysis (DIA) photometry pipeline (Udalski 2003), the MOA DIA photometry pipeline (Bond et al. 2001), and the KMTNet pySIS photometry pipeline (Albrow et al. 2009), respectively. The MiNDSTEp data were reduced using DanDIA (Bramich 2008; Bramich et al. 2013). μFUN data were reduced using DoPHOT (Schechter et al. 1993), and LCO data from the LCO-Spitzer program were reduced using a modified ISIS package (Alard & Lupton 1998; Alard 2000; Zang et al. 2018). The LCO data obtained by the ROME/REA team were reduced using a customized version of the DanDIA photometry pipeline. The Spitzer data were reduced using the photometry algorithm described in Calchi Novati et al. (2015).

It is known that the photometric error bars calculated by the data pipelines can be underestimated (or more rarely overestimated). Various reasons, such as observational conditions, can cause systematic errors. In order to get proper errors of the parameters in the light-curve modeling, we empirically normalize the error bars by using the standard method of Bennett et al. (2008). We use the formula,

$$\sigma_i' = k \sqrt{\sigma_i^2 + \epsilon_{\text{min}}^2},$$  \hspace{1cm} (2)

where $\sigma_i'$ is the ith renormalized error, $\sigma_i$ is the ith error obtained from DIA, and $k$ and $\epsilon_{\text{min}}$ are the renormalizing parameters. We set the value of $\epsilon_{\text{min}}$ to account for systematic errors which dominate at high magnification, and we adjust the value of $k$ to achieve $\chi^2/\text{dof} = 1$. The data from Salerno, LCO SAAO by the LCO-Spitzer program, LCO SSO and SAAO by the ROME/REA project are either too few to give any significant constraint or show systematics and disagreement with other datasets. Therefore, we do not use them for the modeling. We list the calculated error-bar renormalization parameters in Table 1.

3. GROUND-BASED LIGHT CURVE ANALYSIS

3.1. Binary-lens model

The magnification of the binary lens model depends on seven parameters: the time of lens-source closest approach $t_0$, the Einstein radius crossing time $t_E$, the impact parameter in units of the Einstein radius $u_0$, the planet-host mass ratio, $q$, the planet-host separation in units of the Einstein radius, $s$, the angle between the trajectory of the source and the planet-host axis, $\alpha$, and the ratio of the angular source size to the angular Einstein radius, $\rho$. The model flux $f(t)$ of the magnified source at time $t$ is given by,

$$f(t) = A(t)f_S + f_b,$$  \hspace{1cm} (3)

where $A(t)$ is a magnification of the source star, and $f_S$ and $f_b$ are the unmagnified flux from the source and the flux from any unresolved blend stars, respectively.

We also adopt a linear limb-darkening model for the source star,

$$S_\lambda(\vartheta) = S_\lambda(0)[1 - u_\lambda(1 - \cos(\vartheta))],$$  \hspace{1cm} (4)
Table 1. The number of data points in the light curves and the normalization parameters

| Name         | Site          | Collaboration | Aperture(m) | Filter | $k$   | $\epsilon_{\text{min}}$ | $N_{\text{use}}/N_{\text{obs}}$ |
|--------------|---------------|---------------|-------------|--------|------|--------------------------|----------------------------------|
| OGLE         | Chile         | OGLE          | 1.3         | $I$    | 1.660| 0.003                    | 3045/3045                        |
| OGLE         | Chile         | OGLE          | 1.3         | $V$    | 1.301| 0.003                    | 68/68                            |
| MOA          | New Zealand   | MOA           | 1.8         | $R_{\text{MOA}}$ | 1.650| 0.003                    | 7277/7509                        |
| MOA          | New Zealand   | MOA           | 1.8         | $V$    | 1.321| 0.003                    | 240/240                          |
| KMT SSO f03  | Australia     | KMTNet        | 1.6         | $I$    | 1.900| 0.003                    | 2087/2706                        |
| KMT SSO f43  | Australia     | KMTNet        | 1.6         | $I$    | 1.824| 0.003                    | 2080/2678                        |
| KMT CTIO f03 | Chile         | KMTNet        | 1.6         | $I$    | 1.579| 0.003                    | 2304/2486                        |
| KMT CTIO f43 | Chile         | KMTNet        | 1.6         | $I$    | 1.443| 0.003                    | 2195/2363                        |
| KMT SAAO f03 | South Africa  | KMTNet        | 1.6         | $I$    | 2.444| 0.003                    | 1813/2096                        |
| KMT SAAO f43 | South Africa  | KMTNet        | 1.6         | $I$    | 1.900| 0.003                    | 1846/2078                        |
| Danish       | Chile         | MiNDSTEp      | 1.54        | $Z$    | 1.015| 0.003                    | 139/154                          |
| Salerno      | Italy         | MiNDSTEp      | 0.6         | $I$    | 0/5                          |
| LCO SSO      | Australia     | LCO-\textit{Spitzer} | 1.0          | $i'$  | 2.528| 0.003                    | 31/44                            |
| LCO CTIO     | Chile         | LCO-\textit{Spitzer} | 1.0          | $i'$  | 1.129| 0.003                    | 17/17                            |
| LCO SAAO     | South Africa  | LCO-\textit{Spitzer} | 1.0          | $i'$  | 0/19                        |
| CTIO 1.3m    | Chile         | $\mu$FUN      | 1.3         | $I$    | 0.852| 0.003                    | 18/18                            |
| CTIO 1.3m    | Chile         | $\mu$FUN      | 1.3         | $V$    | 0.566| 0.003                    | 3/3                              |
| LCO SSO      | Australia     | ROME/REA      | 1.0         | $g$    | 0/25                        |
| LCO SSO      | Australia     | ROME/REA      | 1.0         | $i'$  | 0/74                        |
| LCO SSO      | Australia     | ROME/REA      | 1.0         | $r$    | 0/29                        |
| LCO CTIO     | Chile         | ROME/REA      | 1.0         | $g$    | 1.110| 0.003                    | 33/33                            |
| LCO CTIO     | Chile         | ROME/REA      | 1.0         | $i'$  | 1.589| 0.003                    | 61/61                            |
| LCO CTIO     | Chile         | ROME/REA      | 1.0         | $r$    | 1.337| 0.003                    | 31/31                            |
| LCO SAAO     | South Africa  | ROME/REA      | 1.0         | $g$    | 0/17                        |
| LCO SAAO     | South Africa  | ROME/REA      | 1.0         | $i'$  | 0/19                        |
| LCO SAAO     | South Africa  | ROME/REA      | 1.0         | $r$    | 0/45                        |
| \textit{Spitzer} | Earth-trailing orbit | \textit{Spitzer} | 0.85        | $L$    | 2.110| ...                       | 26/26                            |

where $S_\lambda(\vartheta)$ is a limb-darkened surface brightness. The effective temperature of the source star estimated from the extinction-free source color presented in Section 4 is $T_{\text{eff}} \sim 5662K$ (González Hernández & Bonifacio 2009). Assuming a surface gravity $\log g = 4.5$ and a metallicity of $\log[M/H] = 0$, we select the limb-darkening coefficients to be $u_I = 0.5494$, $u_V = 0.7105$, $u_R = 0.6343$, $u_Z = 0.6314$, $u_g = 0.7573$, $u_r = 0.6283$ and $u_i = 0.5389$ from the ATLAS model (Claret & Bloemen 2011). For the $R_{\text{MOA}}$ passband, we use the coefficient for $u_{\text{Red}} = 0.5919$, which is the mean of $u_I$ and $u_R$.

We first conducted the light-curve fitting with only ground-based data. We employed the Markov Chain Monte Carlo algorithm (Verde et al. 2003) combined with the image-centered ray-shooting method (Bennett & Rhie 1996; Bennett 2010). We conducted the grid search analysis following the
same procedure in Kondo et al. (2019). First, we performed a broad grid search over \((q, s, \alpha)\) space with the other parameters free. The search ranges of \(q, s,\) and \(\alpha\) are \(-6 < \log q < 0, -0.5 < \log s < 0.6,\) and \(0 < \alpha < 2\pi,\) with 11, 22, and 40 grid points, respectively. Next, we refined all parameters for the best 100 models with the smallest \(\chi^2\) to search for the global best-fit model.

The parameters of the best-fit models are summarized in Table 2. The light curve and the caustic geometry are shown in Figure 1 and Figure 2. As a result of the grid search, we found that the best-fit binary-lens model is favored over the single-lens model by \(\Delta \chi^2 \sim 2330.\) The bottom panels in Figure 1 show the clear deviations of the light curve with respect to the single-lens model from HJD’ \(\sim 8310.9\) to \(\sim 8311.8,\) which are well fitted by the approach to the central caustic for the best binary-lens model. Although the additional magnification from the cusp approach to the planetary caustic is small, the asymmetric feature in the right side of the light curve due to the approach to the central caustic shows clear residuals from the single-lens model, which suggests the existence of a companion. The best binary-lens model suggests that the lens system has a very low mass ratio, \(q \sim 6.9 \times 10^{-5},\) with a normalized separation \(s \sim 0.96.\) It is well known that there is a close/wide degeneracy in high-mag binary-lens events (Griest & Safizadeh 1998; Dominik 1999; Chung et al. 2005), which is due to the similar shape and size of the central caustic between \(s\) and \(s^{-1}.\) From the grid search, we found the best wide binary-lens model \((s > 1)\) has \(q \sim 9.2 \times 10^{-5}\) and \(s \sim 1.14.\) The separation of this wide model is slightly different from the reciprocal of the separation of the close model \((s < 1),\) yielding a different shape and size for the central caustic from those of the best close model. We ruled out the wide model because the best close binary-lens model is favored over the wide model by \(\Delta \chi^2 \sim 268.\) The \(\Delta \chi^2\) is large because the source trajectory is parallel to the lens axis and approaches not only the central caustic but also the planetary caustics.

3.2. Binary-source model

We checked the possibility that the observed light-curve can be explained by the binary-source (1L2S) model because it is known that there is a possible degeneracy between single-lens binary-source (1L2S) model and binary-lens single-source (2L1S) model (Griest & Hu 1993; Gaudi 1998). For the 1L2S model, the total effective magnification of the source stars \(A\) is expressed as follows,

\[
A = \frac{A_1 f_1 + A_2 f_2}{f_1 + f_2} = \frac{A_1 + q_f A_2}{1 + q_f},
\]

where \(A_1\) and \(A_2\) are the magnification of the two sources with model flux \(f_1\) and \(f_2,\) respectively, and \(q_f\) is the flux ratio between the two sources \((= f_2/f_1).\) In order to explain the magnification of the second source, we introduce the additional parameters: the time of lens-source closest approach \(t_{0,2},\) the impact parameter in units of the Einstein radius \(u_{0,2},\) and the ratio of the angular source size to the angular Einstein radius, \(\rho_2.\) We found the best-fit 1L2S model is disfavored relative to the best-fit 2L1S model by \(\Delta \chi^2 \sim 380,\) and we excluded the 1L2S model. The parameters of the best-fit 1S2L model are summarized in Table 2. The light curve of the 1L2S model is shown in Figure 1.

3.3. Ground-Based Parallax

The magnification of the binary lens model with parallax effects need two additional parameters: the North and East components of parallax vector \(\vec{\pi}_E\) in equatorial coordinates, \(\pi_{E,E}\) and \(\pi_{E,N}\) (Gould 2004). The orbital parallax effects are caused by Earth’s orbital motion. In the case of OGLE-2018-BLG-1185, the timescale, \(t_E \sim 15.9\) days, is small compared to Earth’s orbital period, which makes
it less likely to measure the parallax effects. The best-fit parallax model improves the fit slightly by $\Delta \chi^2 \sim 20$, but there is disagreement of the $\chi^2$ improvement between the datasets. The parallax information such as the direction and the value is easily influenced by the systematics in each telescope dataset. Considering these facts, we concluded that we should disregard the parallax information from the ground-based data.

Table 2. The best-fit models for ground-only data

| Parameters | Unit | 2L1S(close) | 2L1S(wide) | 1L2S |
|------------|------|-------------|------------|------|
| $\chi^2$/dof |      | 23221.473/23252 | 23489.306/23252 | 23601.431/23249 |
| $t_{0,1}$ | HJD$'$ | 8310.7772 ± 0.0003 | 8310.7793 ± 0.0003 | 8310.7726 ± 0.0003 |
| $t_{0,2}$ | HJD$'$ | ... | ... | 8311.5874 ± 0.0010 |
| $t_E$ | days | 15.931 ± 0.133 | 16.312 ± 0.144 | 15.730 ± 0.189 |
| $u_{0,1}$ | $10^{-3}$ | 6.877 ± 0.063 | 6.606 ± 0.067 | 7.777 ± 0.131 |
| $u_{0,2}$ | $10^{-3}$ | ... | ... | 8.773 ± 1.515 |
| $q$ | $10^{-5}$ | 6.869 ± 0.229 | 9.164 ± 0.552 | ... |
| $s$ | | 0.963 ± 0.001 | 1.144 ± 0.003 | ... |
| $\alpha$ | radian | 0.114 ± 0.001 | 3.261 ± 0.002 | ... |
| $\rho_1$ | $10^{-3}$ | 3.468 ± 0.083 | <1.026$^a$ | 7.234 ± 0.241 |
| $\rho_2$ | $10^{-3}$ | ... | ... | 1.613 ± 0.956 |
| $q_{f,I}$ | $10^{-2}$ | ... | ... | 1.699 ± 0.192 |
| $f_s$ (OGLE)$^b$ | | 107.777 ± 0.437 | 106.493 ± 0.448 | 108.583 ± 0.550 |
| $f_b$ (OGLE)$^b$ | | 396.165 ± 0.594 | 397.397 ± 0.440 | 393.516 ± 0.587 |

$^a$ The value is the 3σ upper limit.

$^b$ All fluxes are on a 25th magnitude scale, e.g., $I_S = 25 - 2.5 \log(f_S)$.

4. ANGULAR EINSTEIN RADIUS

We can estimate the angular Einstein radius $\theta_E = \theta_s/\rho$ because $\rho$ can be derived by the light-curve fitting and the angular source radius $\theta_s$ can be derived by using an empirical relation between $\theta_s$, the extinction-corrected source color ($V - I$)$_{S,0}$, and the magnitude $I_{S,0}$ (e.g., Boyajian et al. 2014).

We derived the OGLE-IV instrumental source color and magnitude from the light-curve fitting and then converted them to the standard ones by using the following color-color relation from Udalski et al. (2015a):

$$I_{O3} - I_{O4} = (0.182 \pm 0.015) + (-0.008 \pm 0.003)(V - I)_{O3}, \quad (6)$$
$$V_{O3} - V_{O4} = (0.257 \pm 0.015) + (-0.074 \pm 0.004)(V - I)_{O3}. \quad (7)$$

The apparent color and the standard magnitude of the source star are $(V - I)_{S,O4,\text{calib}} = (2.344 \pm 0.031, 20.082 \pm 0.012)$.

We also derived the apparent source color and magnitude from the CT13 measurements in the $I$- and $V$-bands from the light-curve fitting, and then converted them to the standard ones following the
Figure 1. The light curve and models with the ground-based data for OGLE-2018-BLG-1185. Top panel shows the light curve, models, and residuals from the best-fit close binary-lens (2L1S) model. The blue line shows the best-fit close binary-lens (2L1S) model. The red, orange, and green dot lines show the single-lens (1L1S) model, the wide 2L1S model, and the binary-source (1L2S) model, respectively. The left bottom panel and the right panel show the zoom-in of the light curve, where we can find clear deviations of data points from the 1L1S and 1L2S models.

procedure explained in Bond et al. (2017). We cross-referenced isolated stars in the CT13 catalog reduced by DoPHOT (Schechter et al. 1993) with the stars in the OGLE-III map within 120″ of the source star and obtained the color-color relation:

\[ I_{O3} - I_{CT13} = (-0.880 \pm 0.005) + (-0.042 \pm 0.005)(V - I)_{CT13}, \]  
\[ V_{O3} - I_{CT13} = (1.290 \pm 0.004) + (-0.036 \pm 0.004)(V - I)_{CT13}. \]  

The apparent color and magnitude of the source star are \((V - I)_{S, CT13, \text{calib}} = (2.335 \pm 0.025, 20.105 \pm 0.013)\). This color is consistent within 1σ and the magnitude is consistent with \(I_{S, O4, \text{calib}}\) within 2σ. Because the light curve was well covered by the OGLE observations, while it was highly magnified, we adopted \((V - I, I)_{S, O4, \text{calib}}\) as the source color and magnitude.

To obtain the extinction-corrected source color and magnitude, we used the standard method from Yoo et al. (2004). The intrinsic color and magnitude are determined from the source location relative to the color and magnitude of the red clump giant (RCG) centroid in the color-magnitude diagram (CMD). In Figure 3, the red point shows the RCG centroid color and magnitude, \((V - I, I)_{\text{RCG}} = (2.720, 16.325) \pm (0.009, 0.032)\) for the field around the source star. Assuming that the source star
Figure 2. Caustic geometry of the best-fit model. The caustics are shown in red lines. The blue line shows
the source trajectory on the lens plane and the arrow indicates the direction of the source/lens relative
proper motion. The blue open circle indicates the source size and position at $t_0$.

suffers the same reddening and extinction as the RCGs, we compared these values to the expected
extinction-corrected RCG color and magnitude for this field, $(V - I)_{RCG,0} = (1.060, 14.362) \pm
(0.070, 0.040)$ (Bensby et al. 2013; Nataf et al. 2013). As a result, we obtained an extinction of
$A_I = 1.963 \pm 0.051$ and a color excess of $E(V - I) = 1.660 \pm 0.071$. Finally, the intrinsic source color
and magnitude were derived,

$$(V - I, I)_{S,0} = (0.684, 18.119) \pm (0.077, 0.053).$$

As a reference for the later discussion of the future follow-up observations, we also estimated the
intrinsic source magnitudes in $H$- and $K$-bands from the color-color relation in Kenyon & Hartmann
(1995), including a 5% uncertainty. Then, we applied the extinction in the $H$- and $K$-bands, which
were derived from the extinction in the $I$- and $V$-bands of the RCGs according to Cardelli et al.
(1989).

Figure 3 shows that the source is consistent with being part of the standard bulge sequence of
stars, i.e., it falls within the distribution of stars from (Holtzman et al. 1998) after they have been
shifted to the same reddening and extinction as the field for OGLE-2018-BLG-1185. However, the
source also has a similar color to the Sun. Thus, it would also be consistent with being a similar
absolute magnitude to the Sun but somewhat in the foreground, e.g., at $\sim 6$ kpc. Thus, we also
checked how a different assumption about the source would affect our results. If the source was more
in the foreground, it would then suffer less extinction and reddening than the RCGs. However, even
if we assume 10% less extinction and reddening than the RCGs, the value of $\theta_E$ increases by only 7%,
which is still consistent within 1σ with values obtained assuming the same extinction and reddening as the RCGs. We summarize the source color and magnitudes in Table 3.

Applying the empirical formula, $\log(\theta_{\text{LD}}) = 0.501414 + 0.419685(V-I) - 0.2I$ (see Fukui et al. 2015 but also Boyajian et al. 2014), where $\theta_{\text{LD}} \equiv 2\theta_*$ is the limb-darkened stellar angular diameter, we found the angular source radius,

$$\theta_{\text{LD}} = 1.461 \pm 0.109 \text{ µas},$$

$$\theta_* = 0.730 \pm 0.059 \text{ µas}. \quad (11)$$

Finally, we obtained the source angular radius and the lens–source relative proper motion in the geocentric frame,

$$\theta_E = \frac{\theta_*}{\rho} = 0.211 \pm 0.018 \text{ mas},$$

$$\mu_{\text{rel,geo}} = \frac{\theta_E}{t_E} = 4.832 \pm 0.410 \text{ mas yr}^{-1}. \quad (14)$$

This $\theta_E$ value is relatively small, which suggests that the lens is a low-mass star and/or distant from the observer.

### Table 3. The source color and magnitudes

| Parameters | Unit | Source (apparent) | Source (intrinsic)$^a$ | Source (intrinsic)$^b$ |
|------------|------|-------------------|------------------------|------------------------|
| $I$        | mag  | 20.082 ± 0.012 c  | 18.119±0.053           | 18.315±0.053           |
| $V-I$      | mag  | 2.344 ± 0.031 c   | 0.684±0.077            | 0.850±0.077            |
| $H$ $^d$   | mag  | 18.012±0.143      | 17.444±0.095           | · · ·                  |
| $K$ $^d$   | mag  | 17.756±0.145      | 17.394±0.095           | · · ·                  |

$^a$ Extinction-corrected magnitudes assuming that the source star suffers the same reddening and extinction as the RCGs.

$^b$ Extinction-corrected magnitudes assuming that the source star suffers the reddening and extinction of 0.9 times as much as that for the RCGs.

$^c$ The magnitude and color are measured from the light-curve fitting.

$^d$ The magnitudes are estimated from the color-color relation in Kenyon & Hartmann (1995) and the extinction law in Cardelli et al. (1989).

### 5. LENS PHYSICAL PARAMETERS BY BAYESIAN ANALYSIS

If we can measure both the finite source effects and the parallax effects, the lens physical parameters such as the host mass $M_{\text{host}}$ and the distance to the lens $D_L$ are calculated directly, following the equations:

$$M_{\text{host}} = \frac{\theta_E}{(1 + q)\kappa \pi_E}; \quad D_L = \frac{au}{\pi_{\text{rel}} + \pi_S}; \quad \pi_{\text{rel}} = \theta_E \pi_E; \quad \mu_{\text{rel}} = \frac{\theta_E \pi_E}{t_E \pi_E}. \quad (15)$$
**Figure 3.** Color magnitude diagram (CMD). The stars in the OGLE-III catalog within 120″ of the source star are shown with black dots. The green dots indicate the *HST* CMD of (Holtzman et al. 1998), which is transformed to the same reddening and extinction of the field of the event. The red dot shows the centroid of the red clump giant distribution. The colors and magnitudes of the source star and the blend are shown with blue and pink, respectively.

where $\kappa \equiv 4G/(c^2\text{au}) = 8.1439 \text{ mas}/M_\odot$, and $\pi_S = \text{au}/D_S$ is the source parallax. From the ground-based light-curve alone, we are only able to measure $\theta_E$ (via finite source effects), but no meaningful constraint on $\pi_E$ (see Section 3.3).

In order to estimate the probability distributions of $M_L$ and $D_L$, we conducted a Bayesian analysis with the Galactic model of Koshimoto et al. (2021) as a prior. We randomly generated 50 million simulated microlensing event samples. Then we calculated the probability distributions for the lens physical parameters by weighting the microlensing event rate by the measured $t_E$ and $\theta_E$ likelihood distribution. It is important to note that we conducted the Bayesian analysis under the assumption that stars of all masses have an equal probability to host this planet.

We calculated some parameters in addition to the lens physical parameters, $M_L$ and $D_L$. For instance, the lens-source proper motion in the geocentric frame, $\mu_{\text{rel}}$, is converted to that in the heliocentric frame,

$$\mu_{\text{rel, hel}} = \mu_{\text{rel}} + v_{\oplus, \perp} \frac{\pi_{\text{rel}}}{\text{au}},$$

where $v_{\oplus, \perp} = (v_{\oplus, N}, v_{\oplus, E}) = (-0.78, 27.66) \text{ km/s}$ is the projected velocity of Earth at $t_0$.

We also calculated the $I$- and $V$-band magnitudes of the lens from the mass-luminosity relations of main-sequence stars (Kenyon & Hartmann 1995), and the 5 Gyr isochrone for brown dwarfs from Baraffe et al. (2003). Then we estimated $H$- and $K$-band magnitudes of the lens from the color-
color relation in Kenyon & Hartmann (1995), including a 5% uncertainty. In order to estimate the extinction in the foreground of the lens, we assumed a dust scale height of $h_{\text{dust}} = 0.10 \pm 0.02$ kpc (Bennett et al. 2015),

$$A_{\lambda,L} = \frac{1 - e^{-[D_L/(h_{\text{dust}} \sin b)]}}{1 - e^{-[D_S/(h_{\text{dust}} \sin b)]}} A_{\lambda,S},$$

(17)

where the index $\lambda$ refers to the passband: $V$-, $I$-, $H$-, or $K$-band. We obtained the extinction in the $I$- and $V$-band magnitudes of the source from the RCGs in Section 4, and then we converted them to the extinction in the $H$- and $K$-bands according to Cardelli et al. (1989).

The results are shown in Table 4 and Figure 4. According to Figure 4, the lens system is likely to be a super-Earth with a mass of $m_p = 8.1^{+7.6}_{-4.4} M_{\oplus}$ orbiting a late M-dwarf with a mass of $M_{\text{host}} = 0.36^{+0.33}_{-0.19} M_{\odot}$ at a projected separation of $a_\perp = 1.54^{+0.18}_{-0.22}$ au. The system is located $D_L = 7.4^{+0.5}_{-0.9}$ kpc from Earth. For reference, we also plot the source magnitudes in $V$-, $I$-, $H$-, and $K$-band as the red lines; the $H$- and $K$-band magnitudes were estimated in Section 4. We also show the parallax contour derived from the Bayesian analysis in Figure 5.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Probability distribution of lens properties derived from the Bayesian analysis with a Galactic prior and constrained by $t_E$ and $\theta_E$. The vertical blue lines show the median values. The dark-blue and the light-blue regions show the 68.3% and 95.4% confidence intervals. The red vertical lines in the probability distributions of $I$-, $V$-, $H$-, and $K$-band magnitudes show the magnitudes of the source star with extinction.
Figure 5. Left: The parallax contours for OGLE-2018-BLG-1185 expected from the Galactic model of Koshimoto et al. (2021) after imposing the two observational constraints of the angular Einstein radius, $\theta_E$ and the Einstein radius crossing time, $t_E$, on the event rate. The colorbar corresponds to the logarithm of the event rate and the red region indicates higher probability. Center: Including the constraint that $\Delta f_{\text{Spz}} < 4$. Right: Including the full constraint from the Spitzer-“only” parallax.

Table 4. The lens physical parameters

| Parameters | Unit  | Ground-only | Ground + $\Delta f_{\text{Spz}}$ | Ground + $\pi_{E,\text{Spz}}$ | Naive Spitzer-“only” |
|------------|-------|-------------|-----------------------------|-----------------------------|---------------------|
| $M_{\text{host}}$ | $M_\odot$ | $0.36^{+0.33}_{-0.19}$ | $0.37^{+0.35}_{-0.21}$ | $0.091^{+0.064}_{-0.028}$ | $0.073 \pm 0.011$ | $0.070 \pm 0.010$ |
| $m_p$ | $M_\odot$ | $8.1^{+7.6}_{-4.4}$ | $8.4^{+7.9}_{-4.7}$ | $2.1^{+1.5}_{-0.4}$ | $1.7 \pm 0.3$ | $1.6 \pm 0.2$ |
| $D_L$ | kpc | $7.40^{+0.51}_{-0.85}$ | $7.40^{+0.51}_{-0.88}$ | $5.45^{+1.70}_{-0.66}$ | $4.96 \pm 0.74$ | $4.89 \pm 0.66$ |
| $a_\perp$ | au | $1.54^{+0.18}_{-0.22}$ | $1.54^{+0.18}_{-0.22}$ | $1.14^{+0.32}_{-0.15}$ | $1.01 \pm 0.18$ | $0.99 \pm 0.16$ |
| $\pi_E$ | $\mu_{\text{rel, hel}}$ | $0.075^{+0.087}_{-0.036}$ | $0.073^{+0.093}_{-0.035}$ | $0.292^{+0.066}_{-0.120}$ | $0.354 \pm 0.042$ | $0.369 \pm 0.037$ |
| $V$ | mas/yr | $5.04^{+0.43}_{-0.44}$ | $5.06^{+0.43}_{-0.44}$ | $4.86 \pm 0.44$ | $\ldots$ | $\ldots$ |
| $I$ | mag | $29.4^{+2.9}_{-2.0}$ | $29.3^{+3.1}_{-2.0}$ | $34.1^{+5.2}_{-1.6}$ | $\ldots$ | $\ldots$ |
| $H$ | mag | $24.7^{+2.3}_{-2.0}$ | $24.6^{+2.4}_{-2.0}$ | $28.2^{+3.4}_{-1.2}$ | $\ldots$ | $\ldots$ |
| $K$ | mag | $21.3^{+1.7}_{-1.6}$ | $21.2^{+1.9}_{-1.6}$ | $23.9^{+2.6}_{-0.9}$ | $\ldots$ | $\ldots$ |

6. ANALYSIS INCLUDING Spitzer DATA
We measure the microlens parallax vector $\boldsymbol{\pi}_E$ via the “satellite parallax effect”, which can be approximated as:

$$\boldsymbol{\pi}_E = \frac{\text{au}}{D_\perp} \left( \frac{t_{0,\text{sat}} - t_{0,\odot}}{t_E}, u_{0,\text{sat}} - u_{0,\odot} \right),$$

where $D_\perp$ is the Earth-satellite separation projected on the plane of the sky, and $t_{0,\text{sat}}$ and $u_{0,\text{sat}}$ are the time of lens-source closest approach and the impact parameter as seen by the satellite. The Einstein timescale $t_E$ is assumed to be the same for both Earth and the satellite. In practice, we fully model Spitzer’s location as a function of time.

The Spitzer light curve for OGLE-2018-BLG-1185 shows a very weak decline of $\Delta f_{\text{Spz}} \sim 1$ flux unit over the four-week observation period (see Figure 6). This change (rather than, e.g., the value of the flux at the start of observations) is the most robust constraint because it is independent of the unknown blended light. However, the magnitude of the decline is comparable to the level of systematics seen in a few other events (Gould et al. 2020; Hirao et al. 2020; Zang et al. 2020c) and, thus, should be treated with caution. At the same time, even this weak decline indicates a significant parallax effect for the event as seen from Spitzer. We derive a color constraint for the Spitzer data by measuring the $IHL$ color-color relation for clump stars in CT13 $I$ and $H$, and Spitzer $L$. Evaluating this relation at the measured $(I - H)$ color of the source gives the constraint on the Spitzer source flux:

$$I_{\text{CT13}} - L = -4.518 \pm 0.028,$$
which gives an expected source flux from Spitzer of \( f_{\text{Spz}} = 0.6254 \) flux units for the best-fit value of \( I_{\text{CT13}} \). This constraint and the best-fit ground-based model (Table 4) together imply some tension with the observed Spitzer light curve unless there is a significant parallax effect. They predict that the observed Spitzer flux should have been substantially brighter at the start of the Spitzer observations (\( f_{\text{Spz}}(\text{HJD}' = 8313.83) \sim 6 \) flux units) and declined by a total of \( \Delta f_{\text{Spz}} \sim 3.3 \) flux units as compared to the observed \( \Delta f_{\text{Spz}} \sim 1 \) flux unit. This tension can be seen in Figure 6 and suggests that, due to the parallax effect, the event peaked at a lower magnification and/or earlier as seen from Spitzer.

We can use limits on the change in the Spitzer flux (\( \Delta f_{\text{Spz}} \)) to place conservative constraints on the physical properties of the lens. Suppose that systematics affect the Spitzer light curve at the level of 1–2 flux units, i.e., at the level seen in previous work. If the true signal is \( \Delta f_{\text{Spz}} \sim 4 \) flux units, it is very unlikely that systematics would cause us to measure \( \Delta f_{\text{Spz}} = 1 \) flux unit. Therefore, we repeat the Bayesian analysis imposing the constraint \( \Delta f_{\text{Spz}} < 4 \), where \( \Delta f_{\text{Spz}} \) is calculated from Equation (19). The parallax effect can produce a degeneracy in the sign of \( u_0 \). In this case, because \( u_0 \) is small, the effect of this degeneracy is much smaller than the uncertainties (Gould, & Yee 2012), so we only carry out this calculation for the \( u_0 > 0 \) case.

The results are given in Table 4 (as “Ground + \( \Delta f_{\text{Spz}} \)”), Figure 7, and the center panel of Figure 5. This constraint suggests a \( M_{\text{host}} = 0.37^{+0.35}_{-0.21} \, M_\odot \) host with a \( m_p = 8.4^{+7.9}_{-4.7} \, M_\oplus \) planet at a projected separation \( a_\perp = 1.54^{+0.18}_{-0.22} \) au. We adopt these values as our conservative Bayesian estimate of the properties of the lens system.

6.1. Spitzer-“only” Parallax
If we take the Spitzer light curve at face value, we can derive stronger constraints on the parallax using the Spitzer-“only” parallax method. This method has been used in several previous analyses (starting with Gould et al. 2020) to show how the Spitzer light curve constrains the parallax. For this analysis, we hold the microlensing parameters $t_0$, $u_0$, and $t_E$ fixed at values found by fitting the ground-based data and make the assumption that the Spitzer light curve is in the point lens regime. Then, for a grid of parallax values, we fit for the Spitzer flux while applying the color-constraint from Equation (19). We repeat the analysis for $-u_0$, which produces an indistinguishable ground-based light curve and, as expected, only slight variations in the parallax.

The resulting parallax contours are shown in Figure 8. The four minima correspond to the well-known satellite parallax degeneracy (Refsdal 1966; Gould 1994) and the overall arc shape follows the expectation from the Gould (2019) osculating circles formalism. The values for the magnitude of the microlens parallax vector are $\pi_E = 0.35 \pm 0.04$ for the $(u_0 > 0)$ case and $\pi_E = 0.37 \pm 0.04$ for the $(u_0 < 0)$ case. The $3\sigma$ ranges are $\pi_E = [0.18, 0.50]$ and $\pi_E = [0.20, 0.48]$, respectively.

\footnote{In principle, we should calculate the Spitzer magnification using the full planetary model, but in practice, this makes almost no difference because the Spitzer observations start well after the planetary perturbation.}
6.2. Physical Lens Properties from Spitzer Parallax

We can derive the physical properties of the lens by combining the measurement of the parallax from the \textit{Spitzer}-“only” analysis with the measurement of $\theta_E = 0.211 \pm 0.019$ mas from fitting the ground-based light curve. These estimates and their uncertainties are derived from Equation (15) using simple error propagation, and so are the “naive” values of these quantities. For the $(u_0 > 0)$ solution, this yields a lens mass of $M_L = 0.073 \pm 0.011 M_\odot$ and $D_L = 4.96 \pm 0.74$ kpc for $D_S = 7.88$ kpc. This would then imply that the mass of the planet is $m_p = 1.7 \pm 0.3 M_\oplus$ and that it is separated from the host by $a_\perp = 1.01 \pm 0.18$ au. The values for the $(u_0 < 0)$ solution are comparable. See Table 4.

In order to estimate the lens magnitude, we also performed a Bayesian analysis including the $\pi_E$ constraint derived from the \textit{Spitzer}-“only” parallax analysis. First, we took the average of the $\chi^2$ values for the two $(u_0 > 0)$ and $(u_0 < 0)$ solutions for each value of $\pi_{E, \theta}$ and $\pi_{E, t}$. Then, the event rate was weighted by $\exp(-\Delta \chi^2 / 2)$ and the measured $t_E$ and $\theta_E$ constraints to calculate the probability distribution. Table 4 and Figure 9 show the results. The distributions for some of the parameters in Figure 9 are bimodal. In addition to the expected peak for lenses at $D_L \sim 5$ kpc, there is a second peak for lenses with $D_L \sim 7.5$ kpc. This second peak corresponds to events with lenses in the bulge and sources in the far-disk, which were not considered in our naive calculations. For the bimodal distributions, the central values and confidence intervals reported in Table 4 are not a complete description of the distributions and should be considered in context with Figure 9. However, the mass distribution is not subject to this issue. We find that the lens system is likely a terrestrial planet with a mass of $m_p = 2.1^{+1.5}_{-0.4} M_\oplus$ orbiting a very-low-mass (VLM) dwarf with a mass of $M_{\text{host}} = 0.091^{+0.064}_{-0.018} M_\odot$.

6.3. Implications

Hence, if the \textit{Spitzer}-“only” parallax is correct, this would be the second detection of a terrestrial planet orbiting a VLM dwarf from the \textit{Spitzer} microlensing program. The first was OGLE-2016-BLG-1195Lb (Bond et al. 2017; Shvartzvald et al. 2017), which is a $m_p = 1.43^{+0.45}_{-0.32} M_\oplus$ planet orbiting an $M_L = 0.078^{+0.016}_{-0.012} M_\odot$ VLM dwarf at a separation of $a_\perp = 1.16^{+0.16}_{-0.13}$ au. The distance to the OGLE-2016-BLG-1195L system is also comparable: $D_L = 3.91^{+0.42}_{-0.46}$ kpc. One curiosity about OGLE-2016-BLG-1195L is that the lens-source relative proper motion suggests that the lens could be moving counter to the direction of Galactic rotation, which would be unusual for a disk lens.

Therefore, we also consider the implications of the \textit{Spitzer}-“only” $\pi_E$ for constraining the lens motion in OGLE-2018-BLG-1185. First, we note that there is no independent information on the proper motion of the source $\mu_s$ because there is no evidence that the blend, which dominates the baseline object, is associated with the event (see Appendix A). Second, given $D_L \sim 4.9$ kpc, we assume that the lens is in the disk, and therefore, has a proper motion similar to other disk stars. The velocity model of Koshimoto et al. (2021) is based on the Shu distribution function model in Sharma et al. (2014), but the mean velocity and velocity dispersion in the disk are fitted to the Gaia DR2 data (Gaia Collaboration et al. 2018) as a function of the Galactocentric distance, $R$ and the height from the Galactic plane, $z$. The velocity of disk stars at 4.9 kpc is $(v_\phi, v_z) = (207.6^{+42.7}_{-44.0}, -0.4^{+38.8}_{-39.6})$ km s$^{-1}$. Hence, for the velocity dispersion, we use $(\sigma_{v_\phi}, \sigma_{v_z}) = (43.4, 39.2)$ km s$^{-1}$. Table 5 summarizes the disk star velocities and proper motions expected from the Galactic model at $D = 4.9 \pm 0.7$ kpc. The values in the table are derived from the Bayesian analysis with a Galactic prior and constrained by $\theta_E$ and $t_E$. For the Sun’s motion,
we use \((v_R, v_\phi, v_z)_{\text{Sun}} = (-10, 243, 7) \text{ km s}^{-1}\) (for \((R_\odot, z_\odot) = (8160, 25) \text{ pc}\)). We combine the two velocities to estimate the proper motion of disk stars. Finally, by applying Equation 16, we can derive the expected source proper motion \(\mu_S = \mu_L - \mu_{\text{rel, hel}}\) for a given value of the parallax. Figure 10 shows the results for values of \(\pi_E\) out to the 1\(\sigma\) Spitzer-“only” contours for the \((u > 0)\) solution (the results for the \((u < 0)\) solution are nearly identical). The properties of bulge stars are derived from Gaia stars within 5’ of the target: \(\mu_{\text{bulge}}(\ell, b) = (-6.310, -0.163) \pm (0.088, 0.076) \text{ mas yr}^{-1}\) and \(\sigma_{\text{bulge}}(\ell, b) = (3.176, 2.768) \pm (0.062, 0.054) \text{ mas yr}^{-1}\). To account for the uncertainty in the lens motion, we add the proper motion dispersions of the disk and bulge in quadrature. One of the two Spitzer minima suggests a source more than 2\(\sigma\) from the bulge distribution, but the other minimum is consistent with a bulge source at \(\sim 1.5\sigma\). Therefore, there is no reason to believe that the Spitzer \(\pi_E\) requires a lens proper motion in tension with the motion of typical disk stars.

Finally, in order to be included in the statistical samples for the study of the Galactic distribution of planets, Zhu et al. (2017) proposed the criteria:

\[
\sigma(D_{8.3}) < 1.4\text{kpc}; \quad D_{8.3} \equiv \frac{\text{kpc}}{\pi_{\text{rel}} / \text{mas} + 1/8.3}.
\]

We find \(D_{8.3} = 5.15 \pm 0.28 \text{ kpc}\) for the \((u_0 > 0)\) case and \(D_{8.3} = 5.04 \pm 0.28 \text{ kpc}\) for the \((u_0 < 0)\) case by combining the measurement of \(\pi_E\) from the Spitzer-“only” analysis with the measurement of \(\theta_E\) from fitting the ground-based light curve. The small \(\sigma(D_{8.3})\) is consistent with the expectation for the high magnification event as investigated by Gould, & Yee (2012), Shin et al. (2018), and Gould (2019). They show that accurate parallax measurements are possible even if there are only
Figure 10. Test of source proper motion predicted by the Spitzer-“only” parallax. Black points: derived source proper motions for $\pi_E$ within 1$\sigma$ of the minimum for the Spitzer-“only” contours (based on $\mu_{\text{rel, hel}}$). Black cross: mean proper motion for disk stars assuming a distance of $D_L = 4.9$ kpc. Dashed circle: centered on black cross with a radius $\mu_{\text{rel, geo}} = 4.832 \text{ mas yr}^{-1}$. Note that the black cross and dashed circle are merely reference points. Red: 1$\sigma$ error ellipse for the bulge stars as derived from Gaia. Blue: 1$\sigma$ error ellipse for the disk stars derived from $(\sigma_{v,\phi}, \sigma_{v,z})$. Dotted black contours: 1, 2, 3$\sigma$ contours adding the dispersions of the bulge and disk in quadrature. The observed constraints are consistent with a lens in the disk and a source in the bulge.

Therefore, in terms of $\sigma_{D8,3}$ (Zhu et al. 2017), the Spitzer-“only” parallax suggests that the apparent signal is good enough to include OGLE-2018-BLG-1185Lb in the statistical sample of Spitzer events. However, the systematics need be studied and understood before membership in the sample can be definitively evaluated.

7. DISCUSSION AND SUMMARY

We analyzed the microlensing event OGLE-2018-BLG-1185, which was simultaneously observed from a large number of ground-based telescopes and the Spitzer telescope. The ground-based light-curve modeling indicates a small mass ratio of $q = (6.9 \pm 0.2) \times 10^{-5}$, which is close to the peak of the wide orbit exoplanet mass-ratio distribution derived by Suzuki et al. (2016) and investigated further by Udalski et al. (2018) and Jung et al. (2019b). Suzuki et al. (2016) derived the wide orbit
Table 5. Disk star velocities and proper motions at $D = 4.9 \pm 0.7$ kpc

| Star Component | Velocity Component | Unit | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ |
|----------------|--------------------|------|------------|------------|--------|------------|------------|
| Thin Disk      | $v_l$              | km s$^{-1}$ | 110.7      | 163.6      | 205.9  | 242.4      | 280.7      |
|                | $v_b$              | km s$^{-1}$ | -95.0      | -48.8      | -13.7  | 22.4       | 71.1       |
|                | $\mu_{hel,l}$     | mas yr$^{-1}$ | -5.615    | -3.349     | -1.577 | -0.024     | 1.656      |
|                | $\mu_{hel,b}$     | mas yr$^{-1}$ | -4.364    | -2.388     | -0.884 | 0.653      | 2.690      |
| Thick Disk     | $v_l$              | km s$^{-1}$ | 60.7       | 125.2      | 181.4  | 236.5      | 293.7      |
|                | $v_b$              | km s$^{-1}$ | -147.8     | -86.4      | -12.1  | 63.3       | 128.6      |
|                | $\mu_{hel,l}$     | mas yr$^{-1}$ | -7.662    | -4.995     | -2.602 | -0.275     | 2.177      |
|                | $\mu_{hel,b}$     | mas yr$^{-1}$ | -6.577    | -3.987     | -0.808 | 2.379      | 5.102      |
| All            | $v_l$              | km s$^{-1}$ | 103.6      | 161.0      | 204.9  | 242.2      | 281.3      |
|                | $v_b$              | km s$^{-1}$ | -101.1     | -50.5      | -13.6  | 24.4       | 77.4       |
|                | $\mu_{hel,l}$     | mas yr$^{-1}$ | -5.878    | -3.457     | -1.620 | -0.034     | 1.685      |
|                | $\mu_{hel,b}$     | mas yr$^{-1}$ | -4.611    | -2.462     | -0.883 | 0.737      | 2.960      |

planet occurrence rate using a sample of thirty planets, primarily from the MOA-II microlensing survey during 2007–2012. The planet presented here, OGLE-2018-BLG-1185Lb, will be included in an extension of the MOA-II statistical analysis (Suzuki et al., in preparation), and its low mass ratio will help to define the mass ratio function peak.

From the ground-based light-curve modeling, only finite source effect is detected, yielding a measurement of the angular Einstein radius. However, the physical properties of the lens as derived from the light curve are unclear because the observed flux variation of the *Spitzer* light curve is marginal. Using only the constraint from the measured angular Einstein radius and a conservative constraint on the change in the *Spitzer* flux, we estimate the host star and planet masses with a Bayesian analysis under the assumption that stars of all masses have an equal probability to host this planet. This analysis indicates a host mass of $M_{\text{host}} = 0.37^{+0.35}_{-0.21} M_\odot$ and a planet mass of $m_p = 8.4^{+7.9}_{-4.7} M_\oplus$ located at $D_L = 7.4^{+0.5}_{-0.9}$ kpc. By contrast, the *Spitzer* data favor a larger microlensing parallax, which implies a very low-mass host with a terrestrial planet ($M_{\text{host}} = 0.091^{+0.064}_{-0.018} M_\odot$, $m_p = 2.1^{+1.5}_{-0.4} M_\oplus$) that is either in the disk at $D_L \sim 5$ kpc or in the bulge at $D_L \sim 7.5$ kpc (these values include a Galactic prior but are not significantly different from the values without the prior, see Table 4).

Figure 11 compares the Bayesian estimates from the conservative *Spitzer* flux constraint and the full *Spitzer* parallax measurement of the host and planet mass for OGLE-2018-BLG-1185 to those of other planetary systems. The pink circles show the microlens planets without mass measurements, and the red circles show the microlens planets with mass measurements from ground-based orbital parallax effects and/or the detection of the lens flux by high resolution follow-up observations. The red squares represent microlens planets with mass measurements from the satellite parallax effect observed by *Spitzer*. Figure 11 indicates that if the *Spitzer* parallax is correct, this is one of the lowest mass planets discovered by microlensing.

However, the result that this is a terrestrial planet orbiting a very-low-mass (VLM) dwarf in the disk should be treated with caution, because the amplitude of the *Spitzer* signal is at the level of systematics seen in other events. A comparison of these properties to the Bayesian posteriors (Figure
demonstrates that a higher-mass system is preferred given $t_E$, $\theta_E$, and the Galactic priors. At the same time, a VLM-dwarf + terrestrial planet is still within the $2\sigma$ range of possibilities from the Bayesian analysis, especially once the constraint on $\Delta t_{Spz}$ is imposed (Figure 7). Furthermore, Shvartzvald et al. (2017) suggest that such planets might be common. Nevertheless, further investigation is needed in order to assess whether or not the fitted parallax signal (and so the inferred mass) is real.

Adaptive optics observations are one way to test the Spitzer parallax signal. The Bayesian analysis with ground-based + $\Delta t_{Spz}$ constraints indicates the lens K-band magnitude with extinction should be $K = 20.8^{+1.8}_{-1.5}$ mag, which is about 3 magnitudes fainter than the source. By contrast, if the Spitzer-“only” parallax is correct and the lens is a VLM dwarf, it should be $K = 23.3^{+2.9}_{-0.8}$ mag and therefore, much fainter and possibly undetectable. The Bayesian estimate of the heliocentric relative proper motion, $\mu_{rel, hel} = 5.0 \pm 0.4$ mas yr$^{-1}$, predicts that the angular separation between the source and the lens will be $\sim 30$ mas around mid-2024. Thus, the lens can be resolved from the source by the future follow-up observations with Keck or ELTs. If such resolved measurements were made (and the lens were luminous), it would also lead to a direct measurement of $\mu$. The observed magnitude of $\mu$ can serve as a check on $\theta_E$. Additionally, the direction of $\mu$ is the same as the direction of the microlens parallax vector, which could clarify how the Spitzer-“only” parallax contours should be interpreted in the presence of systematics.

If the Spitzer parallax is verified, this event confirms the potential of microlensing to measure the wide-orbit planet frequency into the terrestrial planet regime. Although the number of microlens planets with mass measurements is small for now, observing the satellite parallax effect can continue to increase the numbers. In particular, this effect can be measured for terrestrial planets by simultaneous observations between the ground and L2 (Gould et al. 2003). This can be achieved with the PRIME telescope (PI: Takahiro, Sumi) and Roman Space Telescope (Spergel et al. 2015; Penny et al. 2019) in the mid-2020s.

Software: OGLE DIA pipeline (Udalski2003), MOA DIA pipeline (Bond et al. 2001), KMTNet pySIS pipeline (Albrow et al. 2009), DanDIA (Bramich 2008; Bramich et al. 2013), DoPHOT (Schechter et al. 1993), ISIS (Alard & Lupton 1998; Alard 2000; Zang et al. 2018), Image-centered ray-shooting method (Bennett & Rhie 1996; Bennett 2010).
Figure 11. The mass distribution of the detected exoplanets as of 2021 February 25 from http://exoplanetarchive.ipac.caltech.edu. The purple stars indicate OGLE-2018-BLG-1185. The pink circles show the microlens planets without mass measurements, and the red circles show the microlens planets with mass measurements from ground-based orbital parallax effects and/or the detection of the lens flux by the high resolution follow-up observations. The red squares represent the microlens planets with mass measurements from satellite parallax effects by Spitzer. The blue, yellow, and black dots indicate planets found by the transit, direct imaging, and radial velocity methods, respectively.

REFERENCES
Alard, C. & Lupton, R. H. 1998, ApJ, 503, 325.  
Alard, C. 2000, A&AS, 144, 363.
Yee, J. C., Gould, A., Beichman, C., et al. 2015, ApJ, 810, 155
Yee, J. C., Zang, W., Udalski, A., et al. 2021, arXiv e-prints, arXiv:2101.04696
Yoo, J., DePoy, D. L., Gal-Yam, A., et al. 2004, ApJ, 603, 139
Zang, W., Penny, M. T., Zhu, W., et al. 2018, PASP, 130, 104401.
Zang, W., Shvartzvald, Y., Wang, T., et al. 2020, ApJ, 891, 3
Zang, W., Dong, S., Gould, A., et al. 2020, ApJ, 897, 180.
Zang, W., Shvartzvald, Y., Udalski, A., et al. 2020, arXiv:2010.08732
Zhu, W., Udalski, A., Novati, S. C., et al. 2017, AJ, 154, 210
APPENDIX

A. CONSTRAINTS ON THE BLENDED LIGHT & DISCREPANCY WITH GAIA

The blended light in this event is roughly four times brighter than the source. In principle, the blend could be the lens itself or a companion to either the lens or the source. If so, it could constrain the flux and proper motion of the lens or the proper motion of the source.

From the KMTNet images, we measure the astrometric offset between the source and the baseline object and find an offset of $0\arcsec.175$. This offset is larger than the astrometric uncertainties. Therefore, if it is a companion to the lens or source, it must be a very wide separation companion ($\sim 1000$ au). However, the large separation also suggests that it could be an ambient star unrelated to the microlensing event.

We measure the proper motion of the baseline object based on 10 years of OGLE survey data and find $\mu_{\text{base}}(\text{RA}, \text{Dec}) = (-6.00 \pm 0.26, -4.25 \pm 0.16)$ mas yr$^{-1}$. Because the blend is much brighter than the source, its motion should dominate the measured $\mu_{\text{base}}$. The measured value is very consistent with typical proper motions for normal bulge stars, but not unreasonable for the proper motion of a disk star. Hence, it does not rule out the possibility that the blend is a wide-separation companion to the source or the lens, but it also shows that the blend could easily be an unrelated bulge star.

For completeness, we note that the OGLE measurement of the proper motion of the baseline object is inconsistent with the reported Gaia proper motion of the nearest Gaia source ($4062756831332827136$; Gaia Collaboration et al. 2016). Gaia EDR3 (Gaia Collaboration et al. 2020) reports there is a $G = 20.1$ mag star $0\arcsec.177$ from the OGLE coordinates for the baseline star ($17:59:10.26 -27:50:06.3$). The reported proper motion of this source is $\mu(\text{RA}, \text{Dec}) = (-12.173 \pm 1.247, -9.714 \pm 0.870)$ mas yr$^{-1}$, which is an outlier relative to the typical proper motions for stars in this field. Gaia DR2 (Gaia Collaboration et al. 2018) reports an only slightly less extreme proper motion of $\mu(\text{RA}, \text{Dec}) = (-8.475 \pm 2.234, -4.039 \pm 1.985)$ mas yr$^{-1}$. The nature of this discrepancy is unknown, but because the Gaia proper motion is highly unusual (and the OGLE proper motion is typical), and the Gaia measurement varies significantly between DR2 and EDR3, this suggests a problem with the Gaia measurement.