Spitzer Microlensing Parallax Reveals Two Isolated Stars in the Galactic Bulge

How to cite:
Zang, Weicheng; Shvartzvald, Yossi; Wang, Tianshu; Udalski, Andrzej; Lee, Chung-Uk; Sumi, Takahiro; Skottfelt, Jesper; Li, Shun-Sheng; Mao, Shude; Zhu, Wei; Yee, Jennifer C.; Calchi Novati, Sebastiano; Beichman, Charles A.; Bryden, Geoffrey; Carey, Sean; Gaudi, B. Scott; Henderson, Calen B.; Mróz, Przemek; Skowron, Jan; Poleski, Radoslaw; Szymański, Michał K.; Soszyński, Igor; Pietrukowicz, Paweł; Kozłowski, Szymon; Ulaczyk, Krzysztof; Rybicki, Krzysztof A.; Iwanek, Patryk; Bachelet, Etienne; Christie, Grant; Green, Jonathan; Hennerley, Steve; Maoz, Dan; Natusch, Tim; Pogge, Richard W.; Street, Rachel A.; Tsapras, Yiannis; Albrw, Michael D.; Chung, Sun-Ju; Gould, Andrew; Han, Cheongho; Hwang, Kyu-Ha; Jung, Youn Kil; Ryu, Yoon-Hyun; Shin, In-Gu; Cha, Sang-Mok; Kim, Dong-Jin; Kim, Hyoun-Woo; Kim, Seung-Lee; Lee, Dong-Joo; Lee, Yongseok; Park, Byong-Gon; Bond, Ian A.; Abe, Fumio; Barry, Richard; Bennett, David P.; Bhattacharya, Aparna; Donachie, Martin; Fukui, Akihiko; Hirao, Yuki; Itow, Yoshitaka; Kono, Iona; Koshimoto, Naoki; Alex Li, Man Cheung; Matsubara, Yutaka; Muraki, Yasushi; Miyazaki, Shota; Nagakane, Masayuki; Ranc, Clément; Rattenbury, Nicholas J.; Suematsu, Haruno; Sullivan, Denis J.; Suzuki, Daisuke; Tristram, Paul J.; Yonehara, Atsunori; Dominik, Martin; Hundertmark, Markus; Jørgensen, Uffe G.; Rahvar, Sohrab; Sajadian, Sedighe; Snodgrass, Colin; Bozza, Valerio; Burgdorf, Martin J.; Evans, Daniel F.; Jaime, R. Fiquera; Fujii, Yuri I.; Mancini, Luigi; Longa-Peña, Penélope; Helling, Christiane; Peixinho, Nuno; Rabus, Markus; Southworth, John; Unda-Sanzana, Eduardo and Essen, Carolina von (2020). Spitzer Microlensing Parallax Reveals Two Isolated Stars in the Galactic Bulge. The Astrophysical Journal, 891(1), article no. 3.

For guidance on citations see FAQs.


https://creativecommons.org/licenses/by-nc-nd/4.0/

Version: Accepted Manuscript

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.3847/1538-4357/ab6ff8
Spitzer Microlensing parallax reveals two isolated stars in the Galactic bulge

Weicheng Zang,1 Yossi Shvartzvald,2 Tianshu Wang,1 Andrzej Udalski,3 Chung-Uk Lee,4,5 Takahiro Sumi,6 Jesper Skottfelt,7 Shun-Sheng Li,8,9 Shude Mao,1,8 and Wei Zhu10

Jennifer C. Yee,11 Sebastian Calchi Novati,2 Charles A. Beichman,2 Geoffery Bryden,12 Sean Carey,2 B. Scott Gaudi,13 and Caleb B. Henderson2

(The Spitzer Team)

Przemek Mróz,2 Jan Skowron,2 Radoslaw Poleski,3,13 Michał K. Szymański,3 Igor Soszyński,3 Pawel Pietrukowicz,3 Szymon Kołodziewski,3 Krzysztof Ulaczyk,14 Krzysztof A. Rybicki,3 and Patryk Ivanek3

(The OGLE Collaboration)

Etienne Bachelet,15 Grant Christie,16 Jonathan Green,17 Steve Hennerley,17 Dan Maoz,18 Tim Natusch,16,19 Richard W. Pogge,13,20 Rachel A. Street,15 and Yiannis Tsapras11

(The LCO and μFUN Follow-up Teams)


(The MOA Collaboration)

Martin Dominik,40 Markus Hundertmark,21 Uffe G. Jørgensen,41 Sohrab Rahvar,42 Sedigheh Sadajian,43 Colin Snodgrass,34,14 Valerio Bozza,44,45 Martin J. Burgdorf,47 Daniel F. Evans,48 Roberto Figueira Jaimes,21 Yuri I. Fuhi,49,50 Luigi Mancini,50,51,52 Penelope Longa-Peña,53 Christiane Helling,54 Nuno Peixinho,34 Markus Rabus,55,56 John Southworth,35,57 Eduardo Unda-Sanzana,57 and Carolina von Essen57

(The MINDS/EP Collaboration)

1Physics Department and Tsinghua Centre for Astrophysics, Tsinghua University, Beijing 100084, China
2IPAC, Mail Code 100-22, Caltech, 1200 E. California Blvd., Pasadena, CA 91125, USA
3Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
4Korea Astronomy and Space Science Institute, Daejon 34055, Republic of Korea
5University of Science and Technology, Korea, (UST), 217 Gajeong-ro Yuseong-gu, Daejeon 34113, Republic of Korea
6Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
7Centre for Electronic Imaging, Department of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK
8National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
9School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China
10Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St George Street, Toronto, ON M5S 3H8, Canada
11Center for Astrophysics — Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA
12Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
13Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA
14Department of Physics, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, UK
15Las Cumbres Observatory, 6740 Cortona Drive, suite 102, Goleta, CA 93117, USA
16Auckland Observatory, Auckland, New Zealand
17Kumeu Observatory, Kumeu, New Zealand
18School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 6997801, Israel
19Institute for Radio Astronomy and Space Research (IRASR), AUT University, Auckland, New Zealand
20Center for Cosmology & AstroParticle Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210
21Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg (ZAH), 69120 Heidelberg, Germany

14 Corresponding author: Weicheng Zang
zangwc17@mails.tsinghua.edu.cn
We report the mass and distance measurements of two single-lens events from the 2017 Spitzer microlensing campaign. The ground-based observations yield the detection of finite-source effects, and the microlens parallaxes are derived from the joint analysis of ground-based observations and Spitzer observations. We find that the lens of OGLE-2017-BLG-1254 is a 0.60±0.03M\odot star with $D_{\text{LS}} = 0.53\pm 0.11$ kpc, where $D_{\text{LS}}$ is the distance between the lens and the source. The second event, OGLE-2017-BLG-1161, is subject to the known satellite parallax degeneracy, and thus is either a 0.51±0.12M\odot star with $D_{\text{LS}} = 0.40\pm 0.12$ kpc or a 0.38±0.13M\odot star with $D_{\text{LS}} = 0.53\pm 0.19$ kpc. Both of the lenses are therefore isolated stars in the Galactic bulge. By comparing the mass and distance distributions of the eight published Spitzer finite-source events with the expectations from a Galactic model, we find that the Spitzer sample is in agreement with the probability of finite-source effects occurrence in single lens events.

1. INTRODUCTION

Gravitational microlensing opens a powerful window for probing isolated objects with various masses such as free-floating planets, brown dwarfs, low-mass stars and black holes. At the low-mass end, microlensing has detected several free-floating planet candidates (Sumi et al. 2011; Mróz et al. 2017, 2018, 2019), including a few possible Earth-mass objects. Such discoveries are crucial for testing theories about the origin and evolution of free-floating planets (Ma et al. 2016; Clanton & Gaudi 2017; Veras & Raymond 2012;
Pfyffer et al. 2015; Barclay et al. 2017). For more massive objects (i.e., isolated brown dwarfs), five have been discovered by microlensing: OGLE-2007-BLG-224L (Gould et al. 2009), OGLE-2015-BLG-1268L (Zhu et al. 2016), OGLE-2015-BLG-14821 (Chung et al. 2017), OGLE-2017-BLG-0896 (Shvartzvald et al. 2019), and OGLE-2017-BLG-11862 (Li et al. 2019). Shvartzvald et al. (2019) recently announced the discovery of an isolated, extremely low-mass brown dwarf of \( M \sim 19 M_J \), with proper motion in the opposite direction of disk stars, which indicates that it might be a halo brown dwarf or from a different, unknown counter-rotating population. At the high-mass end, Gould (2000b) estimated that \( \sim 20\% \) of microlensing events observed toward the Galactic bulge are caused by stellar remnants, and specifically that \( \sim 1\% \) are due to stellar-mass black holes, with another \( \sim 3\% \) due to neutron star lenses. The first observed example of this was the long-timescale (\( \sim 640 \) day) event OGLE-1999-BUL-32, for which the microlens parallax measurement indicated this event could be a stellar black hole (Mao et al. 2002). In addition, Wyżykowski et al. (2016) identified 13 microlensing events that are consistent with having a white-dwarf, neutron-star or a black-hole lens in the OGLE-III data base.

In general, for microlensing events due to isolated lenses, the only measured parameter that describes the physical properties of the lens system is the Einstein timescale \( t_E \). Because \( t_E \) depends on the lens mass, the distances to the lens and source, and the transverse velocity (See Equation 17 of Mao 2012), it can only be used to make a statistical estimate of the lens mass. Unambiguous measurements of the lens mass requires two second-order microlensing observables: the angular Einstein radius \( \theta_E \) and the microlens parallax \( \pi_E \). For a lensing object, the total mass is related to the two observables by (Gould 1992, 2000a)

\[
M_L = \frac{\theta_E}{\kappa \pi_E},
\]

and its distance by

\[
D_L = \frac{au}{\pi_{rel} + \pi_S}, \quad \pi_{rel} = \pi_E \theta_E
\]

where \( \kappa \equiv 4G/(c^2 \text{AU}) = 8.144 \text{mas}/M_\odot \), \( \pi_S = au / D_S \) is the source parallax, \( D_S \) is the source distance (Gould 1992, 2004) and \( \pi_{rel} \) is the lens-source relative parallax.

There are three methods to measure the microlens parallax \( \pi_E \). The first one is "orbital microlens parallax", which can be measured when including the orbital motion of Earth around the Sun in modeling (Gould 1992; Alcock et al. 1995). However, this method is generally feasible only for events with long microlensing timescales \( t_E \gg \text{year}/2\pi \) (e.g., Udalski et al. 2018). The second method, "terrestrial microlens parallax", in rare cases can be measured by a combination of simultaneous observations from ground-based telescopes that are well separated (e.g., Gould et al. 2009; Yee et al. 2009). The most efficient and robust method to measure the microlens parallax is to simultaneously observe an event from Earth and a satellite (Refsdal 1966; Gould 1994). That is the "satellite microlens parallax". The feasibility of satellite microlens parallax measurements has been demonstrated by Spitzer microlensing programs (Dong et al. 2007; Udalski et al. 2015b; Yee et al. 2015b; Zhu et al. 2015; Calchi Novati et al. 2015a). Since 2014, the Spitzer satellite has observed more than 700 microlensing events toward the Galactic bulge, yielding the mass measurements of eight isolated lens objects (Zhu et al. 2016; Chung et al. 2017; Shin et al. 2018; Shvartzvald et al. 2019; Li et al. 2019), including two in this work.

For the measurements of the angular Einstein radius \( \theta_E \), Dong et al. (2019) recently reported the angular Einstein radius \( \theta_E \) measurement of microlensing event TCP J05074264+2447555 by interferometric resolution of the microlensed images. However, this method requires a rare, bright microlensing event (for TCP J05074264+2447555, \( K \sim 10.6 \text{ mag} \) at the time of observation). Measurements of the angular Einstein radius \( \theta_E \) are obtained primarily via finite-source effects and an estimate of the angular diameter \( \theta_s \) of the source from its de-reddened color and magnitude (e.g., Kervella & Fouqué 2008; Boyajian et al. 2014)

\[
\theta_E = \frac{\theta_s}{\rho},
\]

where \( \rho \) is the source size normalized by the Einstein radius, which can be measured from the modulation in the lensing light curve with finite-source effects. Such effects arise when the source transits a caustic (where the magnification diverges to infinity) or comes close to a cusp (Gould 1994; Witt & Mao 1994; Nemiroff & Wickramasinghe 1994). Then the source cannot be regarded as a point-like source, and the observed magnification is the integration of the magnification pattern over the face of the source. Finite-source effects are frequently measured in binary/planetary events, for which the caustic structures are relatively large, but they are rarely measured in the case of a single lens event because the caustic is a single geometric point.

Here we present the mass and distance measurements of two Spitzer single-lens microlensing events OGLE-2017-BLG-1161 and OGLE-2017-BLG-1254. The ground-based observations yield a robust detection of finite-source effects for the two events, and the microlens parallaxes are derived from the joint analysis of ground-based observations and
Spitzer observations. Combining the measurements of $\theta_E$ and $\pi_E$, we find that the lenses of the two events are both isolated stars in the Galactic bulge. The paper is structured as follows. In Section 2, we introduce ground-based and Spitzer observations of the two events. We then describe the light curve modeling process in Section 3, and present the physical parameters of the two events in Section 4. Finally, our conclusions and the implications of our work are given in Section 5.

2. OBSERVATIONS AND DATA REDUCTIONS

The observations of OGLE-2017-BLG-1161 and OGLE-2017-BLG-1254 both consist of Spitzer, ground-based survey and ground-based follow-up observations.

The Spitzer observations were part of a large program to measure the Galactic distribution of planets in different stellar environments (Calchi Novati et al. 2015a; Zhu et al. 2017). The detailed protocols and strategies for the Spitzer observations are discussed in Yee et al. (2015a). Specifically, the two events were observed by the Spitzer satellite because they were both high-magnification events, which are more sensitive to planets (Griest & Safizadeh 1998). The Spitzer observations were taken using the 3.6 $\mu$m channel ($L$-band) of the IRAC camera.

Ground-based surveys included the Optical Gravitational Lensing Experiment (OGLE, Udalski et al. 2015a), the Microlensing Observations in Astrophysics (MOA, Sumi et al. 2016), and the Korean Microlensing Telescope Network (KMTNet, Kim et al. 2016). OGLE is in its fourth phase (OGLE-IV), and the observations are carried out using its 1.3 m Warsaw Telescope equipped with a 1.4 deg$^2$ FOV mosaic CCD camera at the Las Campanas Observatory in Chile. The MOA group conducts a high cadence survey toward the Galactic bulge using its 1.8 m telescope equipped with a 2.2 deg$^2$ FOV camera at the Mt. John University Observatory in New Zealand. KMTNet consists of three 1.6 m telescopes, equipped with 4 deg$^2$ FOV cameras at the Cerro Tololo International Observatory (CTIO) in Chile (KMT), the South African Astronomical Observatory (SAAO) in South Africa (KMTS), and the Siding Spring Observatory (SSO) in Australia (KMTA). The majority of observations were taken in the $I$-band for the OGLE and KMTNet groups, and the MOA-Red filter (which is similar to the sum of the standard Cousins $R$- and $I$-band filters) for the MOA group, with occasional observations taken in the $V$-band.

The aim of the ground-based follow-up observations was to detect and characterize any planetary signatures with dense observations, which are crucial if an event is not heavily monitored by the ground-based surveys (e.g., OGLE-2017-BLG-1161) or the ground-based surveys could not observe due to weather (e.g., OGLE-2016-BLG-1045 Shin et al. 2018). The follow-up teams included the Las Cumbres Observatory (LCO) global network, the Microlensing Follow-Up Network (muFUN, Gould et al. 2010) and Microlensing Network for the Detection of Small Terrestrial Exoplanets (MiNDSTep, Dominik et al. 2010). The LCO global network provided observations from its 1.0 m telescopes located at CTIO, SAAO and SSO, with the SDSS-$i'$ filter. The $\mu$FUN team followed the events using the 1.3 m SMARTS telescope at CTIO (CT13) with $V/I/H$-bands (DePoy et al. 2003), the 0.4 m telescope at Auckland Observatory (AO) using a number 12 Wratten filter (which is similar to $R$-band), and the 0.36 m telescope at Kumeu Observatory (Kumeu) in Auckland. The MiNDSTep team monitored the events using the Danish 1.54 m telescope sited at ESOs La Silla observatory in Chile, with a non-standard filter.

We provide detailed descriptions of the observations for OGLE-2017-BLG-1161 and OGLE-2017-BLG-1254 in the next part.

2.1. OGLE-2017-BLG-1161

OGLE-2017-BLG-1161 was discovered by the OGLE collaboration on 2017 June 20. With equatorial coordinates $(\alpha, \delta)_{2000} = (17:41:12.65, -26:44:28.1)$ and Galactic coordinates $(\ell, b) = (1.36, 1.98)$, it lies in OGLE field BLG652, monitored by OGLE with a cadence of 0.5–1 observations per night (Udalski et al. 2015a). This event was located in the gap of two CCD chips of KMTNet BLG15 field, and thus the follow-up observations were important supplements to the sparse observations from the ground-based surveys. The $I/H$-band observations from CT13 intensively covered the falling side of the peak, and its $H$-band data were also used to derive the color of the source because this event suffered from very high extinction ($A_I \sim 4.5$; See Section 4). In addition, OGLE-2017-BLG-1161 was also densely observed by the LCO network, the 0.4 m telescope at Auckland Observatory (AO), and the 0.36 m telescope at Kumeu Observatory (Kumeu). OGLE-2017-BLG-1161 was selected as a “secret” Spitzer target on 2017 June 25 (UT 16:00) because the newest OGLE point (HJD = 2457932.78) indicated a significant rise (consistent with a high-magnification event) and the event was predict to peaked within 1 day, and it was formally announced as a Spitzer target on 2017 June 28. The Spitzer observations began on 2017 June 30 and ended on 2017 July 13 with 16 data points in total.

2.2. OGLE-2017-BLG-1254

OGLE-2017-BLG-1254 was first alerted by the OGLE collaboration on 2017 July 2. The event was located at equatorial coordinates $(\alpha, \delta)_{2000} = (17:57:23.56, -27:13:13.3)$, corresponding to Galactic coordinates $(\ell, b) = (2.80, -1.36)$. It therefore lies in OGLE field BLG645, which has a cadence less than 0.5 observations per night (Udalski et al. 2015a). This event was also identified by MOA group as MOA-2017-
BLG-373 \sim 12.2 \text{ days later (Bond et al. 2001)}, and recognized by KMTNet’s event-finding algorithm as KMT-2017-BLG-0374 (Kim et al. 2018). The KMTNet group observed this event in its two slightly offset fields BLG02 and BLG42, with combined cadence of $\Gamma = 4 \text{ hr}^{-1}$. The LCO, $\mu$FUN, and MiNDSTeP follow-up teams also observed this event. The dense observations during the peak by LCO and MiNDSTeP were important to constrain the finite-source effects. The $H$-band observations taken by CT13 were important for characterizing the source star because this event suffered from very high extinction ($A_I \sim 4.2$; See Section 4). OGLE-2017-BLG-1254 was chosen as a “secret” Spitzer target on 2017 July 2 (UT 20:48) because (1) the model predicted that the event could be a high-magnification event; (2) KMTNet has a high cadence of $\Gamma = 4 \text{ hr}^{-1}$. It was “subjectively” selected on July 6 and became "objective" on July 17 (see Yee et al. 2015a). The Spitzer observations began on 2017 July 7 and ended on 2017 August 3 with a cadence of \sim 1 observation per day.

2.3. Data Reductions

The photometry of OGLE, MOA, KMTNet, LCO, AO, Kumeu, and Danish data were extracted using custom implementations of the difference image analysis technique (Alard & Lupton 1998): Wozniak 2000 (OGLE), Bond et al. 2001 (MOA), Albrw et al. 2009 (KMTNet, LCO, AO, and Kumeu), and Bramich 2008 (Danish). In addition, the CT13 data were reduced by DoPHOT (Schechter et al. 1993). The Spitzer data were reduced using the algorithm developed by Calchi Novati et al. (2015b) for crowded-field photometry.

3. LIGHT CURVE ANALYSIS

3.1. Ground-based data only

For each event, we model the ground-based data using four parameters for the magnification, $A(t)$. These include three Paczyński parameters ($t_0, u_0, \theta_E$) (Paczyński 1986) to describe the light curve produced by a single-lens with a point-source: the time of the maximum magnification as seen from Earth $t_0$, the impact parameter $u_0$ (in units of the angular Einstein radius $\theta_E$), and the Einstein radius crossing time $\theta_E$. In addition, the source size normalized by the angular Einstein radius $\rho$ is needed to incorporate finite-source effects. The flux, $f(t)$, calculated from the model is

$$f(t) = f_s A(t) + f_h,$$

where $f_s$ represents the flux of the source star being lensed, and $f_h$ is any blended flux that is not lensed. The two linear parameters, $f_s$ and $f_h$, are different for each observatory and each filter. In addition, we adopt the linear limb-darkening law to consider the brightness profile of the source star (An et al. 2002)

$$S_\lambda(\theta) = \bar{S}_\lambda \left[1 - \Gamma_\lambda (1 - \frac{3}{2} \cos \theta)\right],$$

where $\bar{S}_\lambda$ is the mean surface brightness of the source, $\theta$ is the angle between the normal to the surface of the source and the line of sight, and $\Gamma_\lambda$ is the limb-darkening coefficient at wavelength $\lambda$. We employ the Markov chain Monte Carlo (MCMC) $\chi^2$ minimization using the emcee ensemble sampler (Foreman-Mackey et al. 2013) to find the best-fit parameters and their uncertainties.

3.2. Satellite parallax

We measure the microlens parallax from the light curve modeling.

$$\bar{\pi}_E \sim \frac{AU}{D_\perp} \left(\Delta u_0, \frac{\Delta t_0}{t_E}\right),$$

where $\Delta t_0$ is the difference in event peak time $t_0$ and $\Delta u_0$ is the difference in impact parameter $u_0$ as seen from the Spitzer satellite and Earth, and $D_\perp$ is the projected separation between the Spitzer satellite and Earth at the time of the event. Generally, only the absolute value of $u_0$ can be measured from the modeling, and thus the satellite parallax measurements usually suffer from a four-fold degeneracy (Refsdal 1966; Gould 1994). We specify the four solutions as $(+, +), (+, -), (-, -)$, and $(-, +)$ using the sign convention described in Zhu et al. (2015). Briefly, the first and second signs in each parenthesis indicate the signs of $u_0, \theta_E$ and $u_0, \theta_E$, respectively. In addition, the Spitzer observations only cover the falling part of OGLE-2017-BLG-1161 which leads to large uncertainty of $\pi_E$. Thus, we include a color-color constraint on the Spitzer source flux $f_{s, \text{Spitzer}}$ to improve the parallax measurement (e.g. Calchi Novati et al. 2015a). This constraint adds a $\chi^2_{\text{penalty}}$ into the total $\chi^2$ (See Equation (2) in Shin et al. 2017 for the form of the $\chi^2_{\text{penalty}}$).

3.3. OGLE-2017-BLG-1161

Using the intrinsic color of the source star (see Section 4.1) and the color-temperature relation of Houdashelt et al. (2000), we estimate the effective temperature of the source to be $T_{\text{eff}} \approx 4450$ K. Applying ATLAS models and assuming a surface gravity of log $g = 2.5$, a metallicity of $[M/H] = 0.0$, and a microturbulence parameter of 1 km s$^{-1}$, we obtain the linear limb-darkening coefficients $u_I = 0.60$ for $I$ band, $u_V = 0.81$ for $V$ band, $u_R = 0.71$ for $R$ band, $u_H = 0.39$ for $H$ band, and $u_L = 0.24$ for $L$ band (Claret & Bloemen 2011). We then employ the transformation formula in Fields et al. (2003), yielding the corresponding limb-darkening coefficients $\Gamma_I = 0.50, \Gamma_V = 0.74, \Gamma_R = 0.62, \Gamma_H = 0.30, \text{and } \Gamma_L = 0.18$. In the light curve modeling, we use $\Gamma_I$ for OGLE, LCO, CT13 $I$-band and Kumeu data, $\Gamma_{AO} = (\Gamma_V + \Gamma_R)/2 = 0.68$ for AO data, $\Gamma_H$ for CT13 $H$-band data, and $\Gamma_L$ for Spitzer data.

To derive the color-color constraint on the Spitzer source flux $f_{s, \text{Spitzer}}$, we extract the Spitzer photometry of red giant bulge stars ($4.0 < I_{\text{OGLE}} - H_{\text{VV}} < 5.5; 17.5 < I_{\text{OGLE}} < 20.5$).
We construct an I by locating it on a color-magnitude diagram (Yoo et al. 2004). Equation (3), we estimate the angular radius \( \theta \) by cross-matching the OGLE-IV \( H - I \) vs. \( K - I \) data. We find that the impact parameter \( u_0 \) is in excellent agreement with the color measured from the photometry. Nevertheless, we derive the \( IHL \) color-color relation using red giant stars (3.6 < \( I - H \) < 5.0; 17.0 < \( I \) < 19.5) for validation of the color-color method. The relation and the \( (I - H) \) color in Section 4.2 suggest that \( (I - H) = 3.82 \pm 0.03 \), which is in excellent agreement with the color measured from the model of \( (I - H) = 3.81 \pm 0.02 \).

3.4. OGLE-2017-BLG-1254

Applying the same procedure as in Section 3.3, we obtain the corresponding limb-darkening coefficients \( \Gamma_I = 0.45, \Gamma_H = 0.55, \Gamma_L = 0.26 \) and \( \Gamma_L = 0.16 \). In the light curve modeling, we use \( \Gamma_I \) for OGLE, KMTNet, LCO, CT13 \( I \)-band and Danish data, \( \Gamma_{MOA} = (\Gamma_I + \Gamma_H)/2 = 0.50 \) for MOA data, \( \Gamma_H \) for CT13 \( H \)-band data, and \( \Gamma_L \) for Spitzer data. We find that the impact parameter \( u_0 \) is consistent with 0 at the \( \sim 2 \sigma \) level.

For this event the Spitzer light curve precisely constrains the microlens parallax without the need of color-color constraint on \( L_{Spitzer} \). Nevertheless, we derive the \( IHL \) color-color relation using red giant stars (3.6 < \( I - H \) < 5.0; 17.0 < \( I \) < 19.5) for validation of the color-color method. The relation and the \( (I - H) \) color in Section 4.2 suggest that \( (I - H) = 3.82 \pm 0.03 \), which is in excellent agreement with the color measured from the model of \( (I - H) = 3.81 \pm 0.02 \).

4. PHYSICAL PARAMETERS: TWO LOW-MASS STARS IN THE GALACTIC BULGE

4.1. OGLE-2017-BLG-1161L

To derive the angular Einstein radius \( \theta_E \) for the lens by Equation (3), we estimate the angular radius \( \theta_e \) of the source by locating it on a color-magnitude diagram (Yoo et al. 2004). We construct an \( I - H \) versus \( I \) color-magnitude diagram by cross-matching the OGLE-IV \( I \)-band and the VVV (Saito et al. 2012) \( H \)-band stars within a \( 2' \times 2' \) square centered on the event (See Figure 3). We estimate the red giant clump to be \( (I - H, I)_{cl} = (4.59 \pm 0.02, 18.90 \pm 0.03) \) and find that the position of the source is \( (I - H, I) = (4.71 \pm 0.01, 18.70 \pm 0.03) \) from OGLE \( I \)-band data and CT13 \( H \)-band data aligned to the VVV magnitudes. From Nataf et al. (2016), we find that the intrinsic color and de-reddened magnitude of the red clump are \( (I - H, I)_{cl,0} = (1.30, 14.39) \). Thus, the intrinsic color and de-reddened brightness of the source are \( (I - H, I) = (1.42 \pm 0.03, 14.19 \pm 0.04) \). These values suggest the source is a K-type giant star (Bessell & Brett 1988). Using the color/surface-brightness relation of Adams et al. (2018), we obtain

\[
\theta_s = 7.4 \pm 0.4 \mu \text{as.}
\]

We derive the angular Einstein radius and the geocentric lens-source relative proper motion

\[
\theta_E = \frac{\theta_s}{\rho} = 0.159 \pm 0.009 \text{ mas};
\]

\[
\mu_{rel} = \frac{\theta_E}{t_E} = 6.11 \pm 0.39 \text{ mas yr}^{-1}.
\]

Using Equation (1), we measure the lens mass,

\[
M = \frac{\theta_E}{\kappa \pi_E} = \begin{cases} 
0.51^{+0.12}_{-0.10} M_\odot \text{ for } \pi_E \approx 0.038 \\
0.38^{+0.13}_{-0.12} M_\odot \text{ for } \pi_E \approx 0.051.
\end{cases}
\]

The lens-source relative parallax for the two cases is

\[
\pi_{rel} = \begin{cases} 
0.0062 \pm 0.0014 \text{ for } \pi_E \approx 0.038 \\
0.0083 \pm 0.0025 \text{ for } \pi_E \approx 0.051,
\end{cases}
\]

which are very small compared to the source parallax \( \pi_S \approx 0.12 \) (Nataf et al. 2016). Thus, the distance between the lens and the source is determined much more precisely than the distance to the lens or the source separately. We measure the lens-source distance,

\[
D_{LS} \approx D_S^2 \frac{\pi_{rel}}{\kappa \pi_E} = \begin{cases} 
0.40 \pm 0.12 \text{ kpc for } \pi_E \approx 0.038 \\
0.53 \pm 0.19 \text{ kpc for } \pi_E \approx 0.051.
\end{cases}
\]

where we adopt the source distance \( D_S = 8.0 \pm 0.8 \) kpc using the Galactic model of Zhu et al. (2017). Because the lens-source distance is \( \lesssim 1 \) kpc and the source is almost certainly a bulge red-clump star, the lens should be an M/K dwarf in the Galactic bulge. We list the derived source star properties in Table 2 and the physical parameters of all the four-fold degenerate solutions in Table 3.

4.2. OGLE-2017-BLG-1254L

We construct an \( I - H \) versus \( I \) color-magnitude diagram via the OGLE-IV \( I \)-band and the VVV \( H \)-band stars within a \( 2' \times 2' \) square centered on the event (See Figure 3). We measure the centroid of the red giant clump \( (I - H, I)_{cl} = (4.28 \pm 0.02, 18.39 \pm 0.03) \) and the position of the source \( (I - H, I) = (4.12 \pm 0.02, 18.53 \pm 0.01) \).
From Nataf et al. (2016), we find that the intrinsic color and de-reddened magnitude of the red clump are $(I - H, I)_{cl,0} = (1.30, 14.35)$, from which we derive the intrinsic color and de-reddened brightness of the source are $(I - H, I)_{S,0} = (1.14 \pm 0.03, 14.51 \pm 0.03)$. Thus, the source is a G-type giant star (Bessell & Brett 1988). Applying the color/surface-brightness relation of Adams et al. (2018), we obtain

$$\theta_* = 5.2 \pm 0.3 \, \mu\text{as}; \quad (17)$$

$$M_L = \frac{\theta_E}{\kappa \pi_E} = 0.60 \pm 0.03 M_\odot; \quad (18)$$

$$D_{LS} \approx D_S^2 \frac{\theta_{rel}}{\Delta U} = 0.53 \pm 0.11 \text{kpc}, \quad (19)$$

where we also adopt the source distance $D_S = 7.8 \pm 0.8$ kpc using the Galactic model of Zhu et al. (2017). Thus, the lens is probably a K dwarf in the Galactic bulge. We list the derived source properties in Table 2 and the physical parameters of OGLE-2017-BLG-1254 in Table 3.

5. DISCUSSION AND CONCLUSION

We have reported the analysis of two microlensing events OGLE-2017-BLG-1161 and OGLE-2017-BLG-1254, each of which displays both finite-source effects detected by the ground-based data and the microlens parallax measured by the joint analysis of the ground-based data and the Spitzer data. Including these two events, the Spitzer microlensing program has measured the mass and distance for eight isolated objects from 2015–2017, yielding an estimate of the apparent detection frequency $\sim 8/328 = 2.4\%$\(^3\). This apparent frequency agrees with the theoretical frequency $\sim 3.3\%$ (Zhu et al. 2016) within 1\(\sigma\) for Poisson statistics. The theoretical frequency assumes that the probability to detect the finite-source effects in single-lens events is the same for ground and Spitzer observations, but the Spitzer data only detected finite-source effects for two events\(^4\) (OGLE-2015-BLG-0763 (Zhu et al. 2016), OGLE-2015-BLG-1482 Chung et al. 2017), with a degeneracy in $\rho$. This is because the Spitzer observations only have a $\Gamma \sim 1$ day\(^{-1}\) cadence and require a 3–10 day turnaround time after selection of the event, leading to the loss of finite-source effect detection from Spitzer observations.

The probability of finite-source effects occurring in a single-lens event is

$$P = \rho \equiv \frac{\theta_*}{\theta_E}. \quad (20)$$

\(^3\) Spitzer observed 524 events from 2015–2017, but only 328 events are single-lens events with a clear Spitzer signal.

\(^4\) For OGLE-2017-BLG-1166, the best-fit Spitzer light curve also shows finite-source effects, but the daily Spitzer data are insufficient for the detection.

This, when combined with the microlensing rate $\Gamma_{\text{lens}} \propto n_{\mu_{\text{rel}}} \theta_E$ ($n$ is the number density), yields the finite-source event rate (Gould & Yee 2012; Shvartzvald et al. 2019)

$$\Gamma_{\text{FS}} = \rho \Gamma_{\text{lens}} \propto n_{\mu_{\text{rel}}} \theta_*.$$  \( (21) \)

We apply the Galactic model described in Zhu et al. (2017) and estimate the probability density distribution of finite-source events based on $n \times \mu_{\text{rel}}$. We average the distributions in the direction of the eight Spitzer finite-source events and assume the source distances are 8.3 kpc for all the events (following Zhu et al. 2017). For events with two degenerate solutions, both solutions are included at half the weight. Figure 4 compares the resulting probability densities for different masses and distances with the eight Spitzer finite-source events. Figure 5 and 6 compare the cumulative distributions of the lens distance and lens mass, respectively. In this comparison, we do not take into account the Spitzer detection efficiency, and possible selection or publication biases. Such detailed analysis is beyond the scope of this paper and will be done in future complete statistical analysis of the Spitzer campaigns.

The observed Spitzer sample agrees with expectations from the Galactic model. The distance distribution of the eight events is consistent with the Galactic model of Zhu et al. (2017) with a Kolmogorov-Smirnov probability of 30.3%, and the mass distribution is consistent with the initial mass function of Kroupa (2001) and Chabrier (2003) with a Kolmogorov-Smirnov probability of 84.9% and 72.3%, respectively. Both the Galactic model and the eight Spitzer events show that the finite-source effects have strong bias toward objects in the Galactic bulge. This is primarily because the stellar number density in the Galactic bulge is significantly higher than that of the Galactic disk, while the lens-source relative proper motions of disk lenses are only slightly higher on average (see Figure 1 and 2 of Zhu et al. 2017). In addition, the finite-source effects are biased toward the more common low-mass objects (M-dwarfs and brown dwarfs). However, Spitzer has no detection of a low-mass brown dwarf ($M_L < 0.04 M_\odot$) in the Galactic bulge, in tension with the expectations from the Galactic model. This is likely due to the 3–10 day delay of the Spitzer observations, which is comparable to the typical microlens timescale for a bulge low-mass brown dwarf is less than 6 days.

Shan et al. (2018) compared 13 well-characterized Spitzer systems (10 binary/planetary lenses and 3 single lenses) with Bayesian predictions from Galactic models and found that they are in excellent agreement. Our preliminary comparison of eight Spitzer single lenses also suggests good agreement with the expectations from the Galactic model. Assuming the empirical rate from 2015–2017 season, we expect another 5–10 detections of finite-source events in 2018 and 2019 Spitzer microlensing campaigns, and thus future
statistical analyses of all Spitzer finite-source events will potentially allow a study of specific stellar populations and test the Galactic model.

W.Z., W.T., S.-S.L. and S.M. acknowledges support by the National Science Foundation of China (Grant No. 11821303 and 11761131004). This work is based (in part) on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech. The OGLE has received funding from the National Science Centre, Poland, grant MAESTRO 2014/14/A/ST9/00121 to AU. This research has made use of the KMTNet system operated by the Korea Astronomy and Space Science Institute (KASI) and the data were obtained at three host sites of CTIO in Chile, SAAO in South Africa, and SSO in Australia.

The MOA project is supported by JSPS KAKENHI Grant Number JP25240004, JP16040006, JP15K08021, and JP17H02871. The research has made use of data obtained at the Danish 1.54m telescope at ESOs La Silla Observatory. CITEUC is funded by National Funds through FCT - Foundation for Science and Technology (project: UID/Multi/00611/2013) and FEDER - European Regional Development Fund through COMPETE 2020 - Operational Programme Competitiveness and Internationalization (project: POCI-01-0145-FEDER-006922). Work by AG was supported by AST-1516842 from the US NSF and JPL grant 1500811. Wei Zhu was supported by the Beatrice and Vincent Tremaine Fellowship at CITA. Work by CH was supported by the grant (2017R1A4A1015178) of National Research Foundation of Korea. YT acknowledges the support of DFG priority program SPP 1992 Exploring the Diversity of Extrasolar Planets (WA 1047/11-1). L.M. acknowledges support from the Italian Minister of Instruction, University and Research (MIUR) through FFABR 2017 fund.

REFERENCES

Mao, S. 2012, Research in Astronomy and Astrophysics, 12, 947
Udalski, A., Szymański, M. K., & Szymański, G. 2015a, AcA, 65, 1
Wozniak, P. R. 2000, AcA, 50, 421
Table 1. Best-fit parameters for OGLE-2017-BLG-1161 and OGLE-2017-BLG-1254 and their 68\% uncertainty range from the MCMC

<table>
<thead>
<tr>
<th>Event</th>
<th>OGLE-2017-BLG-1161</th>
<th>OGLE-2017-BLG-1254</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{0,\odot}$</td>
<td>7933.548(2)</td>
<td>7952.2519(4)</td>
</tr>
<tr>
<td>$u_{0,\odot}$</td>
<td>0.0214(8)</td>
<td>0.0003(10)</td>
</tr>
<tr>
<td>$t_E$</td>
<td>9.5(3)</td>
<td>15.43(6)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.046(15)</td>
<td>0.025(1)</td>
</tr>
<tr>
<td>$\pi_{E,N}$</td>
<td>-0.000(23)</td>
<td>0.0203(7)</td>
</tr>
<tr>
<td>$\pi_{E,E}$</td>
<td>0.039(7)</td>
<td>0.0368(4)</td>
</tr>
<tr>
<td>$\pi_E$</td>
<td>0.039(9)</td>
<td>0.0420(7)</td>
</tr>
<tr>
<td>$I_s$</td>
<td>18.71(3)</td>
<td>18.53(1)</td>
</tr>
<tr>
<td>$I_h$</td>
<td>18.71(3)</td>
<td>21.32(6)</td>
</tr>
<tr>
<td>$\chi^2_{\text{penalty}}$</td>
<td>618.41/617</td>
<td>-</td>
</tr>
<tr>
<td>$\chi^2/\text{dof}$</td>
<td>8254.78/8256</td>
<td>8254.69/8256</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_I$</td>
<td>[mag]</td>
<td>$\sim 4.5$</td>
</tr>
<tr>
<td>$I_S$</td>
<td>[mag]</td>
<td>18.70 $\pm$ 0.03</td>
</tr>
<tr>
<td>$H_S$</td>
<td>[mag]</td>
<td>13.99 $\pm$ 0.03</td>
</tr>
<tr>
<td>$(I - H)_S$</td>
<td>[mag]</td>
<td>4.71 $\pm$ 0.01</td>
</tr>
<tr>
<td>$(I - L)_S$</td>
<td>[mag]</td>
<td>4.55 $\pm$ 0.02</td>
</tr>
<tr>
<td>$I_{S,0}$</td>
<td>[mag]</td>
<td>14.19 $\pm$ 0.04</td>
</tr>
<tr>
<td>$H_{S,0}$</td>
<td>[mag]</td>
<td>12.77 $\pm$ 0.04</td>
</tr>
<tr>
<td>$(I - H)_{S,0}$</td>
<td>[mag]</td>
<td>1.42 $\pm$ 0.03</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>[mas]</td>
<td>7.4 $\pm$ 0.04</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Event</th>
<th>OGLE-2017-BLG-1161</th>
<th>OGLE-2017-BLG-1254</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_E$ [mas]</td>
<td>0.159 $\pm$ 0.009</td>
<td>0.207 $\pm$ 0.008</td>
</tr>
<tr>
<td>$M_L$ [$M_\odot$]</td>
<td>0.50$^{+0.22}_{-0.18}$</td>
<td>0.60 $\pm$ 0.03</td>
</tr>
<tr>
<td>$D_{LS}$ [kpc]</td>
<td>0.40 $\pm$ 0.12</td>
<td>0.53 $\pm$ 0.11</td>
</tr>
<tr>
<td>$\mu_{\text{hel}}$ [mas yr$^{-1}$]</td>
<td>6.11 $\pm$ 0.39</td>
<td>4.90 $\pm$ 0.20</td>
</tr>
</tbody>
</table>
Figure 1. The light curves of event OGLE-2017-BLG-1161. The black and magenta lines represent the best-fit \((-\), \(+\)) model for the ground data with \(I\) and \(H\) band, respectively, and the red line shows the corresponding model for Spitzer. The inset in the top panel shows the peak of the event, with a clear finite-source effect. The circles with different colors are ground-based data points from different collaborations or bands. The red dots are Spitzer data points.
Figure 2. Ground-based and Spitzer data and best-fit model light curves of event OGLE-2017-BLG-1254 for the $(0, +)$ model. Symbols are similar to those in Figure 1.
Figure 3. OGLE-VVV color-magnitude diagrams of a $2' \times 2'$ square centered on OGLE-2017-BLG-1161 (left panel) and OGLE-2017-BLG-1254 (right panel). The red asterisks show the centroid of the red clump. The blue dots indicate the position of the source.
Figure 4. Bayesian probability density distributions from the Galactic model of Zhu et al. (2017) compared to the eight published Spitzer finite-source events. We fix the source distance to 8.3 kpc and then derive the lens distance $D_{8.3}$ for all the events. The predicted mass distribution is derived from the initial mass function of Kroupa (2001). The dots with different colors represent different events. The two dots connected by dash lines represent the two degenerate solutions of one event. The grey lines represent equal probability density. The values on the contours indicate the total probability inside the contours predicted by the Galactic model and the total probability is normalized to unity.
Figure 5. Cumulative distribution of the lens distance from the Galactic model of Zhu et al. (2017) and the eight published Spitzer finite-source events. We fix the source distance of 8.3 kpc and then derive the lens distance $D_{8.3}$ for all the events. The black line represents the distribution predicted by the Galactic model, and the grey lines represents the distribution calculated from the eight events. The observed distribution is consistent with the Galactic model with a Kolmogorov-Smirnov probability of 30.3%.
Figure 6. Cumulative distribution of the lens mass from the initial mass function and the eight published Spitzer finite-source events. The black line represents the distribution predicted by the initial mass function of Kroupa (2001) and the blue line represents the distribution calculated from Chabrier (2003). The observed distribution is consistent with the initial mass functions of Kroupa (2001) and Chabrier (2003) with a Kolmogorov-Smirnov probability of 84.9% and 72.3%, respectively.