



# Systematic KMTNet Planetary Anomaly Search. X. Complete Sample of 2017 Prime-field Planets

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## Abstract

We complete the analysis of planetary candidates found by the KMT AnomalyFinder for the 2017 prime fields that cover  $\sim 13$  deg<sup>2</sup>. We report three unambiguous planets: OGLE-2017-BLG-0640, OGLE-2017-BLG-1275, and OGLE-2017-BLG-1237. The first two of these were not previously identified, while the last was not previously published due to technical complications induced by a nearby variable. We further report that a fourth anomalous event, the previously recognized OGLE-2017-BLG-1777, is very likely to be planetary, although its light curve requires unusually complex modeling because the lens and source both have orbiting companions. One of the three unambiguous planets, OGLE-2017-BLG-1275, is the first AnomalyFinder discovery that has a Spitzer microlens parallax measurement,  $\pi_E \simeq 0.045 \pm 0.015$ , implying that this planetary system almost certainly lies in the Galactic bulge. In the order listed, the four planetary events have planet-host mass ratios  $q$  and normalized projected separations  $s$  of  $(\log q, s) = (-2.31, 0.61)$ ,  $(-2.06, 0.63/1.09)$ ,  $(-2.10, 1.04)$ , and  $(-2.86, 0.72)$ . Combined with previously published events, the 2017 prime fields contain 11 unambiguous planets with well-measured  $q$  and one very likely candidate, of which three are AnomalyFinder discoveries. In addition to these 12, there are three other unambiguous planets with large uncertainties in  $q$ .

*Unified Astronomy Thesaurus concepts:* [Gravitational microlensing \(672\)](#)

## 1. Introduction

We present the analysis of all planetary events that were identified by the KMTNet AnomalyFinder algorithm (Zang et al. 2021, 2022) and occurred during the 2017 season within the six prime KMTNet fields, which contiguously cover  $\sim 13$  deg<sup>2</sup> of the richest microlensing region of the Galactic

bulge, with cadences  $\Gamma = 2\text{--}4 \text{ hr}^{-1}$ . This work follows the publications of complete samples of the 2018 prime (Wang et al. 2022; Hwang et al. 2022; Gould et al. 2022a) and subprime (Jung et al. 2022) AnomalyFinder events, the 2019 prime (Zang et al. 2021; Hwang et al. 2022; Zang et al. 2022) and subprime (Jung et al. 2023) events, and the 2016 prime (Shin et al. 2023) events, as well as a complete sample of all events from 2016 to 2019 with planet-host mass ratios  $q < 10^{-4}$  (Zang et al. 2023). There are 21 subprime fields that cover  $\sim 84 \text{ deg}^2$  of the Galactic bulge with cadences  $\Gamma = 0.2\text{--}1 \text{ hr}^{-1}$ . The above references are (ignoring duplicates) Papers I, IV, II, III, V, VI, VIII, IX, and VII in the AnomalyFinder series. The locations and cadences of the KMTNet fields are shown in Figure 12 of Kim et al. (2018a). Our immediate goal, which we expect to achieve within a year, is to publish all AnomalyFinder planets from 2016 to 2019. Over the longer term, we plan to apply AnomalyFinder to all subsequent KMT seasons, beginning 2021.

For the 2017 prime fields, the AnomalyFinder identified a total of 124 anomalous events (from an underlying sample of 998 events), which it classified as “planet” (16), “planet/binary” (10), “binary/planet” (14), “binary” (77), and “finite source” (7). Among the 77 in the “binary” classification, 33 were judged by eye to be unambiguously nonplanetary in nature. Among the 16 in the “planet” classification, eight were previously published, one of which had been newly discovered by AnomalyFinder, while one planetary event is in preparation but has a very large uncertainty in  $q$ . Among the 10 in the “planet/binary” classification, none were previously known planets, and among the 14 in the “binary/planet” classification one was a previously published planet. Among the 77 classified as “binary,” one was previously published and two others had been recognized as probably planetary (OGLE-2017-BLG-1237 and OGLE-2017-BLG-1777). None of the seven “finite source” events were previously published planets. In sum, the AnomalyFinder recovered nine previously published planets that had been discovered by eye as well as two other planets that had been recognized but not published. In addition, one of its new discoveries (KMT-2017-BLG-0428) has already been published (Zang et al. 2023), while another (OGLE-2017-BLG-0448) is in preparation but with a very large uncertainty in  $q$ . We find that among the remaining candidates two are unambiguously planetary (OGLE-2017-BLG-0640 and OGLE-2017-BLG-1275), while two others have planetary solutions but cannot be unambiguously interpreted (OGLE-2017-BLG-0543 and OGLE-2017-BLG-1694). Hence, we here report analyses of a total of six anomalous events, three that are unambiguously planetary, one that is very likely to be planetary, and two that have competitive planetary and nonplanetary solutions.

Finally, we note that while there are no known planets from among 2017 prime-field KMT events that were not identified as candidates by the AnomalyFinder, there is one known planet, OGLE-2017-BLG-0604 (Han et al. 2020), that does not enter the AnomalyFinder sample because the underlying event was not found by the EventFinder system (Kim et al. 2018a) and so was not subjected to the AnomalyFinder search. Judging by the strength of the planetary signal (Figure 6 of Han et al. 2020), it almost certainly would have been found. However, this omission will have no effect on statistical analyses based on this paper (and other AnomalyFinder papers) because both the detections and planet sensitivity calculations are restricted to

events cataloged by EventFinder and AlertFinder (Kim et al. 2018b).

## 2. Observations

The description of the observations is nearly identical to that in Gould et al. (2022a) and Jung et al. (2022). The KMTNet data are taken from three identical 1.6 m telescopes, each equipped with cameras of  $4 \text{ deg}^2$  (Kim et al. 2016) and located in Australia (KMTA), Chile (KMTC), and South Africa (KMST). When available, our general policy is to include Optical Gravitational Lensing Experiment (OGLE) and Microlensing Observations in Astrophysics (MOA) data in the analysis. However, none of the six events analyzed here were alerted by MOA. OGLE data were taken using their 1.3 m telescope with a  $1.4 \text{ deg}^2$  field of view at Las Campanas Observatory in Chile. For the light-curve analysis, we use only the  $I$ -band data.

As in those papers, Table 1 gives basic observational information about each event. The first column gives the event names in the order of discovery (if discovered by multiple teams), which enables cross identification. The nominal cadences are given in the second column, and the third column shows the first discovery date. The remaining four columns show the event coordinates in the equatorial and galactic systems. Events with OGLE names were originally discovered by the OGLE Early Warning System (Udalski et al. 1994; Udalski 2003). In 2017, the KMT AlertFinder system (Kim et al. 2018b) was not yet operational. Hence all KMT events were discovered postseason by the EventFinder system (Kim et al. 2018a).

Two of the events (OGLE-2017-BLG-1275 and OGLE-2017-BLG-0640) were observed by the UKIRT Microlensing Survey in the  $H$  and  $K$  bands (Shvartzvald et al. 2017) using the UKIRT 3.6 m telescope in Hawaii. We use the UKIRT  $H$ -band data for color determination in both cases (see Section 4), and we also incorporate them into the light-curve modeling. These data are available through the UKIRT microlensing public archive.<sup>17</sup>

OGLE-2017-BLG-1275 and OGLE-2017-BLG-1237 were both observed by Spitzer as part of a large-scale microlensing program (Yee et al. 2015a). The Spitzer observations of OGLE-2017-BLG-1275 are described in Section 3.2.1, while those of OGLE-2017-BLG-1237 do not show a discernible signal and so are not used in this paper.

To the best of our knowledge, there were no ground-based follow-up observations of any of these events.

The KMT and OGLE data were reduced using difference-image analysis (Tomaney & Crofts 1996; Alard & Lupton 1998), as implemented by each group, that is, pySIS (Albrow et al. 2009) and DIA (Woźniak 2000), respectively. To prepare for publication, KMT data were rereduced using a tender loving care (TLC) version of pySIS (Yang et al. 2024), while OGLE data were rereduced using their standard pipeline but centroided on the lens rather than the baseline object.

## 3. Light-curve Analysis

### 3.1. Preamble

With one exception that is explicitly noted below, we reproduce here Section 3.1 of Jung et al. (2022), which

<sup>17</sup> <https://exoplanetarchive.ipac.caltech.edu/docs/UKIRTMission.html>

**Table 1**  
Event Names, Cadences, Alerts, and Locations

Name	$\Gamma$ (hr $^{-1}$ )	Alert Date	R.A. $_{J2000}$	Decl. $_{J2000}$	$l$	$b$
OGLE-2017-BLG-1275	0.8	2017 Jul 10	17:51:39.70	-29:29:52.69	+0.20	-1.42
KMT-2017-BLG-0314	4.0					
OGLE-2017-BLG-0640	0.8	2017 May 13	17:49:51.63	-29:27:41.40	+0.03	-1.06
KMT-2017-BLG-1726	4.0					
OGLE-2017-BLG-1237	0.35	2017 Jul 1	18:06:35.99	-28:19:43.79	+2.84	-3.67
KMT-2017-BLG-0422	2.4					
OGLE-2017-BLG-1777	0.8	2017 Oct 14	17:53:23.25	-29:54:36.00	+0.04	-1.95
KMT-2017-BLG-0282	4.0					
OGLE-2017-BLG-0543	0.13	2017 Apr 13	17:51:19.96	-32:02:29.69	-2.02	-2.66
KMT-2017-BLG-0140	4.0					
OGLE-2017-BLG-1694	3.0	2017 Sep 6	17:59:14.60	-28:34:48.00	-1.83	-2.39
KMT-2017-BLG-2126	4.0					

describes the common features of the light-curve analysis. We do so (rather than simply referencing that paper) to provide easy access to the formulae and variable names used throughout this paper. The reader who is interested in more details should consult Section 3.1 of Gould et al. (2022a). Readers who are already familiar with these previous works can skip this section, after first reviewing the paragraph containing Equation (9) below.

All of the events can be initially approximated by 1L1S models, which are specified by three Paczyński (1986) parameters,  $(t_0, u_0, t_E)$ , that is, the time of lens-source closest approach, the impact parameter in units of  $\theta_E$ , and the Einstein timescale,

$$t_E = \frac{\theta_E}{\mu_{\text{rel}}}; \quad \theta_E = \sqrt{\kappa M \pi_{\text{rel}}}; \quad \kappa \equiv \frac{4 G}{c^2 \text{ au}} \simeq 8.14 \frac{\text{mas}}{M_{\odot}}, \quad (1)$$

where  $M$  is the lens mass,  $\pi_{\text{rel}}$  and  $\mu_{\text{rel}}$  are the lens-source relative parallax and proper motion, respectively, and  $\mu_{\text{rel}} \equiv |\boldsymbol{\mu}_{\text{rel}}|$ . The notation “ $nLmS$ ” means  $n$  lenses and  $m$  sources. In addition, to these three nonlinear parameters, there are two flux parameters,  $(f_S, f_B)$ , that are required for each observatory, representing the source flux and the blended flux.

We then search for “static” 2L1S solutions, which generally require four additional parameters  $(s, q, \alpha, \rho)$ , that is, the planet-host separation in units of  $\theta_E$ , the planet-host mass ratio, the angle of the source trajectory relative to the binary axis, and the angular source size normalized to  $\theta_E$ , that is,  $\rho = \theta_{\text{ast}}/\theta_E$ .

We first conduct a grid search with  $(s, q)$  held fixed at a grid of values and the remaining five parameters allowed to vary in a Markov Chain Monte Carlo (MCMC). After we identify one or more local minima, we refine these by allowing all seven parameters to vary.

We often make use of the heuristic analysis introduced by Hwang et al. (2022) and modified by Ryu et al. (2022) based on further investigation in Gould et al. (2022a). If a brief anomaly at  $t_{\text{anom}}$  is treated as due to the source crossing the planet-host axis, then one can estimate two relevant parameters:

$$s_{\pm}^{\dagger} = \frac{\sqrt{4 + u_{\text{anom}}^2} \pm u_{\text{anom}}}{2}; \quad \tan \alpha = \frac{u_0}{\tau_{\text{anom}}}, \quad (2)$$

where  $u_{\text{anom}}^2 = \tau_{\text{anom}}^2 + u_0^2$  and  $\tau_{\text{anom}} = (t_{\text{anom}} - t_0)/t_E$ . Usually,  $s_{+}^{\dagger} > 1$  corresponds to anomalous bumps and  $s_{-}^{\dagger} < 1$

corresponds to anomalous dips. This formalism predicts that if there are two degenerate solutions,  $s_{\pm}$ , then they both have the same  $\alpha$  and there exists a  $\Delta \ln s$  such that

$$s_{\pm} = s^{\dagger} \exp(\pm \Delta \ln s), \quad (3)$$

where  $\alpha$  and  $s^{\dagger}$  are given by Equation (2). To test this prediction in individual cases, we can compare the purely empirical quantity  $s^{\dagger} \equiv \sqrt{s_{+} s_{-}}$  with the prediction from Equation (2), which we always label with a subscript, that is, either  $s_{+}^{\dagger}$  or  $s_{-}^{\dagger}$ . This formalism can also be used to find “missing solutions” that have been missed in the grid search, as was done, for example, for the case of KMT-2021-BLG-1391 (Ryu et al. 2022).

For cases in which the anomaly is a dip, the mass ratio  $q$  can be estimated,

$$q = \left( \frac{\Delta t_{\text{dip}}}{4 t_E} \right)^2 \frac{s^{\dagger}}{|u_0|} |\sin^3 \alpha|, \quad (4)$$

where  $\Delta t_{\text{dip}}$  is the full duration of the dip. In some cases, we investigate whether the microlens parallax vector,

$$\boldsymbol{\pi}_E \equiv \frac{\pi_{\text{rel}}}{\theta_E} \frac{\boldsymbol{\mu}_{\text{rel}}}{\mu_{\text{rel}}}, \quad (5)$$

can be constrained by the data. When both  $\pi_E$  and  $\theta_E$  are measured, they can be combined to yield

$$M = \frac{\theta_E}{\kappa \pi_E}; \quad D_L = \frac{\text{au}}{\theta_E \pi_E + \pi_S}, \quad (6)$$

where  $D_L$  is the distance to the lens and  $\pi_S$  is the parallax of the source.

To model the parallax effects due to Earth’s orbital motion, we add two parameters  $(\pi_{E,N}, \pi_{E,E})$ , which are the components of  $\boldsymbol{\pi}_E$  in equatorial coordinates. We also add (at least initially) two parameters  $\boldsymbol{\gamma} = [(ds/dt)/s, d\alpha/dt]$ , where  $s\boldsymbol{\gamma}$  are the first derivatives of projected lens-orbital position at  $t_0$ , that is, parallel and perpendicular to the projected separation of the planet at that time, respectively. In order to eliminate unphysical solutions, we impose a constraint on the ratio of

the transverse kinetic to potential energy,

$$\beta \equiv \left| \frac{\text{KE}}{\text{PE}} \right|_{\perp} = \frac{\kappa M_{\odot} \text{yr}^2}{8\pi^2} \frac{\pi_E}{\theta_E} \gamma^2 \left( \frac{s}{\pi_E + \pi_S/\theta_E} \right)^3 < 0.8. \quad (7)$$

It often happens that  $\gamma$  is neither significantly constrained nor significantly correlated with  $\pi_E$ . In these cases, we suppress these 2 dof.

Particularly if there are no sharp caustic-crossing features in the light curve, 2L1S events can be mimicked by 1L2S events. Where relevant, we test for such solutions by adding at least three parameters ( $t_{0,2}$ ,  $u_{0,2}$ ,  $q_F$ ) to the 1L1S models. These are the time of closest approach and impact parameter of the second source and the ratio of the second to the first source flux in the  $I$  band. If either lens-source approach can be interpreted as exhibiting finite source effects, then we must add one or two further parameters, that is,  $\rho_1$  and/or  $\rho_2$ . And, if the two sources are projected closely enough on the sky, one must also consider source orbital motion.

In a few cases, we make kinematic arguments that solutions are unlikely because their inferred proper motions  $\mu_{\text{rel}}$  are too small. If planetary events (or, more generally, anomalous events with planet-like signatures) traced the overall population of microlensing events, then the fraction with proper motions less than a given  $\mu_{\text{rel}} \ll \sigma_{\mu}$  would be

$$p(\leq \mu_{\text{rel}}) = \frac{(\mu_{\text{rel}}/\sigma_{\mu})^3}{6\sqrt{\pi}} \rightarrow 4 \times 10^{-3} \left( \frac{\mu_{\text{rel}}}{1 \text{ mas yr}^{-1}} \right)^3 \quad (\text{old}), \quad (8)$$

where (following Gould et al. 2021) the bulge proper motions are approximated as an isotropic Gaussian with dispersion  $\sigma_{\mu} = 2.9 \text{ mas yr}^{-1}$ .

However, subsequent to the work of Gould et al. (2022a) and Jung et al. (2022), Gould (2022) showed that the proper-motion distribution of observed planetary microlensing events scales  $\propto d\mu_{\text{rel}}(\mu/\sigma_{\mu})^{\nu}$ , where  $\sigma_{\mu} = 3.06 \pm 0.29 \text{ mas yr}^{-1}$  and  $\nu = 1.02 \pm 0.29$ . Hence, in place of Equation (8), we adopt

$$p(\leq \mu_{\text{rel}}) = \frac{(\mu_{\text{rel}}/2\sigma_{\mu})^{\nu+1}}{[(\nu+1)/2]!} \rightarrow \frac{\mu_{\text{rel}}^2}{4\sigma_{\mu}^2} \rightarrow 2.8 \times 10^{-2} \left( \frac{\mu_{\text{rel}}}{1 \text{ mas yr}^{-1}} \right)^2, \quad (9)$$

where we have evaluated at  $\sigma_{\mu} = 3.0 \text{ mas yr}^{-1}$  and  $\nu = 1$ . For example,  $p(\leq 0.5 \text{ mas yr}^{-1}) = 0.7\%$  and  $p(\leq 0.1 \text{ mas yr}^{-1}) = 0.03\%$ .

### 3.2. OGLE-2017-BLG-1275

Figure 1 shows a relatively low-amplitude 1L1S microlensing event punctuated by a dip just  $\Delta t_{\text{anom}} \simeq -0.3$  day before peak, with a full width,  $\Delta t_{\text{dip}} \simeq 3.0$  days. A Paczyński (1986) fit (with the dip excised) yields  $t_E = 13.3$  days and  $u_0 = 0.40$ . Using the formulae from Section 3.1, we obtain  $\tau_{\text{anom}} = -0.02$ ,  $u_{\text{anom}} = 0.40$ ,  $\alpha = 273^\circ$ ,  $s_{\perp}^{\dagger} = 0.82$ , and  $q = 6.5 \times 10^{-3}$ .

The grid search yields three minima, two of which (when refined) form a classic “inner/outer” degenerate pair, whose parameters are in excellent agreement with the heuristic predictions for  $\alpha$  and  $s_{\perp}^{\dagger} = \sqrt{s_{\text{inner}} s_{\text{outer}}}$ , and in qualitative agreement for  $q$ . See Table 2. Note that, as is often the case

(Yee et al. 2021), the source passes outside the planetary wing of a resonant caustic in the “outer” model and inside the planetary caustics in the “inner” model.

Somewhat surprisingly, it also yields a third solution characterized by a caustic-crossing (“wide”) major-image perturbation. In this solution, the dip is produced by the declining magnification just outside of the caustic walls, while the violent caustic crossing itself is finessed by a 0.4 day gap in the data. In addition to being somewhat implausible, this fit is substantially worse, with  $\Delta\chi^2 = 35$ , so we do not further consider it.

While dip-type anomalies are rarely well-fit by 1L2S models, this can happen. Therefore, as a matter of due diligence, we check such models but find that they are excluded by  $\Delta\chi^2 = 95$ .

#### 3.2.1. OGLE-2017-BLG-1275: A Spitzer Planet

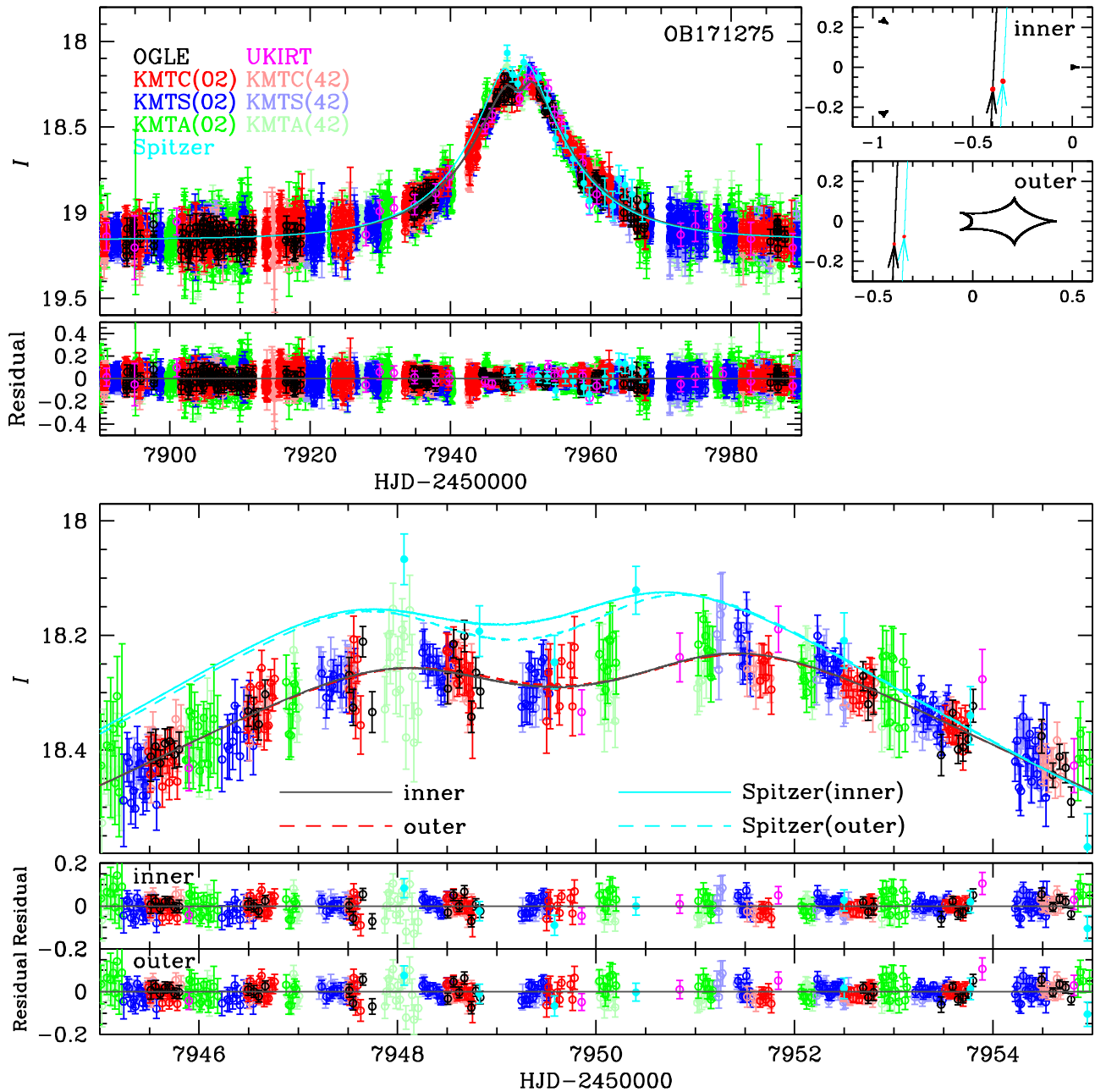
OGLE-2017-BLG-1275 was one of about 1000 microlensing events that were observed by Spitzer during a 6 yr campaign to obtain microlens parallax measurements for planetary events, using the method proposed by Refsdal (1966) of observing simultaneously from Earth and a satellite in solar orbit. In the AnomalyFinder series of papers, we usually leave the analysis of the Spitzer data to future papers, in large part because the Spitzer analysis is usually ongoing independently. However, OGLE-2017-BLG-1275 is the first planet with viable Spitzer data that was newly discovered by AnomalyFinder rather than being recognized while the event was ongoing or during a postseason by-eye review.<sup>18</sup> We therefore break with this tradition and analyze these data here.

By special arrangement, OGLE made a practice of issuing its Monday alerts (i.e., the day for Spitzer uploads) immediately after the end of observations in Chile (UT 10:30), which enabled the Spitzer team to evaluate new candidates by the Spitzer operations deadline, that is, UT 15:00. Despite the fact that OGLE-2017-BLG-1275 was a relatively short and (optically) faint event, OGLE was able to issue its alert 5 days before peak at  $\text{HJD}' = 7944.94$ , just a few hours before the deadline for submitting targets for Spitzer observations. At the time, it was not yet bright enough to be observable by Spitzer, but it was recognized that it had the potential to be a high-magnification event. As such, it was selected as a “secret” Spitzer target. Later, the Spitzer team recognized that it had brightened enough to meet the criterion for Spitzer detection and so announced the event as a “subjective, immediate” target at UT 20:03 on July 11, corresponding to  $\text{HJD}' = 7946.34$ . Hence, by an unusual combination of good luck and aggressive monitoring, Spitzer observations began just 3.25 days after the data that enabled the alert were taken.

According to the protocols of Yee et al. (2015a), planets can only be included in the Spitzer statistical sample if the decision to observe the event was not influenced by the presence of the planet. In one sense, this condition is obviously satisfied, as the planet remained unrecognized for 5 yr. Nevertheless, to be more precise, we see that the Spitzer team announced this event more than a day before the onset of the dip. Hence, this criterion is fully satisfied.

<sup>18</sup> The first AnomalyFinder planet, OGLE-2019-BLG-1053, showed a Spitzer flux change of 1.8 units. Because this is only a few times larger than the systematic errors, Zang et al. (2021) left the investigation of whether it had a measurable parallax to future work.





**Figure 1.** Data (color-coded by observatory) together with the predictions and residuals for two of the three models of OGLE-2017-BLG-1275 specified in Table 2, that is, an “inner”/“outer” pair that explain the “dip” near the peak by a minor-image perturbation. We do not show the third (“wide”) solution, which explains this dip by a major-image perturbation, to avoid clutter and because it is formally excluded by  $\Delta\chi^2 = 35$ . The Spitzer data (cyan), which were taken from solar orbit, show a similar dip near the peak followed by a similar decline, which together imply that the source trajectory as seen by Spitzer was similar to one from the ground (right insets) and hence that the microlens parallax  $\pi_E$  is small.

Often the Spitzer team organizes follow-up observations to enhance the prospects for detecting planets, but they did not do so in this case. It also usually observed the target in the  $H$  band using the SMARTS ANDICAM camera in order to measure the source color. However, in this case, it noted that this field was being observed 1–2 times per day by the UKIRT Microlensing Survey and so saw no need to duplicate these observations. We include the  $H$ -band observations in the modeling and show them in Figure 1. They contribute modestly to excluding the “wide” model, but their main contribution is to the measurement of the source color. See Section 4.1.

The Spitzer data comprise 17 epochs spanning 21.3 days and beginning on 7948.07, that is, 1.9 days before  $t_{0,\oplus}$ . They

overall fall by about 5 flux units during the first half of this period and are roughly flat in the second half. Within the first period, they are roughly flat (possibly with some structure) during the first 2 days. Thus, prior to any detailed analysis, they appear to be broadly consistent with the ground-based light curve, that is, peaking at about the same time, and affected by the dip-type anomaly that is seen from the ground. Hence, they appear to imply a very small  $\pi_E$ .

We proceed cautiously in several steps because Spitzer microlensing data are known to exhibit systematics at roughly the 0.5 flux-unit level. While well below the overall flux variation, these systematics could nevertheless affect the analysis at some level.

**Table 2**  
Ground-only Parameters for OGLE-2017-BLG-1275

Parameters	Inner	Outer	Wide
$\chi^2/\text{dof}$	9823.68/9824	9823.67/9824	9858.66/9824
$t_0 - 2457940$	$9.962 \pm 0.017$	$9.950 \pm 0.017$	$9.918 \pm 0.017$
$u_0$	$0.395 \pm 0.020$	$0.389 \pm 0.019$	$0.399 \pm 0.017$
$t_E$ (days)	$13.41 \pm 0.42$	$13.51 \pm 0.42$	$13.00 \pm 0.34$
$s$	$0.631 \pm 0.014$	$1.092 \pm 0.040$	$1.254 \pm 0.009$
$q$ ( $10^{-3}$ )	$8.25 \pm 1.31$	$9.13 \pm 1.69$	$1.30 \pm 0.23$
$\log q$ (mean)	$-2.084 \pm 0.069$	$-2.041 \pm 0.080$	$-2.889 \pm 0.076$
$\alpha$ (rad)	$4.758 \pm 0.014$	$4.755 \pm 0.013$	$1.718 \pm 0.005$
$\rho$ ( $10^{-2}$ )	$3.4^{+2.7}_{-2.1}$	$3.9^{+3.2}_{-2.5}$	$0.17^{+0.17}_{-0.11}$
$I_S$ [OGLE]	$19.358 \pm 0.074$	$19.373 \pm 0.074$	$19.277 \pm 0.061$
$I_B$ [OGLE]	$21.09^{+0.46}_{-0.31}$	$21.02^{+0.42}_{-0.28}$	$21.62^{+0.73}_{-0.42}$

### 3.2.2. Test of Color Constraints

A key point is that, in contrast to most Spitzer microlensing planets, the case of OGLE-2017-BLG-1275 permits an independent check from the so-called color–color flux constraint. To briefly review, when Refsdal (1966) first advocated microlens parallax observations from solar orbit, he implicitly assumed that the peak and (at least one) wing of the event would be observed from space. Then, the times of peak ( $t_{0,\oplus}$ ,  $t_{0,\text{sat}}$ ) and normalized impact parameters ( $u_{0,\oplus}$ ,  $u_{0,\text{sat}}$ ) could be directly extracted from both light curves. The microlens parallax (in modern notation) could then be “read off”

$$\pi_E = \frac{\text{au}}{D_\perp}(\Delta\tau, \Delta\beta); \quad \Delta\tau \equiv \frac{t_{0,\text{sat}} - t_{0,\oplus}}{t_E},$$

$$\Delta\beta \equiv u_{0,\text{sat}} - u_{0,\oplus}, \quad (10)$$

where  $D_\perp = |D_\perp|$ ,  $|D_\perp|$  is the Earth–satellite vector offset projected on the sky and the two components are, respectively, parallel and perpendicular to this vector. As Refsdal (1966) already recognized, but is better illustrated in Figure 1 from Gould (1994), there is a four-fold degeneracy because  $u_0$  is a signed quantity, but only its amplitude can normally be extracted from a single-observatory light curve. However, while some Spitzer microlensing light curves do essentially meet the conditions implicitly assumed by Refsdal (1966; see Yee et al. 2015b for a spectacular example that looks eerily similar to Figure 1 from Gould 1994), the great majority do not. The main reason for this is that operational constraints imposed a 3–10 days’ delay from the time that the event was recognized until Spitzer observations could begin. A secondary reason is that for disk (although not bulge) lenses, typically  $\pi_{E,E} > 0$ , while Spitzer was in an Earth-trailing orbit, that is, west of Earth, and so these events typically peaked earlier as seen from Spitzer.

It is well-known that for rising events, one cannot accurately predict either  $t_0$  or (especially)  $u_0$  at times  $t$  such that  $(t_0 - t) \gg t_{\text{eff}} \equiv u_0 t_E$ . By the same token, it is equally impossible to recover  $t_{0,\text{sat}}$  and  $u_{0,\text{sat}}$  for satellite data that begin well after peak. However, these difficulties can be greatly ameliorated if the source flux of the space observatory (3.6  $\mu\text{m}$ , i.e.,  $L$  band, in the present case) can be strongly constrained by  $VIL$  or  $IHL$  color–color relations. The  $\pi_E$  contours then take the form of circular arcs (Gould 2019), which are more or less extended according to the size of  $(t_{\text{start}} - t_0)/t_{\text{eff}}$ , where  $t_{\text{start}}$

marks the commencement of the space observations. See Zang et al. (2020) for an extreme example.

In the present case, one could take the orientation that color–color relations are superfluous because the peak is covered. But this also means that color–color relations can provide an external check on systematics: if the unconstrained fits yield Spitzer fluxes that are in strong conflict with the constraint, this would be strong evidence that these fits are dominated by systematics, whereas the contrary result would be evidence that they are not.

### 3.2.3. Spitzer Analysis

We begin by undertaking a Spitzer–“only” analysis, in which the seven standard 2LIS parameters are held fixed at the values given in Table 2 and the 17 Spitzer data points are fit to four parameters ( $\pi_{E,N}$ ,  $\pi_{E,E}$ ,  $f_{S,\text{sat}}$ ,  $f_{B,\text{sat}}$ ). We consider the “inner” and “outer” solutions separately. We do not employ a flux constraint. In this initial test, we consider only the  $u_{0,\oplus} > 0$  solutions, in the expectation (confirmed below) that the  $u_{0,\oplus} < 0$  solutions will be essentially symmetric in  $\pi_{E,N}$ . To ensure that we completely cover the relevant parameter space, we conduct this modeling by a dense grid in  $(\pi_{E,N}, \pi_{E,E})$ , fully covering  $\pi_E < 1$ .

The main result of this test is that for each of the inner/outer pair of solutions, and even without a flux constraint, there is a single, well-localized minimum. These are at  $(\pi_{E,N}, \pi_{E,E}) \simeq (-0.08, +0.02)$  and  $(-0.06, +0.03)$ , for the outer and inner solutions, respectively, with the first favored by  $\Delta\chi^2 \sim 7$ . See Table 3.<sup>19</sup> That is, there is no  $\pm u_{0,\text{sat}}$  degeneracy, such as was predicted by Refsdal (1966) for 1LIS events. The physical reason for this is that the single minima have  $u_{0,\text{sat}} = +0.025$  and  $+0.03$ , respectively, that is, both passing on the same minor-image side of the caustic as is seen from Earth. In the alternate solutions (for 1LIS), these would have  $u_{0,\text{sat}} = -0.025$  and  $-0.03$ , that is, passing on the major-image side of the caustic. Once the planet is included this would have a completely different structure, with a bump instead of a dip. Indeed, for the outer solution case, this impact parameter would have the source passing directly over the caustic. For many Spitzer planets, this 1LIS degeneracy survives because the source does not pass close to any caustics as seen from Spitzer. However, as in the case of the first Spitzer planet, OGLE-2014-BLG-0124 (Udalski et al. 2015), this degeneracy is broken here.

We refine this test by seeding an MCMC at each of the minima derived from the grid. This approach allows us to evaluate the  $(I - L)$  color and its uncertainty (in the absence of a constraint),  $(I - L)_{\text{outer}} = 2.05 \pm 0.16$  and  $(I - L)_{\text{inner}} = 2.14 \pm 0.20$ . These can be compared with the constraint, which is derived in Section 4.1,  $(I - L)_{\text{constraint}} = 2.43 \pm 0.08$ . These are therefore in  $2.1\sigma$  and  $1.3\sigma$  tension, respectively. Of course, only one of these solutions can be correct, so one might infer that the overall tension is at  $1.3\sigma$ , which would be hardly notable. However, we should keep in mind that it is the outer solution that is overall preferred by  $\Delta\chi^2 \sim 7$  (for the Spitzer–“only” data) that is in greater tension. We conclude that the constraint-free measurement and the constraint are in

<sup>19</sup> Note that, as is usually the case in the analysis of Spitzer microlensing planets, the Spitzer magnitudes are uncalibrated. Specifically, we use  $L_{\text{Spitzer}} = 18 - 2.5 \log_{10}(f_{\text{Spitzer}})$ , where  $f_{\text{Spitzer}}$  is the instrumental flux.

**Table 3**  
Spitzer-“only” Parameters for OGLE-2017-BLG-1275

Parameters	Inner (+, +)	Outer (+, +)	Inner (−, −)	Outer (−, −)
$\chi^2/\text{dof}$	19.71/13	13.00/13	19.75/13	13.34/13
$\pi_{E,N}$	$-0.059 \pm 0.029$	$-0.084 \pm 0.022$	$0.062 \pm 0.028$	$0.089 \pm 0.022$
$\pi_{E,E}$	$0.027 \pm 0.015$	$0.022 \pm 0.009$	$0.022 \pm 0.017$	$0.013 \pm 0.011$
$L_S$ [Spitzer]	$17.17 \pm 0.20$	$17.30 \pm 0.16$	$17.17 \pm 0.20$	$17.33 \pm 0.17$
$L_B$ [Spitzer]	$16.60^{+0.20}_{-0.14}$	$16.52^{+0.14}_{-0.11}$	$16.60^{+0.20}_{-0.13}$	$16.50^{+0.14}_{-0.10}$

**Table 4**  
OGLE-2017-BLG-1275 (+, +) Parameters for Ground+Spitzer Data

Parameters	Inner (+, +)	Outer (+, +)	Inner-FREE (+, +)	Outer-FREE (+, +)
$\chi^2/\text{dof}$	9847.41/9838	9844.09/9838	9843.13/9837	9836.90/9837
$t_0 - 2457940$	$9.962 \pm 0.017$	$9.951 \pm 0.017$	$9.961 \pm 0.018$	$9.949 \pm 0.017$
$u_0$	$0.395 \pm 0.020$	$0.390 \pm 0.019$	$0.397 \pm 0.020$	$0.392 \pm 0.020$
$t_E$ (days)	$13.41 \pm 0.42$	$13.50 \pm 0.42$	$13.38 \pm 0.42$	$13.44 \pm 0.42$
$s$	$0.630 \pm 0.013$	$1.089 \pm 0.040$	$0.630 \pm 0.013$	$1.089 \pm 0.039$
$q$ ( $10^{-3}$ )	$8.36 \pm 1.34$	$9.11 \pm 1.63$	$8.35 \pm 1.28$	$9.08 \pm 1.60$
$\log q$ (mean)	$-2.079 \pm 0.069$	$-2.041 \pm 0.078$	$-2.080 \pm 0.067$	$-2.043 \pm 0.077$
$\alpha$ (rad)	$4.755 \pm 0.014$	$4.753 \pm 0.013$	$4.756 \pm 0.013$	$4.754 \pm 0.013$
$\rho$ ( $10^{-2}$ )	$3.0^{+2.7}_{-1.9}$	$3.8^{+3.3}_{-2.4}$	$2.7^{+2.5}_{-1.8}$	$3.4^{+2.9}_{-2.1}$
$\pi_{E,N}$	$-0.025 \pm 0.015$	$-0.032 \pm 0.016$	$-0.054 \pm 0.032$	$-0.083 \pm 0.024$
$\pi_{E,E}$	$0.036 \pm 0.017$	$0.032 \pm 0.014$	$0.029 \pm 0.017$	$0.023 \pm 0.011$
$L_S$ [Spitzer]	$16.92 \pm 0.11$	$16.96 \pm 0.11$	$17.11 \pm 0.23$	$17.31 \pm 0.19$
$L_B$ [Spitzer]	$16.84 \pm 0.12$	$16.81 \pm 0.12$	$16.64^{+0.23}_{-0.16}$	$16.51^{+0.15}_{-0.12}$
$I_S$ [OGLE]	$19.359 \pm 0.074$	$19.371 \pm 0.073$	$19.352 \pm 0.076$	$19.362 \pm 0.074$
$I_B$ [OGLE]	$21.08^{+0.46}_{-0.30}$	$21.03^{+0.42}_{-0.28}$	$21.12^{+0.48}_{-0.32}$	$21.07^{+0.45}_{-0.29}$

**Table 5**  
OGLE-2017-BLG-1275 (−, −) Parameters for Ground+Spitzer Data

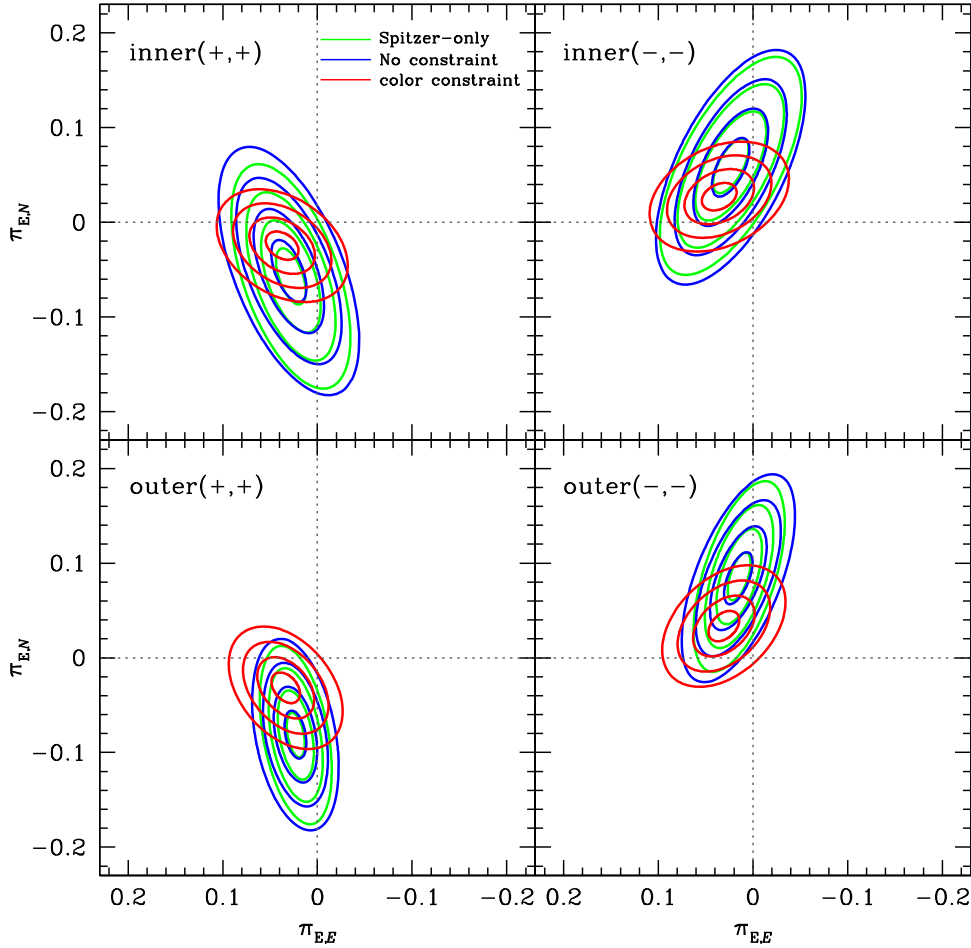
Parameters	Inner (−, −)	Outer (−, −)	Inner-FREE (−, −)	Outer-FREE (−, −)
$\chi^2/\text{dof}$	9847.18/9838	9845.24/9838	9843.58/9837	9836.81/9837
$t_0 - 2457940$	$9.963 \pm 0.018$	$9.951 \pm 0.017$	$9.962 \pm 0.018$	$9.950 \pm 0.017$
$u_0$	$-0.396 \pm 0.021$	$-0.390 \pm 0.020$	$-0.397 \pm 0.020$	$-0.392 \pm 0.020$
$t_E$ (days)	$13.38 \pm 0.42$	$13.48 \pm 0.42$	$13.37 \pm 0.41$	$13.44 \pm 0.42$
$s$	$0.631 \pm 0.014$	$1.089 \pm 0.039$	$0.630 \pm 0.013$	$1.089 \pm 0.038$
$q$ ( $10^{-3}$ )	$8.29 \pm 1.30$	$9.12 \pm 1.60$	$8.29 \pm 1.27$	$9.08 \pm 1.58$
$\log q$ (mean)	$-2.082 \pm 0.068$	$-2.041 \pm 0.076$	$-2.082 \pm 0.067$	$-2.043 \pm 0.076$
$\alpha$ (rad)	$-4.755 \pm 0.013$	$-4.752 \pm 0.013$	$-4.756 \pm 0.013$	$-4.754 \pm 0.013$
$\rho$ ( $10^{-2}$ )	$3.3^{+2.7}_{-2.1}$	$3.8^{+3.2}_{-2.4}$	$2.9^{+2.6}_{-1.8}$	$3.5^{+2.8}_{-2.2}$
$\pi_{E,N}$	$0.027 \pm 0.015$	$0.034 \pm 0.016$	$0.060 \pm 0.030$	$0.087 \pm 0.024$
$\pi_{E,E}$	$0.034 \pm 0.017$	$0.029 \pm 0.015$	$0.022 \pm 0.018$	$0.014 \pm 0.012$
$L_S$ [Spitzer]	$16.91 \pm 0.11$	$16.95 \pm 0.11$	$17.14 \pm 0.22$	$17.31 \pm 0.19$
$L_B$ [Spitzer]	$16.85 \pm 0.13$	$16.82 \pm 0.12$	$16.63^{+0.23}_{-0.15}$	$16.51^{+0.15}_{-0.12}$
$I_S$ [OGLE]	$19.354 \pm 0.075$	$19.369 \pm 0.074$	$19.352 \pm 0.073$	$19.361 \pm 0.074$
$I_B$ [OGLE]	$21.11^{+0.48}_{-0.31}$	$21.04^{+0.43}_{-0.29}$	$21.12^{+0.48}_{-0.31}$	$21.07^{+0.45}_{-0.30}$

qualitative agreement, but we await investigation of the full fits to make a final assessment.

Next we conduct full fits by seeding an MCMC, fitting both the ground and Spitzer data, and then allowing 11 parameters ( $t_0$ ,  $u_0$ ,  $t_E$ ,  $\rho$ ,  $s$ ,  $q$ ,  $\alpha$ ,  $\pi_{E,N}$ ,  $\pi_{E,E}$ ,  $f_{S,\text{sat}}$ ,  $f_{B,\text{sat}}$ ) to vary, while determining the ground observatory flux parameters by a standard linear fit. We seed eight different models, that is, four for each of the outer and inner solutions. In each case, the first seed is the model just described, which we label (+ +) because  $u_{0,\oplus} > 0$  and  $u_{0,\text{sat}} > 0$ . We seed the (− −) model by reversing

the signs of ( $u_0$ ,  $\alpha$ ,  $\pi_{E,N}$ ). Although based on the  $\pi_E$  grid search we do not expect to find (+ −) and (− +) solutions, as a matter of due diligence we seed them according to the prescription of Refsdal (1966). However, we find that indeed these do not converge.

For the four solutions that do converge, that is, (outer and inner)  $\times$  ((+ +) and (− −)), we repeat the fit with and without the flux constraint. The results, shown in Tables 4 and 5, confirm the preliminary assessment based on the Spitzer-“only” analysis. For the inner (+ +) solution, imposing the constraint



**Figure 2.** Contours of  $\Delta\chi^2 = (1, 2, 3, 4)$  for three different fits (as indicated by the colors in the legend), for each of four different geometries (labeled in the four panels). The contours are derived from the means and covariances matrices of the MCMCs from the 12 different models. In all four cases, the Spitzer-“only” (green) and unconstrained ground+Spitzer (blue) fits are in close agreement. After imposing the color constraint (red), the minimum of the inner solution is displaced by  $\sim 1\sigma$ , while the minimum of the outer solution is displaced by  $\sim 2\sigma$ . Note that the  $(+, +)$  and  $(-, -)$  solutions are approximately related by reflections in  $\pi_{E,N}$ .

increases  $\chi^2$  by  $\Delta\chi^2 = 4.3$  for 1 dof, while for the outer solution,  $\Delta\chi^2 = 7.2$ . The numbers are similar for the  $(- -)$  solution. While these results are broadly consistent with statistical fluctuations, they could reflect low-level systematics. However, even if so, these are no more severe than is typical for ground-based data in microlensing events. Hence, we accept the constrained fits from Tables 4 and 5 at face value. Note also that the seven standard parameters are hardly affected by the addition of Spitzer data relative to what was derived in Table 2 based on the ground-only fits.

In Figure 2, we show the  $\pi_E$  contours for the three different fits (Spitzer-“only”, ground+Spitzer without color constraint, and ground+Spitzer with color constraint)<sup>20</sup> for each of the four geometries. Figure 2 shows that the color constraint has three effects. First, it reduces the error bars, primarily in the north direction. It is expected from Equation (10) that the main impact will be on the north direction because the Earth–satellite separation is mainly east–west, so that  $\pi_{E,E}$  is mainly constrained by the location of  $t_{0,\text{sat}}$ , which is directly fit from the light curve and does not depend on the source flux. Second, the best-fit parallax amplitude,  $\pi_E$ , is driven to lower values, by

factors of about 1.4 and 1.9 for the inner and outer solutions, respectively. For the inner solutions, this change is within the error bar, while for the outer solution, it is in mild tension. Third, the parallax amplitude,  $\pi_E$ , is brought into closer agreement among the four solutions.

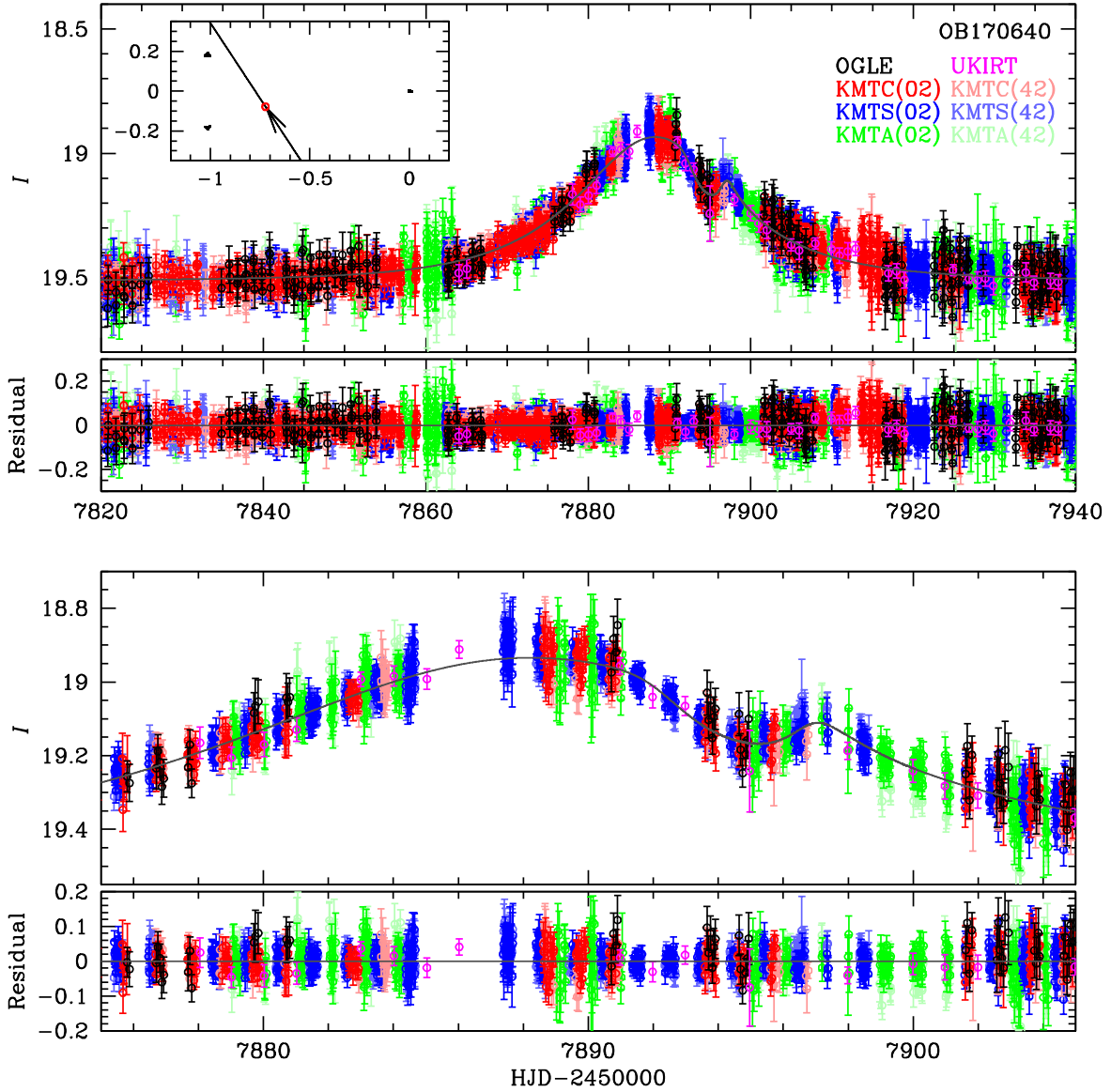
The very small parallax amplitudes,  $\pi_E \sim 0.045 \pm 0.015$ , imply that the host lies in or very near the Galactic bulge. That is, the projected velocities are  $\tilde{v} \equiv au/\pi_E t_E \sim 2900 \text{ km s}^{-1}$ , which is typical of bulge lenses. By comparison, for disk lenses moving according to an idealized flat rotation curve with  $v_{\text{rot}} \simeq 220 \text{ km s}^{-1}$  (and for typical bulge sources),  $\pi_{\text{rel}} = au \mu_{\text{rel}}/\tilde{v} \rightarrow \pi_S(v_{\text{rot}}/\tilde{v}) \sim 0.01 \text{ mas}$ , that is, indicating a lens location where the bulge strongly dominates over the disk. We present a full Bayesian analysis in Section 5.1.

### 3.3. OGLE-2017-BLG-0640

Figure 3 shows a relatively short, relatively low-amplitude 1L1S event, peaking at  $t_0 \simeq 7888.0$  and punctuated by a dip at  $t_{\text{anom}} \simeq 7894.5$  with full width  $\Delta t_{\text{dip}} \simeq 5.5$  days. Although the baseline  $I_{\text{base}} \sim 19.5$  appears faint, the KMT tabulated extinction is unusually high,  $A_I = 4.69$ , implying that the source is likely to be a giant, in which case the blending is likely to be small. Under this assumption a 1L1S fit to the event with the anomaly excised yields  $u_0 = 0.64$  and  $t_E = 15$  days. Then

<sup>20</sup> We also tested for the annual parallax effect in the ground-based data alone. However, due to the short duration of the event,  $\pi_{E,N}$  was effectively unconstrained and the uncertainties in  $\pi_{E,E}$  were large ( $\pm 0.35$ ). Thus, the ground-only constraints are fully consistent with the Spitzer parallax.





**Figure 3.** Data (color-coded by observatory) together with the model prediction for OGLE-2017-BLG-0640. The dip in the light curve at  $\text{HJD}' \sim 7895$  is caused by the source passing over a channel of depressed magnification that threads the two planetary caustics on the opposite side of the host relative to the planet, as illustrated in the inset.

**Table 6**  
Microlens Parameters for OGLE-2017-BLG-0640

Parameters	2L1S
$\chi^2/\text{dof}$	10845.18/10845
$t_0 - 2457880$	$7.917 \pm 0.030$
$u_0$	$0.651 \pm 0.028$
$t_E$ (days)	$14.47 \pm 0.40$
$s$	$0.610 \pm 0.008$
$q$ ( $10^{-3}$ )	$4.87 \pm 0.27$
$\log q$ (mean)	$-2.313 \pm 0.024$
$\alpha$ (rad)	$4.133 \pm 0.009$
$\rho$ ( $10^{-2}$ )	$2.0^{+1.5}_{-1.5}$
$I_S$ [OGLE]	$19.637 \pm 0.078$
$I_B$ [OGLE]	$21.92^{+0.913}_{-0.511}$

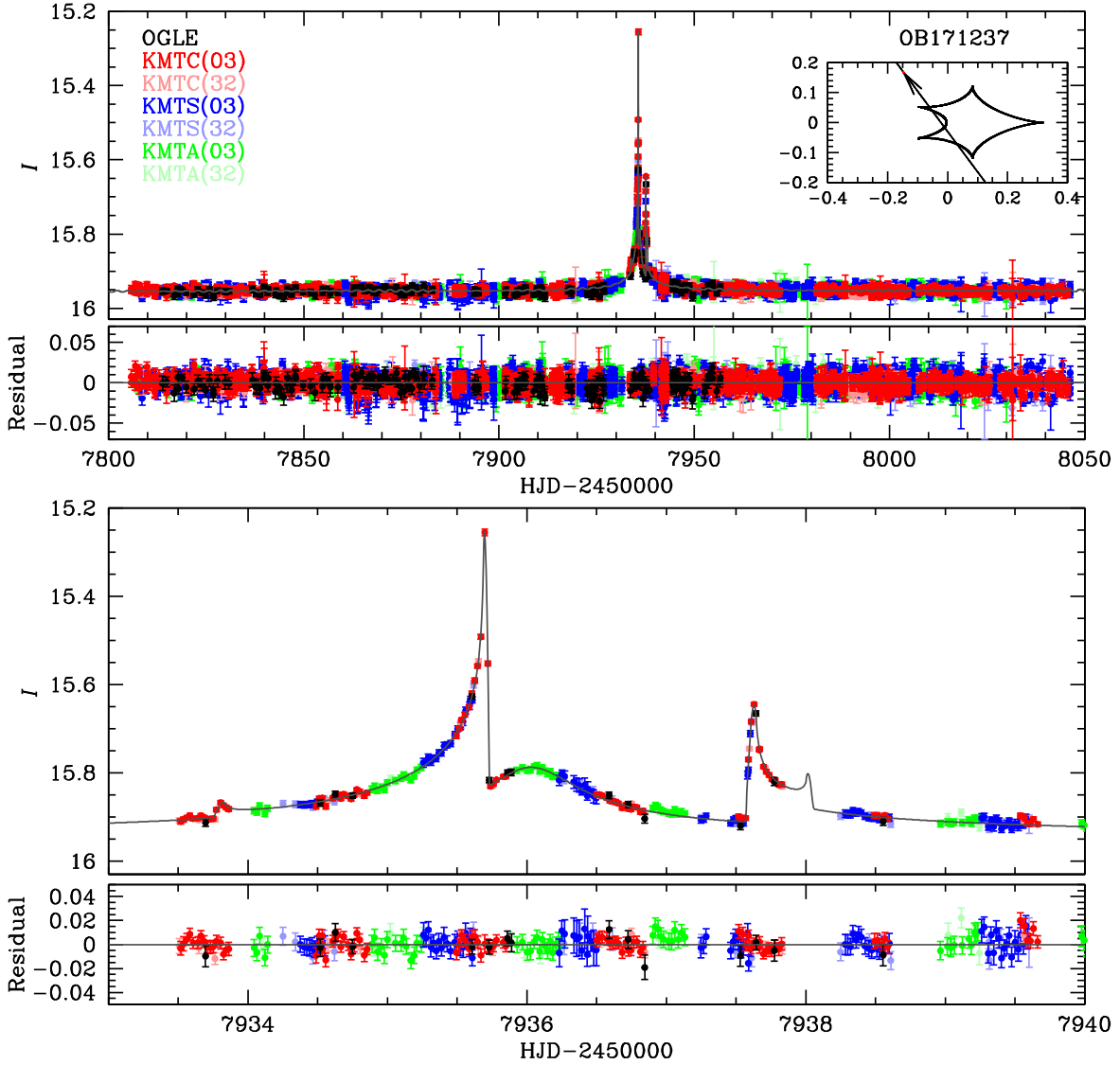
$\tau_{\text{anom}} = 0.43$  and  $u_{\text{anom}} = 0.77$ , implying (from Equations (2) and (4)) that  $\alpha = 236^\circ$ ,  $s_{\text{inner}}^{\dagger} = 0.69$ , and  $q = 5.2 \times 10^{-3}$ .

The grid search returns only one competitive local minimum, whose refined parameters are given in Table 6 and which has

an inner geometry, as illustrated in Figure 3. The heuristic predictions for  $\alpha$  and  $q$  are confirmed, while the fit value  $s_{\text{inner}}$  suggests that there may be another solution at  $s_{\text{outer}} = (s_{\text{inner}}^{\dagger})^2/s_{\text{inner}} = 0.78$ . In fact, the grid search has a minimum with this topology, but it was too strongly disfavored to warrant refinement. As a matter of due diligence, we seed an MCMC with this prediction for  $s_{\text{outer}}$  but find that it is excluded by  $\Delta\chi^2 = 227$ . The fundamental reason for this is that the inner/outer degeneracy is much less severe when (as in the present case),  $\alpha$  is far from  $\pm 90^\circ$  (Zhang et al. 2022). In particular, for OGLE-2017-BLG-0640, the inner trajectory passes close to the second caustic, which generates a weak bump at the end of the dip, whereas the outer trajectory would generate such a weak bump at the beginning of the dip.

### 3.4. OGLE-2017-BLG-1237

OGLE-2017-BLG-1237 shows a clear caustic exit peaking at  $\text{HJD}' = 7935.70$ , followed by a caustic entrance peaking at



**Figure 4.** Data (color-coded by observatory) together with the model prediction for OGLE-2017-BLG-1237. There is a low-amplitude bump at  $HJD' \sim 7936$  flanked by two U-shaped troughs. Together, these imply that the source has passed the central cusp of a resonant caustic and has intersected sections of this caustic before and after the passage. See inset.

$HJD' = 7937.63$ , with a low-amplitude bump between these at  $HJD' = 7936.0$ . Because of the time ordering of these two clear caustic features, there must be an additional entrance before the first (which was, in fact, observed at  $HJD' = 7933.8$ ) and an additional exit after the second (which occurred during a gap in the data). The bump is then almost certainly due to an approach to the cusp associated with the more massive component of the binary lens. That is, the geometry of the caustic system can be inferred by eye. A systematic grid search confirms that there is only one minimum, whose refinement is illustrated in Figure 4 and whose parameters are given in Table 7.

In general, it would be unusual for such an obvious and well-constrained planetary event to escape publication for 6 yr following its occurrence. However, in this case, there is a nearby bright star,  $I = 15.88$ , that lies  $1''.4$  from the lens, which is a double-mode pulsator. The two closely spaced modes have periods  $P = 2.9$  days, with a beat period of 41 days and some additional long-term structure as well. This star lies on the foreground main sequence (see Section 4.3), and it has a Gaia

**Table 7**  
Microlens Parameters for OGLE-2017-BLG-1237

Parameters	2LIS
$\chi^2/\text{dof}$	6616.58/6617
$t_0 - 2457930$	$5.888 \pm 0.004$
$u_0 (10^{-2})$	$1.766^{+0.075}_{-0.108}$
$t_E$ (days)	$27.94^{+1.74}_{-1.13}$
$s$	$1.041 \pm 0.001$
$q (10^{-3})$	$7.93^{+0.35}_{-0.46}$
$\log q$ (mean)	$-2.105 \pm 0.024$
$\alpha$ (rad)	$4.075 \pm 0.005$
$\rho (10^{-4})$	$7.66^{+0.35}_{-0.47}$
$I_S$ [OGLE]	$21.865^{+0.068}_{-0.046}$
$I_B$ [OGLE]	$15.958 \pm 0.001$
$t_*$ (hours)	$0.514 \pm 0.007$

parallax  $\pi = 0.60 \pm 0.14$  mas, seemingly confirming that it is a nearby disk star. While the full amplitude of its variations is only  $\Delta I \sim 0.06$  mag, relative to its own baseline flux, this

amplitude is about 15 times larger than the unmagnified flux of the source star. Thus, the variable created significant difficulties for the light-curve analysis. By chance, the caustic features of the light curve occur near the minimum of the 41 day beat period, so contamination by the variable does not have a major impact on their interpretation. However, the effect, particularly the fractional effect, on the wings of the light curve is much larger, which directly impacts the measurement of  $t_E$  and thus would indirectly impact  $\rho$ ,  $q$ , and other parameters.

To remove this impact, we first carried out photometry of the nearby variable over 2 yr, restricted to KMTC and KMTS, which are both high cadence and high quality. We then fit the resulting light curve (excluding the portion during the microlensing event) to the sum of nine sine waves, each characterized by three parameters (amplitude, period, and phase). When fitting the microlensing light curve, we added a term consisting of a free parameter multiplied by the mathematical representation of the variable light curve. We expect that the amount of contamination from the variable may be a function of seeing, and therefore we tried to find more complicated models that would include both seeing variations and the variable star function. However, these efforts did not lead to significant improvement.

### 3.5. OGLE-2017-BLG-1777

OGLE-2017-BLG-1777 was early recognized as a potentially 2L1S planetary event by C. Han based on his combined analysis of OGLE and KMT data. However, he judged that the light curve could in principle also have been generated by a 1L2S binary-source event. Because of this complication (and the difficulty of ultimately resolving it), detailed analysis was deferred.

Such a detailed analysis was initiated by us as part of the AnomalyFinder series of papers. The orientation of these papers is to thoroughly analyze *all* events that are identified by the KMT AnomalyFinder (Zang et al. 2021) and that have competitive planetary solutions, regardless of whether the events are unambiguously planetary. For example, for 2018, Gould et al. (2022a) and Jung et al. (2022) analyzed (or cataloged from earlier AnomalyFinder papers) not only a total of 17 clear planets but also six other events for which the interpretation of the anomaly was ambiguous.

However, even in this context, OGLE-2017-BLG-1777 is unusually complex. Its light curve is best explained by the lens and source both having companions, with the former being a Jovian mass-ratio planet and the latter being a very low mass (VLM) star or brown dwarf (BD). The event has a number of peculiar features, such as an exceptionally small Einstein radius,  $\theta_E$ , and an exceptionally small lens-source relative proper motion,  $\mu_{\text{rel}}$ . As these two parameters derive from completely independent physical characteristics but could in principle be generated by an incorrect estimate of the normalized source radius,  $\rho$ , their confluence invites caution. If the  $\theta_E$  measurement is correct, then the lens host is (like the source companion) a VLM star or BD. Much, but not all, of the evidence for the planetary companion comes from a single discrepant data point, which was the last one taken by OGLE during 2017. In fact, there are additional issues related to the long-term behavior of the OGLE data that required careful investigation. Hence, it is not a simple matter to properly address all of these issues within the context of a paper that

systematically analyzes many planetary (and possibly planetary) events.

Nevertheless, because the goal of the AnomalyFinder papers is to present comprehensive analyses of all planetary and possibly planetary events, we must address all of these issues. We do so by putting the main thread of the light-curve analysis in this section, while deferring complex technical and semitechnical points to appendices.

The first point is that the light curve is affected in two different ways by a neighbor that lies  $\sim 800$  mas to the west of the source and is brighter than it by  $\sim 4.3$  mag. We analyze these effects and correct the light curve for them, as we discuss in Appendix A.

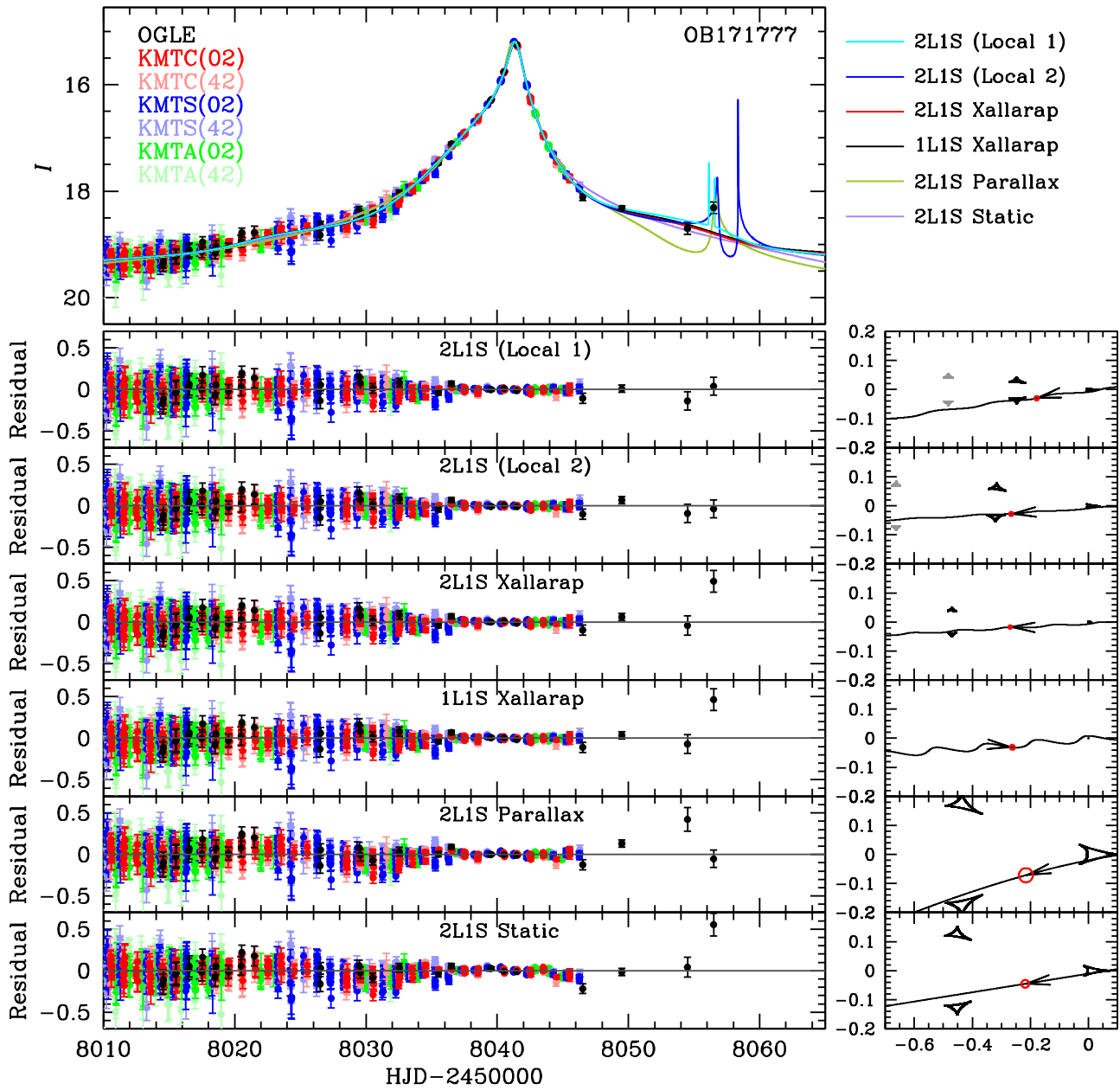
Next, contrary to the usual practice, we begin by introducing all the parameters that are required to describe our final model, rather than recapitulating the history of their gradual introduction as simpler models failed, one by one. This will allow us to comprehensively present the relationship between the final model and these simpler models. The final models as well as several intermediate models are illustrated in Figure 5, while their parameters are given in Tables 8 and 9.

The final model is described by 18 parameters. Seven of these are the standard parameters that are always required to analyze 2L1S events, including all of the other events in this paper, ( $t_0$ ,  $u_0$ ,  $t_E$ ,  $s$ ,  $q$ ,  $\alpha$ ,  $\rho$ ). Four of the parameters are the microlens parallax vector  $\pi_E$  and the linearized transverse lens-orbital motion,  $\gamma$ , as described in Section 3.1. Finally, seven parameters are required to describe the Kepler orbit of the source around the center of mass of itself and its dark companion, that is, the ‘‘xallarap effect.’’

From a microlensing standpoint, xallarap is the inverse of parallax: light-curve distortions are induced by the orbital motion of the source rather than the observer. Hence, in principle, an annual parallax signal can always be imitated by xallarap, provided that the source orbital motion mimics that of Earth. Because of this, standard xallarap parameterization is set so that the measured xallarap parameters will mimic the corresponding parallax parameters for the case that the apparent xallarap is caused by parallax. Thus, while the microlens xallarap parameters are closely related to standard Kepler parameters, they are expressed somewhat differently.

The amplitude and orientation of the source motion (scaled by  $\theta_E$ ) is  $\xi \equiv (\xi_N, \xi_E)$ . As with the parallax,  $\pi_E$ , the direction is expressed with respect to the lens-source relative motion at  $t_0$ . The phase and inclination of the orbit are expressed as  $(\alpha_S, \delta_S)$ , so that in the case that the apparent xallarap is due to parallax, these will be exactly equal to the ecliptic coordinates of the event. Note in particular that edge-on orbits have  $\delta_S = 0^\circ$ , whereas in standard Kepler parameterization, the inclination would be  $i = 90^\circ$ . The period  $P$  and eccentricity  $e$  are exactly the same as in the standard Kepler parameterization. Finally the ‘‘phase’’ of the periastron is measured relative to  $t_0$ . See Appendix B for more details about xallarap.

We briefly summarize how we were led to such a complex model. We began with a standard 2L1S model, which provided a reasonable first approximation to the data but (1) failed to match the final OGLE point and (2) left an oscillatory residual with a period of order 13 days near the peak. See the magenta curve and the bottom panel of residuals in Figure 5. As single-point discrepancies are quite common in microlensing, and this data point was taken at high air mass and in twilight, we initially suppressed the final OGLE point at  $\text{HJD}' = 8056.4965$ .



**Figure 5.** Data (color-coded by observatory) together with the model predictions for OGLE-2017-BLG-1777. Simple 2L1S models (two bottom panels) leave a  $P \sim 13$  days wave of residuals. Adding xallarap but without lens-orbital motion (third panel) removes these but cannot explain the last data point. However, 2L1S models that include xallarap, parallax, and lens-orbital motion (top two panels) give a significantly better fit.

We then added xallarap to the 2L1S fit and found substantial improvement (red curve and third panel of Figure 5). We then investigated whether a second lens was really required to explain the light curve or whether the entire light-curve distortion could be explained just by 1L1S plus xallarap (black curve and fourth panel). We found  $\Delta\chi^2 = \chi^2(1L1S + \text{xallarap}) - \chi^2(2L1S + \text{xallarap}) = 21$  for 3 dof, which would imply a marginal detection of a planet. However, we noticed that the 2L1S+xallarap model predicted a caustic crossing within a few days of the final OGLE data point (which we had previously suppressed). Hence, we carefully examined this point at the image level. Although the observing conditions were not optimal, there proved to be no indicators that artifacts of nonastronomical origin were corrupting the measurement. We then reincluded this point and added lens-orbital motion and parallax to the fit, thereby finding two different models, in

each of which the final OGLE data point was explained by the source passing through the planetary caustic.

The two 18-parameter 2L1S models have an improvement over the 1L1S+xallarap model of  $\Delta\chi^2 = 36$  for 7 dof. Formally (for Gaussian statistics), this would imply a false-alarm probability of  $p \sim 10^{-5}$ . However, there are many reasons for caution. First, microlensing data are known to be non-Gaussian, although it is rare that  $\Delta\chi^2 = 36$  differences between competing models would be questioned. Second, much of this  $\Delta\chi^2$  is due to a single data point that was taken under somewhat difficult conditions. While we have closely vetted this point at the image level, the possibility that we have missed something about it cannot be absolutely ignored. Third, there are several features of the solution, which we summarize in the next two paragraphs, that are very unusual. While unusual things do happen, it is worrisome that they occur in an event for which the planetary interpretation relies on somewhat



**Table 8**  
Intermediate-model Parameters for OGLE-2017-BLG-1777

Parameters	2LIS Static	2LIS Parallax	1LIS Xallarap	2LIS Xallarap
$\chi^2/\text{dof}$	12777.22/11900	12453.50/11898	11922.83/11896	11901.61/11893
$t_0 - 2458040$	$1.184 \pm 0.002$	$1.169 \pm 0.002$	$1.352 \pm 0.003$	$1.255^{+0.013}_{-0.025}$
$u_0 (10^{-2})$	$1.016 \pm 0.002$	$1.987 \pm 0.046$	$0.814 \pm 0.025$	$0.714 \pm 0.023$
$t_E$ (days)	$60.40 \pm 0.91$	$31.74 \pm 0.53$	$81.36 \pm 2.40$	$85.89 \pm 3.03$
$s$	$0.796 \pm 0.004$	$0.801 \pm 0.003$	...	$0.744^{+0.041}_{-0.056}$
$q (10^{-3})$	$6.08 \pm 0.14$	$11.93 \pm 0.29$	...	$0.86^{+0.38}_{-0.20}$
$\log q$ (mean)	$-2.216 \pm 0.010$	$-1.923 \pm 0.010$	...	$-3.045 \pm 0.129$
$\alpha$ (rad)	$2.983 \pm 0.001$	$2.949 \pm 0.003$	...	$3.003 \pm 0.025$
$\rho (10^{-3})$	$13.33 \pm 0.21$	$24.63 \pm 0.37$	$8.24 \pm 0.27$	$5.78 \pm 0.32$
$\pi_{E,N}$	...	$1.371 \pm 0.060$	...	...
$\pi_{E,E}$	...	$1.835 \pm 0.078$	...	...
$\xi_N (10^{-2})$	...	–	$-0.829 \pm 0.151$	$-0.267^{+0.289}_{-0.191}$
$\xi_E (10^{-2})$	...	–	$1.348 \pm 0.045$	$1.098 \pm 0.065$
$\alpha_S$	...	–	$305.0 \pm 23.66$	$334.5^{+14.8}_{-23.1}$
$\delta_S$	...	–	$-15.4^{+5.4}_{-7.2}$	$6.1^{+4.9}_{-11.6}$
Ellipticity	...	–	$0.055 \pm 0.026$	$0.114^{+0.050}_{-0.040}$
Phase	...	–	$0.400 \pm 0.071$	$0.367^{+0.073}_{-0.041}$
Period (days)	...	–	$12.75 \pm 0.14$	$12.62 \pm 0.16$
$I_S$ [OGLE]	$20.390 \pm 0.018$	$19.674 \pm 0.021$	$20.665 \pm 0.032$	$20.695^{+0.033}_{-0.031}$
$t_*$ (hours)	$19.32 \pm 0.10$	$18.77 \pm 0.13$	$16.06 \pm 0.21$	$11.93 \pm 0.42$

**Table 9**  
Final-model Parameters for OGLE-2017-BLG-1777

Parameters	2LIS (Local 1)	2LIS (Local 2)
$\chi^2/\text{dof}$	11886.17/11889	11886.25/11889
$t_0 - 2458040$	$1.251^{+0.015}_{-0.022}$	$1.224 \pm 0.018$
$u_0 (10^{-2})$	$0.945 \pm 0.077$	$0.924 \pm 0.072$
$t_E$ (days)	$65.3 \pm 5.0$	$68.0 \pm 5.3$
$s$	$0.732 \pm 0.031$	$0.704 \pm 0.030$
$q (10^{-3})$	$1.17^{+0.40}_{-0.27}$	$1.63 \pm 0.44$
$\log q$ (mean)	$-2.93 \pm 0.12$	$-2.79 \pm 0.12$
$\alpha$ (rad)	$3.015 \pm 0.017$	$3.008 \pm 0.014$
$\rho (10^{-3})$	$7.67 \pm 0.63$	$6.97 \pm 0.62$
$\pi_{E,N}$	$0.09 \pm 0.29$	$0.02 \pm 0.25$
$\pi_{E,E}$	$0.246^{+0.120}_{-0.080}$	$0.230 \pm 0.090$
$ds/dt$ ( $\text{yr}^{-1}$ )	$3.15^{+0.35}_{-0.46}$	$3.63^{+0.50}_{-0.67}$
$d\alpha/dt$ ( $\text{yr}^{-1}$ )	$0.45 \pm 0.57$	$-1.20^{+0.38}_{-0.56}$
$\xi_N (10^{-2})$	$-0.259^{+0.205}_{-0.132}$	$-0.074 \pm 0.199$
$\xi_E (10^{-2})$	$1.395 \pm 0.092$	$1.416 \pm 0.096$
$\alpha_S$	$324.0 \pm 21.6$	$336.0 \pm 11.6$
$\delta_S$	$-4.5^{+8.3}_{-6.7}$	$7.2^{+3.8}_{-6.1}$
Ellipticity	$0.112 \pm 0.038$	$0.098^{+0.039}_{-0.032}$
Phase	$0.386 \pm 0.056$	$0.363 \pm 0.032$
Period (days)	$12.55 \pm 0.15$	$12.58 \pm 0.16$
$I_S$ [OGLE-IV]	$20.394 \pm 0.090$	$20.407 \pm 0.086$
$t_*$ (hours)	$12.00 \pm 0.51$	$11.40 \pm 0.48$
$\beta$	$0.35^{+0.14}_{-0.11}$	$0.51^{+0.16}_{-0.20}$

uncertain evidence. While the AnomalyFinder papers do not aim to make final decisions about including any particular event in subsequent statistical analyses, they do attempt to provide comprehensive accounts of all the information that is required to make such decisions. We therefore alert the reader to the nature of these issues in the next two paragraphs, while providing systematic accounts in the appendices.

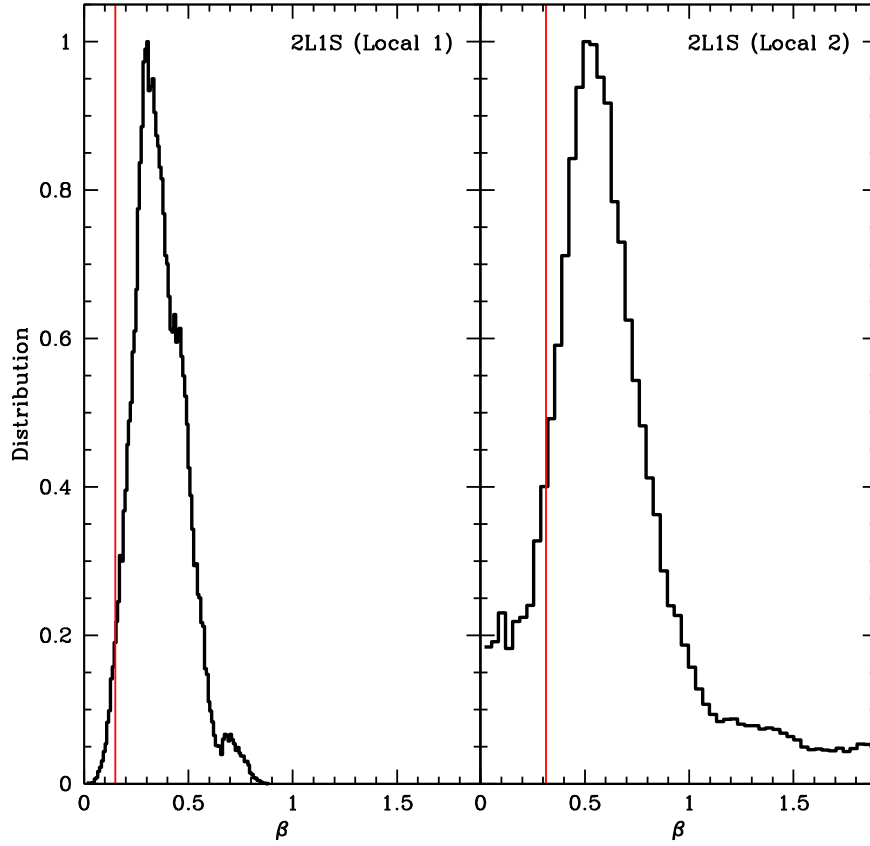
The first issue is that both  $\theta_E$  and  $\mu_{\text{rel}}$  are unusually small. We will show in Section 4.4 that  $\theta_{\text{ast}} \simeq 0.5 \mu\text{as}$ , which implies

$\theta_E \simeq 70 \mu\text{as}$  and  $\mu_{\text{rel}} \simeq 0.4 \text{ mas yr}^{-1}$ . These are both rare for planetary microlensing events. The first depends only on the lens mass and the distances to the lens and source, while the second depends only on the proper motions of the lens and source. Because these are physically independent, but both depend on the same  $\rho$  measurement, they could be a warning sign of a major error in the model. We address this issue in Appendix C.

The second issue is that, as we show in Appendix B, BD and VLM star companions to the source can only be detected via xallarap if both  $\theta_E$  and  $\mu_{\text{rel}}$  are unusually small. Therefore, given that we report the detection of such a xallarap companion, it is not a further surprise that  $\theta_E$  and  $\mu_{\text{rel}}$  are small. On the other hand, it is the case that the presence of such objects in close-in orbits is rare. In particular, the probability of transit for companions in  $P = 12.5$  day orbits about Sun-like stars is  $\sim 4.5\%$ . Such transits would give rise to strong signals in the great majority of stars observed by Kepler and would appear as Jovian-planet-sized companions, which would certainly be investigated. Hence, their low observed frequency shows they are intrinsically rare.

On the other hand, the fact that these two major questions about the event are both entangled with the prediction of the models that the source has a BD or VLM star companion (i.e.,  $M_{\text{comp}} \sim 0.075 M_{\odot}$ , see Appendix B) implies that confirmation of this companion would greatly increase confidence in the solution. We note that the predicted semiamplitude of radial velocity (RV) variations of the source star is  $v \sin i \sim 6.5 \text{ km s}^{-1}$  (see Appendix B), which should be measurable on large telescopes despite the faintness of the source,  $I_S \sim 20.3$ .

Finally, there is one further test that we can make regarding the reality and/or plausibility of this unusually complex lens-source system. One can see from the top two caustic diagrams of Figure 5 (i.e., orbital-motion models) that the planetary caustics moved a substantial distance (0.2 or 0.4 Einstein radii) between  $t_0$  (gray triangles) and the time of the final OGLE point (black



**Figure 6.** Distributions of  $\beta \equiv |\text{KE}/\text{PE}|_{\perp}$ , that is, the ratio of transverse kinetic to potential energy (Equation (7)) for the two solutions of OGLE-2017-BLG-1777. The orbital-motion determination is strongly influenced by the need to match a single, otherwise discrepant, point. See Figure 5. If this point were an artifact, one would expect the inferred  $\beta$  to be either unphysically high ( $\beta > 1$ ) or improbably low ( $\beta \lesssim 0.1$ ). Instead, the distributions are peaked near values that are physically expected, thus increasing the plausibility of these solutions. The red vertical lines are the beta values of best-fit solution for each solution.

contours), a motion that is determined directly by the data (in particular, the time of the final “discrepant” OGLE data point) but that is interpreted as being caused by physical motion of the planet within the context of these models. If the point were spurious, which is the main concern about the reality of these models, then most likely the inferred planetary motion would be either too large to be consistent with Kepler’s laws or would be so small that it would require an improbable projection on the plane of the sky to be consistent with Kepler’s laws. This test can be made in terms of the ratio of the transverse kinetic-to-potential energy parameters,  $\beta$ , which is defined in Equation (7). For face-on circular orbits,  $\beta = 0.5$ , and for a typical range of random projections,  $0.1 \lesssim \beta \lesssim 0.5$ . Figure 6 shows the distributions of  $\beta$  based on the MCMCs for the two solutions. In both cases, we see that the peaks of these distributions are both relatively compact and overlap the expected range. Logically, this test would only require that this be true of at least one of these solutions, but in any case, it is true of both. The fact that the inferred orbital motion is consistent with expectations from Kepler’s laws adds to the credibility of these planetary solutions but does not prove that they are correct.

### 3.6. OGLE-2017-BLG-0543

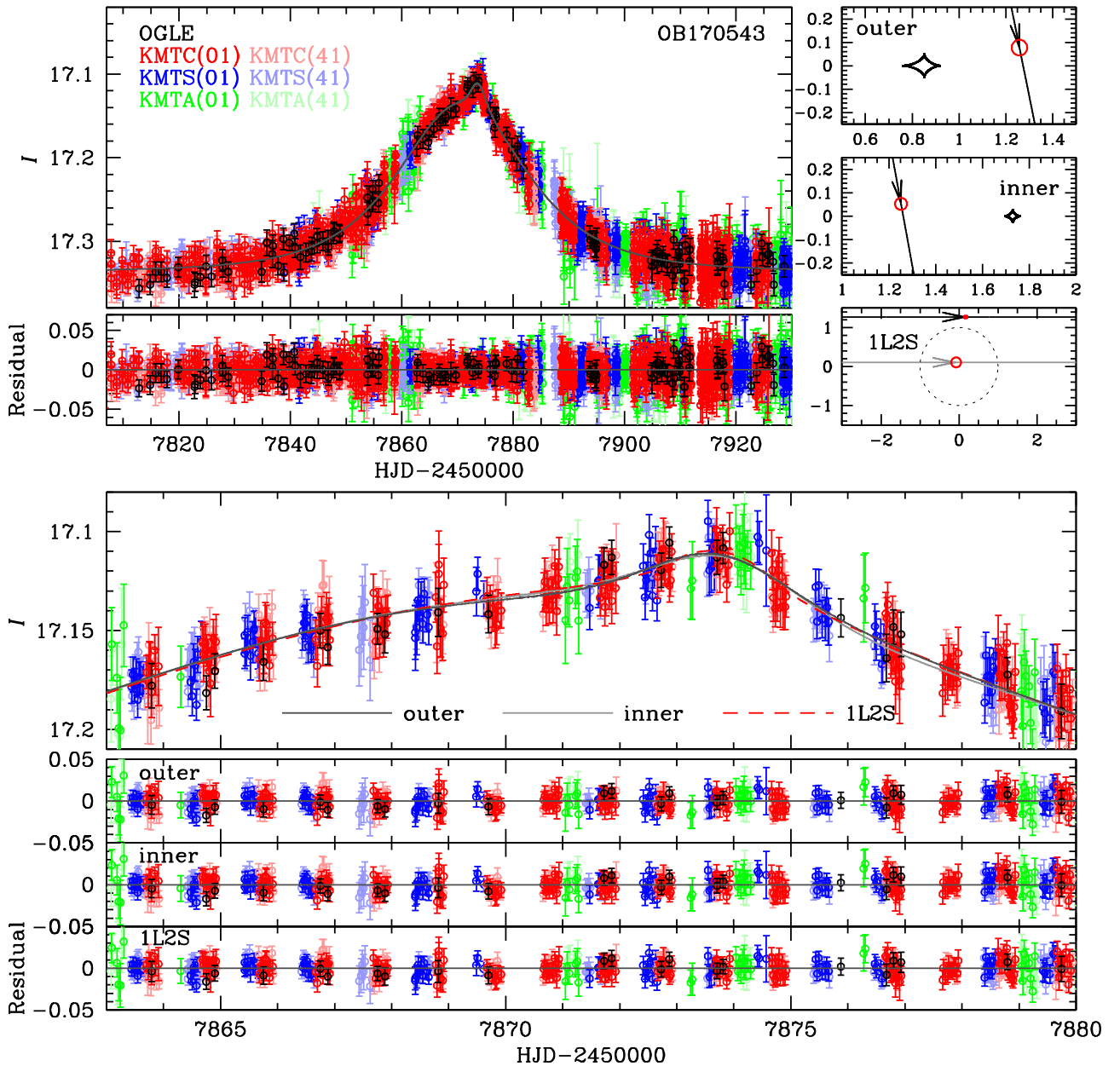
Figure 7 shows a relatively short, low-amplitude 1L1S event that is punctuated by a short bump at  $t_{\text{anom}} = 7873.5$ , that is,  $\Delta t_{\text{anom}} = +2.5$  days after the peak at  $t_0 = 7871$ . Taking account of the KMT tabulated extinction,  $A_I = 2.24$ , the baseline object has  $I_{0,\text{base}} \sim 15.1$ , corresponding to a giant.

Assuming, as is likely, it is unblended or only weakly blended,  $u_0 = 1.25$  and  $t_E = 12$  days. Then  $\tau_{\text{anom}} = 0.21$ ,  $u_{\text{anom}} = 1.27$ ,  $\alpha = 80^\circ.5$ , and  $s_{\perp}^{\dagger} = 1.82$ .

The grid search returns two local minima. We find (as is common for such low-amplitude events) that the division of the baseline flux into source and blend fluxes is poorly constrained, and so we set  $f_B = 0$ , which (as mentioned above) is plausible. The resulting parameters are shown in Table 10. The heuristic predictions for  $\alpha$  are correct to within  $\sim 2^\circ$ . The prediction  $s_{\perp}^{\dagger} = 1.82$  is in excellent agreement with  $s^{\dagger} \equiv \sqrt{s_{\text{outer}} s_{\text{inner}}} = 1.82$ .

As for any smooth-bump anomaly, we must check for alternative 1L2S solutions. After applying the same  $f_B = 0$  constraint, we indeed find such a solution, which is illustrated in Figure 7 and summarized in Table 10. This solution is disfavored by only  $\Delta\chi^2 = 2.9$ , which is well below the level needed to securely claim the detection of a planet. In some cases there can be additional arguments that could be made against the 1L2S solution. For example, it might predict an implausibly low proper motion,  $\mu_{\text{rel}} = \theta_{\text{ast}}/t_{\text{ast}}$ . In Section 4.5, we will show that  $\theta_{\text{ast}} \simeq 5 \mu\text{as}$ . From Equation (9), we would have to be able to constrain  $\mu_{\text{rel}} \lesssim 1 \text{ mas yr}^{-1}$  to contribute significantly to such an argument, which would in turn require a restriction  $t_{\text{ast}} > 44$  hr. However, this value is nearly within the  $1\sigma$  range for both  $t_{\text{ast}}$  and  $t_{\text{ast},2}$ . Hence, no such argument can be made.

Another possible argument could be made if the 1L2S model predicted a substantially different color than the one measured from the light curve. However, first, the second source is predicted to lie  $-2.5 \log q_F = 6.0$  mag below the primary.



**Figure 7.** Data (color-coded by observatory) together with the model predictions for OGLE-2017-BLG-0543. The bump at  $\text{HJD}' \sim 7873.7$  can be fit either by a weak cusp approach due to a planet (upper two inset panels) or a companion of the source passing the primary lens. Because these, respectively, 2L1S and 1L2S models cannot be distinguished from the data, the nature of the lens system remains undetermined.

Because the primary is a giant in or just below the clump, such a secondary would have a similar color to the primary, so even a precise color measurement could not distinguish between the 2L1S and 1L2S predictions. Second, the  $V$ -band signal from the secondary (assuming that the 1L2S model is correct) is too weak to measure its color.

Therefore, while it is possible that the anomaly in OGLE-2017-BLG-0543 is due to a planet, the 1L2S model also provides a plausible solution, and it certainly cannot be confidently excluded. Hence, this event should not be cataloged as planetary.

### 3.7. OGLE-2017-BLG-1694

Figure 8 shows an approximately 1L1S event with a weak anomaly near peak, plausibly a postpeak bump. The underlying

1L1S curve is itself somewhat ambiguous because it is consistent with a range of timescales,  $t_E$ , or (because  $t_{\text{eff}} = u_0 t_E$  and  $f_S t_E$  are approximate invariants), equivalently, a range of  $f_S$  or  $u_0$ . Because both the 1L1S event and the anomaly are ambiguous, we dispense with a heuristic analysis and proceed directly to the grid search. This yields nine different solutions that are within  $\Delta\chi^2 < 10$  of the minimum, plus some additional ones that are somewhat worse. Two of these, with  $(s, q) = (0.637, 0.023)$  and  $(1.926, 0.019)$ , form a close-wide pair of a major-image perturbation and are planetary in nature. A third is also planetary, but with a resonant caustic geometry and  $(s, q) = (1.16, 0.0016)$ . See Table 11. For this reason, the event is included in the present paper as a “possible planet.” However, another two, with  $(s, q) = (0.492, 0.051)$  and  $(1.892, 0.062)$ , form a close-wide pair of a minor-image perturbation and are in the BD regime. See Table 12. And the

**Table 10**  
Microlens Parameters for OGLE-2017-BLG-0543

Parameters	Outer	Inner	1L2S
$\chi^2/\text{dof}$	8614.517/8615	8631.408/8615	8617.388/8614
$t_0 - 2457870$	$0.882 \pm 0.050$	$1.040 \pm 0.042$	$0.791 \pm 0.057$
$u_0$	$1.251 \pm 0.003$	$1.242 \pm 0.003$	$1.276^{+0.007}_{-0.006}$
$t_E$ (days)	$12.080 \pm 0.061$	$12.083 \pm 0.061$	$12.104 \pm 0.077$
$s$	$1.518 \pm 0.027$	$2.185 \pm 0.037$	...
$q$ ( $10^{-3}$ )	$4.250 \pm 0.727$	$4.430 \pm 0.672$	...
$\log q$ (mean)	$-2.373 \pm 0.074$	$-2.354 \pm 0.066$	...
$\alpha$ (rad)	$1.373 \pm 0.007$	$1.389 \pm 0.006$	...
$\rho$	$0.079 \pm 0.052$	$0.061^{+0.049}_{-0.038}$	$0.114^{+0.093}_{-0.072}$
$t_{0,2} - 2457870$	...	...	$3.802 \pm 0.080$
$u_{0,2}$	...	...	$0.093^{+0.018}_{-0.024}$
$\rho_2$	...	...	$0.086^{+0.044}_{-0.054}$
$q_F$ ( $10^{-3}$ )	...	...	$3.656 \pm 0.643$
$I_S$ [KMTC]	$17.336 \pm 0.001$	$17.336 \pm 0.001$	$17.336 \pm 0.001$
$I_B$ [KMTC]	...	...	...
$I_{S,2}$ [KMTC]	...	...	$23.433 \pm 0.192$

remaining four are clearly in the stellar regime. See Table 13. Finally, in Table 11, we show one other planetary model that is just beyond our  $\Delta\chi^2 < 10$  threshold. The residuals of all these models are shown in Figure 8. As there is no way to distinguish among them, the event cannot be cataloged as planetary. Moreover, we find that there is a 1L2S solution whose  $\chi^2$  is similar to (actually slightly better than) those of the 2L1S solutions. See Table 14. This reinforces the ambiguous character of this event.

#### 4. Source Properties

As in Section 3.1, above, we begin by reproducing (with minor modifications) the preamble to Section 4 of Jung et al. (2022). Again, this is done for the convenience of the reader. Readers who are familiar with Jung et al. (2022) may skip this preamble.

If  $\rho$  can be measured from the light curve, then one can use standard techniques (Yoo et al. 2004) to determine the angular source radius,  $\theta_{\text{ast}}$ , and so infer  $\theta_E$  and  $\mu_{\text{rel}}$ :

$$\theta_E = \frac{\theta_{\text{ast}}}{\rho}; \quad \mu_{\text{rel}} = \frac{\theta_E}{t_E}. \quad (11)$$

However, in contrast to the majority of published by-eye discoveries (but similar to most of new AnomalyFinder discoveries reported in Zang et al. 2021, 2022; Gould et al. 2022a; Hwang et al. 2022), most of the planetary events reported in this paper have only upper limits on  $\rho$ , and these limits are mostly not very constraining. As discussed by Gould et al. (2022a), in these cases,  $\theta_{\text{ast}}$  determinations are not likely to be of much use, either now or in the future. Nevertheless, the source color and magnitude measurement that are required inputs for these determinations may be of use in the interpretation of future high-resolution observations, either by space telescopes or adaptive optics (AO) on large ground-based telescopes (Gould 2022). Hence, like Gould et al. (2022a), we calculate  $\theta_{\text{ast}}$  in all cases.

Our general approach is to obtain pyDIA (Albrow 2017) reductions of KMT data at one (or possibly several) observatory/field combinations. These yield the microlensing light curve and field-star photometry on the same system. We

then determine the source color by regression of the  $V$ -band light curve on the  $I$ -band light curve and the source magnitudes in  $I$  by regression on the best-fit model. Similarly to Gould et al. (2022a), we calibrate these color–magnitude diagrams (CMDs) using published field star photometry from OGLE-III (Szymański et al. 2011) or OGLE-II (Kubiak & Szymański 1997; Udalski et al. 2002; Szymański 2005) photometry whenever these are available. However, while five of the six events analyzed in this paper have OGLE-III photometry, for two of these (OGLE-2017-BLG-1275 and OGLE-2017-BLG-0640), the field is heavily extinguished. For the first, this leads us to rely on a combination of  $V/H$  data, as described in Section 4.1. For the second, we carry out the analysis using an  $I/H$  CMD, as described in Section 4.3. For the sixth event, OGLE-2017-BLG-0543, we work directly in the KMTC pyDIA magnitude system. Because the  $\theta_{\text{ast}}$  measurements depend only on photometry relative to the clump, they are unaffected by calibration. In the current context, calibration is only needed to interpret limits on lens light, which is not an issue for this event because it is not reliably detected as a planet.

We then follow the standard method of Yoo et al. (2004). We adopt the intrinsic color of the clump ( $V - I_{0,\text{cl}} = 1.06$  from Bensby et al. (2013) and its intrinsic magnitude from Table 1 of Nataf et al. (2013). We obtain  $[(V - I), I]_{0,S} = [(V - I), I]_S + [(V - I), I]_{0,\text{cl}} - [(V - I), I]_{\text{cl}}$ . We convert from  $V/I$  to  $V/K$  using the  $V/K$  color–color relations of Bessell & Brett (1988) and then derive  $\theta_{\text{ast}}$  using the relations of Kervella et al. (2004a, 2004b) for giant and dwarf sources, respectively. After propagating errors, we add 5% in quadrature to account for errors induced by the overall method. These calculations are shown in Table 15. Where there are multiple solutions, only the one with the lowest  $\chi^2$  is shown. However, the values of  $\theta_{\text{ast}}$  can be inferred for the other solutions by noting the corresponding values of  $I_S$  in the event-parameter tables and using  $\theta_{\text{ast}} \propto 10^{-I_S/5}$ . In any case, these are usually the same within the quoted error bars.

Where relevant, we report the astrometric offset of the source from the baseline object.

Comments on individual events follow.

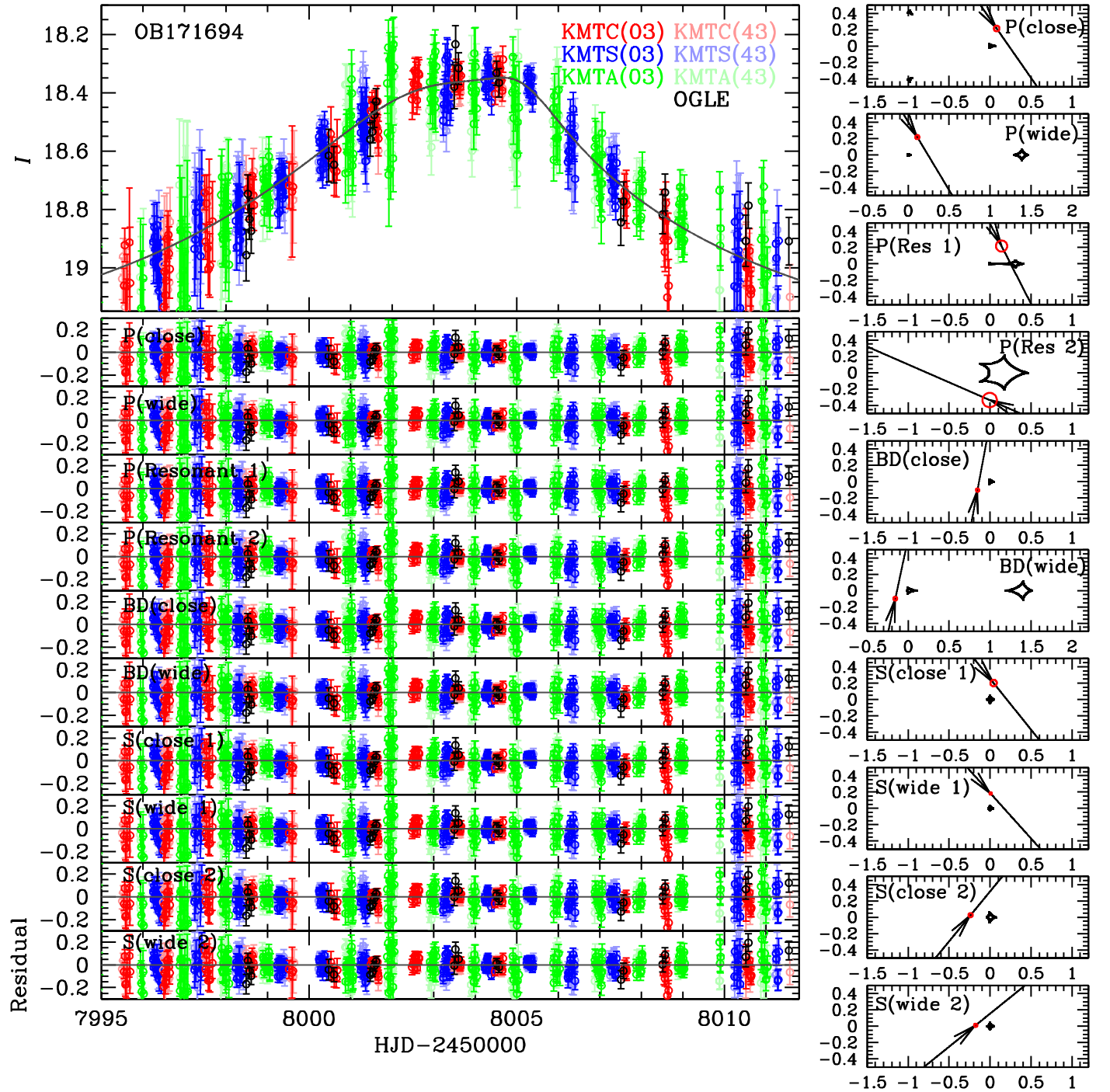
##### 4.1. OGLE-2017-BLG-1275

For OGLE-2017-BLG-1275, we start by analyzing the source color primarily using  $I/H$  data (as opposed to  $V/I$  data). We do so for two reasons. First, the source is very reddened, which leads to substantially smaller error bars on individual  $H$ -band observations compared with those in the  $V$  band. Second, contrary to most of the AnomalyFinder planets, this event has Spitzer data, for which we require a color–color relation. These are overall both easier to determine and more reliable in  $IHL$  than  $VIL$  because the former is based on a shorter extrapolation.

Toward this end, we construct an  $I$  versus  $I - H$  CMD by matching field star photometry from UKIRT and OGLE-III, which are both calibrated. See Figure 9.

The  $H$ -band light curve is already on the same scale as the field stars. We align the KMTC02 pySIS photometry (used in the fits) to KMTC02 pyDIA by regression and then to OGLE-III based on field stars. The comparison yields an offset  $\Delta(I - H) = -0.60 \pm 0.05$  of the source relative to the clump. Adopting  $(I - H)_{0,\text{cl}} = 1.29$  from Bensby et al. (2013) and Bessell & Brett (1988), this implies  $(I - H)_{0,S} = 0.69 \pm 0.05$ .





**Figure 8.** Data (color-coded by observatory) together with model predictions for OGLE-2017-BLG-1694. Although the light-curve distortion is unambiguously detected, it can be fit by numerous, widely differing models. Hence, no definite conclusions can be drawn about the lens system.

From its  $I$ -band magnitude,  $\Delta I = +2.10$  mag below the clump, the source is a turnoff star or subgiant. In terms of surface gravity, these are much closer to dwarfs than giants. Therefore, we estimate the corresponding  $(V-I)$  color using the dwarf star color-color relations of Bessell & Brett (1988), finding  $(V-I)_{0,S} = 0.65 \pm 0.05$ . This is certainly possible, particularly within the errors, but it is relatively blue for a star of this magnitude.

Therefore, we conduct an independent assessment using  $V/I$  photometry. Because of severe extinction, our normal procedure of evaluating  $(V-I)_{0,S}$  from a single observatory-field combination yields statistical errors of  $\sigma(V-I)_s \sim 0.14$  mag,

which is too large to obtain a useful check. We therefore combine four such measurements from KMTC02, KMTC42, KMTS02, and KMTS42, finding  $\Delta(V-I)$  (relative to the clump) of  $(-0.22 \pm 0.13)$ ,  $(-0.17 \pm 0.14)$ ,  $(-0.41 \pm 0.16)$ , and  $(-0.24 \pm 0.14)$ , respectively. As these are mutually consistent ( $\chi^2 = 1.4$  for 3 dof), we combine them to obtain  $\Delta(V-I) = -0.25 \pm 0.07$ , which is substantially redder than the  $H$ -band-based determination. To proceed further, we convert this to  $(I-H)_{0,S} = 0.91 \pm 0.09$  using the dwarf star tables from Bessell & Brett (1988). Hence the two determinations are separated by  $2.1\sigma$  and are therefore in mild tension. To reflect this tension, we adopt their weighted average,

**Table 11**  
Planet Models for OGLE-2017-BLG-1694

Parameters	Close	Wide	Resonant 1	Resonant 2
$\chi^2/\text{dof}$	10193.24/10193	10194.72/10193	10193.56/10193	10215.75/10193
$t_0 - 2458000$	$3.349 \pm 0.032$	$3.359 \pm 0.039$	$3.390 \pm 0.031$	$3.286 \pm 0.069$
$u_0$	$0.193 \pm 0.016$	$0.204 \pm 0.017$	$0.222 \pm 0.014$	$0.322 \pm 0.028$
$t_E$ (days)	$15.77 \pm 0.74$	$15.65 \pm 0.80$	$14.93 \pm 0.62$	$13.07 \pm 0.65$
$s$	$0.637 \pm 0.077$	$1.926 \pm 0.169$	$1.164 \pm 0.017$	$1.104 \pm 0.040$
$q$ ( $10^{-2}$ )	$2.321^{+1.625}_{-0.909}$	$1.915^{+1.000}_{-0.624}$	$0.156^{+0.049}_{-0.036}$	$3.409 \pm 0.715$
$\log q$ (mean)	$-1.63 \pm 0.23$	$-1.71 \pm 0.19$	$-2.80 \pm 0.12$	$-1.47 \pm 0.09$
$\alpha$ (rad)	$0.965 \pm 0.052$	$1.022 \pm 0.037$	$1.095 \pm 0.019$	$3.548 \pm 0.045$
$\rho$	$0.035 \pm 0.022$	$0.025^{+0.019}_{-0.016}$	$0.068 \pm 0.006$	$0.088^{+0.024}_{-0.036}$
$I_S$ [KMTC]	$20.429 \pm 0.096$	$20.363 \pm 0.097$	$20.293 \pm 0.079$	$19.877 \pm 0.118$
$I_B$ [KMTC]	$19.678 \pm 0.047$	$19.712 \pm 0.053$	$19.753 \pm 0.047$	$20.114^{+0.171}_{-0.127}$

**Table 12**  
Brown Dwarf Models for OGLE-2017-BLG-1694

Parameters	Close	Wide
$\chi^2/\text{dof}$	10201.45/10193	10201.27/10193
$t_0 - 2458000$	$3.410 \pm 0.031$	$3.386 \pm 0.032$
$u_0$	$0.134 \pm 0.009$	$0.136 \pm 0.010$
$t_E$ (days)	$18.80 \pm 0.87$	$19.24 \pm 0.92$
$s$	$0.492 \pm 0.016$	$1.892 \pm 0.076$
$q$ ( $10^{-2}$ )	$5.05 \pm 0.84$	$6.20 \pm 1.12$
$\log q$ (mean)	$-1.300 \pm 0.074$	$-1.209 \pm 0.081$
$\alpha$ (rad)	$4.897 \pm 0.019$	$4.920 \pm 0.025$
$\rho$	$0.021^{+0.018}_{-0.013}$	$0.023^{+0.019}_{-0.015}$
$I_S$ [KMTC]	$20.820 \pm 0.079$	$20.785 \pm 0.084$
$I_B$ [KMTC]	$19.526 \pm 0.024$	$19.536 \pm 0.026$

$(I - H)_{0,S} = 0.74$ , but also adopt a larger error than the standard error of the mean (0.046 mag), namely,  $\sigma(I - H)_{0,S} = 0.07$ . For purposes of homogeneous reporting in Table 15, we note that this is equivalent to  $(V - I)_{0,S} = 0.69 \pm 0.05$ .

We now apply this  $(I - H)_{0,S}$  color measurement to determine the  $(I - L)_S$  color constraint by applying an empirical *IHL* color–color relation derived by matching field stars from OGLE-III, UKIRT, and Spitzer. However, the only stars bright enough to enter an empirical determination based on field stars are giants, so we must take account of the fact that the *IHL* color–color relation is different for giants and dwarfs (including the object of interest, i.e., the microlensed source). This process is illustrated in Figure 10. In the main panel, the *IHL* relations from Bessell & Brett (1988) are shown for dwarfs and giants, in red and black, respectively. The green line segment shows the slope (1.24) of the empirical color–color relation derived by matching field stars from OGLE-III, UKIRT, and Spitzer. The length of this segment represents the range of colors of the stars that entered the determination. Its height is set to match its center to the black curve. The key point is that the slopes of the black curve and the green line are the same in this region. If this were not the case, it would mean that Bessell & Brett (1988) had made a serious error, that there was some problem with one of the three data sets that we are using, or that the *IHL* relation of bulge giants was substantially different from local giants. The magenta line extrapolates the linear relation represented by the green segment to bluer colors. The inset shows the offset of the dwarf *IHL* relation from this extrapolation, while the blue vertical line indicates the color of the microlensed source.

The empirical *IHL* relation from field stars is  $(I - L) = 1.24 [\Delta(I - H)] + 3.146$ , where  $\Delta(I - H)$  is the offset from the observed clump centroid  $(I - H)_{\text{cl}} = 3.58$  or  $(I - H)_{0,\text{cl}} = 1.29$ .

Finally, the color constraints must be applied to light-curve photometry, for example,  $I_{\text{KMTC02,pysis}}$ , which is offset from calibrated OGLE-III CMD photometry by  $I_{\text{KMTC02,pysis}} - I = -0.08$ . Combining all these terms,

$$(I_{\text{KMTC02,pysis}} - L) = 1.24[\Delta(I - H)] + 3.146 + (I_{\text{KMTC02,pysis}} - I) + \Delta(I - L), \quad (12)$$

where the last term is given by the inset in Figure 10. This yields  $(I_{\text{KMTC02,pysis}} - L) = 2.43 \pm 0.08$ .

We also place constraints on the blended light. In the light-curve fits, only about 16% of the baseline light is attributed to the blend. Nevertheless, this may be partly due to the difficulty of carrying out point-spread function (PSF) photometry of the baseline object in crowded bulge fields. Therefore, we more conservatively adopt  $I_B > 20.5$ , which constrains the lens flux,  $I_L \geq I_B > 20.5$ . We expect this to provide only a very weak constraint because the  $\pi_E$  measurement already confines the lens to be in or near the bulge, so this limit only implies  $M_{I,L} > I_B - I_{\text{cl}} + M_{I,\text{cl}} > 3.1$ , which, among stars that are in or near the bulge, would only rule out those that have already evolved off the main sequence. Moreover, to be ruled out, such stars would need proper motions  $\mu_{\text{rel}} \equiv \theta_E/t_E = \kappa M \pi_E/t_E \gtrsim 10 \text{ mas yr}^{-1}$ , which are themselves relatively rare. Nevertheless, for completeness, we will include this constraint in the Bayesian analysis of Section 5.1. Note that the blend is *not* displayed in Figure 9 because its color is not known.

#### 4.2. OGLE-2017-BLG-0640

Because this field is highly extinguished and the source is intrinsically red,  $(V - I)_S$  cannot be measured from the KMT data. Fortunately, this event lies within the UKIRT Microlensing Survey (Shvartzvald et al. 2017), so we are able to determine  $\theta_{\text{ast}}$  from an *I/H* CMD. See Figure 9. Although the CMD is based on a relatively small ( $1'$ ) circle centered on the event, there is strong differential extinction. That is, without extinction, the mean *I*-band magnitude of clump stars would be approximately independent of color, while the CMD shows that the bluer clump stars are, on average, substantially brighter than the redder ones. If this effect were due to a pure gradient in extinction across the field. The clump center at the location of the event would simply be the center of this tilted structure. We have investigated the CMD on smaller angular scales and find no evidence against the gradient hypothesis. We therefore adopt the center of the structure for the position of the clump (red dot). The source is  $\Delta(I - H) = -0.21 \pm 0.03$  mag bluer than the clump. To put this on a homogeneous basis with other

**Table 13**  
Star Models for OGLE-2017-BLG-1694

Parameters	Close 1	Wide 1	Close 2	Wide 2
$\chi^2/\text{dof}$	10198.91/10193	10196.59/10193	10194.32/10193	10198.98/10193
$t_0 - 2458000$	$3.596 \pm 0.039$	$3.226 \pm 0.033$	$3.063 \pm 0.062$	$3.667 \pm 0.036$
$u_0$	$0.163 \pm 0.011$	$0.130 \pm 0.014$	$0.203 \pm 0.015$	$0.117 \pm 0.014$
$t_E$ (days)	$17.02 \pm 0.78$	$21.50_{-1.84}^{+2.66}$	$15.80 \pm 0.79$	$26.62_{-2.54}^{+3.39}$
$s$	$0.329 \pm 0.012$	$4.228 \pm 0.652$	$0.389 \pm 0.021$	$4.397 \pm 0.324$
$q$ ( $10^{-2}$ )	$46.5_{-9.0}^{+13.2}$	$43.1_{-21.1}^{+41.2}$	$36.1_{-4.8}^{+8.6}$	$170.2_{-50.2}^{+77.1}$
$\log q$ (mean)	$-0.326 \pm 0.100$	$-0.356 \pm 0.303$	$-0.426 \pm 0.087$	$0.236 \pm 0.156$
$\alpha$ (rad)	$0.895 \pm 0.033$	$0.848 \pm 0.025$	$5.416_{-0.049}^{+0.065}$	$5.613 \pm 0.039$
$\rho$	$0.040_{-0.025}^{+0.032}$	$0.015_{-0.010}^{+0.015}$	$0.026_{-0.017}^{+0.026}$	$0.020_{-0.013}^{+0.016}$
$I_S$ [KMTC]	$20.622 \pm 0.079$	$20.669 \pm 0.078$	$20.392 \pm 0.092$	$20.450 \pm 0.075$
$I_B$ [KMTC]	$19.593 \pm 0.030$	$19.576 \pm 0.028$	$19.697 \pm 0.048$	$19.668 \pm 0.037$

entries in Table 15, we use Bessell & Brett (1988) to translate this offset to  $\Delta(V-I) = -0.14 \pm 0.02$ , that is,  $(V-I)_{0,S} = 0.92 \pm 0.02$ . Due to the fact that the source is a clump giant suffering heavy extinction, we cannot place any useful constraint on blended light.

#### 4.3. OGLE-2017-BLG-1237

As in all but one of the events in this paper, we align our measurements to the OGLE-III CMD. To measure the source color, we rely on KMTC03 pyDIA, for which there are two highly magnified  $V$ -band points on the night of  $\text{HJD}' = 7935$  and four moderately magnified points on  $\text{HJD}' = 7936$  and  $7937$ . The relatively small scatter of the regression of these points (when combined with the mean from the relatively unmagnified points) confirms that the measurement is not strongly affected by the bright variable at  $1''.4$ . This is impressive, given the variable is 6.4 mag brighter than the source in  $V$  band. However, as mentioned in Section 3.4, the amplitude of this double-mode pulsator is close to its minimum during these 3 days of high and relatively high magnification.

Combining the resulting  $\theta_{\text{ast}} = 0.318 \pm 0.024 \mu\text{as}$  measurement from Table 15 and the parameters from Table 7 yields

$$\theta_E = \frac{\theta_{\text{ast}}}{\rho} = 415 \pm 37 \mu\text{as};$$

$$\mu_{\text{rel}} = \frac{\theta_{\text{ast}}}{t_{\text{ast}}} = 5.42 \pm 0.41 \text{ mas yr}^{-1}. \quad (13)$$

Given the proximity of the clump-giant blend at  $\sim 0''.5$  and the bright variable at  $\sim 1''.4$ , we are unable to place useful constraints on the light from the lens.

#### 4.4. OGLE-2017-BLG-1777

Because of the central role of OGLE-IV photometry in the removal of the complex trend (Appendix A), we determine  $I_{0,S}$  by calibrating OGLE-IV photometry to OGLE-III (i.e.,  $I_{\text{OGLE-III}} = I_{\text{OGLE-IV}} + 0.064 \pm 0.001$ ), but we still evaluate  $(V-I)_{0,S}$  using KMT data as described in the preamble to this section. Indeed, we carry out these procedures twice, once using KMTC42 data and the second time using KMTS42 data. We thereby find  $(V-I)_{S,\text{OGLE-III}}^{\text{KMTC42}} = 2.005 \pm 0.030$  and  $(V-I)_{S,\text{OGLE-III}}^{\text{KMTC42}} = 1.951 \pm 0.025$ . We adopt a calibrated value  $(V-I)_S = 1.97 \pm 0.02$ , which then implies  $(V-I)_{0,S} = 0.64 \pm 0.03$ . See Table 15.

**Table 14**  
1L2S Parameters for OGLE-2017-BLG-1694

Parameters	1L2S
$\chi^2/\text{dof}$	10191.42/10192
$t_0 - 2458000$	$3.00_{-0.20}^{+0.16}$
$u_0$	$0.218 \pm 0.021$
$t_E$ (days)	$15.811 \pm 0.923$
$\rho$	$0.098 \pm 0.064$
$t_{0,2} - 2458000$	$5.112 \pm 0.071$
$u_{0,2}$	$0.070 \pm 0.022$
$\rho_2$	$0.073_{-0.041}^{+0.028}$
$q_F$	$0.084_{-0.043}^{+0.071}$
$I_S$ [KMTC]	$20.425 \pm 0.120$
$I_B$ [KMTC]	$19.893 \pm 0.073$
$I_{S,2}$ [KMTC]	$23.210_{-0.517}^{+0.663}$

The resulting  $\theta_{\text{ast}} = 0.490 \pm 0.036 \mu\text{as}$  then implies for the two solutions,

$$\theta_E = \begin{matrix} 63.9 \pm 4.7 \\ 72.1 \pm 5.3 \end{matrix} \mu\text{as}; \quad \mu_{\text{rel}} = \begin{matrix} 358 \pm 26 \\ 382 \pm 28 \end{matrix} \mu\text{as yr}^{-1}, \quad (\text{Local } 1) \quad (14)$$

We note that two of the ‘‘alarming’’ features of these 2L1S models, namely, the very small  $\theta_E$  and  $\mu_{\text{rel}}$ , are qualitatively similar for the single-lens/xallarap model:  $\theta_E^{\text{1L1S}} = 52.5 \mu\text{as}$  and  $\mu_{\text{rel}}^{\text{1L1S}} = 236 \mu\text{as yr}^{-1}$ .

Finally, we assess the limits on light from the lens based on both KMTC42 and KMTC42 pyDIA astrometry and on a comparison of KMT pyDIA astrometry with astrometry from OGLE-III and OGLE-IV. We reference all positions to the bright giant because it is in all four of these catalogs and because its position is likely to be well determined.

We find that the offset of the lens position (determined from the difference image) is  $\Delta\theta(E, N)_L = (825, 100) \text{ mas}$  and  $(821, 111) \text{ mas}$  for KMTC42 and KMTC42, respectively, which confirms that both the lens position and the giant neighbor position are well determined.

There are no stars detected near the position of the source in any of the four star catalogs that we investigated: OGLE-III, OGLE-IV, KMTC42, and KMTC42. However, there are several nearby stars that are detected at roughly comparable distances from the bright star, albeit in different directions. The closest such star is in the OGLE-IV catalog, which is separated by  $\Delta\theta(E, N)_{\text{N1}}^{\text{O-IV}} = (320, -750) \text{ mas}$  with  $I = 18.99$ . Hence, the scalar separation is 815 mas, which is comparable to 830 mas for the microlensed source. Again, however, these are separated in angle by  $75^\circ$ , so N1 cannot be the microlensed

**Table 15**  
CMD Parameters

Name	$(V - I)_S$	$(V - I)_{cl}$	$(V - I)_{S,0}$	$I_S$	$I_{cl}$	$I_{cl,0}$	$I_{S,0}$	$\theta_*$ ( $\mu\text{as}$ )
OGLE-2017-BLG-1275	N.A.	$3.65 \pm 0.05$	$0.69 \pm 0.05$	$19.40 \pm 0.05$	$17.30 \pm 0.03$	14.43	$16.53 \pm 0.06$	$1.516 \pm 0.121$
OGLE-2017-BLG-0640	N.A.	N.A.	$0.92 \pm 0.02$	$18.92 \pm 0.08$	$18.78 \pm 0.10$	14.44	$14.58 \pm 0.13$	$4.961 \pm 0.417$
OGLE-2017-BLG-1237	$1.85 \pm 0.03$	$1.93 \pm 0.03$	$0.98 \pm 0.04$	$21.80 \pm 0.06$	$15.45 \pm 0.05$	14.35	$20.70 \pm 0.08$	$0.318 \pm 0.024$
OGLE-2017-BLG-1777	$1.97 \pm 0.02$	$2.39 \pm 0.02$	$0.64 \pm 0.03$	$20.46 \pm 0.09$	$16.03 \pm 0.04$	14.44	$18.87 \pm 0.10$	$0.490 \pm 0.036$
OGLE-2017-BLG-0543	$3.03 \pm 0.07$	$3.05 \pm 0.03$	$1.04 \pm 0.08$	$17.22 \pm 0.01$	$16.88 \pm 0.04$	14.55	$14.89 \pm 0.04$	$4.959 \pm 0.477$
OGLE-2017-BLG-1694	$1.94 \pm 0.08$	$2.10 \pm 0.04$	$0.90 \pm 0.11$	$20.56 \pm 0.10$	$15.60 \pm 0.06$	14.55	$19.51 \pm 0.12$	$0.497 \pm 0.079$

**Note.**  $(V - I)_{cl,0} = 1.06$ .

source. Nevertheless, we can say that if the microlensed source were as bright as N1, it would have been detected, and therefore we can put an upper limit on the lens light  $I_L > 19.0$ .

#### 4.5. OGLE-2017-BLG-0543

The characterization of the lens system is ambiguous, and so we include the CMD analysis only for completeness. The source photometry and inferred  $\theta_{ast}$  are given in Table 15. Among the six events in this paper, OGLE-2017-BLG-0543 is the only one without calibrated photometry. However, because the determination of  $\theta_{ast}$  requires only relative photometry, this is not a fundamental limitation. We note that the source is consistent with being unblended.

#### 4.6. OGLE-2017-BLG-1694

As was the case for OGLE-2017-BLG-0543, the characterization of the lens system is ambiguous, and so we include the CMD analysis only for completeness. The source photometry and inferred  $\theta_{ast}$  are given in Table 15. By subtracting the source flux (derived from fitting the pyDIA light curve to the best model and transforming to the OGLE-III calibrated system) from the OGLE-III baseline flux, we find blended flux with  $I_B = 20.25$ . However, we do not show this blend in Figure 9 because we have no information about its color. That is, OGLE-III does not list a color for the baseline object, while KMT pyDIA does not resolve this object. We note that the baseline object lies within about 200 mas of the source, but we do not investigate the astrometry in detail.

### 5. Physical Parameters

To make Bayesian estimates of the lens properties, we follow the same procedures as described in Section 5 of Gould et al. (2022a). We refer the reader to that work for details. Below, we repeat the text from Section 5 of Jung et al. (2022) for the reader's convenience.

In Table 16, we present the resulting Bayesian estimates of the host mass  $M_{host}$ , the planet mass  $M_{planet}$ , the distance to the lens system  $D_L$ , and the planet-host projected separation  $a_{\perp}$ . For two of the four planetary events, there are two or more competing solutions. For these cases (following Gould et al. 2022a), we show the results of the Bayesian analysis for each solution separately, and we then show the ‘‘adopted’’ values below these. For  $M_{host}$ ,  $M_{planet}$ , and  $D_L$ , these are simply the weighted averages of the separate solutions, where the weights are the product of the two factors at the right side of each row. The first factor is simply the total weight from the Bayesian analysis. The second is  $\exp(-\Delta\chi^2/2)$ , where  $\Delta\chi^2$  is the  $\chi^2$  difference relative to the best solution. For  $a_{\perp}$ , we follow a

similar approach provided that either the individual solutions are strongly overlapping or one solution is strongly dominant. If neither condition is met, we show the two values separately.

We present Bayesian analyses for four of the six events, but not for OGLE-2017-BLG-0543 and OGLE-2017-BLG-1694, for which we cannot distinguish between competing interpretations of the event. See Sections 3.6 and 3.7. Figure 11 show histograms for  $M_{host}$  and  $D_L$  for these four events.

#### 5.1. OGLE-2017-BLG-1275

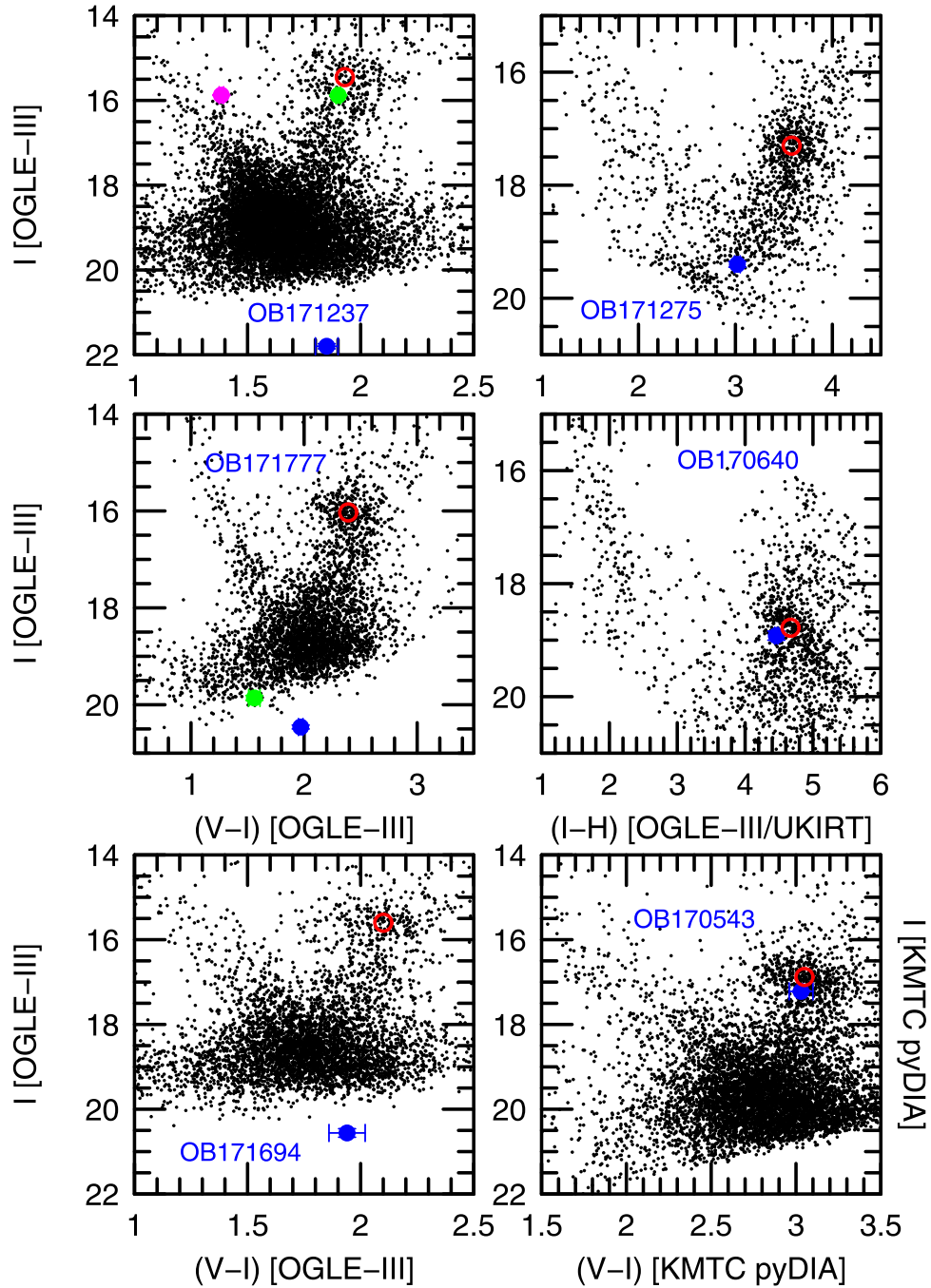
OGLE-2017-BLG-1275 has four solutions, inner(++), inner(--), outer(++), and outer(--), upon which there are a total of four constraints, that is, on  $t_E$ ,  $\rho$ ,  $\pi_E$ , and  $I_L$ . The first comes from Tables 4 and 5, that is,  $\chi^2_{t_E} = (t_{E,sim} - t_{E,table})^2 / \sigma_{t_E}^2$ , where  $t_{E,sim}$  is the timescale of the simulated event. The second is found by calculating  $\rho_{sim} = \theta_{E,sim} / \theta_{ast}$ , where  $\theta_{E,sim}$  is the Einstein radius of the simulated event and  $\theta_{ast}$  is from Table 15, and then applying the  $\chi^2(\rho)$  envelope function from Figure 12. We note that, even at the  $1\sigma$  level, this constraint only implies  $\mu_{rel} \gtrsim 0.8 \text{ mas yr}^{-1}$ , which is hardly constraining, but we nevertheless include this constraint for completeness. For the third, we find

$$\chi^2(\pi_E) = \sum_{i,j=1}^2 (a_i - a_{i,0})(a_j - a_{j,0})b_{ij} \quad b \equiv c^{-1}, \quad (15)$$

where the  $a_i$  are the  $\pi_E$  components for the simulated event, while  $a_{i,0}$  and  $c_{ij}$  are the mean and covariance matrix of  $\pi_E$  as derived from the MCMC. These have very similar values and error bars as the median-based values shown in Tables 4 and 5, with correlation coefficients, +0.35 (inner(++)), -0.32 (inner(--)), +0.39 (outer(++)), and -0.40 (outer(--)). The final constraint is  $I_L > 20.5$ , as discussed in Section 4.1.

For all four solutions, the planet mass peaks near  $M_{planet} \sim 6 M_{Jup}$ , while the host is near the M dwarf/K dwarf boundary. Note that the distance is  $D_L \sim 7.7 \text{ kpc}$ , that is, close to the Galactocentric distance, regardless of whether it belongs to the bulge or disk populations. Also note that the latter is prohibited by  $\pi_E$  measurements for the (+, +) solutions because their directions are kinematically inconsistent with disk objects. The projected planet-host separation is either about 1.2 au or 2.2 au. By comparison, for an  $M_{host} \sim 0.6 M_{\odot}$  host, the snow line is about  $a_{snow} = 2.7 \text{ au}(M_{host}/M_{\odot}) = 1.62 \text{ au}$ . Hence, this is a relatively rare case for microlensing, in which the planet could be well inside the snow line, although because  $a_{\perp}$  is bimodal, it may well be beyond the snow line, even in projection.





**Figure 9.** CMDs for all six events, indicated by, for example, OB171275 for OGLE-2017-BLG-1275. The red clump and the source position are shown in red and blue, respectively. Where relevant, the blended light is shown in green. For OB171237, the bright variable at  $1''.4$  is shown in magenta. When there are multiple solutions, we only show the source and blend for the lowest- $\chi^2$  solution.

Finally, we note that the posterior estimate of the proper motion is  $\mu_{\text{rel}} = 6.7 \pm 2.2 \text{ mas yr}^{-1}$ . Based on this estimate, the lens and source will be separated by  $\Delta\theta \sim 87 \pm 29 \text{ mas}$  in 2030, which is a plausible date for first light on AO on extremely large telescopes (ELTs). Hence, it is likely that the lens mass could be more precisely measured at AO first light (Gould 2022).

### 5.2. OGLE-2017-BLG-0640

OGLE-2017-BLG-0640 has one solution, upon which there are two constraints, that is, on  $t_E$  and  $\rho$ . The first comes from Table 6, while the second comes from the  $\rho$ -envelope function

shown in Figure 12, which is then combined with the  $\theta_{\text{ast}}$  value from Table 15 to yield a constraint on  $\theta_E$ .

The planet is of Jovian mass, and the host is an M dwarf, while the system is most likely in the Galactic bulge. The planet lies just beyond the snow line in projection.

The posterior proper-motion estimate is  $\mu_{\text{rel}} = 7.2 \pm 2.4 \text{ mas yr}^{-1}$ , which would imply a similar estimate for the separation at ELT AO first light as in the case of OGLE-2017-BLG-1275. However, the contrast ratio is expected to be much larger because the source is a giant (rather than a subgiant), while the lens is predicted to be a middle M dwarf (rather than near the boundary of M dwarfs and K dwarfs). Hence, it may

**Table 16**  
Physical Properties

Event Models	Physical Properties				Relative Weights	
	$M_{\text{host}} (M_{\odot})$	$M_{\text{planet}} (M_J)$	$D_L$ (kpc)	$a_{\perp}$ (au)	Gal.Mod.	$\chi^2$
OB171275						
Inner(+,+)	$0.60 \pm 0.22$	$5.30 \pm 1.96$	$7.74 \pm 0.82$	$1.14 \pm 0.36$	0.502	0.190
Outer(+,+)	$0.60 \pm 0.22$	$5.75 \pm 2.10$	$7.72 \pm 0.82$	$2.02 \pm 0.63$	0.532	1.000
Inner(-,-)	$0.65 \pm 0.24$	$5.67 \pm 2.05$	$7.69 \pm 0.89$	$1.21 \pm 0.36$	0.903	0.213
Outer(-,-)	$0.65 \pm 0.23$	$6.23 \pm 2.21$	$7.65 \pm 0.90$	$2.14 \pm 0.63$	1.000	0.563
Adopted	$0.63 \pm 0.23$	$5.90 \pm 2.20$	$7.69 \pm 0.90$	$2.09 \pm 0.63$		
OB170640	$0.32^{+0.32}_{-0.18}$	$1.62^{+1.64}_{-0.94}$	$6.63^{+1.09}_{-1.45}$	$1.14 \pm 0.38$		
OB171237	$0.46^{+0.30}_{-0.24}$	$3.80^{+2.49}_{-1.99}$	$6.03^{+0.94}_{-1.53}$	$2.53^{+0.50}_{-0.64}$		
OB171777						
2L1S (Local 1)	$0.038^{+0.030}_{-0.014}$	$0.046^{+0.037}_{-0.017}$	$7.74 \pm 0.81$	$0.39 \pm 0.06$	0.539	1.000
2L1S (Local 2)	$0.046^{+0.042}_{-0.017}$	$0.078^{+0.073}_{-0.028}$	$7.74 \pm 0.82$	$0.43^{+0.08}_{-0.07}$	1.000	0.961
Adopted	$0.044^{+0.042}_{-0.017}$	$0.067^{+0.073}_{-0.030}$	$7.74 \pm 0.82$	$0.41 \pm 0.08$		

**Table 17**  
AnomalyFinder Planets in KMT Prime Fields for 2017

Event Name	KMT Name	$\log q$	$s$	References
KB170428 <sup>a</sup>	KB170428	-4.30	0.88	Zang et al. (2023)
OB171434	KB170016	-4.24	0.98	Udalski et al. (2018)
OB170482	KB170084	-3.87	1.07	Han et al. (2018)
KB170165	KB170165	-3.87	0.95	Jung et al. (2019)
OB170406	KB170243	-3.16	1.13	Hirao et al. (2020)
OB171777 <sup>b</sup>	KB170282	-2.86	0.72	This paper
OB170640	KB171726	-2.31	0.61	This paper
OB171237	KB170422	-2.10	1.04	This paper
OB171275 <sup>c</sup>	KB170314	-2.06	1.09	This paper
OB171049	KB170370	-2.02	1.32	Kim et al. (2020)
OB171375 <sup>c</sup>	KB170078	-1.88	0.84	Han et al. (2020)
OB171522	KB170460	-1.80	0.95	Jung et al. (2018)
OB170173 <sup>d</sup>	KB171707	-4.61	1.54	Hwang et al. (2018)
OB170448 <sup>d</sup>	KB170090	-4.30	3.16	Zhai et al. (2024)
OB170373 <sup>d</sup>	KB171529	-2.81	1.38	Skowron et al. (2016)
OB170543 <sup>e</sup>	KB170140	-2.37	1.52	This paper
OB171694 <sup>d,f</sup>	KB172126	-1.64	0.64	This paper

**Notes.** Event names are abbreviations for, for example, KMT-2017-BLG-0165 and OGLE-2017-BLG-1434.

<sup>a</sup> Minor  $s$  degeneracy.

<sup>b</sup> Exceptionally complex model.

<sup>c</sup>  $s$  degeneracy.

<sup>d</sup> Large  $q$  degeneracy.

<sup>e</sup> 1L2S/2L1S degeneracy.

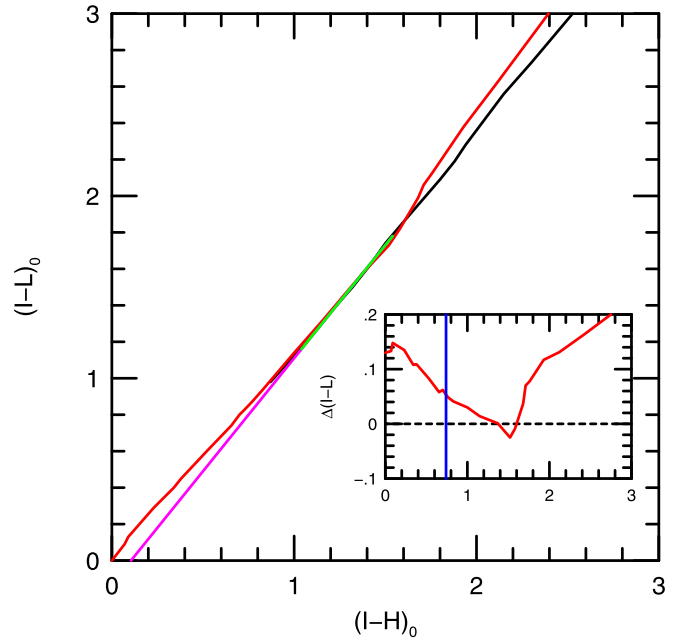
<sup>f</sup> Planet/binary degeneracy.

be more challenging to resolve the lens and source separately for OGLE-2017-BLG-0640 than for OGLE-2017-BLG-1275.

### 5.3. OGLE-2017-BLG-1237

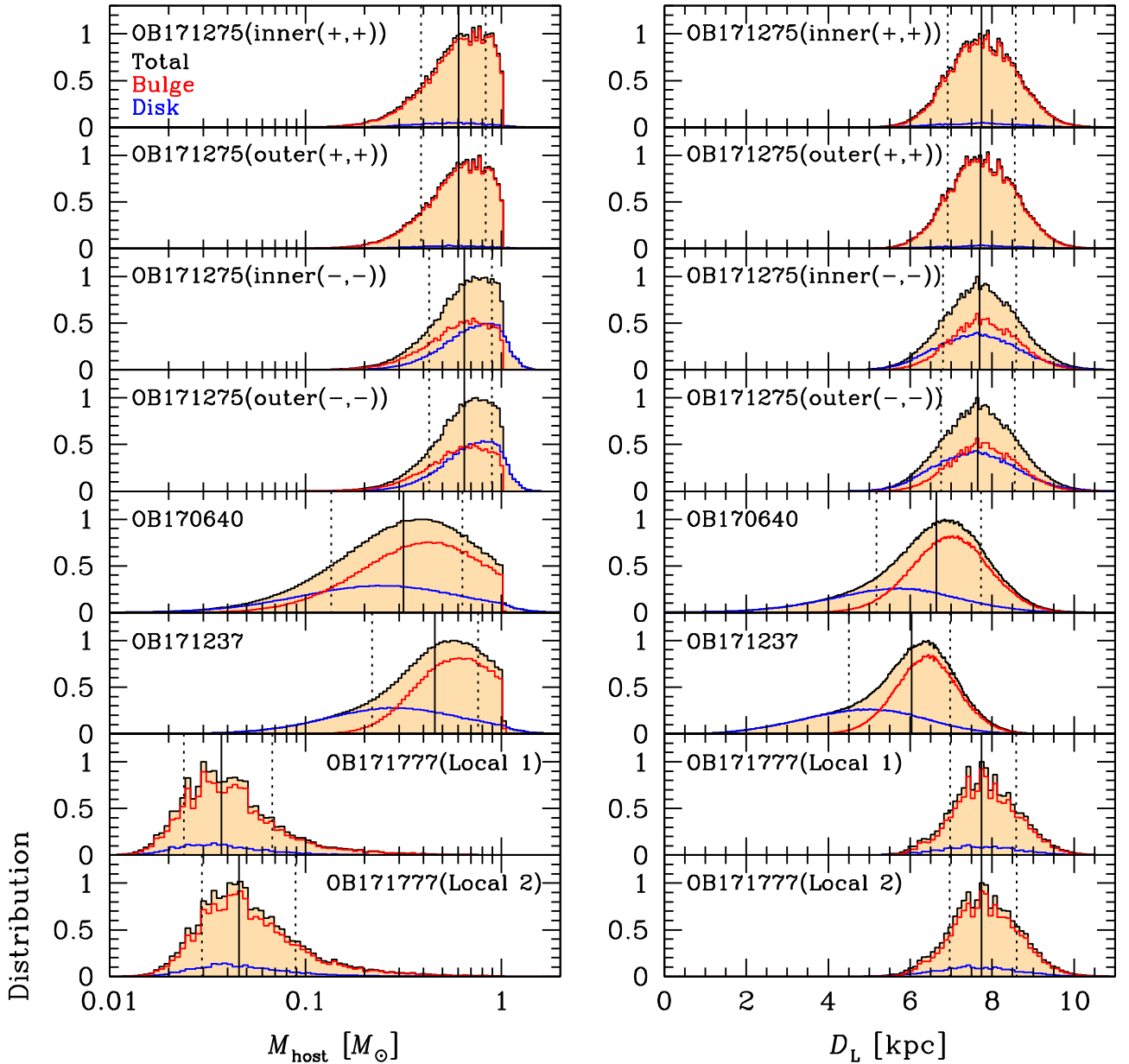
OGLE-2017-BLG-1237 has one solution, upon which there are two constraints, that is, on  $t_E$  and  $\theta_E$ , which come from Table 7 and Equation (13), respectively.

The planet is estimated to be several Jupiter masses, while the host is an early M dwarf. Similar to OGLE-2017-BLG-0640, the system most likely lies in the bulge. The planet lies well beyond the snow line.



**Figure 10.** Empirical  $IHL$  color-color relation for giants (black) and dwarfs (red) determined from local stars by Bessell & Brett (1988). The green line segment shows the slope of the relation that we derived from bulge giants (whose range is represented by the length of the segment) from OGLE-III, UKIRT, and Spitzer (OUS) data, which has been transposed to the local relation, showing excellent agreement with the slope of the black curve. The magenta line is the extrapolation of the green relation to a bluer range. The inset shows the offset between the magenta and red curves. The  $(I-L)$  color of the dwarf (actually turnoff) source is determined by applying the extrapolated OUS relation and then correcting this using the inset relation at the color of the source (blue).

In this case, the proper motion is directly measured (rather than being estimated from the Bayesian analysis as in the previous two events):  $\mu_{\text{rel}} = 5.4 \pm 0.4 \text{ mas yr}^{-1}$ . The source is faint, meaning that the lens and source can certainly be resolved at ELT AO first light. In fact, it may well be possible to resolve the lens earlier than that using 10 m class telescopes. However, light from the clump-giant blend at  $0''.5$  may make this difficult. Hence, this issue should be carefully evaluated before undertaking such observations.



**Figure 11.** Histograms of the host mass (left) and lens distance (right) for the three unambiguously planetary events, plus one very likely candidate (OB171777), as derived from the Bayesian analyses. Disk (blue) and bulge (red) distributions are shown separately, with their total shown in black.

#### 5.4. OGLE-2017-BLG-1777

The OGLE-2017-BLG-1777 event has two solutions, upon which there are a total of four constraints, that is, on  $t_E$ ,  $\rho$ ,  $\pi_E$ , and  $I_L$ . The first two come from Tables 8 and 9. The second then yields  $\theta_E = \theta_{\text{ast}}/\rho$ , where  $\theta_{\text{ast}}$  is given in Table 15. The third applies Equation (15) to the mean values and errors of  $\pi_E$ , which are similar to the values in Tables 8 and 9, with correlation coefficients  $-0.15$  and  $+0.12$  for locals 1 and 2, respectively. The final constraint is  $I_L > 19.0$ , as discussed in Section 4.4.

The lens system is composed of a bulge BD (or possibly VLM star) orbited by a Neptune-class planet. Insofar as the concept of “snow line” applies to such systems, the planet lies well within the snow line. As we have discussed, the proper motion is extraordinarily low,  $\mu_{\text{rel}} = 0.37 \pm 0.03 \text{ mas yr}^{-1}$ , which would make it impossible to resolve the source and lens (even if the latter proves to be luminous) using ELT AO

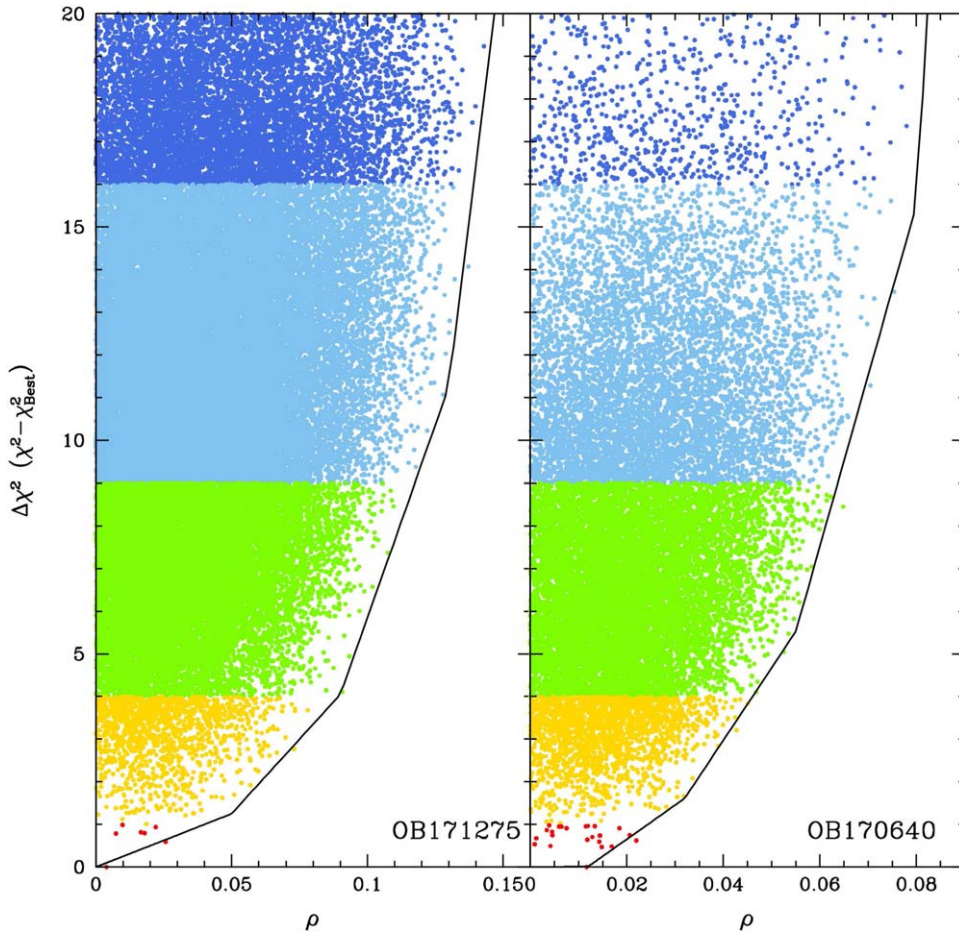
for at least several decades. On the other hand, if the lens is luminous, the two could conceivably be resolved using the VLTI GRAVITY interferometer (Dong et al. 2019). However, as we have emphasized, the first additional observation that should be made to clarify the nature of this system is to measure the RV variations induced by the putative BD (or VLM star) companion to the source.

#### 5.5. OGLE-2017-BLG-0543

Because OGLE-2017-BLG-0543 has viable nonplanetary explanations, we do not carry out a Bayesian analysis.

#### 5.6. OGLE-2017-BLG-1694

Because OGLE-2017-BLG-1694 has viable nonplanetary explanations, we do not carry out a Bayesian analysis.



**Figure 12.** Envelope functions (line segments) based on MCMC data (points), giving  $\Delta\chi^2(\rho)$  for OGLE-2017-BLG-1275 and OGLE-2017-BLG-0640. Note that at, for example,  $2\sigma$ ,  $\rho < 0.09$  and  $\rho < 0.045$ , so that  $\mu_{\text{rel}} = \theta_{\text{ast}}/\rho t_E$  is constrained to be  $\mu_{\text{rel}} \gtrsim 0.46 \text{ mas yr}^{-1}$  and  $\mu_{\text{rel}} \gtrsim 2.80 \text{ mas yr}^{-1}$ , for OGLE-2017-BLG-1275 and OGLE-2017-BLG-0640, respectively. Thus, the  $\rho$  limit is completely unconstraining for the first case and mildly constraining for the second. See Equation (9).

## 6. Discussion

In this paper, we have completed the analysis of planetary (and possibly planetary) events from the 2017 KMT prime fields that were identified as candidates by the KMT AnomalyFinder system. The sample contains 11 unambiguous planets with unambiguous mass-ratio measurements and one other event for which we judge the planetary interpretation to be very likely. In addition there are three unambiguous planets that have very large uncertainties in  $q$ . See Table 17. While it is not the jurisdiction of this paper to decide which planets will ultimately enter the statistical sample, for purposes of this discussion we will adopt 12. This can be compared to similar estimates of this number for three other AnomalyFinder prime-field years of 11 (2016), 19 (2018), and 13 (2019). The first of these estimates is derived from Table 12 of Shin et al. (2023), while the latter two are derived from Figure 20 of Jung et al. (2023). These numbers imply a mean and standard deviation of  $13.75 \pm 3.59$ . By comparison, there are only two complete analyses of AnomalyFinder subprime fields, that is, 2018 and 2019, for which Figure 20 of Jung et al. (2023) indicates 14 and 12 planets, respectively. Adopting Poisson errors (rather than errors derived from scatter), we estimate an average rate (and standard error of the mean) of  $26.75 \pm 3.15$  AnomalyFinder planets per year. Thus, we can expect a statistical sample of  $267 \pm 33$  planets from 10 yr of KMT data, 2016–2026

(excluding 2020 due to COVID-19), which is the current horizon of the KMTNet project.<sup>21</sup> Another relevant statistic is that three of the 12 planets in Table 17 were first identified by AnomalyFinder, whereas the remainder were first identified by eye. For the 4 yr of 2016–2019, these ratios are 3/11, 3/12, 8/19, and 8/13. The higher fractions for the two most recent years may be random fluctuations, but they might also be explained by the factor  $\sim 2$  shorter interval between the time that the events were discovered and the time that the AnomalyFinder search was carried out.

Three of the four planets that we have reported call for special notice: OGLE-2017-BLG-1275, OGLE-2017-BLG-1237, and OGLE-2017-BLG-1777.

OGLE-2017-BLG-1275 is the first planet with a Spitzer parallax measurement that was originally discovered by AnomalyFinder. This discovery raises the question of whether there could be additional planets with Spitzer parallax measurements that remain “hidden” in the data. The Spitzer microlensing program ended in 2019, so all such AnomalyFinder planets will be identified when the 2016–2017 subprime analyses are complete. However, additional Spitzer planets that presently remain hidden could be discovered by another

<sup>21</sup> For a Poisson process, the detection of  $N_1$  events during a time  $t_1$  implies a mean and standard deviation of  $N_2 = (t_2/t_1)[N_1 \pm \sqrt{2N_1}]$  during a subsequent time  $t_2$ . Hence, the uncertainty is  $\sqrt{2[(6/4)^2 \times 55 + (8/2)^2 \times 26]} = 33$ .



channel. The AnomalyFinder search is applied to the end-of-year pySIS pipeline data, whereas all published KMT planets are based on TLC pySIS rereductions. These often have substantially better  $\Delta\chi^2 = \chi^2(1L1S) - \chi^2(2L1S)$  compared with the pipeline pySIS. Because TLC is labor intensive, it would be prohibitive to rereduce all  $\sim 1000$  Spitzer events, but this would be feasible for promising subsets, such as all events with  $A_{\max} > 5$  and Spitzer coverage that might plausibly yield a parallax measurement.

OGLE-2017-BLG-1237 is notable because it lies just  $1''.4$  from a variable, whose full amplitude of variations is about 15 times brighter than the source flux. Fortunately, the variable is sufficiently regular that the impact of these variations on the event can be accurately modeled based on data taken when the source is essentially unmagnified.

OGLE-2017-BLG-1777 is remarkable in several respects, some of which are related to one another. First, like OGLE-2017-BLG-1237, the original light curve had to be corrected for effects from a neighboring bright star (see Appendix A). Second, both the Einstein radius  $\theta_E$  and the proper motion  $\mu_{\text{rel}}$  are unusually small, leading to a concern that both might be a product of an incorrect measurement of  $t_{\text{ast}}$ . We investigate this issue in Appendix C and conclude that this is not likely to be the case. Third, there is a  $P \sim 13$  days oscillation in the light curve in the neighborhood of the peak. After exploring a wide range of models, we concluded that this feature could only be explained by xallarap: orbit of the source star around an unseen companion. The implied mass of this companion is close to the boundary between BDs and VLM stars. We show in Appendix B that detection of such low-mass source companions is greatly enhanced for events with low  $\theta_E$  and low  $\mu_{\text{rel}}$ . Finally, only by including lens-orbital motion in the microlens model are we able to explain the final, otherwise discrepant, data point from the 2017 season. Although this might seem to be an ad hoc solution for this single point, the resulting orbital-motion parameters are strongly peaked in the range that is expected for Kepler orbits. The concatenation of these unusual features gave us some pause regarding this planetary candidate, but we finally concluded that it was very likely to be real. We argued that this complex solution could be partially verified by RV measurements of the source, which would be aimed at confirming the predicted  $v \sin i \sim 6.5 \text{ km s}^{-1}$  amplitude of source motion, with a period of  $P \sim 12.7$  days.

### Acknowledgments

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UKIRT was supported by NASA and operated under an agreement among the University of Hawaii, the University of Arizona, and Lockheed Martin Advanced Technology Center; operations were enabled through the cooperation of the East Asian Observatory. The collection of the 2017 data reported here was furthermore partially supported by NASA grant Nos. NNX17AD73G and NNG16PJ32C. This paper makes use of data from the UKIRT microlensing surveys (Shvartzvald et al. 2017) provided by the UKIRT Microlensing Team and services at the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to use data produced from observations conducted on this mountain.

### Appendix A

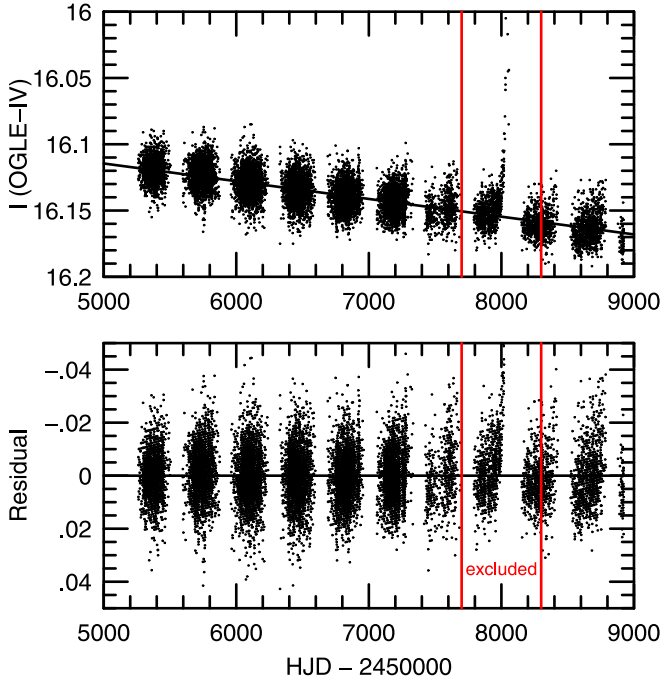
#### Light-curve Correction for OGLE-2017-BLG-1777

There is a long-term, linear decline in the baseline flux of this event, which is clearly manifest in the 10 yr OGLE-IV light curve. See Figure 13. As we will show, the physical origin of this trend is well understood, and even if it were not, the trend itself is precisely measured. Hence, it could easily be removed. However, a more detailed analysis shows that while this “fix” may appear obvious, it is also not correct.

Before discussing the origin of this effect, we start by noting that the high baseline flux shown in Figure 13 ( $I \sim 16$ ) is an artifact, which results from the fact that the OGLE alert was based on the apparent light curve of a neighboring catalog star that is a giant of this magnitude. The underlying OGLE light curves are simply DIA photometry, to which OGLE adds the flux from the catalog star before converting to a magnitude system. This routine procedure has absolutely no impact on the light-curve analysis, unless the modeled source flux exceeds this baseline flux, in which case it might trigger concerns about “negative blending,” which certainly does not apply to OGLE-2017-BLG-1777.

However, in the present case, the actual source is much closer to another star from the OGLE-IV catalog (constructed in 2010), which is 810 mas from the one that triggered the OGLE alert. Hence, it was just by bad luck that OGLE triggered on the “wrong star.” This does happen from time to time (also with KMT triggers), but it does not cause any substantive problems. Thus, while it would not make any difference to the modeling, it might give a more accurate impression of possible blended light to add in the nearer ( $I \sim 19$ ) catalog star, rather than the giant. Nevertheless, we retain the standard OGLE reduction at this stage because this giant is the cause of both the linear slope and the additional effects that we will uncover.

The underlying cause of the trend is the proper motion of this bright star away from the source. By comparing KMT difference images from the event in 2017 to reference images in the same year, we find that at  $t_0$ , this catalog star lay 835 mas approximately due west of the source. Using Gaia DR3 (Gaia Collaboration et al. 2016, 2018), we find that in the frame of the Galactic bulge (which basically sets the astrometric alignment of the images before they are subtracted) the source is moving at the relatively high speed of  $\mu_{\parallel} = 5.5 \text{ mas yr}^{-1}$



**Figure 13.** Long-term linear trend in the OGLE-IV light curve of OGLE-2017-BLG-1777. The magnitudes are constructed by first doing difference-image photometry, then adding in the flux of the “baseline object,” and finally converting to magnitudes. The baseline object is unrelated to the microlensing event, but it accounts for the long-term trend seen here. The fit is a simple linear fit in magnitudes, with the region enclosed by red lines excluded from the fit. More detailed investigations are carried out in flux units. See Appendix A.

parallel to this separation vector. Hence, as time goes on, less and less of the flux from this star is in the tapered PSF aperture that is used to measure the flux. Approximating the PSF as a Gaussian, one easily finds that flux falling in the tapered aperture,  $F_{\text{app}}$ , is related to the flux of this contaminating star,  $F_{\text{star}}$ , by

$$F_{\text{app}} = F_{\text{star}} \exp \left[ -\ln 4 \left( \frac{\theta}{\text{FWHM}} \right)^2 \right], \quad (\text{A1})$$

where FWHM is the seeing. To zeroth order, this excess flux disappears when the reference image is subtracted from the current image prior to doing difference-image photometry. However, at next order, one measures the change with time, which is most conveniently expressed in magnitudes relative to  $F_{\text{star}}$ ,

$$\begin{aligned} \frac{dI_{\text{star}}}{dt} &= \mu_{\parallel} \frac{dI_{\text{star}}}{d\theta} = \frac{\mu_{\parallel}}{F_{\text{star}}} \frac{-2.5}{\ln 10} \frac{dF_{\text{app}}}{d\theta} \\ &= 10 \log 2 \frac{\mu_{\parallel} \theta_0}{\text{FWHM}^2} \exp \left[ -\ln 4 \left( \frac{\theta_0}{\text{FWHM}} \right)^2 \right], \quad (\text{A2}) \end{aligned}$$

where  $\theta_0$  is the evaluation of  $\theta$  at some reference time, such as the peak of the event,  $t_0$ . Adopting the median OGLE seeing  $\text{FWHM} = 1''.32$ , this yields  $dI_{\text{star}}/dt = 4.56 \text{ mmag yr}^{-1}$ , which can be compared to the empirical value shown in Figure 13 of  $dI_{\text{star}}/dt = 4.89 \text{ mmag yr}^{-1}$ . This qualitative agreement shows that we have a reasonably good analytic understanding of this effect.

Unfortunately, this understanding is not as good as one might hope. While it is plausible that the predicted slope should

not be identical to the empirical slope (because the PSF is not actually Gaussian), Equation (A2) predicts that the magnitude of the offset at fixed time should vary  $\propto x \exp(-x)$ , where  $x \equiv \ln 4(\theta_0/\text{FWHM})^2$ . However, when we include this dependence on FWHM in the fit,  $\chi^2$  does not improve but on the contrary gets slightly worse.

This means that we would not have been able to blindly apply the results from the OGLE fit to the KMT data sets, that is, scaling by  $x \exp(-x)$  according to the median FWHM. We note that if we fit for the slope parameters for each observatory (as part of a general fit to a microlensing model), using KMT data from only 2017, the errors are 30–50 times larger for KMT than for OGLE. This is about what one would expect based on an effective time baseline that is 15 times shorter and sample sizes that are, on average, eight times smaller, that is,  $15 \times \sqrt{8} \sim 40$ . Nevertheless, despite these large errors, we found that the slopes for the six KMT observatory/field combinations were much closer to zero than to the slopes predicted by scaling to the extremely well-measured, long-term OGLE slope.

Motivated, by this apparent conflict, we investigated whether the OGLE data actually showed any evidence for an intraseason slope or whether the slope seen in Figure 13 was entirely due to discrete, downward jumps between seasons, despite the fact that such a model would appear to be extremely ad hoc. Surprisingly, we found that the data are consistent with this seemingly bizarre hypothesis. We carried out a linear fit of the form  $F(t) = \sum_{i=1}^3 a_i f_i(t)$ , where  $f_1(t) = 1$ ,  $f_2(t) = \text{nint}(Y(t))$ ,  $f_3(t) = Y(t) - \text{nint}(Y(t))$ , and  $Y(t) \equiv (\text{HJD}' - 7900)/365.25$ , that is, a constant, plus an annual jump term, plus an intraseason slope term. We found  $a_i = (5.46658, -0.02708, -0.0065) \pm (0.00070, 0.00016, 0.00260)$ . That is, the intraseason slope was constrained (at  $1\sigma$ ) to be  $>10$  times smaller than the multiyear slope,  $|a_3| \ll \sigma_3 = 0.096|a_2|$ .

A plausible physical cause is differential refraction: as the field moves toward the east over a season, the image of the neighboring bright star moves closer to the source, causing the measured flux to increase. We confirm that this explanation is consistent by fitting for a continuous slope and an hour-angle term. We find that the continuous term is virtually identical to  $a_2$  above, while the hour-angle term has the opposite sign and effectively cancels the continuous term during each season. Assuming that this explanation is correct, the cancellation must be accidental. That is, the continuous term is proportional to the neighbor brightness and the proper motion, while the differential refraction term depends on the neighbor brightness, color, and position. Hence, for example, if the proper motion had been double, but the other parameters remained the same, the continuous term would double and the in-season slope would be half of the long-term slope, rather than zero.

Because we are less confident of the multiyear stability of KMT photometry, we cannot make such a precise measurement of the intraseason slope for the KMT observatories as for OGLE. However, as mentioned above, what triggered our detailed investigation of the structure of the OGLE baseline light curve was that the intraseason KMT slope is consistent with zero. Therefore, we adopt the following treatment of the data.

#### 1. OGLE

Use only 2016, 2017, 2018 data.

Add  $\Delta F(t) = -0.027[\text{Year} - 2017]$  to each measurement.

## 2. KMT

Use only 2017 data.

Do not modify flux measurements.

Finally, we remove the zero point of the OGLE baseline flux,  $I_{\text{base}} = 16.156$ , and replace it with  $I_{\text{base}} = 20.000$ . This is set somewhat brighter than the best-fit source magnitude  $I_S = 20.4$  to avoid negative total fluxes for measurements with downward statistical fluctuations, which would prohibit display in magnitude-based figures. As emphasized above, the choice of baseline flux has absolutely no effect on the analysis. However, choosing a baseline that is close to the source flux enables clearer simultaneous visualization of the light-curve evolution at all magnifications, which span a factor of order 100.

## Appendix B

### Xallarap Detections of Low-mass Companions to the Source

To date, microlensing experiments have discovered and published of order 200 substellar objects, that is, planets and BDs. While a few of these are isolated BDs (e.g., OGLE-2007-BLG-0224, Gould et al. 2009) or possibly isolated planets (Mróz et al. 2017; Gould et al. 2022b; Koshimoto et al. 2023), the overwhelming majority are companions to stars.

However, shortly after Mao & Paczyński (1991) first proposed lensing systems as a new channel for finding planetary and binary systems, Griest & Hu (1992) suggested that microlensing could also be used to find and characterize binary stars. Griest & Hu (1992) mainly focused on single-lens binary-source (1L2S) events in which the binary source could be approximated as static and thus the companion was detected entirely via its changing magnification during the event. However, in their Figure 12, they already give an example that betrays dramatic dynamical effects, that is, periodic oscillations. They argue that such examples will be very rare, and they acknowledge that they had to adopt extraordinarily improbable parameters to generate the oscillations shown in their figure. Moreover, while they do not say so explicitly, the form of their figure shows that both components of the binary are luminous, indeed of equal brightness.

Han & Gould (1997) considered a range of flux ratios for the two sources and showed (their Figure 3) that the light-curve oscillations would be dramatically larger if the companion were effectively dark (panel (c)) than if the two components were equally luminous (panel (a)). When their Figure 3(c) was shown at a meeting, Chris Stubbs shouted out from the audience “xallarap,” and that name has stuck. Prior to that meeting, this neologism had only been used for the nemesis of the Green Lantern DC Comics character.

Although Han & Gould (1997) had carried out their study with the aim of developing methods to better characterize microlensing events (and so, in particular, the lenses), the main practical impact of microlensing xallarap over the ensuing years was (similar to its DC Comics character namesake) as a nuisance. It was soon realized that any microlensing parallax signal (light-curve oscillations due to Earth’s annual motion; Gould 1992) could be duplicated with infinite precision by xallarap, provided that the source companion had the same period, eccentricity, and phase as Earth and that the inclination of the binary orbit was the same as the ecliptic latitude of the event. Thus, in a large fraction of events in which the microlens

parallax is apparently detected, some effort is made to argue that the alternative xallarap interpretation is unlikely.

The main method for doing this was introduced by Poindexter et al. (2005). If one does a systematic search for xallarap solutions (typically with the eccentricity  $e \equiv 0$  because the data normally do not support higher-order models) and the solution’s three xallarap parameters ( $P$ ,  $\alpha$ ,  $\delta$ ), that is, the period, phase, and inclination, are well localized near those predicted from Earth’s orbit, then it is extremely improbable that the effects are due to xallarap. On the other hand, such xallarap searches do sometimes yield solutions with much better  $\chi^2$  than the parallax solution and with parameters far from those of Earth, for example,  $P = 0.5$  yr. In such cases, the parallax solution is rejected in favor of xallarap.

To understand the challenges of detecting substellar and other low-mass lenses using xallarap, we begin by expressing the binary-source companion-host mass ratio  $Q$  in terms of observables. Combining Kepler’s third Law with Newton’s third Law, we obtain

$$\frac{Q^3}{(1+Q)^2} = Z \equiv \frac{4\pi^2 a_1^3}{GM_S P^2} = \frac{(a_1/\text{au})^3}{(P/\text{yr})^2 (M_S/M_\odot)}, \quad (\text{B1})$$

where  $a_1$  is the semimajor axis of the source orbit about the center of mass,

$$a_1 = \xi \theta_E D_S. \quad (\text{B2})$$

Provided that  $\theta_E$  can be measured and  $D_S$  can be reliably estimated, then  $Z$  is an empirically determined quantity. For the case of substellar companions, that is,  $Q \ll 1$ , the solution to Equation (B1) is very well approximated by

$$Q = Z^{1/3} + \frac{2}{3} Z^{2/3}, \quad (\text{B3})$$

but is adequately approximated for what follows by  $Q \rightarrow Z^{1/3}$ . Further, to avoid clutter in what follows, we simply assume that the source mass and distance are  $M_S = 1 M_\odot$  and  $D_S = 8$  kpc. We also note that an important point of principle is that for  $Z$  to be an “observable,”  $\theta_E$  must be measured, which requires that the lens transit the source, that is,  $\rho \lesssim u_0$ . Because, in almost all cases,  $\theta_{\text{ast}} \ll \theta_E$ , this implies that  $\rho \ll 1$ , and therefore  $u_0 \ll 1$ . Hence, we can assume that the xallarap features will take place at lens-source normalized separations  $u \lesssim 0.5$ , where the magnification scales  $A \simeq u^{-1}$  and hence small displacements  $\eta \ll u$  within the Einstein ring induce magnification changes  $\Delta A \sim \eta A^2$  and thus fractional flux changes of  $\Delta A/A \sim \eta A$ . For definiteness, let us assume that these can be reliably detected and characterized if they are at least  $\epsilon = 3\%$ . As a benchmark, we characterize the requirement of “low-mass companion” as  $Q < 0.08$ . Then, applying the various approximations just described, we infer that to be detectable,  $Q$  is constrained by

$$Q = \frac{\xi \theta_E D_S / \text{au}}{(P/\text{yr})^{2/3}} \gtrsim \frac{8 \epsilon \theta_E / \text{mas}}{A (P/\text{yr})^{2/3}}, \quad (\text{B4})$$

where  $A$  is the magnification at which the xallarap effect is effectively being detected, that is, when the companion is at maximum projected separation, and where we have made use of the identity  $\text{mas} = \text{au}/\text{kpc}$ . This will occur when  $|t - t_0| = P/4$ , that is,  $A = t_E / |t - t_0| = 4t_E/P$ . Noting that



$\mu_{\text{rel}} = \theta_E/t_E = 4\theta_E/PA$ , we obtain

$$Q \gtrsim 0.044 \frac{\epsilon}{3\%} \left[ \frac{1}{A} \left( \frac{\theta_E}{0.1 \text{ mas}} \right) \left( \frac{\mu_{\text{rel}}}{\text{mas yr}^{-1}} \right)^2 \right]^{1/3}. \quad (\text{B5})$$

If we ignore for the moment the factor  $A^{1/3}$ , then Equation (B5) implies that it is difficult to probe into the low-mass regime and extremely difficult to probe the planetary regime (nominally  $Q \lesssim 0.012$ ) regime. This is because events with either  $\theta_E \lesssim 0.1 \text{ mas}$  or  $\mu_{\text{rel}} \lesssim 1 \text{ mas yr}^{-1}$  are each rare, so the combination is very rare. Moreover, only events with  $\theta_E$  measurements can yield  $Q$  determinations, and these require  $u_0 \lesssim \rho$ , which occurs with probability  $p \sim \theta_{\text{ast}}/\theta_E$  or typically  $p \sim 0.6\%(\theta_E/0.1 \text{ mas})$  for dwarf sources and  $p \sim 6\%(\theta_E/0.1 \text{ mas})$  for giant sources. Finally, there must actually be low-mass companions in these relatively short  $P$  orbits.

To understand the potential for enhanced sensitivity from possible high magnification, we restrict consideration to companions that are no closer than three stellar radii on the grounds that nearer ones are likely to be rare, that is,  $A < \theta_E/3\theta_{\text{ast}}$ . We can then rewrite Equation (B5) as

$$Q \gtrsim 0.025 \frac{\epsilon}{3\%} \left[ \frac{\theta_{\text{ast}}}{6 \mu\text{as}} \left( \frac{\mu_{\text{rel}}}{\text{mas yr}^{-1}} \right)^2 \right]^{1/3}, \quad (\text{B6})$$

where we have normalized the source radius to that of a typical first-ascent giant.<sup>22</sup> Thus, under the assumptions of this calculation, giant sources cannot probe the planetary regime at all, while dwarf sources, being about 10 times smaller, could marginally probe it.

Thus, this method would not appear to be a promising one for learning about hot low-mass companions. And these poor prospects may have contributed to the paucity of systematic investigations of the method.

Nevertheless, OGLE-2017-BLG-1777 appears to contain such a low-mass source companion. Adopting (for the moment)  $D_S = 8 \text{ kpc}$  and  $M_S = 1 M_\odot$ , and inserting  $(P, \xi, \rho)$  from Table 9 (and  $\theta_{\text{ast}}$  from Section 4.4) into Equations (B1) and (B2), we obtain

$$Z^{1/3} = 0.0687 \pm 0.0084; \quad Q = 0.0718 \pm 0.0088 \quad (\text{Local 1}) \quad (\text{B7})$$

and

$$Z^{1/3} = 0.0769 \pm 0.0120; \quad Q = 0.0808 \pm 0.0126 \quad (\text{Local 2}) \quad (\text{B8})$$

for the two solutions shown in Table 9. We then reinsert the dependence on  $D_S$  and  $M_S$  to find

$$\begin{aligned} M_{\text{comp}}(\text{Local 1}) &= (0.0718 \pm 0.0084) M_\odot \frac{D_S}{8 \text{ kpc}} \left( \frac{M_S}{M_\odot} \right)^{2/3} \\ M_{\text{comp}}(\text{Local 2}) &= (0.0808 \pm 0.0126) M_\odot \frac{D_S}{8 \text{ kpc}} \left( \frac{M_S}{M_\odot} \right)^{2/3}. \end{aligned} \quad (\text{B9})$$

That is, both solutions indicate source companions that are very close to the star/BD boundary.

The predicted semiamplitude of the RV of the source due

to its companion is -

$v \sin i = 2\pi(a_1/P)\cos(\delta_S)/\sqrt{1-e^2} \rightarrow 2\pi(a_1/P)$ , where we have suppressed the extremely small (and oppositely signed) corrections due to inclination and eccentricity. Explicitly,

$$v \sin i \simeq 2\pi \frac{a_1}{P} = \begin{aligned} &(6.28 \pm 0.77) \text{ km s}^{-1} \frac{D_S}{8 \text{ kpc}}, \quad (\text{Local 1}) \\ &(7.03 \pm 1.10) \text{ km s}^{-1} \frac{D_S}{8 \text{ kpc}}, \quad (\text{Local 2}) \end{aligned} \quad (\text{B10})$$

## Appendix C

### Are the Low Values of $\theta_E$ and $\mu_{\text{rel}}$ for OGLE-2017-BLG-1777 Connected?

Because the detection of VLM stars and substellar objects via xallarap requires a combination of very improbable characteristics, that is, very small  $\theta_E$ , very small  $\mu_{\text{rel}}$ , and  $\rho \lesssim u_0$ , as well as the presence of a close-in VLM star substellar companion to the source, one must be concerned that some rare effect is artificially generating the appearance of one or more of these characteristics. In this Appendix, we investigate the circumstances that could lead to simultaneous underestimates of  $\theta_E$  and  $\mu_{\text{rel}}$ .

We begin by pointing out that the parameter combination  $\theta_E/\mu_{\text{rel}}$  appears to be an ‘‘invariant,’’ that is, it seems to depend only on directly observable characteristics of the light curve. If correct, this would make the identification of such exceptional events relatively immune to misinterpretation in that, even if  $\theta_E$  were systematically underestimated, it would only mean that  $\mu_{\text{rel}}$  was overestimated. The formulation of this invariance will then allow us to explore potential Achilles' heels to this comforting argument and to investigate whether these apply to OGLE-2017-BLG-1777 in particular.

Although it is not essential, we assume that the photometry has been transformed to a calibrated system. This will avoid unnecessary complications, and in any case, it is true of the event under examination. We can then write

$$\theta_E \mu_{\text{rel}} = \left( \frac{\theta_{\text{ast}}}{t_{\text{ast}}} \right)^2 t_E = \frac{f_{0,S} t_E}{\pi S t_{\text{ast}}^2} \simeq 10^{0.4 A_I} \frac{f_S t_E}{\pi S t_{\text{ast}}^2}, \quad (\text{C1})$$

where  $S = f_{0,S}/\pi\theta_{\text{ast}}^2$  is the surface brightness, which depends only on the dereddened source color,  $(V-I)_{0,S} = (V-I)_S - E(V-I)$ . We examine the five parameters  $(A_I, E(V-I), (V-I)_S, f_S t_E, t_{\text{ast}})$  from the standpoint of ‘‘what could go wrong,’’ keeping in mind that pathological cases must be considered.

The extinction  $A_I$  and reddening  $E(V-I)$  are model independent because they are evaluated directly from the red clump position on the CMD, without reference to the microlensing data. In principle, it is possible for this evaluation to fail catastrophically if there is a small dense cloud directly in front of the source, so that its extinction is very different from the clump stars in its neighborhood. This would be extremely rare, but the possibility must be considered when the alternative is an extremely unlikely combination of  $\theta_E$  and  $\mu_{\text{rel}}$ .

The source color  $(V-I)_S$  is model independent because it can be derived from regression of the  $V$ -band flux on the  $I$ -band flux. Hence, one must carefully check whether  $(V-I)_S$  has been properly measured, but this concern is not related to issues of a possibly incorrect model.

<sup>22</sup> Note, however, that clump giants must be excluded because they would have swallowed any such companions prior to the helium flash.



The parameter combination  $f_S t_E$  is an invariant for high-magnification events,  $A_{\max} \gg 1$ . We now show that this is because, like  $(V-I)_S$ , it can be derived from model-independent regression of the data. At intermediate magnification,  $1 \ll A \ll A_{\max}$  (and excluding regions of the light curve that are impacted by short anomalies), we have  $u = \sqrt{u_0^2 + (t - t_0)^2/t_E^2} \rightarrow |t - t_0|/t_E$  and  $A \rightarrow 1/u \rightarrow t_E/|t - t_0|$ . Therefore, the time evolution of the observed flux relative to the baseline flux is  $F(t_i) - f_{\text{base}} = [A(t_i) - 1]f_S \simeq A(t_i)f_S = f_S t_E/|t_i - t_0|$ . Thus, because  $F(t)$ ,  $f_{\text{base}}$ ,  $t_i$ , and  $t_0$  are all direct observables,  $f_S t_E$  is tightly constrained. Stated otherwise,  $f_S t_E$  can essentially be evaluated as a regression of  $F(t_i)$  on  $|t_i - t_0|^{-1}$  at intermediate magnifications. While  $f_S t_E$  is never measured this way, any model that fits the data will obey it. Hence,  $f_S t_E$  is a robust, model-independent invariant.

The source self-crossing time,  $t_{\text{ast}} = \rho t_E$ , is often called an “invariant” because it changes very little as  $t_E$  is held fixed at various different values. That is, within such a restricted class of models, the duration of the “bump,”  $t_{\text{bump}}$ , that is caused by the source transiting a caustic is related to  $t_{\text{ast}}$  by some definite factor  $t_{\text{ast}} = k t_{\text{bump}}$ , which is determined by the overall geometry. Then, because  $t_{\text{bump}}$  is given directly by the data,  $t_{\text{ast}}$  is invariant. However, the factor  $k$  can be different from one class of models to another. For example, if the form of the bump is that of a generic caustic crossing (e.g., Figure 1 from Gould & Andronov 1999), then  $k = (\sin \psi)/2$ , where  $\psi$  is the angle of the source trajectory relative to the caustic. If the event has been modeled with a source trajectory of  $\psi = 90^\circ$ , but the true caustic crossing has  $\psi = 10^\circ$ , that is, the long duration of  $t_{\text{bump}}$  has been attributed to a slow source rather than an acute crossing, then  $t_{\text{ast}}$  would be overestimated by a factor  $\sin(90^\circ)/\sin(10^\circ) = 5.8$ .

We now examine how well each of these factors is constrained for the case of OGLE-2017-BLG-1777. The absolute and relative extinction,  $A_I$  and  $E(V-I)$ , are not major concerns. If there were a small dust cloud in front of the source, then it would be intrinsically bluer than we have inferred. However, it is already near the limit of the observed color range for bulge dwarfs. Moreover, unless this cloud had very unusual properties, the net effect of making the source brighter and bluer would be to reduce  $\theta_{\text{ast}}$ , relative to our estimate, which is the opposite of what would be needed to explain the small value of  $\theta_E \mu_{\text{rel}}$ . In principle, there could be a hole in the dust, but this is extraordinarily unlikely because it would require a strongly correlated behavior among physically independent dust clouds along the line of sight.

The  $(V-I)_S$  source color is measured from two different sites, each to good statistical precision based on several magnified V-band points and in good agreement with each other.

The argument for the invariance of  $f_S t_E$  could in principle be undermined for cases of strong parallax because the approximation  $A \rightarrow 1/u \rightarrow t_E/|t - t_0|$  would no longer be strictly valid. See, for example, Smith et al. (2003). Nevertheless, we note that for the collection of very different physical models in Tables 8 and 9, some with and some without parallax, we have  $f_S t_E = (6.99, 6.78, 7.19, 7.48)$  days, where we have expressed the source flux  $f_S$  on an  $I = 18$  scale. The full range of this variation is only  $\sim 10\%$ , despite the large parallax of one solution.

Hence, the major potential issue is  $t_{\text{ast}}$ , for which the concern is heightened by the fact that the light curve does not exhibit either of the two classical forms, that is, those associated with fold caustics (e.g., Figure 1 from Gould & Andronov 1999) or with point caustics (e.g., Figure 1 from Gould et al. 2009). Hence, one should first be concerned that finite-source effects are detected at all. One piece of evidence that they are is that  $\rho$  is measured to  $\lesssim 10\%$  in all the models. We further explored the possibility that the  $\rho$  measurements were spurious by fitting to  $\rho = 0$  models. However, these models completely failed to match the observed light curve near the peak.

An additional concern for xallarap models is that the directly observable duration of the finite-source effects can be affected by internal motion of the source relative to its center of mass. In the present case, we also have, for the final model, orbital motion of the lens, which can also produce this effect. As an overall check we can compare the  $t_{\text{ast}}$  values for the various models, which are shown in Tables 8 and 9. Indeed, we find a full range of variation of about a factor 1.6. The largest difference is between models that include or exclude xallarap, showing that internal motion can be a big effect. There is also a factor 1.4 difference between 2LIS and 1LIS models that both allow for xallarap. Hence, the difference largely stems from the “cusp entrance” form of the first versus the “point caustic” form of the second.

Thus, as expected, among the five factors, the one that deviates most from invariance is  $t_{\text{ast}}$ . Nevertheless, its range of variation, allowing for very different physical models, is still modest compared with the extreme values of  $\theta_{\text{ast}}$  and  $\mu_{\text{rel}}$ .

We conclude that these extreme values are unlikely to have been generated by problems in the modeling.

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