

**The First Circumbinary Planet Found by Microlensing:
OGLE-2007-BLG-349L(AB)b**

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ABSTRACT

We present the analysis of the first microlensing event, OGLE-2007-BLG-349, to reveal a circumbinary planet. This high magnification event has a strong planetary signal that is best fit with a mass ratio of $q \approx 3.4 \times 10^{-4}$, but the data deviate significantly from this best fit binary lens model. So, we have searched for models with an additional lens mass, either another planet or another star. We find acceptable light curve fits with two classes of models: 2-planet models and circumbinary planet models, both which explain the deviation from the best binary lens model almost equally well. The light curve also reveals a significant microlensing parallax effect, which constraints the mass of the lens system to be $M_L \approx 0.7M_\odot$. We also have Hubble Space Telescope (HST) images that resolve the lens and source stars from their neighbors. These images clearly indicate the changing magnification of the source and excess flux superimposed on the position of the source. This excess flux is consistent with the predicted flux from the circumbinary models, where the lens mass is shared between two stars, but there is not enough flux to be consistent with the 2-planet models, where the lens mass is due to a single host star. So, only the circumbinary models are consistent with the HST data. The ratio of the planet:center-of-mass separation to the separations of the two stars is $\gtrsim 30$, so unlike most of the circumbinary planets found by Kepler, the planet does not orbit near the stability limit.

Subject headings: gravitational lensing: micro, planetary systems

1. Introduction

One of the main features of the observational study of extrasolar planets has been the continuing stream of surprise observational discoveries. These include planets orbiting a pulsar (Wolszczan & Frail 1992), hot jupiters (Mayor & Queloz 1995), systems of short period, low-density planets in tightly packed orbits (Lissauer 2011), and circumbinary planets (Doyle et al. 2011) close to the stability limit. Circumbinary planets and planets in close binary systems are very difficult to detect with the radial velocity method, but Kepler has proved quite adept at finding such systems (Doyle et al. 2011; Welsh et al. 2012, 2015; Orosz et al. 2012; Kostov et al. 2013, 2014, 2015). Gravitational microlensing has demonstrated the ability to detect such systems (Bennett et al. 1999; Gould et al. 2014; Poleski et al. 2014; Udalski et al. 2015) (either circumbinary planets or planets orbiting one

member of a relatively close binary). Two of these claimed microlensing planets in binary systems have turned out to be incorrect, MACHO-97-BLG-41 (Bennett et al. 1999; Albrow et al. 2000; Jung et al. 2013) and OGLE-2013-BLG-0723 (Udalski et al. 2015; Han et al. 2016), but this is largely an issue that can be addressed by greater care in event modeling. These events still help to establish the sensitivity of the microlensing method to planets in close binary systems, because in each case, the light curve measurements do definitively distinguish between the triple-lens, planetary models, and the close binary models without a planet.

In this paper, we present the first circumbinary planet found by microlensing, OGLE-2007-BLG-349Lc. The signal for this event is dominated by the microlensing effect of a Saturn mass ratio planet, but the very central part of the planetary binary lens light curve does not fit the data. As we show in Section 3, the light curve can be fit by models with an additional lens mass, either another planet or another star. However, the light curve data does not tell us which of these models is correct. Nevertheless, the light curve does reveal finite source effects and a microlensing parallax signal that allow us to determine the lens system mass, as we discuss in Section 4.

In Section 4.2, we present Hubble Space Telescope (HST) observations of the OGLE-2007-BLG-349 lens system and source star. These observations clearly indicate excess flux at the position of the source, which is consistent with the circumbinary models but not the two-planet models. If the stellar mass of the lens system is divided into two masses, then it is substantially fainter (~ 1.6 mag) in the I -band than a single host star would be. And it is only such a faint lens system that is consistent with the HST images, and so it is the HST observations that select the circumbinary model over the two-planet models. In Section 4.3, we add the lens brightness constraint to our light curve modeling in order to confirm this conclusion, and we find that two-planet models with an extremely faint host star (presumably a white dwarf) do better than the best two-planet models with a main sequence host star. But, these models are still substantially worse than the circumbinary models, so they are excluded.

We consider adaptive optics observations of the source and lens stars in Section 5, and we find that these observations provide modest support for the circumbinary interpretation of this light curve. Finally, in Section 6, we discuss the implications of this discovery for our understanding of the properties of exoplanets.

2. Light Curve Data and Photometry

Microlensing event OGLE-2007-BLG-349, at RA = 18:05:24.43, DEC = $-26:25:19.0$, and Galactic coordinates $(l, b) = (4.3802, -2.5161)$, was identified as a microlensing candidate by the Optical Gravitational Lensing Experiment (OGLE) Collaboration Early Warning System (EWS) (Udalski et al. 1994) and announced on 2007 July 2. Later that month, the event was independently identified and announced by the MOA Collaboration as MOA-2007-BLG-379. In mid-to-late August, this event was recognized as a potential high magnification event, with high sensitivity to

planets, by the μ FUN, Robonet and the PLANET microlensing follow-up groups, so they started observations prior to peak magnification. On 2007 Sep 4, the planetary anomaly was first identified in the OGLE data by the μ FUN and OGLE groups at $\text{HJD}' = \text{HJD} - 2450000 = 4348.5$. Despite the fact that this event occurred near the end of the Galactic bulge observing season, the combined data of the OGLE and MOA survey groups and the μ FUN, Robonet, and PLANET microlensing follow-up groups, we achieved nearly complete coverage of the light curve peak, with the largest data gap of only 55 minutes.

The data set we use in this analysis consists of microlensing survey data from the OGLE 1.3m telescope in Chile in the I -band and the MOA 1.8m telescope in New Zealand in the custom MOA- R -band, which is equivalent to the sum of the Cousins $R+I$ -bands, as well data from 6 telescopes operated by microlensing follow-up groups. Four of these telescopes are operated by the Microlensing Follow-up Network (μ FUN). μ FUN provided V , I , and H -band data from the 1.3m SMARTS telescope at CTIO in Chile, I -band data from the 1.5m Palomar telescope in California, and unfiltered data from the 0.35m Bronberg Observatory telescope in South Africa and the 0.4m Vintage Lane Observatory (VLO) telescope in New Zealand. The RoboNet Collaboration has provided R -band data from the 2m Faulkes North Telescope (FTN), and the Probing Lensing Anomalies NETwork (PLANET) collaboration provided I -band data from the 1.0m Canopus Observatory telescope. We exclude from the analysis data from several μ FUN observatories that were unable to obtain data near the light curve peak.

The data were reduced with various implementations of the difference imaging method (Tomaney & Crotts 1996). The MOA and OGLE data were reduced with their respective pipelines (Bond et al. 2001; Udalski 2003). The PLANET data was reduced with a version of ISIS (Alard & Lupton 1998), and the RoboNet data was reduced with the RoboNet pipeline (Bramich 2008). Most of the μ FUN data was reduced with the OGLE pipeline, but the CTIO H -band data was reduced with PySIS (Albrow et al. 2009).

We follow the usual method (Yee et al. 2012) to improve the photometric error bars with the following formula

$$\sigma = K \sqrt{\sigma_0^2 + \sigma_{\min}^2}, \quad (1)$$

where σ_0 is the error bar estimate provided by the photometry code. The error bar correction parameters K and σ_{\min} for each data set are listed in Table 1. These error bar modifications are made based on an approximately correct reference model to give $\chi^2/\text{d.o.f} = 1$ for each data set. The corrected error bars are normally then used to make more accurate estimates for the uncertainties in the physical parameters of the lens system, and the selection of the correct model does not depend on the error bar corrections. In this case, however, there are competing models, so one might be concerned that the final conclusions could be dependent on which model light curve is used to determine the error bar modification parameters. Fortunately, in this case, the competing two-planet and circumbinary light curves are so similar that the choice of the reference model does not have a significant effect on the choice between models.

3. Light Curve Models

The preliminary modeling of this event was done independently using the methods of Dong et al. (2006, 2009b) and Bennett (2010) to first search for the parameters of the planet that dominates the anomaly signal. This light curve is strongly dominated by the signal of a Saturn mass-ratio planet with parameters quite similar to the model circulated by one of us (DPB) within 24 hours of the first detection of the planetary anomaly. (The basic geometry of the event was identified even earlier by two of us: AC and NJR.)

The best fit binary lens (star+planet) model is shown in Figure 1, and the parameters of this model are given in Table 2, including a significant microlensing parallax signal. (We use polar coordinates for the microlensing parallax vector, such that $\pi_{E,N} = \pi_E \cos \phi_E$ and $\pi_{E,E} = \pi_E \sin \phi_E$.) This model provides a good fit to most of the light curve peak, but it does not fit the central part of the light curve at $48.65 \lesssim \text{HJD} - 2454300 \lesssim 48.82$, or $t \approx t_0$. This is the part of the light curve where we would expect to see the signal of another lens mass: a second planet or a stellar binary companion to the host star. So, we performed another initial condition grid search to explore possible triple-lens models. We fixed the parameters describing the best fit planetary binary model, and did the grid search over the parameters that describe the additional mass. There are two parameters describing the position of the third mass and one parameter describing its mass fraction. Using both methods, we search for three categories of solutions: 2-planet models, models with the planet orbiting one member of a wide stellar binary, and models with a close stellar binary orbited by a circumbinary planet. Our initial triple lens fits were done with static models, but the period of the

Table 1. Error Bar Modification Parameters

Data Set	K	σ_{\min}
OGLE- <i>I</i>	0.979	0.006
MOA-(<i>R+I</i>)	0.932	0.007
CTIO- <i>I</i>	1.500	0.003
CTIO- <i>H</i>	2.142	0.003
FTN- <i>R</i>	2.598	0.003
Palomar- <i>I</i>	1.605	0.004
Canopus- <i>I</i>	0.974	0.002
Bronberg- <i>Un</i>	1.048	0.012
VLO- <i>Un</i>	1.312	0.008

Note. — Passband *Un* refers to unfiltered imaging.

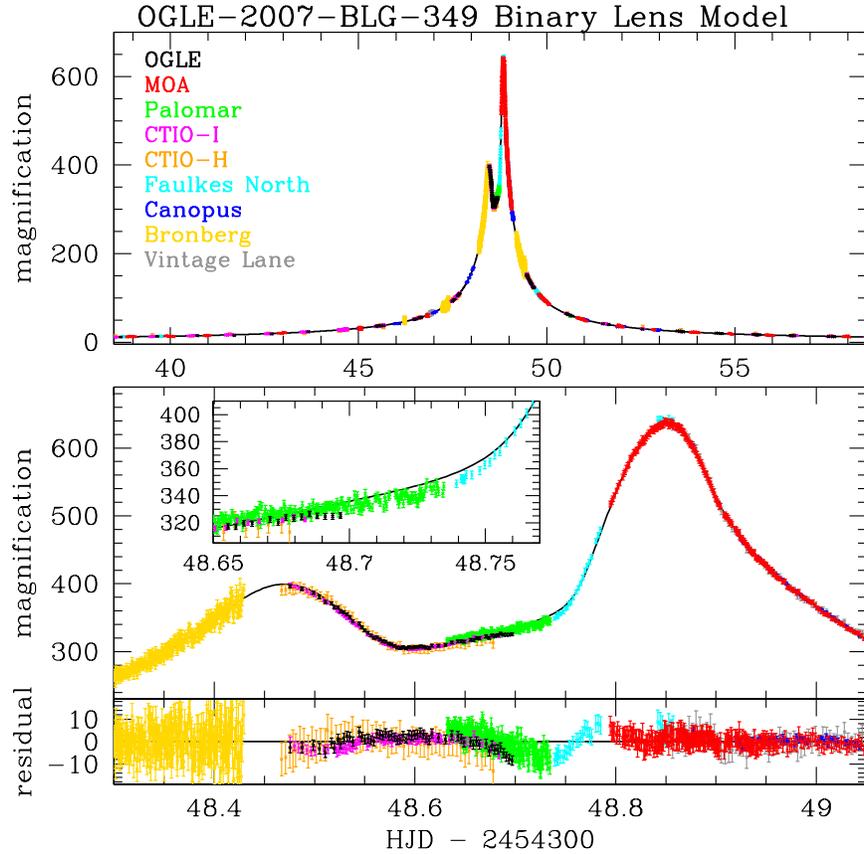


Fig. 1.— Best fit single planet light curve. Top panel shows the 20 days centered on the light curve peak, and the middle and bottom panels show the light curves and the residuals for the central day of the light curve. The single planet model matches all the major light curve features, but there are significant residuals at $48.65 \lesssim \text{HJD} - 2454300 \lesssim 48.82$. This is quite close to the t_0 value of the fit, which is the time when a light curve feature due to an additional mass would be expected.

Table 2. Best Fit Nonlinear Model Parameters

parameter	units	1-planet	2-planet	circumbinary
t_E	days	116.703	113.520	117.720
t_0	HJD'	4348.7534	4348.7469	4348.7465
u_0		-0.0021516	0.0020581	-0.0019818
$d_{1\text{cm}}$		1.25268	0.79607	0.81468
d_{23}		-	0.95046	0.019905
$\theta_{1\text{cm}}$	radians	4.40140	1.89437	4.35940
ϕ_{23}	radians	-	-3.07611	0.36989
ϵ_1	10^{-4}	3.7794	3.7669	3.4099
ϵ_2		0.999622	8.5025×10^{-6}	0.46479
ϵ_3		-	0.999615	0.53487
t_*	days	0.06614	0.06930	0.07064
\dot{d}_{23x}	days $^{-1}$	-	0.0	0.010478
\dot{d}_{23y}	days $^{-1}$	-	0.0	-0.006360
$1/T_{\text{orb}}$	days $^{-1}$	-	0.0	0.059380
π_E		0.09693	0.19070	0.17458
ϕ_E	radians	1.69255	2.50170	0.62638
θ_E	mas	1.1828	1.1158	1.1138
M_L	M_\odot	1.4984	0.7185	0.7835
I_S	mag	-	20.325	20.378
I_L	mag	-	19.634	21.465
$I_{SL}(t_{H2})$	mag	-	19.162	20.009
V_S	mag	-	22.334	22.375
H_S	mag	-	18.226	18.267
fit χ^2		4237.56	3382.64	3382.25
dof		3571	3568	3566

Note. — HJD' = HJD – 2,450,000. The reference time for the microlensing parallax and orbital motion parameters is $t_{\text{fix}} = 4349$.

stellar binaries for the circumbinary planet models will only be ~ 10 days. Since the duration of the light curve peak is ~ 0.5 days, binary orbital motion is likely to be important for these circumbinary models. So, after finding the best fit static circumbinary models, we include orbital motion of the two stars for these models.

All three categories of models that we explore can provide a substantial improvement to the light curve over the single planet model, but only the 2-planet and circumbinary models (with orbital motion) can provide a good fit to the light curve data. The best fit 2-planet and circumbinary model parameters are given in Table 2, and the best fit light curves are shown in Figure 2. The parameters we use are the same as used in the analysis of the first triple lens microlensing event, the two-planet event, OGLE-2006-BLG-109 (Gaudi et al. 2008; Bennett et al. 2010). The coordinates are based on the center-of-mass system, with a system of total mass M . The length parameters are normalized by the Einstein radius of this total system mass, $R_E = \sqrt{(4GM/c^2)D_S x(1-x)}$, where $x = D_L/D_S$ and D_L and D_S are the lens and source distances, respectively. (G and c are the Gravitational constant and speed of light, as usual.) t_E is the Einstein radius crossing time, while t_0 and u_0 are the time and separation of closest approach of the source to the center-of-mass. The separation between mass-1 and the center-of-mass of masses 2 and 3 is given by $d_{1\text{cm}}$, and d_{23} is the distance between masses 2 and 3. The lens axis is defined as the vector between mass 1 and the mass 2+3 center-of-mass. and $\theta_{1\text{cm}}$ is the angle between the source trajectory and the lens axis, while ϕ_{23} is the angle between the line connecting masses 2 and 3 and the lens axis. The mass fractions of each of the 3 masses are ϵ_1 , ϵ_2 , and ϵ_3 , but these parameters are not independent

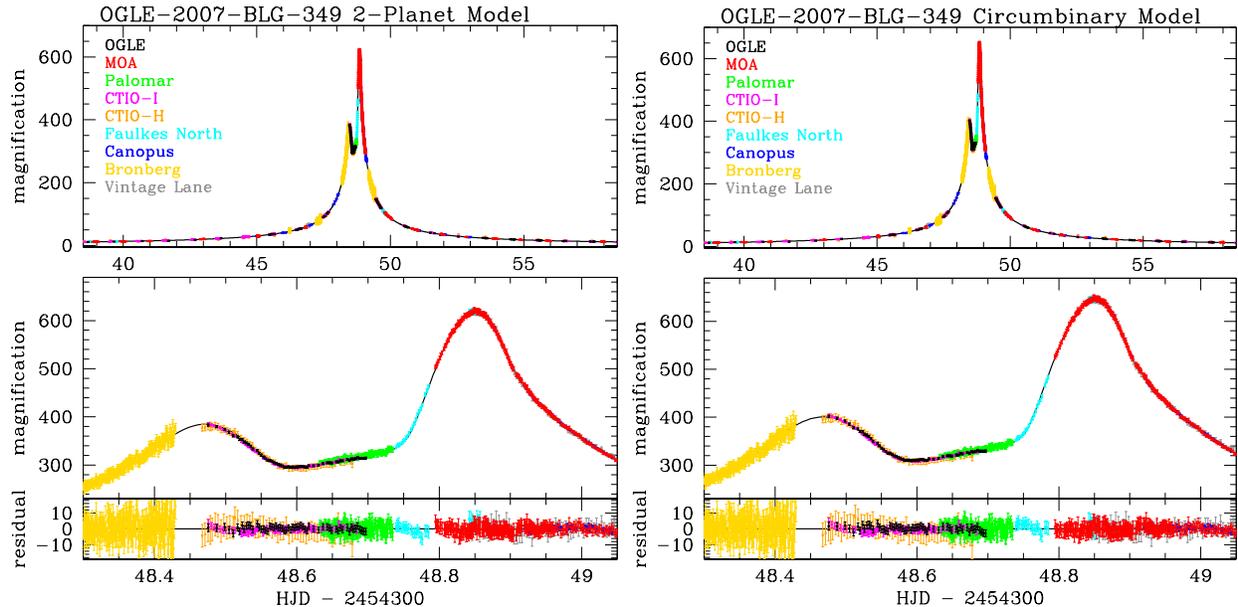


Fig. 2.— Best fit 2-planet (left) and circumbinary (right) light curves with the parameters given in Table 2. Both models fit the light curve almost equally well.

since $\epsilon_1 + \epsilon_2 + \epsilon_3 \equiv 1$. The source radius crossing time is given by t_* . Microlensing parallax is described by π_E and ϕ_E , as described above. The orbital motion of masses 2 and 3 is described by three parameters. The instantaneous velocity along the lens axes is given by \dot{d}_{23x} , while \dot{d}_{23y} gives the velocity perpendicular to the lens axis. (This lens axis is defined to be the line between mass-1 and the center-of-mass of the mass-2 plus mass-3 system.) The orbits are constrained to be circular with a period of T_{orb} , and we use $1/T_{\text{orb}}$ as a fit parameter.

As can be seen from Table 2 and Figure 2, the light curve data do not distinguish between the best 2-planet and models. The χ^2 values for the two models are nearly identical, with the best circumbinary model favored over the best 2-planet model by $\Delta\chi^2 = 0.39$, but the 2-planet model has two fewer degrees of freedom, because of the 3 additional orbital parameters and one constraint to be explained below in Section 4.

Both the 2-planet and circumbinary models appear to fit the light curve data equally well, but there are subtle differences that are apparent in the residuals plotted in the bottom panel of each light curve figure. These residual panels also reveal low-level systematic discrepancies between the different data sets.

Figure 3 shows close-ups of the caustic configuration for the three best-fit models with the source trajectories given by the grey lines. The orbital motion of the two stars causes the caustics to move for the circumbinary model. They are displayed at 4.8 hour intervals starting at

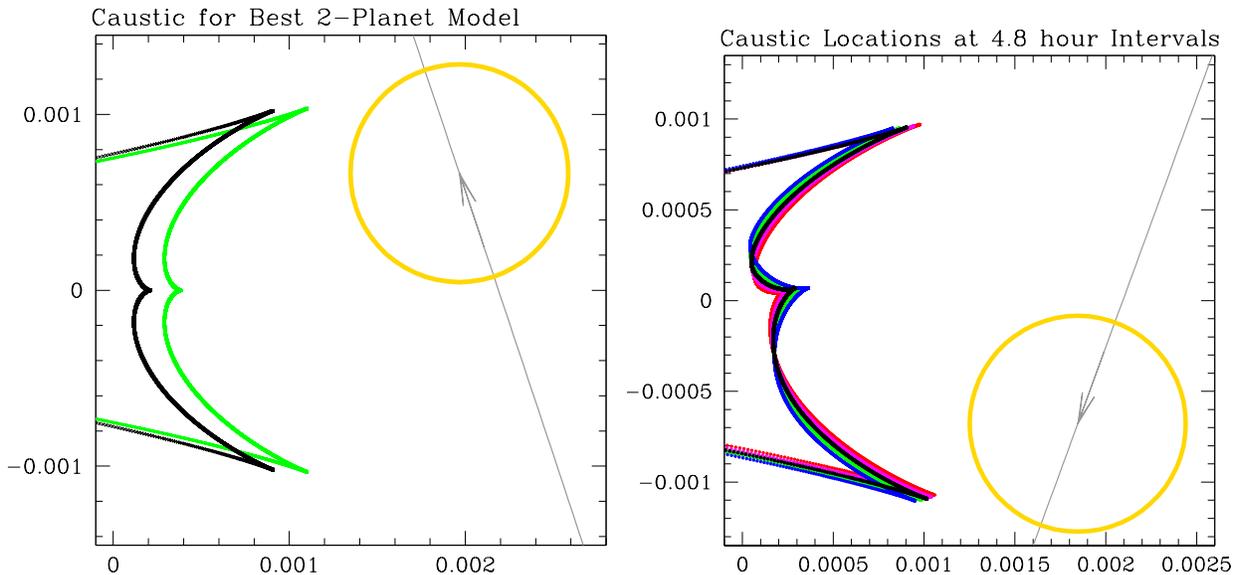


Fig. 3.— OGLE-2007-BLG-349 caustics for the best 1-planet model (in green) and the best 2-planet model (in black) on the left and for the best fit circumbinary planet model at 4.8 hr intervals on the right. The gold circle indicates the source size, and the grey line indicates the source trajectory with an arrow indicating the source position at $t = t_0$ and direction of motion.

$t = 4348.25$ in units of $\text{HJD}' = \text{HJD} - 2450000$. The sequence of caustic curves is red, magenta, black, cyan and blue.

3.1. Microlensing Parallax

An important feature of the OGLE-2007-BLG-349 light curve is the microlensing parallax signal. We find that the microlensing parallax effect improves the χ^2 by $\Delta\chi^2 = 152.8$ as indicated in Figures 4. The parallax signal is quite clear in the second and third panels of this figure. Figure 5 shows the cumulative difference between the best fit parallax and non-parallax models. This indicates that the parallax signal is centered between the time of the peak and the time of the maximum acceleration of Earth (by the Sun) in the directions perpendicular to the line-of-sight, as

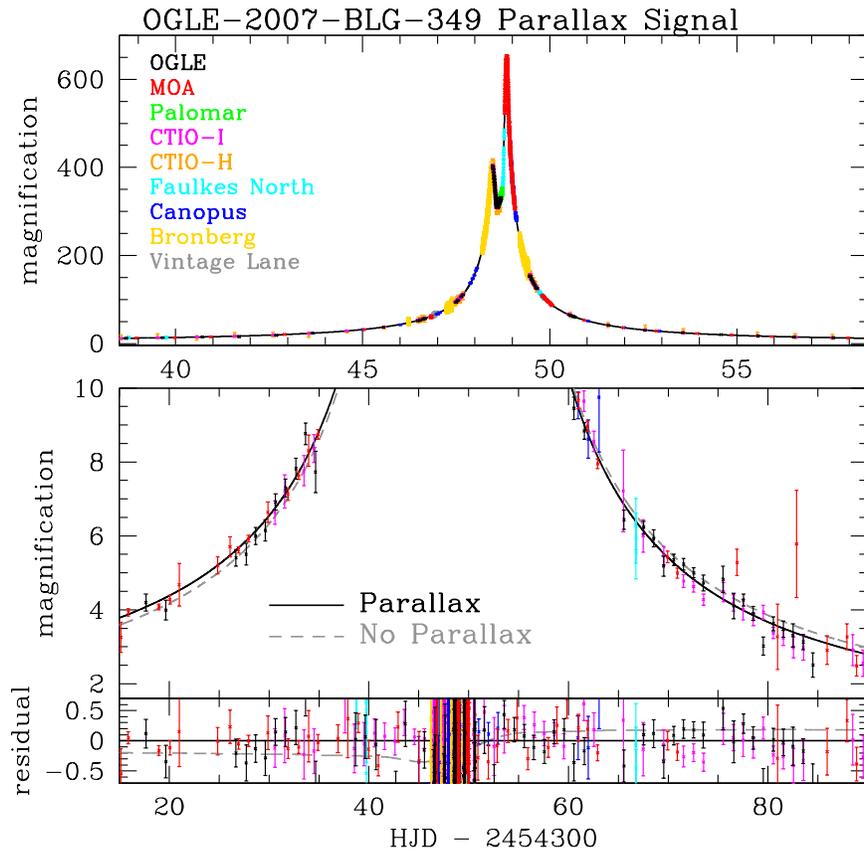


Fig. 4.— Comparison of the best two-planet microlensing model with and without microlensing parallax plotted as solid black and dashed grey curves, respectively. Much of the parallax signal comes in the moderate magnification wings of the light curve. From the bottom panel, we can see the data are well above the no-parallax light curve prior to the peak and below the no-parallax light curve after the peak.

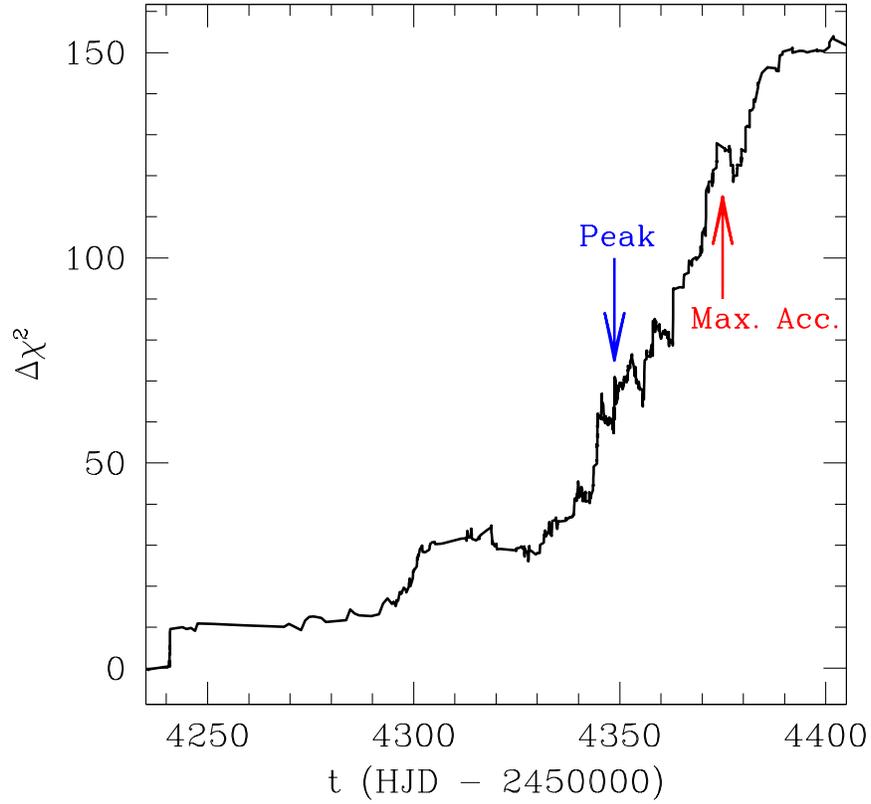


Fig. 5.— The difference in the cumulative $\Delta\chi^2$ between the best fit non-parallax and parallax circumbinary models as a function of time, with the final $\Delta\chi^2 = 152.8$ for the full light curve. This indicates that the signal is centered between the light curve peak and the time of maximum acceleration of Earth in the direction perpendicular to the line-of-sight. This exactly where we expect the signal to be strongest.

expected for a real microlensing parallax signal.

There are two contributions to the microlensing parallax signal: orbital parallax due to the Earth’s orbital motion around the Sun (Gould 1992; Alcock et al. 1995) and terrestrial parallax (Gould et al. 2009), due to observations from telescopes at different locations on the Earth. The measurement of orbital parallax is fairly common, particularly for events like OGLE-2007-BLG-349 with durations $t_E > 100$ days that occur near the beginning or end of the Galactic bulge observing season, when the acceleration of Earth was nearly perpendicular to the line-of-sight. (OGLE-2007-BLG-349 reached peak magnification on 2007 September 5, just about 3 weeks before the acceleration of Earth is perpendicular to the line-of-sight. The orbital parallax signal is much stronger than the terrestrial parallax signal, and is dominated by the three data sets which observed the event at modest magnification, MOA, OGLE, and μ FUN-CTIO, with $\Delta\chi^2$ values of 46.6, 46.0, and 54.1, respectively. Since the acceleration of Earth is almost entirely in the East-West direction, the East component of the orbital parallax solution is much more strongly constrained than the North component.

Terrestrial parallax is normally quite difficult to measure because the Einstein radius projected to the position of the solar system, \tilde{r}_E , is usually a few AU or more, which is a few $\times 100,000$ larger than the separation of telescopes on the ground. For ultra-high magnification events with a relatively large π_E value, like OGLE-2007-BLG-224 (Gould et al. 2009), with a peak magnification of $A_{\max} > 2000$, the signal can become quite strong. For events like OGLE-2007-BLG-349, presented in this paper, the terrestrial parallax signal is detectable, but relatively weak. However, terrestrial parallax does not have the strong East-West bias that orbital parallax has. With data at or near the light curve peak from Northern Hemisphere telescopes, like the Faulkes North Telescope (FNT) in Hawaii, along with Southern Hemisphere telescopes, like the MOA telescope in New Zealand and the CTIO and OGLE telescopes in Chile, we have some leverage on the North-South component of terrestrial parallax. So, the terrestrial parallax helps to constrain the North component of π_E , which is weakly constrained by orbital parallax.

High magnification events usually have several degeneracies. There is a degeneracy between close and wide solutions with $d_{1\text{cm}} \simeq 0.81$ and $d_{1\text{cm}} \simeq 1.23$, respectively. There is also a degeneracy between $u_0 > 0$ and $u_0 < 0$ solutions that would be exact if there was no microlensing parallax (representing the two reflections of the lens plane with respect to the projected orbit of Earth). In this case, the $u_0 > 0$ are excluded by the terrestrial parallax signal. The best $u_0 > 0$ and $u_0 < 0$ solutions have nearly identical χ^2 values when terrestrial parallax is excluded from the modeling, but the $u_0 > 0$ models are disfavored by $\Delta\chi^2 = 28$ when we include terrestrial parallax. This difference in χ^2 comes from the FNT, CTIO, MOA and OGLE telescopes. We will explore these alternative models in more detail after applying the Hubble Space Telescope constraints on the lens system brightness.

4. Lens System Properties

For events with measurable of the microlensing parallax signals, it is possible to determine the lens system mass if the angular Einstein radius, θ_E , can also be determined (Gould 1992; An et al. 2002),

$$M_L = \frac{\theta_E c^2 \text{AU}}{4G\pi_E} = \frac{\theta_E}{(8.1439 \text{ mas})\pi_E} M_\odot . \quad (2)$$

Thus, we require the determination of the angular Einstein radius in order to determine the lens system mass. Fortunately, the sharp planetary light curve features enable a precise measurement of the source radius crossing time, t_* , and this provides a determination of the angular Einstein radius, $\theta_E = \theta_* t_E / t_*$, if we know the angular radius of the source star, θ_* , which can be determined from the dereddened source magnitude and color (Kervella et al. 2004; Boyajian et al. 2014; Adams et al. 2016) We determine θ_* in Section 4.1. The lens system distance can also be determined from π_E and θ_E ,

$$D_L = \frac{1}{\pi_E \theta_E + \pi_S} , \quad (3)$$

assuming that the distance to the source, $D_S = 1/\pi_S$ (and its parallax, π_S) is known.

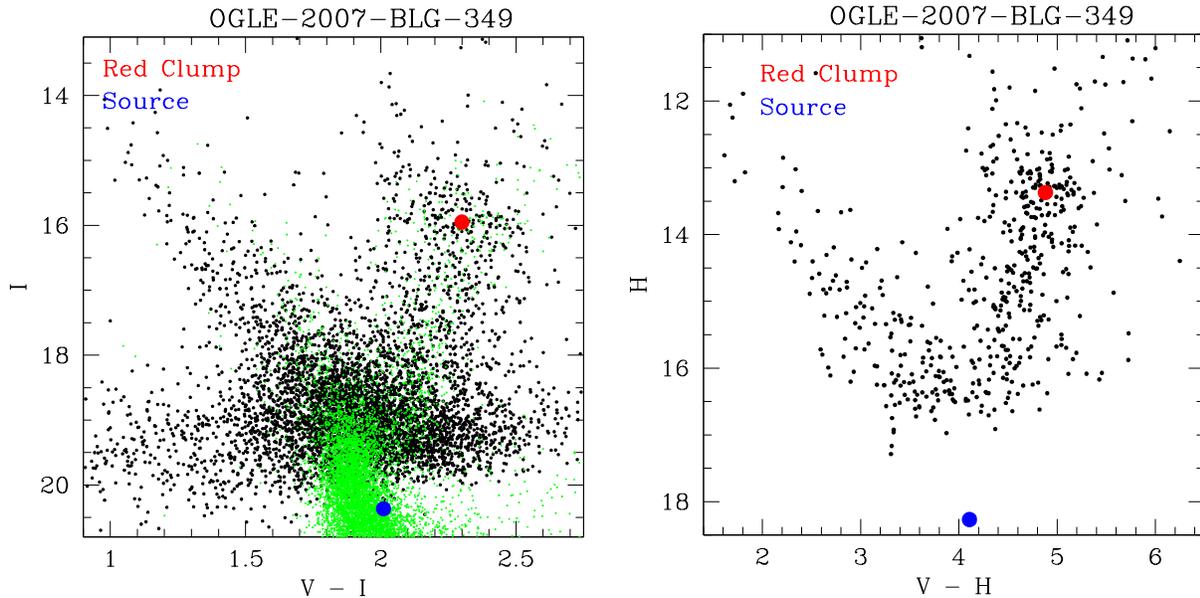


Fig. 6.— The $(V - I, I)$ and $(V - H), H$ color magnitude diagrams (CMD) of the stars in the OGLE-III catalog (Szymański et al. 2011) within $90''$ of OGLE-2007-BLG-349. The green points are the Baade’s Window CMD from Holtzman et al. (1998) shifted to the same extinction as the OGLE-2007-BLG-349 field. The H -band magnitudes shown in the right panel come from IRSF images that have been calibrated to 2MASS. The red spots indicate the red clump giant centroid, and the blue spots indicates the source magnitudes and colors.

4.1. Calibration and Source Radius

Figure 6 shows color magnitude diagrams (CMD) of stars within $90''$ of the OGLE-2007-BLG-349 microlensing event. The V and I magnitudes come from the OGLE-III photometry catalog (Szymański et al. 2011), and the H -band magnitudes come from images from the IRSF telescope that have been calibrated to the 2MASS catalog (Carpenter 2001). The stars identified in these IRSF images have been cross-matched to the OGLE-III catalog, but not every star gives a good match. The IRSF images were taken in worse seeing than the OGLE-III catalog images, so some of the matches between the VI and H -band photometry have uncertainties due to blending where stars resolved in the OGLE images appear likely to be blended in the IRSF photometry. We do not include these stars in our $(V - H), H$ CMD, so the number of stars included in this CMD is smaller than in the $(V - I, I)$ CMD.

These CMDs allow us to estimate the extinction toward the field centered on the source star location. From these CMDs (and the $(I - H), H$ CMD, which is not shown), we identify the centroid of the red clump giant distribution at $I_{\text{rc}} = 15.95 \pm 0.10$, $(V_{\text{rc}} - I_{\text{rc}}) = 2.30 \pm 0.05$, $(V_{\text{rc}} - H_{\text{rc}}) = 4.88 \pm 0.15$ and $(I_{\text{rc}} - H_{\text{rc}}) = 2.58 \pm 0.10$. Comparison to the assumed intrinsic (dereddened) properties of red clump giant stars (Bennett et al. 2010; Nataf et al. 2013), $M_{I_{\text{rc}}} = -0.13 \pm 0.10$, $(V - I)_{\text{rc}0} = 1.06 \pm 0.05$, $(V - H)_{\text{rc}0} = 2.23 \pm 0.07$, and $(I - H)_{\text{rc}0} = 1.17 \pm 0.07$. Fitting these constraints to the Cardelli et al. (1989) extinction law gives $R_v = 3.033$, $A_H = 0.541$, $A_I = 1.818$, and $A_V = 3.083$.

The V and I source magnitudes were determined by calibrating the CTIO- V , and I light curves to the OGLE-III catalog (Szymański et al. 2011) and H source magnitudes were determined by calibrating to the 2MASS-calibrated IRSF photometry. The V and I calibrations were done using DoPHOT (Schechter, Mateo, & Saha 1993) light curves in order to put them on the same photometric scale as the CTIO CMD that was matched to the OGLE-III CMD shown in Figure 6, while the CTIO H -band calibrations were done with a SoDoPHOT reduction (Bennett et al. 1993) for the same reason. (Note that the OGLE-III light curve photometry is not on the same scale as the OGLE-III catalog, and an OGLE CMD on the same scale as the OGLE-III light curve data was not available.) The calibrated source magnitudes, V_S , I_S , and H_S , for the best unconstrained models are displayed in Table 2.

With calibrated source magnitudes and an estimate of the extinction, we are now nearly ready to determine the angular source radius, using an color-angular-size relation such as that of Kervella et al. (2004) or Boyajian et al. (2014), but in fact, we have more information about the source star. Cohen et al. (2008) took advantage of the extremely high magnification of this event to obtain a high resolution spectrum of the source star, when it was magnified by a factor of ~ 400 . This allows the metallicity of the source star to be determined, and we use the determination by Bensby et al. (2013), who find $[\text{Fe}/\text{H}] = +0.42 \pm 0.26$. This high metallicity is consistent with the CMD location of the source on the red edge of the bulge main sequence (see Figure 6). Since metallicity is known to perturb the color-angular-size relations, we asked the authors of Boyajian et al. (2014) to derive

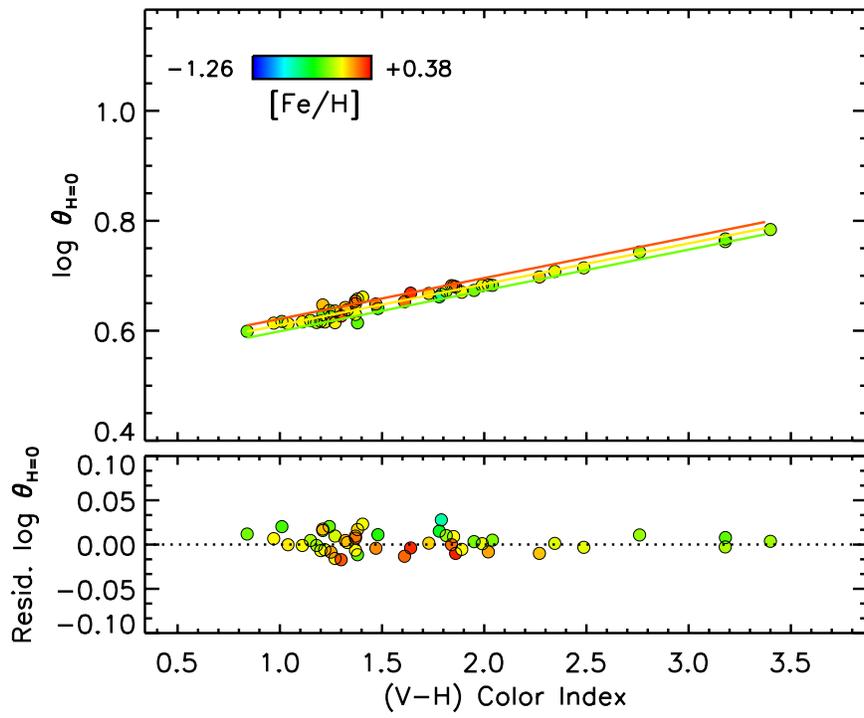


Fig. 7.— The $V - H$, H angular source size relation from the analysis of Boyajian et al. (2014), including the effect of metallicity

a relation using the dereddened H and V magnitudes including the effect of metallicity. The result is shown in Figure 7, which shows the data and following fit to the data.

$$\log_{10}(2\theta_*/\text{mas}) = 0.53598 + 0.07427(V_{S0} - H_{S0}) + 0.04511[\text{Fe}/\text{H}] - 0.2H_{S0} . \quad (4)$$

as shown in Figure 7. The subscripts $S0$ indicate extinction-corrected source magnitudes. If we assume a 1.5% uncertainty in the model, 2.7% uncertainty from the $[\text{Fe}/\text{H}]$ error bar, 0.1 mag uncertainty in $(V_{S0} - H_{S0})$ and 0.02 mag calibration uncertainty for H_{S0} , then we find a 3.6% uncertainty for this relation. (Note that this does not include the light curve model uncertainty in H_{S0} , which will be handle by a different part of our analysis.)

Now that we have a formula for the angular source radius, θ_* , we can determine that angular Einstein radius, $\theta_E = \theta_* t_E / t_*$ for each light curve model. This allows us to determine the lens mass, using equation 2. The lens distance can also be determined using Equation 3, provided that the source distance, D_S , is known.

Table 2 gives the masses corresponding to the best fit 2-planet and circumbinary models, which are $M_L = 0.7185M_\odot$ and $0.7835M_\odot$, respectively, from equation 2. If we assume a source distance of 8 kpc, equation 3 indicates lens system distances of $D_L = 2.96$ kpc and 3.13 kpc, respectively.

4.2. Hubble Space Telescope Images

Shortly after the planetary signal was discovered in the OGLE-2007-BLG-349 light curve, a Hubble Space Telescope Directors Discretionary proposal was submitted to use the Wide Field

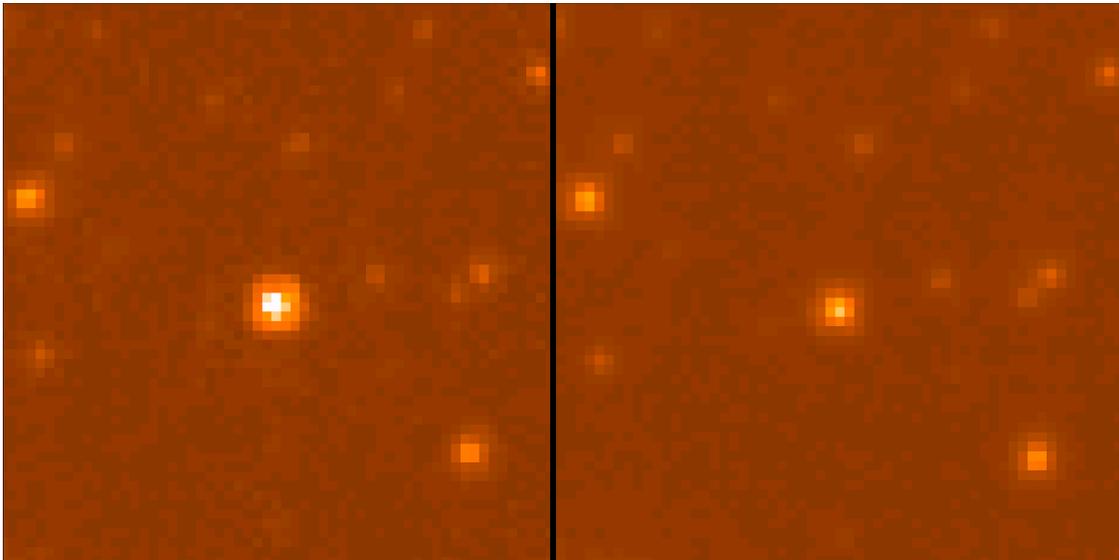


Fig. 8.— HST WFPC2 F814W images of the OGLE-2007-BLG-349 target, while magnified by a factor of $A = 3.470$ in the left panel and nearly unmagnified by $A = 1.037$ in the right panel.

Planetary Camera 2 (WFPC2) to observe this event. This proposal was approved as HST program GO/DD-11352. This program consisted of one short visit with a total of 320 seconds of exposures in the WFPC2 F814W passband on 8 October 2007, some 33 days after peak magnification, as well as one longer visit on 4 May 2008, 243 days after peak magnification. The longer visit included a total of 1280 seconds of exposures in each of the F555W and F814W passbands. The first visit occurred when the microlensing magnification was a factor of $A = 3.470$, and the magnification dropped to $A = 1.037$ by the time of the second observation. Close-ups of summed images centered on the OGLE-2007-BLG-349 target from each visit are shown in Figure 8, and the change in magnification of the target is clearly visible.

These HST images were reduced by two independent reduction codes. The primary reduction used the reduction code of Anderson & King (2000) and Anderson & King (2004), calibrated to the OGLE-III database (Szymański et al. 2011), and the secondary reduction used HSTPHOT (Dolphin 2000). The two reductions agree to better than 0.01 mag in absolute calibration and better than 0.004 mag in the difference in magnitudes between the two epochs. The primary reductions give $I_{\text{HST}} = 18.963 \pm 0.004$ mag at $\text{HJD}' = 4382.0353$ and $I_{\text{HST}} = 20.117 \pm 0.009$ mag at $\text{HJD}' = 4590.7740 \equiv t_{H2}$, where $\text{HJD}' = \text{HJD} - 2450000$. This later measurement of $I_{\text{HST}} = 20.117 \pm 0.009$ mag, at a magnification of $A = 1.036$, is substantially brighter than the source magnitudes from the best fit models presented in Table 2. It is substantially fainter than the combined source plus lens magnitude for the best 2-planet model, but it is close to the combined source plus lens magnitude for the best fit circumbinary model. This suggests that a circumbinary model is preferred, as a 2-planet model with a main sequence host would appear to be too bright to match the HST data, while a 2-planet system orbiting a white dwarf would be too faint. But, to determine if the 2-planet models are really excluded, we need to consider more than the best fit models. We must determine which models are consistent with both the light curve data and the HST images.

4.3. Light Curve Models with Hubble Space Telescope Constraint

In order to determine which of our models are consistent with the HST imaging data, we perform a set of constrained fits in which the lens system is forced to match the HST observations. We consider 3 different possibilities:

1. 2-planet, 1-star model with a single main sequence host star.
2. 2-planet, 1-star model with a single white dwarf host star of negligible brightness.
3. 1-planet, 2-star model, with a circumbinary planet orbiting a pair of main sequence stars.

In principle, we could also consider circumbinary planets orbiting a binary consisting of a at least one white dwarf, but the primary goal of this exercise is to establish that this is, in fact, a circumbinary

planet. Also, white dwarfs generally form at a late stage of stellar evolution, after earlier stages of stellar evolution that may have removed planets from the vicinity of the Einstein ring, where they are detectable by microlensing. (Mass loss by stars on the giant or super-giant branch or during planetary nebula formation could shift planets to wide orbits or unbind them from their former host star, depending on the details of the mass loss processes.)

At a Galactic latitude of $b = -2.5161^\circ$, and a lens distance of ~ 3 kpc, the lens system is likely to be behind about 3/4 of the dust that is in the foreground of the source. We model the dust with a simple exponential scale height of $h_{\text{dust}} = 0.10 \pm 0.02$ kpc, (Drimmel & Spergel 2001) so that the extinction in the foreground of the lens is given by.

$$A_{i,L} = \frac{1 - e^{-|D_L/(h_{\text{dust}} \sin b)|}}{1 - e^{-|D_S/(h_{\text{dust}} \sin b)|}} A_{i,S} , \quad (5)$$

where the index i refers to the passband, I in this case.

For possibility #2, a two planet model with a white dwarf host all the detectable flux comes from the source star, which is directly determined by the fit. So, the uncertainty in the extinction plays no role. Therefore, for these models we constrain the very slightly lensed source brightness at the time of the second epoch HST observation ($\text{HJD}' = 4590.7740$) to be $I = 20.117 \pm 0.010$.

For possibilities #1 and #3, we require a mass-luminosity relation, and we use the same empirical mass-luminosity that we used in Bennett et al. (2015). We use the mass-luminosity relations of Henry & McCarthy (1993), Henry et al. (1999) and Delfosse et al. (2000) in different mass ranges. For $M_L > 0.66 M_\odot$, we use the Henry & McCarthy (1993) relation; for $0.12 M_\odot < M_L < 0.54 M_\odot$, we use the Delfosse et al. (2000) relation; and for $0.07 M_\odot < M_L < 0.10 M_\odot$, we use the Henry et al. (1999) relation. In between these mass ranges, we linearly interpolate between the two relations used on the boundaries. That is we interpolate between the Henry & McCarthy (1993) and the Delfosse et al. (2000) relations for $0.54 M_\odot < M_L < 0.66 M_\odot$, and we interpolate between the Delfosse et al. (2000) and Henry et al. (1999) relations for $0.10 M_\odot < M_L < 0.12 M_\odot$.

The extinction is also an important uncertainty for possibilities #1 and #3. We use equation 5 to estimate the extinction, but we also need to include a reasonable uncertainty for this model. About one third of the flux at $\text{HJD}' = 4590.7740$ is due to the lens, so an 11% uncertainty in the extinction in the foreground of the lens would correspond to a 3.7% uncertainty in the combined lens plus source flux, or a 0.04 mag uncertainty when combined with the 0.01 mag uncertainty assumed for the HST calibration. We therefore apply the constraint $I_{SL}(t_{H2}) = 20.117 \pm 0.040$ on the combined source plus lens flux at $\text{HJD}' = t_{H2} = 4590.7740$.

For the circumbinary models, the fit parameters (along with θ_*) determine the source distance, if we insist that the stellar orbits be circular. (The modeling employs circular orbits, but these can be interpreted as second order approximations to any bound orbit. See Bennett et al. 2010 for more discussion of this point.) With θ_E and π_E determined, we know the mass of the lens system, via equation 2, and the 5 parameters describing the orbit, d_{23} , ϕ_{23} , \dot{d}_{23x} , \dot{d}_{23y} , and $1/T_{\text{orb}}$ in Einstein radius units. We only need the distance to the lens system to convert these to physical units, and

Table 3. Best Fit Nonlinear Model Parameters with HST *I*-band Flux Constraint

param.	units	circumbinary					
		2-planet		$u_0 < 0$		$u_0 > 0$	
		MS	WD	$d_{1\text{cm}} < 1$	$d_{1\text{cm}} > 1$	$d_{1\text{cm}} < 1$	$d_{1\text{cm}} > 1$
t_E	days	112.353	99.134	117.813	121.063	119.193	120.201
t_0	HJD'	4348.7472	4348.7467	4348.7466	4348.7520	4348.7459	4348.7511
u_0		0.002079	0.002357	-0.001980	-0.002053	0.001963	0.002075
$d_{1\text{cm}}$		0.79585	0.79657	0.81405	1.22505	0.81517	1.22574
d_{23}		1.05325	0.95900	0.01876	0.01953	0.01755	0.01810
$\theta_{1\text{cm}}$	rad	1.89685	1.89281	4.35873	4.35939	1.91718	1.91596
ϕ_{23}	rad	-3.07190	-3.08244	0.35366	0.38212	-0.42309	-0.42652
ϵ_1	10^{-4}	3.8017	4.3465	3.4234	3.3036	3.3662	3.3435
ϵ_2		9.340×10^{-6}	7.679×10^{-6}	0.45978	0.43262	0.49609	0.49114
ϵ_3		0.99961	0.99956	0.53987	0.56705	0.50357	0.50854
t_*	days	0.06972	0.06910	0.07067	0.07073	0.07102	0.07062
\dot{d}_{23x}	days $^{-1}$	0.0	0.0	0.010025	0.011933	0.007818	0.009919
\dot{d}_{23y}	days $^{-1}$	0.0	0.0	-0.007809	-0.004706	0.003867	0.003223
$1/T_{\text{orb}}$	days $^{-1}$	0.0	0.0	0.07339	0.070847	0.026716	0.057804
π_E		0.37694	0.14948	0.20015	0.22651	0.157274	0.16079
ϕ_E	rad	2.83260	2.40571	0.53276	0.45268	0.70152	0.63376
θ_E	mas	1.1032	1.0468	1.1139	1.1278	1.1153	1.1253
M_L	M_\odot	0.3594	0.8599	0.6834	0.6114	0.8710	0.8594
I_S	mag	20.298	20.149	20.377	20.412	20.395	20.410
I_L	mag	21.034	-	21.771	21.710	21.613	21.598
$I_{SL}(t_{H2})$	mag	19.859	20.126	20.082	20.094	20.058	20.064
V_S	mag	22.324	22.187	22.376	22.405	22.387	22.396
H_S	mag	18.215	18.077	18.268	18.298	18.279	18.288
fit χ^2		3473.30	3417.87	3384.45	3389.37	3412.42	3417.01
dof		3569	3569	3567	3567	3567	3567

Note. — HJD' = HJD – 2,450,000.

this is given by equation 3 (assuming that we already know D_S). But, we already know the size of the orbit in physical units, via Kepler’s third law, since we know the period and the mass. So, we can use this information to invert equation 3 and solve for the source distance. From the CMD in Figure 6, we see that the source lies on the red side of the bulge main sequence, and know that the red color is explained by the high metallicity measured by Bensby et al. (2013). So, it is safe to assume that the source is located in the bulge. We therefore apply a constraint on the implied distance to the source in the circumbinary models, $D_S = 7.8 \pm 1.4$ kpc, assuming the bulge distance estimate by Nataf et al. (2013) at the Galactic longitude of this event.

Table 3 gives the parameters of the best fit models with the source plus lens I -band magnitude (I_{SL}) constraint imposed at the time, t_{H2} , of the second epoch of HST observations. The two-planet models are so significantly disfavored that we can exclude them based on these constrained fits. The best two-planet model with a main sequence host is disfavored by $\Delta\chi^2 = 88.85$ with respect to the best circumbinary model, and the two-planet model with a dark stellar remnant host is disfavored by $\Delta\chi^2 = 33.38$. For the main sequence host case, $\Delta\chi^2 = 60.06$ comes from the $I_{SL}(t_{H2})$ constraint and $\Delta\chi^2 = 28.79$ comes from the difference in the light curve model fits. In the case of a dark stellar remnant host, the entire $\Delta\chi^2$ difference comes from the light curve difference. These χ^2 differences are sufficient to exclude both the two-planet and white dwarf host models. If we assume Gaussian random errors, then the probability of the best non-circumbinary solution is 4×10^{-7} . A very conservative choice would be to substitute $\Delta\chi^2/2$ for $\Delta\chi^2$ into the χ^2 probability distribution formula. This is equivalent to assuming that the correlations non-Gaussianity of the errors have the same effect as increasing each error bar (and constraint) by a factor of $\sqrt{2}$. With this assumption, the probability of the best non-circumbinary model would be 2×10^{-4} , so even with a very conservative assumption about the effects of non-Gaussian and correlated errors, it is only the circumbinary planetary models that are viable. We also note that the circumbinary models can be confirmed by observing the lens stars with the predicted brightness of $I_L = 21.74 \pm 0.24$ separating from the source at the predicted rate of $\mu_{\text{rel}} = 3.42 \pm 0.15$ mas/yr. (These number come from the MCMC calculations discussed later in this section.)

For the circumbinary models, we present the best fit model parameters for each of the degenerate solutions, with $u_0 < 0$ or $u_0 > 0$ and with $d_{1\text{cm}} < 1$ or $d_{1\text{cm}} > 1$, in Table 3. The $u_0 > 0$ models have smaller parallaxes and therefore larger host star masses, and this means that they are disfavored by the $I_{SL}(t_{H2})$ constraint by $\Delta\chi^2 = 27.97$. The wide models with $d_{1\text{cm}} \approx 1.225$ are also slightly disfavored by $\Delta\chi^2 = 4.92$.

In order to determine the ranges of parameters and properties that are consistent with the observed light curve and HST constraint, we have performed a series of Markov Chain Monte Carlo (MCMC) (Verde et al. 2003) runs. We follow the usual procedure (Bennett et al. 2008) of weighting each class of models with the weight function, $e^{-\Delta\chi^2/2}$, where $\Delta\chi^2$ refers to the χ^2 difference between the local χ^2 minimum and the global χ^2 minimum (with $u_0 < 0$ and $d_{1\text{cm}} < 1$). For the $u_0 < 0$, $d_{1\text{cm}} > 1$ models, the penalty is $\Delta\chi^2 = 4.92$, which corresponds to a weight of 0.085, but for the $u_0 > 0$ models the penalties are $\Delta\chi^2 = 27.97$ (for $d_{1\text{cm}} < 1$) and $\Delta\chi^2 = 27.97$ (for $d_{1\text{cm}} > 1$) and

Table 4. Constrained Circumbinary Nonlinear MCMC Model Parameters

parameter	units	MCMC Values
t_E	days	120 ± 4
t_0	HJD'	4348.7472 ± 0.0015
u_0		-0.00196 ± 0.00007
$d_{1\text{cm}}$	close mod.	0.8147 ± 0.0015
$(d_{1\text{cm}})$	wide mod.	1.2254 ± 0.0022
d_{23}		0.0193 ± 0.0009
$\theta_{1\text{cm}}$	radians	4.3582 ± 0.0030
ϕ_{23}	radians	0.357 ± 0.054
ϵ_1		$(3.34 \pm 0.12) \times 10^{-4}$
ϵ_2		0.470 ± 0.081
ϵ_3		0.530 ± 0.081
t_*	days	0.07075 ± 0.00043
\dot{d}_{12x}	days ⁻¹	0.0099 ± 0.0021
\dot{d}_{12y}	days ⁻¹	-0.0068 ± 0.0041
$1/T_{\text{orb}}$	days ⁻¹	0.104 ± 0.033
π_E		0.228 ± 0.035
ϕ_E	radians	0.460 ± 0.088
μ_{rel}	mas/yr	3.42 ± 0.15
I_S	mag	20.384 ± 0.037

Note. — HJD' = HJD – 2,450,000. The close model is preferred over the wide model by $\Delta\chi^2 = 4.92$.

$\Delta\chi^2 = 32.56$ (for $d_{\text{lcm}} > 1$), corresponding to weights of 8×10^{-7} and 9×10^{-8} , respectively. The weights for the $u_0 > 0$ models are so small that they don't contribute to the average microlens model parameters, shown in Table 4. The physical parameters of the lens system from these MCMC runs are given in Table 5. The system consists of a planet of $69 \pm 11M_{\oplus}$ orbiting binary stellar system, consisting of two M-dwarfs with masses of $0.35 \pm 0.06M_{\odot}$ and $0.27 \pm 0.06M_{\odot}$. These stars have a semi-major axis of $0.075^{+0.024}_{-0.014}$ AU and a period of 10^{+4}_{-3} days. The two-dimensional separation of the planet from the stellar center-of-mass is $2.5^{+0.4}_{-0.3}$ AU, which implies a median semi-major axis of ~ 2.9 AU and an orbital period of about 6 years if we assume a random orbital orientation. But, if the line-of-sight separation between the planet and binary stars is large, the semi-major axis and orbital period could be substantially larger than this.

5. VLT/NACO Observations of the Source Plus Lens System

We have also obtained two epochs of adaptive optics observations in the infrared *JHK* passbands with the Very Large Telescope (VLT) NACO instrument with a $28'' \times 28''$ field-of-view (FOV). The first *H*-band observations were taken at $\text{HJD}' = 4386.046880$, when the magnification was about a factor of 3, and the second epoch observations were taken at $\text{HJD}' = 4686.144531$, when the magnification was only about 1%. This small field-of-view made calibration of the VLT/NACO

Table 5. Physical Parameters

Parameter	units	value	2- σ range
D_L	kpc	2.67 ± 0.34	2.07-3.40
$M_{\text{A+B}}$	M_{\odot}	0.62 ± 0.10	0.45-0.84
M_{A}	M_{\odot}	0.35 ± 0.06	0.25-0.48
M_{B}	M_{\odot}	0.27 ± 0.06	0.15-0.39
m_c	M_{\oplus}	69 ± 11	49-93
$a_{\perp\text{AB}}$	AU	0.058 ± 0.006	0.047-0.070
a_{AB}	AU	$0.077^{+0.023}_{-0.014}$	0.054-0.143
P_{AB}	days	$9.6^{+4.7}_{-2.4}$	6.0-25.0
$a_{\perp\text{CMc}}$	AU	$2.46^{+0.41}_{-0.31}$	1.91-3.89
V_L	mag	25.16 ± 0.32	24.53-25.81
I_L	mag	21.71 ± 0.24	21.24-22.19
H_L	mag	18.84 ± 0.20	18.44-19.25

Note. — Uncertainties are 1- σ parameter ranges.

data very difficult, and, in fact, we were unable to find a satisfactory calibration of these data. We were able to calibrate the CTIO H-band data as discussed in Section 4.1, and so from the CTIO H -band light curve, we know the H -band source magnitude.

Each of the different models presented in Table 3 has different prediction for the combined lens plus source magnitude at the times of the two different observations. The observations give a magnitude difference of 0.87 ± 0.08 between the two epochs. This compares to the 0.733, 0.581, and 1.056 source plus lens H -band magnitude difference between the first and second epochs for the circumbinary, 2-planet plus main sequence host, and 2-planet plus stellar remnant host models, respectively. These differ from the measured value by 1.7σ , 3.6σ , and 3.1σ , respectively. So, the VLT/NACO data also favor the circumbinary model over the 2-planet models.

6. Discussion and Conclusions

In the previous section, we have established that although the OGLE-2007-BLG-349 light curve can be explained by models with one star and two planets, it is only the circumbinary planet models that can explain both the light curve and the HST observations. So, the system consists of two host stars, OGLE-2007-BLG-349LA and OGLE-2007-BLG-349LB, orbited by a planet somewhat less massive than Saturn. Although it was the first circumbinary planet to be observed, it was not the first circumbinary planet to be published, as 10 circumbinary planets (Doyle et al. 2011; Welsh et al. 2015; Kostov et al. 2015) have been discovered by the Kepler mission.

One puzzle with the circumbinary planets discovered in the Kepler data is that most of them are located quite close to the stability limit (Holman & Wiegert 1999), as shown in Figure 9. That is, if they were moved to orbits with slightly smaller semi-major axes, they would quickly become dynamically unstable. Holman & Wiegert (1999) find that circumbinary orbits are unstable within $a_c \simeq (2.28 \pm 0.01) + (3.8 \pm 0.3)e + (1.7 \pm 0.1)e^2$, where e is the eccentricity of the binary orbit and a_c is measured in unites of the stellar binary semi-major axis. If we assume $e \approx 0.1$, we find $a_c = 2.7$. Given the median semi-major axis of the OGLE-2007-BLG-349LAB binary, or $a \simeq 0.075$ AU, the likely three-dimensional ~ 2.9 AU separation between the OGLE-2007-BLG-349L(AB)c planet, we estimate the planet orbits at $\sim 14a_c$. This compares to most of the Kepler circumbinary planets that orbit at $< 2a_c$, and the widest orbit Kepler circumbinary planet (Kostov et al. 2015) that orbits at $7a_c$.

The fact that the first circumbinary planet found by microlensing has an orbital separation well beyond Kepler’s sensitivity region provides modest support to the idea that circumbinary planets form in the outer disk, relatively far from the orbital stability limit (Kley & Haghighipour 2014; Bromley & Kenyon 2015; Silsbee & Rafikov 2015) instead of in situ (Meschiari 2014). In principle, this new microlensing discovery could provide strong evidence that circumbinary planets are substantially more common far from the stability limit than close to the stability limit. Microlensing is most sensitive to both planets and stellar companions at separations close to the Einstein

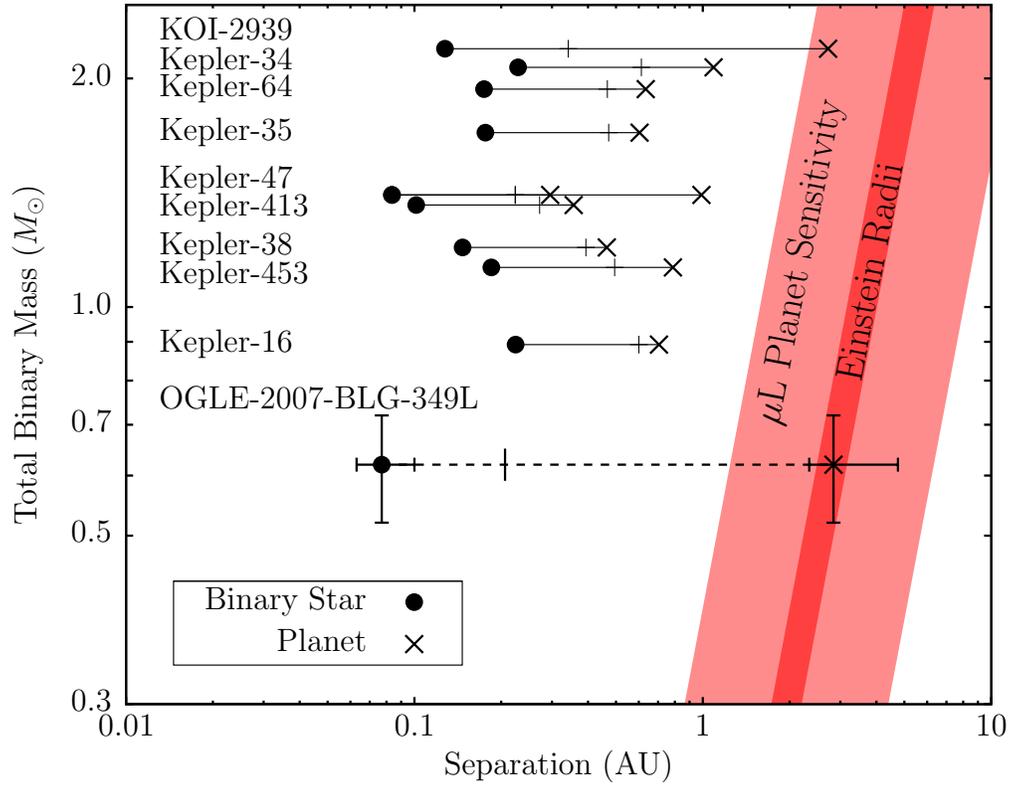


Fig. 9.— Comparison of host star masses and orbital separations for the known circumbinary planet systems. The circular spots show the orbital separations of the host stars, while the orbital separations of the planet sfrom the stellar centers of mass are marked with “x”s. The red region gives the typical Einstein radius as a function of mass and the light red region gives the approximate range of planetary microlens sensitivity.

radius, However, for event OGLE-2007-BLG-349, the ratio of the two-dimensional separation between the planet and center-of-mass and between the two stars is 42. Such a large ratio was only detectable because of the very high magnification of this event, but circumbinary planets with a smaller separation ratio should be detectable for a much larger class of lower-magnification events. The fact that no other circumbinary planets have been found by microlensing might be considered to imply that circumbinary planets with smaller separation ratios are more rare. However, there is circumstantial evidence suggesting that we may be inefficient at identifying such events in our data.

Gould et al. (2014) presented another two-star plus one planet event, OGLE-2013-BLG-0341, which was interpreted as a wide binary with a planet orbiting one of the two stars, although there are circumbinary models with very similar light curves. This was also a high magnification event with the signal dominated by the stellar binary instead of by the planet (like OGLE-2007-BLG-349). However, the lens-source alignment was such that the source crossed a planetary caustic feature prior to reaching high magnification. This made it obvious that the lens system included a planet, but we were very lucky to have this planetary feature detected. And the analysis showed that the planet was required to fit the data even if the low-magnification planetary feature was not seen. This suggests that there should be many more two-star plus one planet events in the data that we have already collected, but that we are not efficient at finding planetary signals in events that are dominated by stellar binary microlensing features. So, we recommend a systematic search for planetary signals in the light curves of strong stellar binary events. If a large population of circumbinary planets are found, it will add to the $\sim 10\%$ frequency of circumbinary planets found in short period orbits (Armstrong et al. 2014). Circumbinary planetary systems can be quite efficient at ejecting planets (Sutherland & Fabrycky 2016; Smullen et al. 2016), so they could contribute to the large population of rogue planets found by microlensing (Sumi et al. 2011).

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