The Astrophysical Journal, 628:L109–L112, 2005 August 1

A JOVIAN-MASS PLANET IN MICROLENSING EVENT OGLE-2005-BLG-071

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Received 2005 May 20; accepted 2005 June 17; published 2005 July 18

ABSTRACT

We report the discovery of a several-Jupiter–mass planetary companion to the primary lens star in microlensing event OGLE-2005-BLG-071. Precise ($\lesssim$1%) photometry at the peak of the event yields an extremely high signal-to-noise ratio detection of a deviation from the light curve expected from an isolated lens. The planetary character of this deviation is easily and unambiguously discernible from the gross features of the light curve. Detailed modeling yields a tightly constrained planet-star mass ratio of $q = m_p/M = 0.0071 \pm 0.0003$. This is the second robust detection of a planet with microlensing, demonstrating that the technique itself is viable and that planets are not rare in the systems probed by microlensing, which typically lie several kiloparsecs toward the Galactic center.

Subject headings: Galaxy: bulge — gravitational lensing — planetary systems

1. INTRODUCTION

As compared with the other three methods that have successfully detected extrasolar planets, microlensing has unique features, both positive and negative. Unlike pulsar timing (Wolszczan & Frail 1992), radial velocities (Mayor et al. 2004; Marcy et al. 2005; references therein), and transits (Udalski et al. 2002; Konacki et al. 2003; Bouchy et al. 2004; Alonso et al. 2004), which rely on the detection of photons from the host star and thus are biased toward nearby systems, microlensing is sensitive to mass and therefore can detect planets many kiloparsecs from the Sun. Microlensing is potentially very sensitive to extremely low mass (e.g., Mars-like) planets because, in contrast to all other methods, the strength of the signal can be quite large ($\gtrsim$10%), and the signal-to-noise ratio falls with the planet's mass only as $m_p^{1/2}$. Microlensing is unique in its ability to detect wide-separation planets with periods that exceed the duration of the experiment.

Microlensing, like most other indirect methods, is primarily sensitive to the planet-star mass ratio $q = m_p/M$. However, the microlensing planet host stars are distant and superposed on a background source star, so the brightness and mass of the host star are often only weakly constrained. Just as the $m_p \sin i$ ambiguity for radial velocity planet detections can be broken if the planet happens to transit its host, so microlensing can yield star and planet masses in special circumstances as well (Bennett & Rhie 2002; Gould et al. 2003). Microlensing detections occur only at a single epoch, so one measures only the planet-star separation at a particular moment, not the orbit.

To date, there has been only one robust detection of a planet using the microlensing technique (Bond et al. 2004). Here we report on the second detection of a planet by microlensing, which was enabled by the rapid response of a number of observing

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teams to high-magnification microlensing events, which are intrinsically the most sensitive to planets. This detection demonstrates that the microlensing method has reached maturity, and that the planets to which the method is sensitive are not rare.

2. HIGH-MAGNIFICATION PLANETARY MICROLENSING EVENTS

When a stellar lens in a microlensing event has a planetary companion, the binary nature of the lens results in caustics (closed curves of formally infinite magnification) in the magnification pattern. If the source passes over or close to one of these caustics, the light curve exhibits a short-lived deviation from the standard Paczyński (1986) single-lens form that betrays the presence of the planet (Mao & Paczyński 1991). The great majority of planetary companions generate two distinct types of caustics: one "central caustic" that lies close to the host star, and one or two "planetary caustics" depending on whether the planet lies outside or inside the Einstein ring. As one moves the planet closer to the Einstein ring, both types of caustics grow, and they eventually merge into a single "resonant caustic."

Gould & Loeb (1992) pointed out that planets in Jupiter-like orbits around stars on the line of sight to the Galactic bulge would coincidentally lie fairly close to the Einstein ring. Hence, they should generate large and, so, easily detectable planetary caustics. This optimistic assessment encouraged early efforts to detect planets. Because planetary caustics are much larger than central caustics, in an unbiased sample of microlensing events the overwhelming majority of planetary anomalies will be generated by planetary caustics, and for this reason they were the focus of early efforts.

Nevertheless, central caustics play a crucial role in current microlensing planet searches. Exactly because they are "central," central caustics can be probed only in very high magnification events, that is, events in which the source passes very close to the primary lens and so to the central caustic. These events are very rare, but when they do occur, the source is essentially *guaranteed* to pass over or close to the central caustic if a planet is present (Griest & Safizadeh 1998; Bond et al. 2002; Rattenbury et al. 2002). Since very high magnification events can be identified as they are unfolding, they can be intensively monitored over their peak to a degree that is not feasible for the much more frequent garden-variety microlensing events. As a result, modern microlensing follow-up groups such as PLANET (Albrow et al. 1998) and μFUN (Yoo et al. 2004) now tend to focus much of their effort on identifying and following the rare high-magnification (HM) events. Moreover, both the major survey teams, OGLE (Udalski et al. 1993) and MOA (Bond et al. 2001), switch over from survey mode to follow-up mode when events undergo HM or other effects that warrant closer monitoring.

The problem of identifying HM events is actually quite severe. The great majority of HM sources are faint, and as a result the photometry of the early light curve is generally too poor to accurately predict their HM character well in advance. As a result, fewer than a dozen HM ($A_{\rm max} \gtrsim 100$) events have been intensively monitored altogether (Albrow et al. 2001; Gaudi et al. 2002; Rhie et al. 2000; Bond et al. 2001; Abe et al. 2004; Yoo et al. 2004; Dong et al. 2005).

The OGLE-III Early Warning System (EWS; Udalski 2003) now annually alerts bulge microlensing events at the rate of 600 per year. This provides a potentially rich source of HM events. In order to better harvest this potential, as well as to react quickly to microlensing anomalies, OGLE has now implemented the Early Early Warning System (EEWS), which detects anomalies in real time.

3. EVENT RECOGNITION AND OBSERVATIONAL DATA

The original alert on OGLE-2005-BLG-071 was triggered by EWS (Udalski 2003) on 2005 March 17 based on observations by OGLE-III. The alert predicted that the event would peak about 1 month later on $\mathrm{HJD}' \equiv \mathrm{HJD} - 2{,}450{,}000 = 3880 \pm 8$, with $A_{\rm max} > 3$. Based on a new OGLE point (HJD′ 3477.9) less than 3 days before the lens-source point of closest approach, as well as its own data (acquired starting HJD′ 3472.7), μFUN issued a general alert (HJD′ 3478.20) that the event was peaking at high magnification. This triggered more intensive observations the next night by OGLE and by μFUN Chile.

A single-lens fit to these new observations resulted in a substantially worse χ^2 than previous fits, and so μFUN then issued a second alert (HJD′ 3478.97) saying that an anomaly had begun. This was confirmed with the first OGLE observation on the following night (HJD′ 3479.73). At this point, both OGLE and all μFUN stations attempted to observe the event intensively and continued to do so for the next four nights. OGLE was able to obtain data from Chile during almost the entire period and indeed issued an EEWS alert on HJD′ 3481.94 reporting on a second rise. Two New Zealand μFUN observatories (Farm Cove and Auckland) obtained substantial data including 6 continuous hours on the falling sides of each of the "twin peaks" of the light curve, and μFUN observations from Palomar Observatory yielded coverage of the second peak, thereby bridging the rise and fall covered by OGLE and Farm Cove/Auckland, respectively. A small amount of additional data covering the second peak was obtained from Kitt Peak. MOA immediately responded to the original HM alert to obtain data on the rise toward the first peak, as well as all four nights of the anomaly. PLANET/RoboNet, which had already made prepeak observations beginning HJD′ 3470.1, responded to the anomaly alert, catching the decline of the first peak from the Faulkes Telescope North, in Hawaii, and the second from the Canopus telescope (Tasmania).

It was soon realized that the anomaly was short-lived, and on HJD′ 3482.9 the light curve returned to the normal single-microlens shape. The first results of modeling of the light curve of the event, announced on HJD′ 3483.9 by OGLE, suggested the possibility that the anomaly was due to a low-mass companion, well into the planetary regime. This result was subsequently confirmed by independent modeling conducted by other teams.

We present data from OGLE (1.3 m telescope at Las Campanas Observatory in Chile, operated by the Carnegie Institution of Washington), MOA (0.6 m at Mount John Observatory in New Zealand), μFUN Chile (SMARTS 1.3 m telescope at CTIO), Palomar (60 inch [1.5 m] robotic telescope), MDM (Hiltner 2.4 m at Kitt Peak), Auckland (0.35 m Nustrini Telescope at Auckland Observatory), Farm Cove (0.25 m Meade at Farm Cove Observatory), Faulkes North (2.0 m in Hawaii), and Canopus (1.0 m at Hobart, Tasmania).

4. ONLY A PLANET CAN EXPLAIN THIS LIGHT CURVE

Figure 1 shows the data from the various observatories together with a binary lens model. The model shown has a very small mass ratio, $q = 0.0071$, and is clearly a good fit to the data. The event is therefore consistent with a planetary lens; however, the question remains whether there might be other nonplanetary models that fit the data equally well, that is, binary lens models with $q \sim O(1)$. Binary lens models have seven lens parameters plus $2n$ flux parameters, where $n = 10$ is the number of observatory/filter combinations. Three parameters are the same as for single lenses: the time of closest approach to the lens "center" t_0, the impact parameter (normalized to the angu-

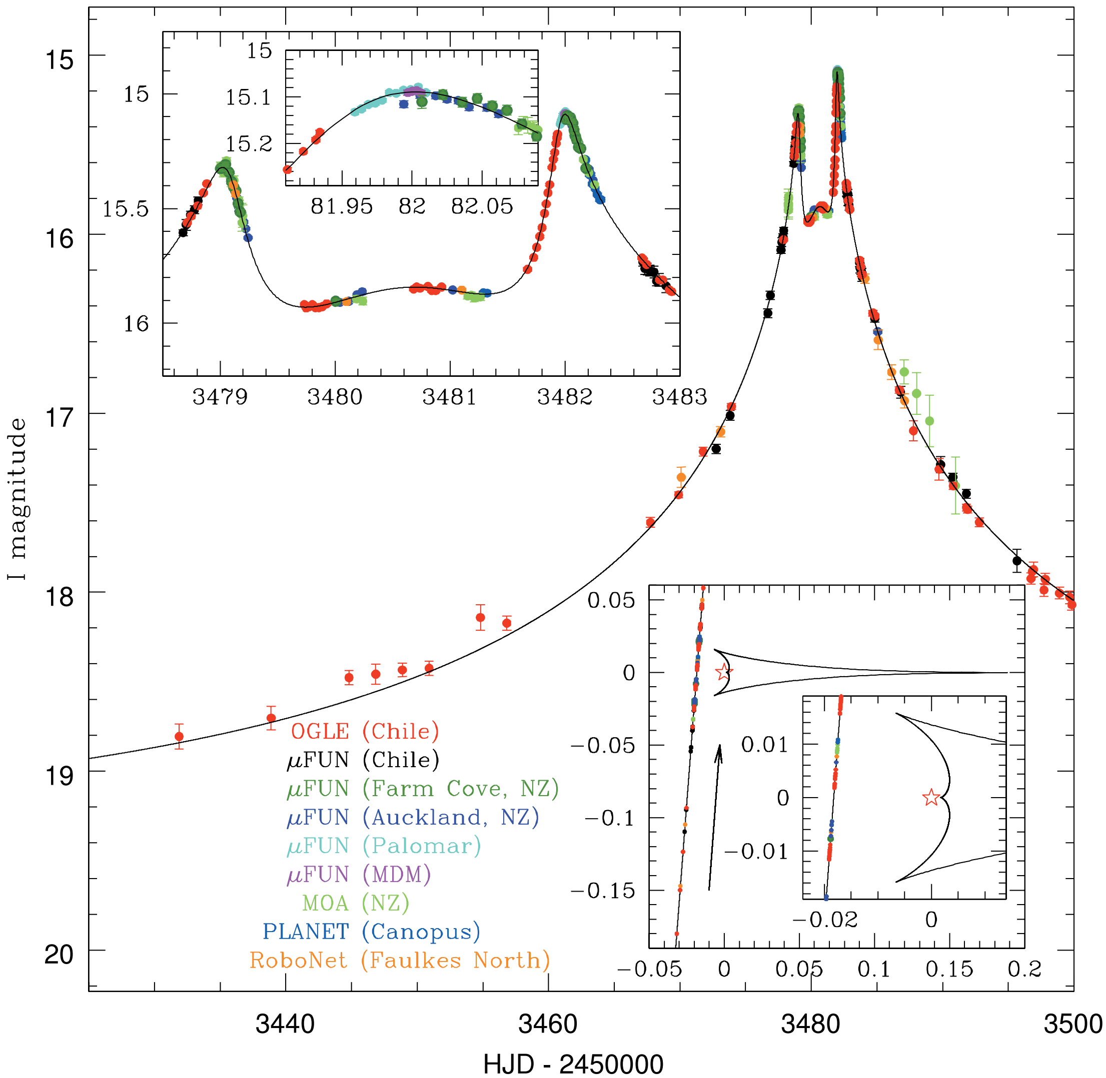

FIG. 1.—Light curve of OGLE-2005-BLG-071, showing it contains a planet. Apart from the anomaly near the peak, this was an ordinary high-magnification event, implying the caustic is small. The triple peak (two large symmetric peaks surrounding a small peak) shows the source passed three cusps of a caustic, the middle one being weak (*insets*), which implies a normalized star-companion separation $b \sim 1$. The interval between peaks (and so cusps) is $\Delta t = 3$ days, implying the shear induced by the companion is small, $\gamma = \Delta t/4t_E < 0.02$, so the mass ratio q of the companion is also small, $q = \gamma b^2 \lesssim 0.03$. More detailed fitting shows $q = 0.0071$.

lar Einstein radius θ_E) u_0, and the Einstein radius crossing time t_E. Three parameters specify the lens geometry: the mass ratio q, the separation of the two components (normalized to θ_E) b, and the angle of source-lens relative motion with respect to the binary axis α. In addition, if the source is resolved by the magnification pattern, one must specify the ratio of the source size to the Einstein radius, $\rho = \theta_*/\theta_E$. Finally, for each observatory/filter combination there is a source flux f_s and a background flux f_b such that the total flux is $f = Af_s + f_b$, where A is the magnification.

Given that the parameter space is obviously very large and somewhat complex, how do we know that there are no non-planetary solutions? One way to tell is to conduct a wide search for solutions, which we have done. However, it is also useful to have analytic arguments to ensure that a solution is not lurking in a corner of parameter space that one did not try.

The following argument rests just on the gross features of the light curve: First, the anomaly occurs near the peak of an otherwise normal event, when it is 3 mag above baseline, so $A > 16$, that is, the normalized source-lens separation is $u < 0.06$. This already implies that the caustic is small and so must be either a central caustic (generated by a wide or close companion) or the "central-caustic end" of a resonant caustic. The central caustics of wide and close binaries (with $b \leftrightarrow b^{-1}$) are mathematically nearly identical (Dominik 1999; An 2005), and the central-caustic end of a resonant caustic is very similar to these. The twin-peaked structure can only be generated by the source's passing close to, but not over, two cusps of this central caustic. Peaks can also be caused by passing over a caustic, but in that case they are highly asymmetric, with a much faster rise for the first peak and a much faster decline for the second. This alternate scenario is clearly ruled out by the form of the light curve. Third, there is a small "bump" between these two peaks. This can only be caused by passing a third, much weaker cusp. All these features are matched by the caustic geometry shown in the lower right inset to Figure 1 and cannot be matched by caustics that lack this three-pronged morphology.

The fact that the two peaks are of almost equal height implies that the source must pass nearly perpendicular to the binary axis, $\alpha \sim \pm 90°$. The fact that the middle peak is so much weaker than the outer two implies that the caustic is extremely asymmetric. Such asymmetric caustics occur only when b is close to unity: for $b \gg 1$ or $b \ll 1$, the caustics are diamond shaped.

TABLE 1
OGLE-2005-BLG-071 Model Parameters

Model	t_0 (HJD − 2,453,400)	u_0	t_E (days)	q	b	α (deg)	I_s (mag)	I_b (mag)	χ^2 (1092 dof)
Wide	80.6791 ± 0.0020	0.0236 ± 0.0013	70.9 ± 3.3	0.0071 ± 0.0003	1.294 ± 0.002	274.23 ± 0.04	19.53	21.29	1105.6
Close	80.6919 ± 0.0023	0.0225 ± 0.0012	73.9 ± 3.5	0.0067 ± 0.0003	0.758 ± 0.001	274.48 ± 0.05	19.59	21.05	1127.6

For definiteness, we now consider the wide-binary case, $b > 1$. Since the central caustic is similar to a Chang-Refsdal (1979) caustic, its full width is equal to 4γ, where $\gamma = q/b^2$ is the shear, so the time to cross between these cusps is $\Delta t = 4qt_E/b^2$. Equating this to the time between the peaks, $\Delta t \sim 3$ days, yields $q = b^2(0.75\ \text{days}/t_E)$. Since the blending is known from the full fit to the light curve, t_E is well determined from the fit to the light curve away from the peak. However, even ignoring this information, the maximum q can be found from the minimum allowed t_E, which is obtained by assuming no blending. This minimum is $t_E \sim 40$ days. That is, $q < 0.019b^2$, or $q \lesssim 0.03$. This limit is already very close to the planet regime. Moreover, the accumulated constraints on b, q, and α imply that the allowed parameter space is small and, so, was easily and exhaustively searched. A virtually identical argument applies to the $b < 1$ case, yielding a planet of virtually the same mass. The best-fit parameters for both wide and close solutions are given in Table 1.

The event is still in its late phases. When it reaches baseline, a more detailed analysis of the light curve may permit measurements of additional parameters, in particular the mass of the lens star. Based on a preliminary analysis of finite-source effects during the second peak and parallax effects in the wings of the event (cf. An et al. 2002), we constrain the host mass to be $0.08\ M_\odot < M < 0.5\ M_\odot$, implying that the planet lies in the range $0.05 < m_p/M_{\rm Jup} < 4$. The corresponding range of distances is 1.5 kpc $< D_l <$ 5 kpc.

We obtain an upper limit on the lens-star flux, $I_l > 21.3$, by analyzing good-seeing OGLE images constrained by astrometry derived from a *Hubble Space Telescope* image taken on HJD′ 3513.6. Our estimate of the mass/distance range is fully consistent with this limit, implying that the lens star cannot be heavier. When a second *HST* image is taken after the event, the flux from the lens primary will be constrained even more precisely.

5. DISCUSSION

The discovery of a planet in OGLE-2005-BLG-071 has several important implications. First, being the second such detection, it shows that microlensing planets are not a fluke. While the Poisson statistics of a single detection were consistent with extremely low rates, two detections make the low-rate hypothesis implausible.

Second, OGLE-2005-BLG-071 is the first secure HM planetary event. While Griest & Safizadeh (1998) long ago identified these central-caustic probing events as a potentially rich vein for planet hunting, the technical difficulties in recognizing HM events in real time and in adequately monitoring their peak have limited their application to a few events. With the coming on line of OGLE EEWS and the increasing sophistication of follow-up teams, excellent coverage of HM events is becoming more common, if not quite routine.

Finally, in addition to being a fruitful path to planets in general, central-caustic events are at present the only practical method for finding Earth-mass planets around main-sequence stars using current technology. Although OGLE-2005-BLG-071 contains a giant planet, the fact that it was detected at extremely high signal-to-noise ratio demonstrates that planets of much lower mass can also be detected.

Support for OGLE was provided by Polish MNII grants 2P03D02124 and 2P03D01624, NSF grant AST 02-04908, and NASA grant NAG 5-12212. A. U. was supported by grant SP13/2003 from the Foundation for Polish Science. A. G. and S. D. were supported by NSF grant AST 02-01266. D. D., A. G., and R. P. were supported by NASA grant NNG04GL51G. A. G.-Y. was supported by NASA through a Hubble Fellowship. B. S. G. was supported by a Menzel Fellowship from the Harvard College Observatory. C. H. was supported by the SRC program of the Korea Science and Engineering Foundation. B.-G. P. acknowledges support from the Korea Astronomy and Space Science Institute. MOA thanks the University of Canterbury for making available the Mount John Observatory 0.6 m telescope. Work by MOA is supported by the Marsden Fund of New Zealand and the Ministry of Education, Culture, Sports, Science and Technology of Japan. The Mount Canopus Observatory is operated by the University of Tasmania with financial assistance from David Warren. RoboNet is a PPARC-funded project led by Liverpool John Moores University on behalf of a consortium of ten UK universities. The Faulkes Telescope North is operated with support from the Dill Faulkes Educational Trust.

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