

DIRECT DETECTION OF GIANT CLOSE-IN PLANETS AROUND THE SOURCE STARS OF CAUSTIC-CROSSING MICROLENSING EVENTS

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ABSTRACT

We propose a direct method to detect close-in giant planets orbiting stars in the Galactic bulge. This method uses caustic-crossing binary microlensing events discovered by survey teams monitoring the bulge to measure light from a planet orbiting the source star. When the planet crosses the caustic, it is more magnified than the source star; its light is magnified by two orders of magnitude for Jupiter size planets. If the planet is a giant close to the star, it may be bright enough to make a significant deviation in the light curve of the star. Detection of this deviation requires intensive monitoring of the microlensing light curve using a 10-meter class telescope for a few hours after the caustic. This is the only method yet proposed to directly detect close-in planets around stars outside the solar neighborhood.

planetary systems — gravitational lensing

1. INTRODUCTION

One of the scientific goals of microlensing searches towards the Galactic bulge is the detection of planets orbiting the primary lenses. These searches are conducted in the following manner: One of the microlensing searches, EROS (Glicenstein 2000) or OGLE (Udalski et al. 1994) or the now terminated MACHO program (Alcock et al. 1996) launches an electronic alert of an ongoing microlensing event. These events are then monitored by follow-up groups such as the PLANET (Albrow et al. 1998), MPS (Rhie et al. 1999), or GMAN (Alcock et al. 1997d) collaborations. While the searching teams typically monitor stars \sim once per day, the follow-up campaigns, with a network of telescopes around the globe, sample much more frequently. A planet orbiting the primary lens with semi-major axis a in the “lensing zone”, $0.6 - 1.5R_E$ (Mao & Paczyński 1991; Gould & Loeb 1992), where the Einstein radius, R_E is

$$R_E = \left(\frac{4GM}{c^2} \frac{D_L D_{LS}}{D_S} \right)^{1/2}, \quad (1)$$

may cause detectable deviations from the standard microlensing light curve (see Sackett 1999 for a review). Here, D_L , D_S , and D_{LS} are respectively the distances to the lens, the source star, and between the lens and source stars. For a bulge source lensed by a $0.3 M_\odot$ lens, the lensing zone, where one is most sensitive to planets, is in the range $1.2 - 3.2$ AU.

In this paper, we discuss another means by which a microlensing follow-up experiment may detect a planet, in this case a giant planet close ($a \lesssim 0.1$ AU) to the *source* star. Confounding prior expectations, such close-in planets are found to be relatively common. They have been detected by several collaborations (Mayor & Queloz 1995, Cochran et al. 1997, Noyes et al. 1997; see Marcy & Butler 1998 for a review) and can be found around $\sim 1\%$ of all stars (Marcy & Butler 2000).

Since direct detection is most sensitive to planets close

to the source ($a \lesssim 0.1$ AU), it is complementary to the traditional microlensing light curve deviation method which can only detect planets in the lensing zone ($a \simeq 1 - 3$ AU). Unlike other methods of planet detection, such as radial velocity measurements or astrometric shifts¹, this method can be used to directly detect planets in the bulge of our Galaxy, thus allowing us to compare planet formation under conditions different from those in the solar neighborhood.

1.1. Caustics

All strong gravitational lenses produce “caustics,” regions in which a point source is (formally) infinitely magnified. In reality, no source is truly point-like, and the passage of the source through the caustic allows us to spatially resolve the source. Already, limb-darkening profiles have been measured in sources as far away as the Small Magellanic Cloud (Afonso et al. 2000), and it has been proposed that star-spots could be imaged when a source passes through a caustic (Heyrovský & Sasselov 2000; Han et al. 2000; Bryce & Hendry 2000). In this paper, we examine the possibilities of directly detecting light from a planet as it passes through a caustic.

There are several different types of caustics depending on the lens configuration. A single point lens has a point caustic corresponding to perfect alignment between the source and the lens, when the image of the source is the Einstein ring. These events are rare since they require such perfect alignment. In the case of binary lenses, the caustics form a network of “folds” and “cusps.” The caustic structure of binary lenses is cataloged in Schneider & Weiss (1986) and Erdl & Schneider (1993).

Because caustics form closed curves, a caustic light curve generically has pairs of crossings. The time of the second caustic crossing can often be predicted days in advance, allowing for scheduling of detailed monitoring of the caustic crossing.

The best studied caustic crossing event, which allows us to illustrate the technology, is MACHO-98-SMC-1 (Al-

¹It may also be possible to indirectly detect planets orbiting stars in the Galactic bulge using occultation.

cock et al. 1999), an event which took place in the Small Magellanic Cloud. The MACHO group first sent an alert indicating that a microlensing event was taking place. After the first caustic crossing, the MACHO group launched a second alert with a rough prediction of when the second caustic crossing would occur. As the second caustic crossing approached, predictions of its time became more accurate so that when it occurred, several groups were able to devote all their telescope time for one night to the observation of this one event. Notably, the passage of the source through the caustic was imaged every ~ 5 minutes by the PLANET collaboration (Albrow et al. 1999) from South Africa, followed immediately, and with similar sampling frequency by the EROS collaboration (Afonso et al. 1998) from Chile. A combined analysis of this event involving data from the MACHO/GMAN, EROS, PLANET, OGLE and MPS collaborations was published in (Afonso et al. 2000).

Several other caustic crossings have been studied with similar sampling frequency, by the MACHO/GMAN and PLANET collaborations (Alcock et al. 2000; Albrow et al. 2000). Roughly 7% of all microlensing events are caustic crossing events (Udalski et al. 2000).

Near a fold caustic, the magnification of a single point is (Schneider, Ehlers, & Falco 1992)

$$A = A_0 + \Theta(-u_{\perp})(u_{\perp}/u_r)^{1/2} \quad (2)$$

where u_{\perp} is the distance of the source to the caustic normal to the caustic in units of the projected Einstein radius, u_r is the length scale of the caustic in units of the projected Einstein radius, A_0 is the magnification not associated with the caustic, and Θ is a step function. For typical binary lenses, u_r and A_0 are $\mathcal{O}(1)$. The magnification of a uniform disk by a fold caustic is discussed in (Schneider & Weiss 1987). The maximum magnification is $1.4(u_r/\rho_*)^{-1/2}$, where ρ_* is the radius of the stellar disk in units of the projected Einstein radius, while the average magnification during the crossing is $(u_0/\rho_*)^{1/2}$. Note that since the planet is smaller than the source star, it is more highly magnified.

2. SCALING RELATIONS

The fraction of light reflected by a planet is

$$f \simeq 10^{-4} p \left(\frac{R_p}{R_{\text{Jup}}} \right)^2 \left(\frac{0.05 \text{ AU}}{a} \right)^2 \phi \quad (3)$$

where p is the albedo, R_p is the radius of the planet, a is the distance of the planet from the star, and ϕ is the fraction of the illuminated surface of the planet visible by the observer, which depends on the inclination and phase of the orbit.

For a source located in the Galactic bulge at $D_S = 8$ kpc and a binary lens at a distance of $D_L = 6$ kpc, the typical magnification of a planet of radius R_p as it crosses the caustic is

$$A = 10^2 \left(\frac{R_{\text{Jup}}}{R_p} \right)^{1/2} \left(\frac{M_{\text{lens}}}{1 M_{\odot}} \right)^{1/2} \quad (4)$$

so that, during the caustic crossing, the fractional deviation of the light curve due to the planet is

$$\delta_p \simeq 1\% p \left(\frac{R_p}{R_{\text{Jup}}} \right)^{1.5} \left(\frac{0.05 \text{ AU}}{a} \right)^2 \left(\frac{M_{\text{lens}}}{1 M_{\odot}} \right)^{1/2} \phi. \quad (5)$$

The duration of the planetary caustic crossing will be quite brief. The typical planet diameter crossing time scale is

$$t_p = 12 \frac{R_p}{R_{\text{Jup}}} \frac{100 \text{ km s}^{-1}}{v_{\perp}} \text{ minutes} \quad (6)$$

where v_{\perp} is the component of the velocity of the planet normal to the caustic and the line of sight. This velocity is made up of two components, the velocity of the planet around its star, and the velocity of the star relative to the caustic. In addition, the planet will not be uniformly illuminated and thus the width of crossing will depend on the star/planet geometry at the time of the crossing. For example, the caustic crossing from a “quarter-moon” planet with the terminator parallel to the caustic will have an effective width that is two times smaller than that arising from a “quarter-moon” planet with the terminator perpendicular to the caustic.

Thus, we see that direct detection of a giant close-in planet requires relative photometry accurate to better than 1% and a sampling frequency of minutes. The Poisson noise for $I = 19.7$ (a G0V star at 8 kpc with 1 mag of extinction), assuming an overall throughput of 0.1 is

$$\sigma \simeq 0.5\% \left(\frac{t_{\text{exp}}}{1 \text{ min.}} \right)^{-1/2} \left(\frac{D}{10 \text{ m}} \right)^{-1}, \quad (7)$$

where t_{exp} is the total exposure time and D is the diameter of the telescope. Therefore, for $t_p = t_{\text{exp}} = 12$ min., the planet will be detected with a signal-to-noise of $\delta/\sigma \approx 6$ for a 10 meter telescope.

In addition to the caustic crossing, one may be able to detect the planet in the pre-crossing phase. Ultimately, the magnification of the planet inside the crossing depends on the geometry of the lens, but can reach a factor of typically around 10. In this case, before the planet crosses the caustic, the source will be approximately 0.1% brighter than after the caustic crossing. This brightening lasts much longer than the caustic crossing, $\Delta t \approx 20$ hours ($a_{\perp}/0.05 \text{ AU}$) ($100 \text{ km s}^{-1}/v_{\perp}$) where a_{\perp} is the planet-star distance normal to the caustic. Since of order 50 times more measurements will be taken of this deviation than of the caustic, but the deviation is of order 10 times smaller, the pre-caustic component will have a signal-to-noise of roughly half that of the planetary caustic crossing.

This level of photometric precision and temporal sampling will challenge present day microlensing searches, but may be possible with future microlensing follow-up searches.

3. SAMPLE LIGHT CURVES

In the previous section, we derived simple scaling relations to estimate the magnitude of the deviation one might expect during a caustic-crossing event from a close-in giant planet orbiting the source. We now present a few sample

light curves to confirm our estimates from § 2 and illustrate the effect.

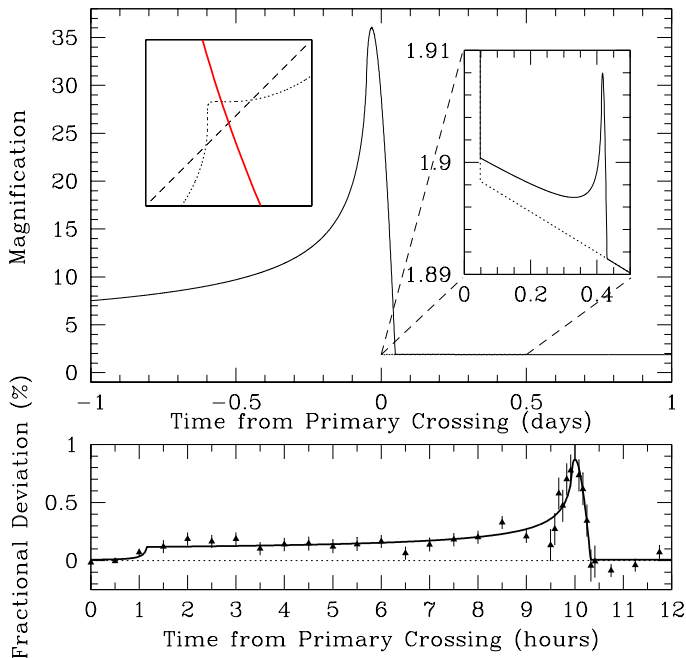


FIG. 1 Top panel: Magnification as a function of time from the primary caustic crossing. The lens is an equal-mass binary at 6 kpc with total mass $1 M_{\odot}$. The source system is an analog of HD 209458 at 8 kpc: a G0V primary with a planet of radius $1.27 R_{\text{Jup}}$ and semi-major axis $a = 0.0467$ AU. The top-left inset shows the geometry of the source system trajectory: the dashed line shows the path of the primary while the dotted line is the path of the secondary. The solid line is the caustic. The right inset shows a blow-up of the light curve immediately after the primary caustic crossing both with (solid curve) and without (dashed curve) the planet. Bottom panel: The fractional deviation from the single-source (i.e. no planet) light curve as a function of time from the primary caustic crossing. The points with error bars are simulated photometric measurements for a $I \simeq 20$ mag star assuming 5 minute exposures on a 10 m telescope and photon noise limited precision. Data outside the planet caustic crossing has been binned in 30 min intervals. In this case, the deviation would be detected with a signal-to-noise of 20.

We adopt typical lens parameters for events toward the Galactic bulge: we assume the lens is an equal-mass binary at 6 kpc with total mass $1 M_{\odot}$, projected separation of $1 R_{\text{E}}$, and transverse velocity $v = 150 \text{ km s}^{-1}$. We begin by assuming the source system is an analog of HD 209458 at 8 kpc: a G0V primary with a planet of radius $1.27 R_{\text{Jup}}$ and semi-major axis $a = 0.0467$ AU (Charbonneau et al. 2000) and the planet orbit plane is face on to the observer. The resulting light curve is shown in Figure 1. Confirming our estimates from § 2, we find that the fractional deviation is $\sim 0.1\%$ for the first ~ 9 hours after the primary caustic crossing, and $0.5 - 1.0\%$ in the ~ 30 min. interval during which the planet is crossing the caustic.

To illustrate the diversity of features possible, in Figure 2 we show light curves one would expect under various assumptions about the lens and source systems. If the planet is very close to the primary $a \lesssim 0.03$ AU, relatively large $R_p \gtrsim 1.5 R_{\text{Jup}}$, or the lens has a low mass $M_{\text{lens}} \lesssim 0.3 M_{\odot}$, then the magnitude of the deviation can

be quite substantial $\delta_p \gtrsim 1\%$, and may be detectable by current microlensing follow-up surveys (at least for bright

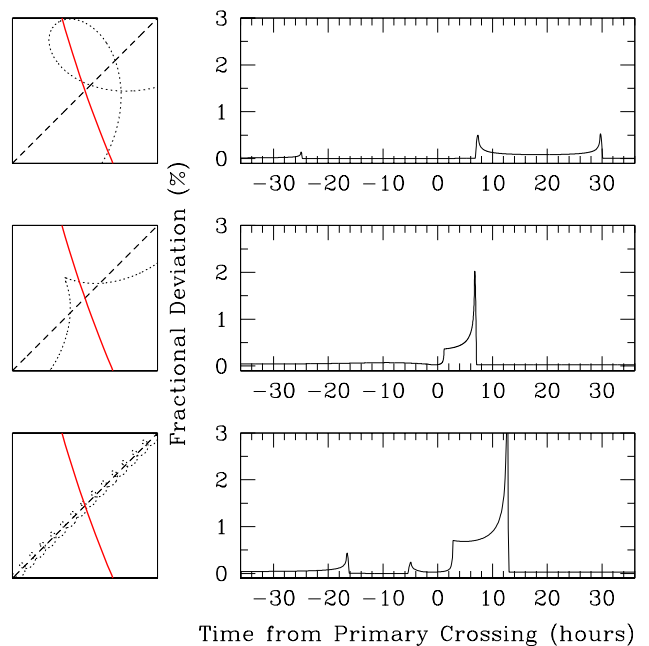


FIG. 2 The right panels show the fractional deviation from the single-source (i.e. no planet) light curve as a function of time from the primary caustic crossing for three different assumptions of the lens and/or planet parameters. In all cases, the primary is a G0V star at 8 kpc. For each panel, the geometry of the source system trajectory is shown to the left. Line types are the same as in Fig. 1. Top panels: Lens mass $M_{\text{lens}} = 0.3 M_{\odot}$, lens distance $D_L = 7$ kpc, lens transverse velocity $v = 60 \text{ km s}^{-1}$. The planet has a radius $R_p = 1.27 R_{\text{Jup}}$ with semi-major axis $a = 0.0467$ AU (as in Fig. 1). Middle panels: $M_{\text{lens}} = 0.3 M_{\odot}$, $D_L = 6$ kpc, $v = 150 \text{ km s}^{-1}$, $R_p = 1.5 R_{\text{Jup}}$, $a = 0.03$ AU. Bottom panels: $M_{\text{lens}} = 1.0 M_{\odot}$, $D_L = 2$ kpc, $v = 20 \text{ km s}^{-1}$, $R_p = 1.5 R_{\text{Jup}}$, $a = 0.03$ AU.

sources). Also, if the period of the planetary orbit is smaller than the time it takes for diameter of the orbit to traverse the caustic, then the planet will cross the caustic three (or more) times. As we discuss in § 4, this would allow one to extract additional information about the planet.

4. DISCUSSION

The current microlensing follow-ups are only marginally able to detect planets around bright source stars by this method. They will only detect the closest in, largest, slowest moving giant planets around relatively bright sources, with low signal to noise and only a handful of photometric measurements. However, these follow-up experiments currently use only 1 meter class ground based telescopes and are further hindered by their relatively poor seeing in extremely crowded fields. A follow-up program involving 1 night on a 10m class telescope with adaptive optics should be able to provide millimagnitude photometry of 19th magnitude bulge sources with 5 minute time resolution, and have a good chance of finding a close in giant planet around the source if one is there to be found.

How many planets per year could be detected? Currently, ~ 50 events are alerted toward the Galactic bulge each year; future upgrades may provide as many as ~ 500

alerts per year. Caustic crossing binaries comprise $\sim 7\%$ of all events (Udalski et al. 2000). Assuming that the fraction of stars in the bulge with close planets is similar to the local neighborhood, $\sim 1\%$, than we would expect to detect of order 1 planet per year. This would require a total ~ 400 hours per season on 10m-class telescopes.

Although the simple detection of a planet around a bulge star is interesting, ultimately, one would like to measure physical parameters of the planet: its radius, semi-major axis, and albedo. Unfortunately, the observables are complicated functions of not only these parameters, but also the inclination and phase of the orbit and the mass and distance to the lensing system. For example, the time scale of the caustic crossing depends on not only the radius of the planet, but also on the projected velocity of the planet around its star and the phase of the planet (a crescent planet will appear to have a smaller radius than a full planet).

Given excellent data on one caustic crossing, it would be possible to determine the effect of the phase of the planet on the width of the caustic crossing from the shape of the crossing alone. The required level of data will probably not be possible with a 10-meter class telescope, but should be possible with a 100-meter telescope such as the OWL (Gilmozzi et al. 1998). Even then, it still will not be possible to recover the velocity of the planet, and therefore impossible to measure its radius. However, if the transverse velocity of the star normal to the caustic is smaller than the velocity of the planet, it is possible that there will be three caustic crossings. If all three are detected, each with its own time and its own time scale, then the

orbit can be solved, and the radius determined, even without inferring the planetary phase from small fluctuations in the light curve.

Irrespective of whether or not the orbit can be solved, planetary caustic crossings act like a telescope with tremendous angular resolution perpendicular to the caustic. The angular dependence of the planetary albedo may be observable. In the future, enormous telescopes such as the OWL may be able to achieve enough temporal resolution to see the bands and red spot on a Jupiter around a star clear across the Galaxy.

5. CONCLUSIONS

We have shown that the presence of a giant close-in planet around the source star of a caustic crossing microlensing event could generate an order 1% deviation in the light curve. This deviation would be detectable with a 10 meter class telescope making measurements every few minutes over the course of a night. In some cases, the planet will transit the caustic more than once, allowing for complete solution of the orbit and a determination of the radius and albedo of the planet. Follow-up with 100 meter class telescopes may allow for resolution of limb darkening and spots or bands on the surface of these planets.

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REFERENCES

- Afonso, C., et al. 1998, *A&A*, 337, L17
 Afonso, C., et al. 2000, *ApJ*, in press
 Albrow, M., et al. 1998, *ApJ*, 509, 687
 Albrow, M., et al. 1999, *ApJ*, 512, 619
 Albrow, M., et al. 2000, in preparation
 Alcock, C., et al. 1996, *ApJ*, 463, L67
 Alcock, C., et al. 1997, *ApJ*, 491, 436
 Alcock, C., et al. 1999, *ApJ*, 518, 44
 Alcock, C., et al. 2000, *ApJ*, submitted (astro-ph/9907369)
 Bryce, H. & Hendry, M. 2000, in "Microlensing 2000: A New Era of Microlensing Astrophysics", ed. P. Sackett & J. Menzies, to be published in ASP Conference Proceedings Series
 Charbonneau, D., et al. 2000, *ApJ*, 529, L45
 Cochran, W.D., et al. 1997, *ApJ*, 483, 457
 Erdl, H., & Schneider, P. 1993, *A&A*, 268, 453
 Gaudi, B.S. 1998, *ApJ*, 506, 533
 Gilmozzi, R. et al. 1998, *SPIE*, 3352, 778
 Glicenstein, J.-F. 2000, in "Microlensing 2000: A New Era of Microlensing Astrophysics", ed. P. Sackett & J. Menzies, to be published in ASP Conference Proceedings Series
 Gould, A., & Loeb, A. 1992, *ApJ*, 396, 104
 Han, C., et al. 2000, *MNRAS*, in press
 Heyrovský, D., & Sasselov, D. 2000, *ApJ*, 529, 69
 Mao, S., & Paczyński, B. 1991, *ApJ*, 374, 37
 Marcy, G., & Butler, R. 1998, *ARA&A*, 36, 57
 Marcy, G., & Butler, R. 2000, *PASP*, 112, 137
 Mayor, M., & Queloz, D. 1995, *Nature*, 378, 355
 Noyes, R.W., et al. 1997, *ApJ*, 483, L111
 Rhie, S.H., et al. 1999, *ApJ*, 522, 1037
 Sackett, P.D. 1999, in *Planets outside the Solar System: theory and observations*, eds. J.-M. Mariotti & D. Alloin (NATO-ASI Ser. C; Kluwer), 189
 Schneider, P., & Weiss, A. 1986, *A&A*, 164, 237
 Schneider, P., & Weiss, A. 1987, *A&A*, 171, 49
 Schneider, P., Ehlers, J., & Falco, E.E. 1992, *Gravitational Lenses* (Berlin, Springer)
 Udalski, A., et al. 1994, *Acta Astron.*, 44, 227
 Udalski, A., et al. 1993, *Acta Astron.*, 47, 169
 Udalski, A., et al. 2000, *Acta Astron.*, submitted (astro-ph/0002418)