CHARACTERIZATION OF MICROLENSING PLANETS WITH MODERATELY WIDE SEPARATIONS

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ABSTRACT
In future high-cadence microlensing surveys, planets can be detected through a new channel of an independent event produced by the planet itself. The two populations of planets to be detected through this channel are wide-separation planets and free-floating planets. Although they appear as similar short timescale events, the two populations of planets are widely different in nature and thus distinguishing them is important. In this paper, we investigate the lensing properties of events produced by planets with moderately wide separations from host stars. We find that the lensing behavior of these events is well described by the Chang–Refsdal lensing, and the shear caused by the primary not only produces a caustic but also makes the magnification contour elongated along the primary-planet axis. The elongated magnification contour implies that the light curves of these planetary events are generally asymmetric, and thus the asymmetry can be used to distinguish the events from those produced by free-floating planets. The asymmetry can be noticed from the overall shape of the light curve and thus can hardly be missed unlike the very short duration central perturbation caused by the caustic. In addition, the asymmetry occurs regardless of the event magnification, and thus the bound nature of the planet can be identified for majority of these events. The close approximation of the lensing light curve to that of the Chang–Refsdal lensing implies that the analysis of the light curve yields only the information about the projected separation between the host star and the planet.

Key words: gravitational lensing – planetary systems

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1. INTRODUCTION

The microlensing signal of a planet is a short-term perturbation to the smooth standard single-lens light curve of the primary-induced lensing event occurring on a background source star. For the detections of short-duration microlensing signals of planets, current lensing searches are being conducted in combination of survey and the follow-up observations, where the survey observations aim to maximize the number of detections of lensing events by monitoring a large area of sky; and follow-up observations are focused on intensive monitoring of the events detected by the survey observations. Under this strategy, events can be followed up while they are undergoing lensing magnification and thus only planets within a certain range, the so-called lensing zone (Gould & Loeb 1992), can be detected.

If the monitoring frequency of survey observations is sufficiently high, planets can be detected through a channel of an independent event produced by the planet itself. Currently, the MOA Collaboration (Bond et al. 2002) is devoting a portion of observation time for high-frequency survey by using its telescope with a 2.18 deg² field of view. It is also planning to upgrade the telescope for an even wider field of view of 4.0 deg² (F. Abe 2009, private communication). In 2009, the OGLE Collaboration (Udalski et al. 2003) plans to increase the field of view of the camera from 0.4 deg² to 1.4 deg² for higher monitoring frequency (A. Udalski 2009, private communication). KMTNet (Korea Microlensing Telescope Network) is a planned experiment to achieve continuous resolution of planetary lensing signals of down to sub-Earth-mass planets by using a network of three 1.6 m telescopes to be located in Chile, South Africa, and Australia (B. Park 2009, private communication). Together with a 4.0 deg² field of view of each telescope, the experiment will monitor the same field every 10 minutes. MPF (Microlensing Planet Finder) is a space-based experiment proposed to NASA to achieve a similar cadence to KMTNet (D. Bennett 2009, private communication). With the enhanced monitoring frequency of these experiments, the efficiency of planet detection will greatly improve.

The two populations of planets to be additionally detected from high-frequency surveys are wide-separation planets and free-floating planets (Han 2007). Although appearing as similar short timescale events, the two populations of planets are widely different in nature. Therefore, it is important to distinguish the two populations. In this paper, we investigate the characteristics of events produced by bound planets with wide separations and examine the feasibility of distinguishing them from those produced by free-floating planets.

The paper is organized as follows. In Section 2, we briefly describe the lensing properties of planetary events. In Section 3, we investigate the lensing properties of events produced by planets with moderately wide separations and examine whether these properties can be used for distinguishing the planets from free-floating planets. We also investigate what kind of information about wide-separation planets can be obtained from the analysis of light curves. In Section 4, we compare the proposed method with other methods. We summarize and conclude in Section 5.

2. PLANETARY LENSING

The planetary lensing behavior is described by the formalism of binary lensing with a small mass-ratio companion. For binary lensing, the equation of lens mapping from the lens plane to the source plane is expressed as (Mao & Paczyński 1991)

\[ \xi = z - \frac{1}{z} - \left( \frac{q}{1-q} \right) \frac{1}{z - z_p}, \] (1)

where \( \xi = \xi + i\eta \) and \( z = x + iy \) represent the complex notations of the source and the image positions, respectively,
the primary is at the center, $z_p$ represents the position of the planet, $\bar{z}$ denotes the complex conjugate of $z$, and $q$ represents the planet/primary mass ratio. Here, all lengths are normalized by the Einstein radius corresponding to the total mass of the lens system, $\theta_E$. One important characteristic of binary lensing is the formation of caustics, which represent the set of source positions on which the lensing magnification of a point source becomes infinite. As a result, the magnification pattern in the region around the caustic deviates from the smoothly varying pattern in the region away from the caustic, and thus events resulting from source trajectories passing close to the caustic produce noticeable perturbations in lensing light curves. The set of caustics forms closed curves, each of which is composed of concave curves that meet at cusps. For planetary lensing, there exist two sets of caustics. One tiny “central caustic” is located close to the primary lens. The other “planetary caustic” with a relatively large size is located away from the primary at the position of

$$\zeta_c = s(1 - s^{-2}),$$  

where $s$ is the normalized separation vector to the position of the planet from the position of the primary. The size of the planetary caustic as measured by the separation between the two cusps on the star–planet axis is (Han 2006a)

$$\Delta \xi_c \propto \frac{4q^{1/2}}{s(s^2 - 1)^{1/2}}.$$  

For a wide-separation planet, the size of the caustic decreases as $\Delta \xi_c \propto s^{-3}$.

If a lensing event is produced by the approach of a source trajectory close only to the magnification region around the planetary caustic induced by a wide-separation planet, the resulting light curve, to the first order of approximation, appears as a single-lens light curve produced by the planet itself. For a planet with a moderately wide separation, however, the magnification pattern exhibits deviations from single lensing due to the lensing influence of the primary. For planets with separations in this regime, the magnification pattern is approximated by the Chang–Refsdal lensing. The Chang–Refsdal lensing represents single lensing superposed on a uniform background shear (Chang &Refsdal 1979, 1984; Mao 1992; An &Evans 2006). The lens-mapping equation of the Chang–Refsdal lensing is represented by

$$\zeta = z - \frac{1}{\bar{z}} + \gamma \bar{z},$$

where $\gamma$ is the shear. For the case of the planetary lensing with a wide-separation planet, the shear exerted by the primary lens on the magnification region of the planet is

$$\gamma \sim \frac{m_s/m_p}{\hat{s}^2} = \frac{1}{(1 + q)s^2} \sim \frac{1}{s^3},$$

where $m_s$ and $m_p$ are the masses of the primary star and the planet, respectively, and $\hat{s} = [(1 + q)/q]^{1/2}s \sim q^{-1/2}s$ is the planetary separation normalized by the Einstein radius corresponding to the mass of the planet, $\theta_{E,p}$. The shear induces a single caustic that forms around the lens. The caustic has the shape of a hypocycloid with four cusps. The size of the caustic as measured by the separation between the two confronting cusps is

$$\Delta \xi_{c,C-R} \sim 4 \gamma \sim 4s^{-2},$$

where the caustic size is normalized by $\theta_{E,p}$. The shear decreases rapidly with the increase of the planetary separation. As a result, for an event produced by a very wide separation planet, it becomes difficult to distinguish the resulting light curve from that of an event produced by a free-floating planet.

3. LENSING BY WIDE-SEPARATION PLANETS

To investigate the lensing properties of events produced by wide-separation planets, we produce maps of magnification pattern in the region around the planets. For events produced by small-mass planets, the size of the source star is not negligible compared to the Einstein radius of the planet and thus the finite-source effect is important. We take the effect into consideration by using the ray-shooting method. In this method, a large number of light rays are uniformly shot from the observer plane through the lens plane and then collected in the source plane. Then, the lensing magnification considering the finite-source effect is computed by comparing the number density of rays within the source radius with the density on the lens plane. In addition, this method is easily applicable to any form of lensing as long as the mapping equation is known, and thus allows us to study both planetary and Chang–Refsdal lensing with minor modification of the computation code.

Figure 1 shows the constructed maps of magnification pattern for planets with various separations from the host star. For each map, the temperature scale represents the magnification where brighter tone implies higher magnification. Contours are drawn at the levels of the single-lens magnifications corresponding to the normalized lens–source separations of $u = 0.1, 0.2, 0.3, \ldots, 1.0$, respectively, i.e., $A(u) = (u^2 + 2)/u(u^2 + 4)^{1/2}$. The panels in the upper row show the regions around the planetary caustic with $|\xi_p| \leq 1.5$ and $|\eta_p| \leq 1.5$, where $(\xi_p, \eta_p)$ are the coordinates centered at the center of the planetary caustic, $\hat{\xi}_p$ is aligned with the star–planet axis, and lengths are normalized by $\theta_{E,p}$. The planets have a common mass ratio of $q = 6 \times 10^{-3}$. We assume a ratio of the source radius $\theta_s$ to the Einstein radius of the primary lens of $\theta_s/\theta_E \approx 0.003$, which is a typical value for Galactic bulge events occurring on a bright main-sequence star. When normalized by the Einstein radius of the planet, this corresponds to $\theta_s/\theta_{E,p} \sim 0.04$. The maps in the second row show the blowups of the box regions in the corresponding upper panels. The panels in the lower row show the maps constructed by using the mapping equation of the Chang–Refsdal lensing.

From the investigation of the maps, we find the following properties of the magnification pattern.

1. The caustic occupies a small portion of the area enclosed by the Einstein ring of the planet.
2. The Chang–Refsdal lensing is a good approximation for planets with moderately wide separations of $s \gtrsim 3$.
3. The shear caused by the primary star not only induces a caustic but also makes the magnification contour elongated along the star–planet axis.

The properties of wide-separation planetary events have several important implications in characterizing planets to be detected through the channel of independent events in future lensing surveys. First, the small size of the caustic implies that the bound nature of a planet can be identified from the caustic-induced perturbation (Han & Kang 2003) only for a small fraction of high-magnification events with source trajectories approaching close to the central caustic. If it is assumed that the perturbation region extends up to twice of the caustic size, the chance to be perturbed by the caustic is $\sim 2 \times (\Delta \xi_{c,C-R}/2) \sim$
Maps of magnification pattern of wide-separation planets with various separations from the host star. The separation $s$ is normalized by the Einstein radius corresponding to the mass of the primary, $\theta_E$. The planets have a common mass ratio of $q = 6 \times 10^{-3}$, and the source star has a radius of $0.03 \theta_E$ or equivalently $0.04 \theta_{E,p}$, where $\theta_{E,p}$ is the Einstein radius corresponding to the planet mass. For each map, the temperature scale represents the magnification where brighter tone implies higher magnification. Contours are drawn at the levels of the single-lens magnifications corresponding to the normalized lens–source separations of $u = 0.1, 0.2, 0.3, \ldots, 1.0$, respectively. The upper panels show the regions around the planetary caustic with $|\xi_p| \leq 1.5$ and $|\eta_p| \leq 1.5$, where $(\xi_p, \eta_p)$ are the coordinates centered at the center of the planetary caustic and lengths are normalized by $\theta_{E,p}$. The panels in the middle row show the blowups of the box region in the corresponding upper panels. The panels in the bottom row show the maps constructed based on Chang–Refsdal lensing.

Figure 2. Light curve of events produced by wide-separation planets with various separations from the host star. The source trajectories responsible for the individual light curves are marked in the corresponding panels in Figure 1. For each color, the solid curves are based on exact planetary lensing while the dashed curve is based on Chang–Refsdal lensing. Note that the timescale $t_E$ corresponds to the planetary mass.

4$s^{-2}$ among the events produced by the entrance of the source star within the Einstein ring of the planet. This corresponds to $\sim 16\%$ of all events produced by a planet with $s = 5$.

Second, the elongation of the magnification contour implies that the light curves of events produced by planets with moderately wide separations are in general asymmetric (Night et al. 2008), and thus the asymmetry of the light curve can be used to identify the bound nature of the planet. Figure 2 shows several examples of light curves resulting from the source trajectories marked in the corresponding panels in Figure 1. The perturbation induced by the caustic lasts only for a very short duration considering that the timescale $t_E$ corresponds to the planetary mass.

4. DISCUSSION

Besides the methods of using the central perturbation and the asymmetry of the light curve, wide-separation planets can also be distinguished from free-floating planets by using other methods. One method is using an additional bump in the lensing light curve produced by the primary star. This method is applicable to events where the source trajectory passes the magnification region of the planet and also approaches the magnification zone of the primary (Di Stefano & Scalzo 1999). The disadvantage of this method is that only a fraction of events produce bumps and the fraction decreases with the increase of the star–planet separation.

Another photometric method is analyzing the baseline flux of the event. If nonzero baseline flux is measured and the source
of the baseline flux is identified as the lens itself, the planet can be identified as a bound planet. The source of the baseline flux can be identified from high-resolution images obtained by using instruments such as the Hubble Space Telescope, the Very Large Telescope (VLT), or the Keck telescopes. However, the applicability of this method is limited by the telescope time for high-resolution follow-up observations.

Finally, the two populations of planets can also be distinguished by conducting astrometric follow-up observations. Due to the much longer range of astrometric lensing effect than photometric effect combined with the much larger mass of the primary than the planet, the primary star will affect the centroid motion of the source star induced by the planet (Han 2006b). This method requires astrometric observations by using high-precision interferometers such as those to be mounted on space-based platforms, e.g., the Space Interferometry Mission, or on very large ground-based telescopes, e.g., VLT or Keck. Therefore, the application of this method is also limited by the telescope time for follow-up observations.

5. CONCLUSION

We investigated the lensing properties of events produced by the approach of the source trajectory only to the magnification region of a planet with a moderately wide separation from the host star. We found that the lensing behavior of these events is well described by the Chang–Refsdal lensing, and the shear caused by the primary not only produces a caustic but also makes the magnification contour elongated along the primary–planet axis. The elongated shear implies that the light curves of these planetary events are generally asymmetric, and thus the asymmetry can be used to distinguish the events from those produced by free-floating planets. We, therefore, propose to model the light curves of short timescale events with either planetary or Chang–Refsdal lensing even though the light curves seemingly appear to be single-lensing ones. The asymmetry can be noticed from the overall shape of the light curve and thus can hardly be missed unlike the very short duration central perturbation caused by the caustic. In addition, the asymmetry occurs regardless of the event magnification, and thus the bound nature of the planet can be identified for majority of events. The close approximation of the lensing light curve to that of the Chang–Refsdal lensing implies that the analysis of the light curve yields only the information about the projected separation between the host star and the planet.

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