DISTINGUISHING BETWEEN PLANETARY AND BINARY INTERPRETATIONS OF MICROLENSING CENTRAL PERTURBATIONS UNDER THE SEVERE FINITE-SOURCE EFFECT

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ABSTRACT

Within the current strategy of microlensing planet searches focusing on high-magnification events, wide and close binaries give rise to important sources of contamination that imitate planetary signals. For the purpose of finding systematic differences, we compare the patterns of central perturbations induced by a planet and a binary companion under the severe finite-source effect. We find that the most prominent difference shows up in the morphology of the edge features with negative excess that appears at the edge of the circle with its center located at the caustic center and a radius equivalent to the source radius. It is found that the feature induced by a binary companion forms a complete annulus, while the feature induced by a planet appears as several arc segments. This difference provides a useful diagnostic for immediate discrimination of a planet-induced perturbation from that induced by a binary companion, where the absence of a well-developed dip in the residual from the single-lensing light curve, at both or either of the moments of the caustic center’s entrance into and exit from the source star surface, indicates that the perturbation is produced by a planetary companion. We find that this difference is basically caused by the difference between the shapes of the central caustics induced by the two different types of companion.

Key words: gravitational lensing – planets and satellites: general

1. INTRODUCTION

Microlensing planets are being discovered at an increasing rate and the total number of detections has now reached eight (Bond et al. 2004; Udalski et al. 2005; Beaulieu et al. 2006; Gould et al. 2006; Gaudi et al. 2008; Dong et al. 2009; Bennett et al. 2008). The microlensing signal of a planet is a brief perturbation to the smooth standard light curve of the primary-induced lensing event occurring on a background star. To achieve the monitoring frequency required to detect short-duration planetary signals, current planetary lensing searches are being conducted using a combination of survey and follow-up observations, where alerts of ongoing lensing events are issued by the survey observations (OGLE: Udalski et al. 1994, MOA: Bond et al. 2001) and the alerted events are intensively monitored by the follow-up observations (Micro-FUN: Dong et al. 2006, PLANET: Kubas et al. 2008). However, the number of telescopes available for follow-up observations is far smaller for intensive monitoring of all alerted events (Dominik et al. 2008) and thus observations are focused on events which can maximize the planet detection probability with follow-up observations. Currently, the prime targets of follow-up observations are high-magnification events for which the source trajectories always pass close to the perturbation region around the central caustic induced by a planet and thus planet detection efficiency is intrinsically high (Griest & Safizadeh 1998).

Although high-magnification events yield high sensitivity to planets, interpretation of the observed perturbation often suffers from several potential degeneracies. There are two major degeneracies causing this complication. The first well-known wide/close degeneracy arises due to the fact that the perturbation induced by a planet with a projected separation in units of the Einstein ring, \( s \), is very similar to the perturbation induced by a planet with a separation \( 1/s \) (Dominik 1999; An 2005; Chung et al. 2005).1 The other degeneracy arises due to the fact that a central perturbation of a high-magnification event can also be produced by a very close \((s \ll 1)\) or a very wide \((s \gg 1)\) binary with roughly equal mass components. Hereafter, we refer to the latter degeneracy as the “planet/binary” degeneracy. In the sense that the planet/binary degeneracy causes indeterminacy of both of the mass ratio and the separation between the lens components, while the wide/close degeneracy causes ambiguity only in the separation, the planet/binary degeneracy poses a more serious problem in the interpretation of an observed perturbation. Fortunately, the perturbations induced by a planet and a binary are intrinsically different and thus it would be possible to determine whether the perturbation is caused by a planet or a binary. However, distinguishing between the two interpretations usually requires detailed modeling which demands a time-consuming search for a solution in the vast parameter space. Therefore, a simple diagnostic that can resolve the planet/binary degeneracy would be very helpful not only for the prompt interpretation of an observed perturbation but also for the establishment of the observational setup optimizing the coverage of the characteristic features helping to resolve the degeneracy. Han & Gaudi (2008) provided such a diagnostic but this diagnostic applies to a subset of light curves with double-peak features.

Recently, Dong et al. (2009) reported a planet detected from the analysis of a new type of high-magnification event where the angular extent of the perturbation region induced by the planet is significantly smaller than the angular size of the source and thus the finite-source effect is very severe. The main perturbation features of this event are double spikes in the residuals, which are approximately centered at the times when the lens enters and exits the source. In the 2008 season, several more such events were detected (A. Gould 2008, private communication; P. Fouque 2008, private communication), implying that events with these features might be common. From detailed investigation, Han & Kim (2009) found that spike features commonly appear for planetary-lensing events affected by the severe finite-source effect and thus they can be used for the diagnosis of the existence of a planet. However, they noted that such features

1 We note that the wide/close degeneracy occurs not only for planetary events but also for binary events in general (Dominik & Hirshfeld 1996).
can also be produced by a wide or close binary companion and thus the existence of the feature does not necessarily confirm the planetary interpretation of the perturbation.

In this Letter, we investigate the systematic differences between the patterns of central perturbation induced by a planet and a binary companion. From this, we identify a diagnostic that can be used to immediately distinguish between the planetary and binary interpretations. We also investigate the origin of the difference.

2. PERTURBATION PATTERN

The pattern of central perturbations is basically determined by the caustic shape. The shapes of the caustics induced by a planet and a binary companion are intrinsically different and thus the resulting patterns of the perturbations produced by the two types of lens systems will be different.

For a wide binary system, the central caustic has a hypocycloid shape with four cusps. When the horizontal and vertical widths of the caustic are measured as the separations between the two confronting cusps located on and off the binary axis, respectively, the ratio of the vertical to horizontal widths is represented by (Han et al. 2005)

\[ R_b \sim \left( \frac{1 - \gamma}{1 + \gamma} \right)^{1/2}; \quad \gamma = \frac{q}{(1 + q)s^2}, \]  

where \( \gamma \) represents the shear exerted by the companion. As the binary separation increases, the shear decreases and the width ratio becomes \( R_b \to 1 \), implying that the horizontal and the vertical widths are nearly identical for a wide binary. In addition, the shape of the caustic is symmetric with respect to both of the binary axis and the axis normal to the binary axis. The caustic induced by a close binary is approximately identical to that of the wide binary with a separation of \( s^{-1} \).

In contrast, the central caustic induced by a planet has an elongated wedge-like shape. The width ratio of the planetary central caustic defined in a similar way to that of the binary case is represented by (Chung et al. 2005)

\[ R_p \sim \frac{(s - s^{-1})[\sin^3 \phi]}{(s + s^{-1} - 2 \cos \phi)^2}, \]  

where \( \cos \phi = (3/4)(s + s^{-1})\{1 - [32/9(s + s^{-1})^2]\}. For a range of planetary separations where the size of the central caustic is not negligible (see Han 2009), the width ratio of the central caustic is substantially smaller than unity, implying that the caustic is elongated along the planet primary axis. In addition, three of the four cusps of the caustic lean toward the primary direction. As a result, the caustic is not symmetric with respect to the axis normal to the planet primary axis.

Another important factor that affects the perturbation pattern is the effect of the finite size of a source star. The lensing magnification affected by the finite-source effect corresponds to the magnification averaged over the source star surface. As a result, the signal of the companion is smeared out by the finite-source effect and the degree of the effect depends on the ratio of the caustic size to the size of the source star.

2.1. Excess Maps

To see the difference between the patterns of central perturbations induced by a planet and a binary companion under the severe finite-source effect, we construct maps of magnification excess around the central caustics of the individual lens systems. The magnification excess is defined as

\[ \epsilon = \frac{A - A_0}{A_0}, \]  

where \( A \) and \( A_0 \) represent the lensing magnifications with and without the companion, respectively. To compute the magnification, we use a ray-shooting based algorithm developed by Dong et al. (2006). The algorithm is optimized for high-magnification events and saves computation time by limiting the range of ray shooting on the image plane to a narrow annulus around the Einstein ring. We take the finite-source effect into consideration by modeling the source brightness profile as

\[ \frac{I(\theta)}{I_0} = 1 - \Gamma \left( 1 - \frac{3}{2} \frac{\cos \theta}{q} \right) - \Lambda \left( 1 - \frac{5}{4} \cos^{1/2} \theta \right), \]  

where \( \theta \) is the angle between the normal direction to the source-star surface and the line of sight. We adopt a linear and a square-root limb-darkening coefficient of \( (\Gamma, \Lambda) = (-0.46, 1.11) \).

Figures 1 and 2 show the constructed excess-pattern maps represented in color scales. In each figure, the map in the upper left panel is constructed by considering the finite-source effect while the map in the lower left panel is for a point source. The abscissa of the map is parallel with the axis connecting the two lens components and the center is located at the caustic center, which is located at a position with an offset from the position of the primary, given by

\[ \delta = \begin{cases} \frac{s^{-1}q}{1 + q} & \text{for } s > 1, \\ -s[(1 + q)^{-1} - 1] & \text{for } s < 1, \end{cases} \]  

where the sign is positive when the offset vector is directed toward the companion and vice versa. The companion is located on the right and all lengths are normalized by the source radius. Colors are chosen such that the regions with brown and blue-tone colors represent, respectively, the areas where the magnification is higher than the single-lensing magnification without the companion. For each contour, the color scale becomes darker at the excess levels of \( \epsilon = 2\%, 4\%, 8\%, 16\%, \) and 32\%, respectively.

From the maps, one finds several features that commonly appear in the perturbation patterns of both planetary and binary cases. The first feature is a region of little excess inside a circle with its center located at the caustic center and a radius corresponding to that of the source star (dashed circle in each map). The other feature is the perturbation regions that appear at the edge of the circle with either positive or negative excess. Han & Kim (2009) pointed out that the very small excess inside the circle is caused by the cancellation of the positive and negative excesses by the finite-source effect. They also indicated that the feature at the edge of the circle (hereafter we refer to this feature as the “edge feature”) is formed by the break of the balance between the positive and negative excesses due to a partial coverage of the strong excess region around the caustic by the source star. These features in combination result in a distinctive signal of a companion in the residual of a light curve, which is characterized by a spike of either positive or negative excess at the moment when the center of the caustic enters or exits the source star and a flat residual region between the spikes. See Figure 3 of Han & Kim (2009).
2.2. Diagnosis

Along with the similarities, we find that there also exist systematic differences between the patterns of the perturbations induced by a planet and a binary companion. The most prominent difference shows up in the morphology of the edge features with negative excess. It is found that the feature induced by a binary companion forms a complete annulus, while the feature induced by a planet appears as several arc segments. We find that this trend holds for nearly all planetary systems with mass ratios $q \lesssim 10^{-2}$ and separations where the planet detection efficiency is important. See Figure 1 of Han (2009).

To search for the origin of these differences, we produce additional maps showing the region enclosed by the source star at the time when it is located at various positions of the annulus where the negative-edge features systematically occur. These maps are presented on the right sides of Figures 1 and 2. From close examination of the perturbation pattern, it is found that the morphological differences between the planetary and binary cases are basically caused by the difference in the shape of the caustics. The shape of the caustic induced by the planet lacks symmetry. As a result, the location of the source position where the overall excess is negative depends on the orientation of the source position with respect to the caustic. For example, when the source is located at the position on the annulus toward the direction of the sharp-pointed cusp marked as “1,” the number of strong negative excess regions within the area encompassed by the source star is three (two just outside the fold caustics and the other inside the caustic) while there exists only a single strong positive excess region (the one extending from the cusp), resulting in overall negative excess. By contrast, when the source is located at the opposite position marked as “4,” there are equal numbers of positive and negative excess regions of three, respectively, and thus the resulting excess is very small. In contrast to the shape of the planet-induced caustic, the shape of the binary-induced caustic is more symmetric and thus the regions of negative excess appear in all regions along the annulus.

The systematic difference in the morphology of the perturbation patterns enables one to distinguish between the perturbations caused by planetary and binary companions. Due to the continuity of the negative-edge feature in the excess pattern, the perturbation in the light curve of a lensing event induced by a wide-separation binary will have well-developed negative spikes in the residual at both moments when the caustic center enters and exits the source star. On the other hand, the edge feature induced by a planet is split into segments and thus the resulting light curve will not often have a negative spike in the residual at both or either of the moments of entrance and exit. Therefore, the absence of the double negative-spike feature can be used as a simple diagnostic to immediately distinguish the planetary interpretation from the binary interpretation.

In Figure 3, we present residuals of lensing light curves of several example planetary (solid curve) and binary events (dotted curve) for binary stars.
Figure 3. Residuals of lensing light curves from a single-lensing one for examples of planetary and wide-separation binary events. Note that for the case of the binary, well-developed negative spikes occur at both moments when the center of the caustic enters and exits the source star. On the other hand, a negative spike may not occur at one (middle panel) or both of the moments (upper panel). The source trajectories responsible for the individual events are marked in Figures 1 and 2 with the corresponding Roman numbers. Time is normalized by the duration required for the lens to cross the source radius, $t_c$.

curve), where the source trajectories responsible for the individual events are marked in Figures 1 and 2 with the corresponding Roman numbers. For the binary case, there always exist two well-developed negative spikes. For the planetary case, on the other hand, there can be no (upper panel) or only a single (middle panel) spike. Setting a critical value of the magnification excess to define the term “well-developed spike” is not easy due to the variation of the perturbation pattern combined with the difficulty in the conversion of the observed flux into magnification. Nevertheless, the term can be defined in the observational point of view as a well-resolved dip in the residual observed with high enough precision. Under this definition, a spike with deviation $\geq 3\%$ can be well resolved considering that the photometric precision of the current follow-up observations reaches $\sim 1\%$ at the peaks of high-magnification events. We note that a planet can produce perturbations with double negative-spike features as shown in the lower panel of Figure 3. Therefore, the existence of double negative spikes does not necessarily confirm that the perturbation is caused by a binary companion. In this case, the proposed diagnostic cannot be used and detailed modeling is required to distinguish between the two interpretations.

3. CONCLUSION

We compared the patterns of central perturbations induced by a planet and a binary companion under the severe finite-source effect. We found that the most prominent difference shows up in the morphology of the edge features with negative excess, where the feature induced by a binary companion forms a complete annulus, while the feature induced by a planet appears as several arc segments. This difference provides a useful diagnostic for immediate discrimination of a planet-induced perturbation from that induced by a binary companion, where the absence of a well-developed dip in the residual from the single-lensing light curve, at both or either of the moments of the caustic center’s entrance into or exit from the source star surface, indicates that the perturbation is produced by a planetary companion. We found that this difference is basically caused by the difference between the shapes of the central caustics induced by the two different types of companions.

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