THE IMPORTANCE OF BINARY GRAVITATIONAL MICROLENSING EVENTS THROUGH HIGH-MAGNIFICATION CHANNEL

CHEONGHO HAN AND KYU-HA HWANG

Department of Physics, Chungbuk National University, Cheongju 361-763, Republic of Korea; cheongho@astroph.chungbuk.ac.kr, kyuha@astroph.chungbuk.ac.kr

Received 2009 October 5; accepted 2009 November 4; published 2009 December 3

ABSTRACT

We estimate the detection efficiency of binary gravitational lensing events through the channel of high-magnification events. From this estimation, we find that binaries in the separation ranges of $0.1 \lesssim s \lesssim 10$, $0.2 \lesssim s \lesssim 5$, and $0.3 \lesssim s \lesssim 3$ can be detected with $\sim 100\%$ efficiency for events with magnifications higher than $\lambda = 100$, 50, and 10, respectively, where $s$ represents the projected separation between the lens components normalized by the Einstein radius. We also find that the range of high efficiency covers nearly the whole mass-ratio range of stellar companions. Due to the high efficiency in wide ranges of parameter space, we point out that the majority of binary-lens events will be detected through the high-magnification channel in lensing surveys that focus on high-magnification events for efficient detections of microlensing planets. In addition to the high efficiency, the simplicity of the efficiency estimation makes the sample of these binaries useful in the statistical studies of the distributions of binary companions as functions of mass ratio and separation. We also discuss other implications of these events.

Key words: gravitational lensing

Online-only material: color figure

1. INTRODUCTION

If a star is gravitationally microlensed by a lens system composed of two masses, the resulting light curve can dramatically deviate from the smooth and symmetric one of a single-lens event. This deviation is caused by the formation of caustics for binary-lens systems. The caustics represent the source positions at which the lensing magnification of a point source becomes infinite. The set of caustics forms one, two, or three close curves each of which is composed of concave curves that meet at points. By analyzing the light curve of a binary-lens event, it is possible to obtain information about the lens system because the structure of the caustic system and the resulting light curve vary depending on the mass ratio and the projected separation between the components of binary lenses.

Since the pioneering work by Chang & Refsdal (1980, 1984), binary lensing has been a subject of intense theoretical studies. Schneider & Weiss (1986) made a comprehensive study of binary lenses in order to learn about caustics in quasar microlensing. Witt (1990) developed a simple algorithm for finding caustics of binary lenses. Witt & Mao (1995) studied lensing magnification inside caustic and found that the minimum magnification, when the source is inside a caustic, is greater than 3. Rhie (1997) found the maximum number of images for multiple-lens systems. With the beginning of microlensing surveys, theoretical studies became even more active. Gaudi & Gould (1997) pointed out that microlensing is an efficient method to detect close binaries. Di Stefano & Perna (1997) mentioned various channels of detecting binaries including repeating events. Dominik (1999b) studied the lensing behavior in the extreme cases of binary separations and mass ratios. Dominik (1999a) and Albrow et al. (1999b) mentioned possible degeneracies in modeling light curves of binary-lens events. Han et al. (1999) and Han (2001) studied the astrometric behavior of binary-lens events. Bozza (2000, 2001) derived analytic expressions for the location of caustics and studied the motion of images of microlensed stars. Gaudi & Petters (2002a, 2002b) investigated the photometric and astrometric behaviors in the region very close to caustics. Graff & Gould (2002) devised a method to measure the mass of the binary-lens system from the analysis of light curves of caustic-crossing events. In addition to the theoretical studies, binary-lens events were actually detected from various surveys (Udalski et al. 1994, 1998; Alcock et al. 1999; Alard et al. 1995; Afonso et al. 2000; Albrow et al. 1999a, 2000, 2001; An et al. 2002; Smith et al. 2002; Albrow et al. 2002; Abe et al. 2003; Kubas et al. 2005; Jaroszynski et al. 2004; Cassan et al. 2004; Jaroszynski et al. 2005, 2006).

With the active research in both theoretical and observational fields, binary microlensing has developed into a useful tool to study stellar astrophysics. The most active field of application is the stellar atmosphere for which microlensing is used to probe detailed structures on the surface of source stars by using the high resolution of caustic-crossing events (Albrow et al. 1999a, 2001; Abe et al. 2003). Microlensing can also be used to probe the distributions of binary companions of Galactic stars as functions of mass ratio and separation. These binary distributions provide important observational constraints on theories of star formation. Since microlensing is sensitive to low-mass companions that are difficult to be detected by other methods, it is, in principle, possible to make complete distribution down to the lower mass limit of binary companions. Despite the importance, the progress of this application of binary lensing has been stagnant. There are two main reasons for this. The first reason is caused by the difficulty in estimating the detection efficiency of binary-lens events. In previous lensing surveys, most binary-lens events were discovered through the channel of caustic-crossing events in which the caustic crossings were accidentally discovered from the sudden rise of the source star flux. Due to the haphazard nature of caustic crossings, it was difficult to estimate the detection efficiency that is essential for the statistical studies of binary companions. The second reason is that microlensing
is mainly sensitive to binaries over a narrow range of projected separations. This limits especially the study of the distribution of binary separations.

When the first microlensing surveys (MACHO: Alcock et al. 1993; EROS: Aubourg et al. 1993) were started, the prime scientific goal was constraining the Galactic dark matter in the form of massive compact halo objects. However, the most important science of the current lensing surveys (OGLE: Udalski et al. 2003; MOA: Bond et al. 2002; PLANET: Beaulieu et al. 2006; μFUN: Yoo et al. 2004) is the detection of extrasolar planets. With the change of the goal, the observational strategy of the surveys also changed. These changes include the employment of early warning system and the operation of follow-up observations. Another important change is the adoption of an observational strategy focusing on high-magnification events for which the probability of planet detection is high (Griest & Safizadeh 1998).

In this paper, we emphasize the importance of binary-lens events to be detected through the high-magnification channel, especially for the statistical studies of Galactic binaries. We demonstrate the high efficiency of the high-magnification channel to binaries in a wide range of parameter space and the simplicity of the efficiency estimation. We also discuss other implications of these events.

2. BINARY CAUSTICS

The number, size, and shape of caustics induced by binary lenses vary depending on the mass ratio, \( q \), and the projected separation, \( s \), between the lens components in units of the Einstein radius corresponding to the total mass of the binary, \( \theta_\text{E} \). It is customary to divide the topology of binary caustics into three categories of intermediate, close, and wide binaries.

Intermediate binaries refer to the case for which the separation between the lens components is in the range (Erdl & Schneider 1993)

\[
(1 + q)^{1/4} (1 + q^{1/3})^{-3/4} < s < (1 + q)^{-1/2} (1 + q^{1/3})^{3/2}.
\]

In this case, there exists a single large caustic with six cusps. Caustics induced by intermediate binaries are often referred to as resonant caustics because they are produced when the binary separation is similar to the Einstein radius of the lens system.

Close binaries refer to the case for which the separation is smaller than those of intermediate binaries. In this case, there are a single major caustic with four cusps and two small outlying caustics with three cusps. The center of the major caustic is located approximately at the center of mass of the binary system. The size of the central caustic becomes smaller as the separation becomes smaller. In the limiting case of a close binary with \( s \ll 1 \), the lensing behavior is approximated as that of a single lens with a mass equivalent to the total mass of the binary and the location at the center of mass of the binary.

Wide binaries refer to the case for which the separation is larger than those of intermediate binaries. In this case, there exist two four-cusp caustics each of which is associated with each lens component. The size of each caustic becomes smaller as the separation increases. In the limiting case of \( s \gg 1 \), the lensing behavior is approximated as that of two independent single lenses located at the positions of the individual lens components.

3. DETECTION EFFICIENCY

In this section, we demonstrate that high-magnification events provide an important channel to detect binary companions in wide ranges of binary parameters. For this, we construct the distributions of efficiency as functions of the binary separation and the mass ratio.

The efficiency is estimated as follows. For a binary with a given set of the projected separation \( s \) and the mass ratio \( q \), we produce many light curves of binary-lens events resulting from source trajectories with impact parameters and orientation angles with respect to the binary axis distributed in the ranges of \( u_0 \leq u_{0,\text{th}} \) and \( 0 \leq \alpha \leq 2\pi \), respectively. Here, \( u_{0,\text{th}} \) represents the threshold impact parameter to the source trajectory corresponding to a threshold magnification \( A_{\text{th}} \), which represents the minimum magnification required for intensive follow-up observations. For each binary-lens light curve, we also produce a single-lens light curve that approximates the light curve of the binary event. We then compare the two light curves and compute the fractional deviation \( \epsilon = (A - A_\text{th})/A_\text{th} \), where \( A \) and \( A_\text{th} \) represent the lensing magnifications of the binary and single-lens events, respectively. We then estimate the detection efficiency as the fraction of events with fractional deviations greater than a threshold value, \( \epsilon_{\text{th}} \), among the total number of tested events. To see the distribution of efficiency, we repeat the procedure for binaries with different values of \( s \) and \( q \).

Caustics induced by close or wide binaries can be very small and thus perturbations induced by such caustics are vulnerable to the effect of finite-source size. We, therefore, consider the effect in our efficiency computation. For this, we use the ray-shooting technique (Schneider & Weiss 1986; Kayser et al. 1986; Wambsganss 1997; Dong 2006). In this technique, a large number of light rays are uniformly shot from the observer plane through the lens plane and then collected on the source plane; and the magnification map of a region on the source plane is obtained by the ratio of the number densities of rays on the source plane to that on the lens plane. With the constructed magnification map, the light curve of an event is obtained from a one-dimensional cut on the map. We accelerate this process by restricting the region of ray shooting only in the region around the caustic and use a simple semi-analytic approximation in other parts of the source plane (Pejcha & Heyrovský 2009; Gould 2008). In addition, we keep the information of the positions of the light rays arriving at the target in the buffer memory of a computer so that it can be readily used for fast computation of magnifications. For the source radius normalized by the Einstein radius, we use \( \rho_\star = 0.003 \) by adopting the value of a typical Galactic bulge event occurring on a bright main-sequence source star.

Figure 1 shows the constructed distributions of the efficiency as gray-scale maps in the parameter space of \((s,q)\) for three different threshold magnifications of \( A_{\text{th}} = 10, 50, \) and 100. We note that the cases with \( q < 1 \) and \( q > 1.0 \) represent that the source trajectory approaches closer to the heavier and lighter component of the binary, respectively. We set the threshold deviation as \( \epsilon_{\text{th}} = 0.1 \).

From the distributions, we find that the efficiency is high for wide ranges of separation and mass ratio. For a threshold magnification of \( A_{\text{th}} = 100 \), we find that the efficiency is \( \sim 100\% \) for binaries with separations in the range of \( 0.1 \lesssim s \lesssim 10 \). The region of high efficiency is substantial even for lower threshold magnifications. We find that the ranges of 100% efficiency are \( 0.2 \lesssim s \lesssim 5 \) and \( 0.3 \lesssim s \lesssim 3 \) for events with magnifications greater than \( A_{\text{th}} = 50 \) and 10, respectively. We also find that the range of high efficiency covers nearly the whole mass-ratio range of stellar companions.

The high efficiency is due to the existence of central caustics induced by close or wide binaries. The lensing behavior of a
wide binary with $s \gg 1$ is well described by the Chang–Refsdal lensing. In this regime, the width of the caustic is approximated as

$$\xi_c \sim \frac{4q}{s^2(1+q)}. \quad (2)$$

Then, for a wide-separation binary with $s = 10$ and $q = 1.0$, the caustic width is $\xi_c \sim 0.02$ as measured by $\theta_E$. This corresponds to the $\xi \sim 0.03$ as measured by the Einstein radius corresponding to the mass of the binary component to which the source trajectory approaches more closely, $\theta_E$. The perturbation extends outside the caustic. Assuming that the region of detectable perturbation extends twice of the caustic size, it is found that perturbations can be detected for events with $A \gtrsim 30$. For close binaries, the caustic size of a binary with a separation $s$ is equivalent to the caustic size of a wide binary with a separation $s^{-1}$. Therefore, the lower limit of the separation range roughly corresponds to the inverse of the upper limit.

1 Actually, there exists asymmetry between the efficiency distributions of the regions with $s < 1$ and $s > 1$. This asymmetry is caused by the difference of the single-lens approximations between close and wide binaries. For an event produced by a close binary, the light curve of the event is approximated as that of a single lens with a mass corresponding to the total mass of the binary. For an event produced by a wide binary, on the other hand, the light curve is approximated as the light curve produced by a single-lens event with a mass corresponding to the mass of the lens component that the source trajectory approaches closer and thus the Einstein radius is smaller by $\theta_E/(1+q)^{1/2}$. Then, although the size of the two caustics induced by a close binary and a wide binary with separations $s$ and $s^{-1}$ are equivalent as measured by $\theta_E$, the caustic size measured by $\theta_E$ is bigger. As a result, the efficiency is higher for wide binaries compared to close binaries with corresponding inverse separations. The asymmetry between the distributions in the regions of wide binaries with $q < 1$ and $q > 1$ is caused by the fact that heavier companions induce larger caustics. This asymmetry does not occur for close binaries because the two masses are close and thus the source does not distinguish the two.

4. IMPLICATIONS

The high efficiency of the high-magnification channel in detecting binary companions has several important scientific implications. First, it implies that high-magnification events will provide a major channel of detecting binaries in lensing surveys that focus on high-magnification events for efficient detections of microlensing planets. Due to the location of perturbations similar to those induced by planets, perturbations induced by binary companions will be densely monitored by follow-up observations. In addition, the perturbations will be observed with high precision since they occur when the magnification is high. Being observed with high time resolution and photometric precision, it will be possible to accurately characterize the physical parameters of the individual binary systems.

Second, the sample of binaries to be detected through high-magnification channel will make it possible to study the binary distributions due to the simplicity of efficiency estimation. Unlike the accidental detections of binary events in previous surveys, binaries probed by the high-magnification channel are detected under a simple criterion that the peak magnification is greater than a certain threshold. As a result, it will be possible to statistically investigate the binary properties.

Another quality of the high-magnification channel is that it enables us to detect planets in binary systems. This is possible because both planet and binary companions produce perturbations in a common central region and thus the signatures of both companions can be simultaneously detected in the light curves of high-magnification events. Two types of planets in binaries can be detected. The first type is a planet orbiting one of a wide binary system (Lee et al. 2008). The other type is a planet orbiting a close binary system (Han 2008). Planets of the former type were discovered by radial velocity surveys (Konacki 2005; Eggenberger et al. 2006). However, no firm detection of planets...
of the latter type has been reported because radial velocity surveys avoid short-term binaries as target stars. The chance to detect such planets by using the transit method is also very low because these planets tend to have wide orbits. Therefore, microlensing is an important method for the discoveries of planets with two simultaneously rising suns.

5. DISCUSSION

To see the efficiency of high-magnification channel to binary events in actual lensing surveys, we search the data of microlensing surveys in the 2009 season for binary events. From this search, we find that there exist seven binary-lens events that were detected through the high-magnification channel. We list the events in Table 1 along with the lensing parameters. The fact that these events comprise 70% of all detected binary-lens events corroborates our claim that high-magnification events provide the major channel of detecting binary-lens events in current lensing surveys. For all of these events, the perturbations were densely observed by follow-up observations, enabling us to characterize the binary systems up to the well-known close/wide degeneracy.

The fact that central perturbations produced by a planet and a binary companion occur near the peak of the light curve brings up a question of the possibility to distinguish the two perturbations of different origins. Although both binary and planetary systems can produce central caustics, the resulting perturbations induced by the two lens populations are different. The basis of this difference lies in the difference in shape between the caustics of the two lens populations. The shape of binary caustics varies such that the caustic is elongated along the binary axis when the separation is of the order of the Einstein radius, and it becomes more symmetric as the separation deviates from the Einstein radius. For a low-mass companion such as a planet, the companion should be located close to the Einstein radius to produce noticeable perturbations. As a result, the central caustic induced by a planet has an elongated shape. On the other hand, the central caustic induced by a close/wide binary companion has a symmetric diamond shape. Therefore, detailed modeling of observed light curves enables us to discriminate between the two interpretations.

In many cases, the two types of perturbations can be immediately distinguished from characteristic features. Several such diagnostic features were already proposed. Han & Gaudi (2008) proposed a diagnostic based on the difference in the shape of the intrapeak region of double-peaked high-magnification events. They found that the shape of the intrapeak region is smooth and concave for binary lensing, while it tends to be either boxy or convex for planetary lensing due to the existence of the small, weak cusp of the planetary central caustic located between the two stronger cusps. Han (2009) proposed another diagnostic that can be applicable to perturbations affected by severe finite-source effect. He 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. Then, the absence of a well-developed dip in the residual from the single-lensing light curve at 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. Han et al. (2009) found that a short timescale caustic-crossing feature occurring at a moderate magnification with an additional secondary perturbation is a typical feature of binary-lens events and thus can be used as a diagnostic to discriminate between the binary and planetary interpretations.

6. CONCLUSION

In this paper, we emphasized the importance of binary-lens events to be discovered through the channel of high-magnification events. Due to the high efficiency in wide ranges of parameter space, we pointed out that majority of binary-lens events will be detected through the high-magnification channel in current planetary microlensing surveys. In addition to the high efficiency, the simplicity of the efficiency estimation makes the sample of these binaries useful in the statistical studies of the distributions of binary companions as functions of mass ratio and separation.

This work is supported by the Creative Research Initiative program (2009-0081561) of the National Research Foundation of Korea. We thank A. Gould and B. S. Gaudi for providing helpful comments.

REFERENCES

Abe, F., et al. 2003, A&A, 411, L493
Alard, C., et al. 2000, ApJ, 522, 340
Albrow, M. D., et al. 1999a, ApJ, 522, 1011
Albrow, M. D., et al. 1999b, ApJ, 522, 1022
Albrow, M. D., et al. 2000, ApJ, 534, 894
Albrow, M. D., et al. 2001, ApJ, 549, 759
Alstern, M. D., et al. 2002, ApJ, 572, 1031
Afonso, C., et al. 2000, ApJ, 532, 340
Afonso, C., et al. 2000, ApJ, 532, 340
Beaulieu, J.-P., et al. 2006, Nature, 439, 437
Beaulieu, J.-P., et al. 2006, Nature, 439, 437
Bond, I. A., et al. 2002, ApJ, 572, 1031
Bozza, V. 2000, A&A, 355, 423
Bozza, V. 2001, A&A, 374, 13
Bozza, V. 2001, A&A, 374, 13
Bond, I. A., et al. 2002, MNRAS, 331, L19
Bond, I. A., et al. 2002, ApJ, 572, 1031
Beaulieu, J.-P., et al. 2006, Nature, 439, 437
Bozza, V. 2000, A&A, 355, 423
Bozza, V. 2001, A&A, 374, 13
Bozza, V. 2001, A&A, 374, 13
Bozza, V. 2001, A&A, 374, 13
Cassan, A., et al. 2004, A&A, 419, L1
Chang, K., &Refsdal, S. 1980, Nature, 286, 138
Chang, K., &Refsdal, S. 1984, A&A, 132, 168
Di Stefano, R., &Perna, R. 1997, ApJ, 488, 55
Dominik, M. 1999a, A&A, 341, 943
Dominik, M. 1999b, A&A, 349, 108
Dong, S., et al. 2006, ApJ, 642, 842
Eggenberger, A., Mayor, M., Naef, D., Pepe, F., Queloz, D., Santos, N. C., Udry, S., &Lovis, C. 2006, A&A, 447, 1159
Erdl, H., &Schneider, P. 1993, A&A, 268, 453
Gaudi, B. S., &Gould, A. 1997, ApJ, 482, 83
Gaudi, B. S., &Petters, A. O. 2002a, ApJ, 574, 970
Gaudi, B. S., &Petters, A. O. 2002b, ApJ, 580, 468
Gould, A. 2008, ApJ, 681, 1593
Graff, D. S., &Gould, A. 2002, ApJ, 580, 253
Griest, K., &Safizadeh, N. 1998, ApJ, 500, 37
Han, C. 2001, MNRAS, 325, 1281
Han, C. 2008, ApJ, 676, L53
Han, C. 2009, ApJ, 691, L9
Han, C., Chun, M.-S., &Chang, K. 1999, ApJ, 526, 405
Han, C., &Gaudi, B. S. 2008, ApJ, 689, 53
Han, C., et al. 2009, ApJ, 705, 1116
Jaroszynski, M., et al. 2004, Acta Astron., 54, 103
Jaroszynski, M., et al. 2005, Acta Astron., 55, 159
Jaroszynski, M., et al. 2006, Acta Astron., 56, 307
Kayser, R., Refsdal, S., &Stabell, R. 1986, A&A, 166, 36
Konacki, M. 2005, Nature, 436, 230
Kubas, D., et al. 2005, A&A, 435, 941
Lee, D., et al. 2008, ApJ, 672, 623
Pejcha, O., &Heyrovský, D. 2009, ApJ, 690, 1772
Rhie, S. H. 1997, ApJ, 484, 63
Schneider, P., &Weiss, A. 1986, A&A, 164, 237
Smith, M. C., et al. 2002, MNRAS, 336, 670
Udalski, A., et al. 1994, ApJ, 436, L103
Udalski, A., et al. 1998, Acta Astron., 48, 431
Udalski, A., et al. 2003, Acta Astron., 53, 291
Wambsganss, J. 1997, MNRAS, 284, 172
Witt, H. J. 1990, A&A, 236, 311
Witt, H. J., &Mao, S. 1995, ApJ, 447, L105
Yoo, J., et al. 2004, ApJ, 616, 1204