Where are the binary source gravitational microlensing events? II

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Accepted 1998 July 29. Received 1998 July 29; in original form 1998 June 12

ABSTRACT
Despite the same multiplicity of lenses and sources, the frequency of detection of binary source events is relatively very low compared with that of binary lens events. Dominik pointed out that the rarity of binary source events is caused mainly by the large difference in amplification between the component stars. In this paper, we determine that the fraction of events with similar source star amplifications is as large as ~8 per cent, and thus show that the very low detection rate for binary source events cannot be explained by this effect alone. By carrying out realistic simulations of binary source events, we find that a significant number of binary source events are additionally missed from detection for various other reasons. First, if the flux ratio between the component stars is very large, the light curve of the bright star is hardly affected by the light from the faint star. Secondly, if the separation is too small, the binary source stars behave like a single star, making it difficult to separate the binary source event from a single source event. Finally, although the probability of detecting binary source events increases as the source separation increases, some fraction of binary source events will still be missed because the light curves of these events will mimic those of single source events with longer time-scales and larger values of the impact parameter.

Key words: binaries: general – gravitational lensing.

1 INTRODUCTION
Experiments to detect massive astronomical compact halo objects (MACHOs) by monitoring light variations of stars caused by gravitational microlensing have been carried out, and nearly 300 events have been detected (Ansari et al. 1996; Alcock et al. 1997; Udalski et al. 1997; Alard & Guibert 1997). When both the lens and source are approximated as point sources, the light curve of a lensing event is related to the lens–source separation in units of the Einstein ring radius \( r_E \) by

\[
A(u) = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}}; \quad u^2 = \beta^2 + \left( \frac{t - t_0}{t_E} \right)^2,
\]

where \( \beta \) is the impact parameter and \( t_0 \) is the time of maximum amplification. The Einstein ring radius-crossing time (Einstein time-scale) is related to the physical parameters of the lens system by

\[
t_E = \frac{r_E}{v}; \quad r_E = \left( \frac{4GM_D \Delta D}{c^2 D_{ls}} \right)^{1/2},
\]

where \( M \) is the mass of the lens, \( v \) is the lens–source transverse speed, and \( D_{ol}, D_{ls}, \) and \( D_{os} \) are the separations between the observer, lens and source.

The lensing light curve deviates from the ideal form in equation

(1) if either the lens or the source is composed of binaries: binary–lens (BLL) and binary–source lensing (BSL) events. Currently, six candidate BLL events have been reported by various groups (MACHO LMC 1, Dominik & Hirshfeld 1994, 1996; OGLE 7, Udalski et al. 1994; DUO 2, Alard, Mao & Guibert 1995; MACHO LMC 9, Bennett et al. 1996; MACHO Bulge 95-12, Pratt et al. 1995; MACHO Bulge 96-3, Stubbs et al. 1997). In contrast, the frequency of BSL events is relatively very low despite the same multiplicity of lenses and sources, and only a single candidate BSL event has been reported (MACHO LMC 96-2, Becker et al. 1997). To account for the rarity of BSL events, Dominik (1998) pointed out that for a typical BSL event the separation between the component source stars is very large, resulting in a large difference in impact parameters between the component binary source stars. In these cases, the light curve of the highly amplified source star is barely affected by the light from the star with low amplification, making the observed BSL light curve difficult to distinguish from that of a single source lensing (SSL) event.

In this paper, we determine that the fraction of events with similar source star amplifications is as much as ~8 per cent, and thus show that the very low detection rate for BSL events cannot be explained by this effect alone. By carrying out realistic simulations of BSL events, we find that a significant fraction of BSL events are additionally missed from detection for various other reasons. First, if the flux ratio between the component stars is very large, the light curve of the bright star is hardly affected by the light from the faint star. Secondly, if the separation is too small, the binary
source stars behave like a single star, making it difficult to separate the BSL event from a SSL event. Finally, although the probability of detecting BSL events increases as the source separation increases, some fraction of BSL events will be still missed because the light curves of these events will mimic those of SSL events with longer time-scales and larger values of the impact parameter.

2 BSL EVENTS

The light curve of a BSL event is the superposition of the light curves from the individual source stars and is represented by

\[ A_{\text{BSL}} = \frac{\sum_{i=1}^{2} F_{0,i} A(u_i)}{\sum_{i=1}^{2} F_{0,i}} = \frac{2}{\sum_{i=1}^{2} F_{0,i}} \int B(u_i) \, du_i, \quad (3) \]

where \( i = 1, 2 \) denote the primary (brighter) and companion (fainter) source stars respectively, \( F_{0,i} \) are their unamplified fluxes, \( F_i = F_{0,i}/\sum F_{0,i} \) are the contributions of individual source star fluxes to the total flux, and \( A(u_i) \) are the amplifications of the individual source stars. If there is no blending, \( F_i = 1 - F_i \).

The lens–source separations for the BSL event are related to the lensing parameters by

\[ u_i^2 = \beta_i^2 + \frac{(1 - l_{0,i})^2}{t_E^2}. \quad (4) \]

Therefore, compared with the three lensing parameters \((t_E, l_0, \beta)\) that must be fitted to a SSL event, a fit to a BSL event light curve requires six parameters \((F_j, t_E, l_0, \beta_j)\). However, for various reasons the light curves of BSL events are often difficult to distinguish from those of SSL events, resulting in a low rate of identification of BSL events. In the following sections, we investigate these reasons for the scarcity of detected BSL events and estimate what fraction of the actual number of BSL events is missed for these reasons.

Griest & Hu (1992) performed a comprehensive study of the types of BSL events, and estimated the frequencies of individual types. They also determined the fraction of BSL events, the light curves of which can be distinguished from those of SSL events. For the determination of this fraction, they counted events as detectable as long as they belonged to some specific categories, such as ‘double-peaked’ and ‘asymmetric’. However, this approach tends to overestimate the detectable BSL event fraction because, for example, not all asymmetric or double-peaked events can be readily detectable. In addition, they restricted attention to microlensing events expected to be seen toward the Large Magellanic Cloud (LMC). The events seen toward the Galactic bulge (the vast majority of events detected to date) are substantially different from those toward the LMC, both in signal-to-noise ratio and in distribution of source types. We therefore undertake a new analysis of BSL events, focusing on Galactic bulge events and using \( \chi^2 \) (rather than an event-classification) formalism.

3 BSL EVENTS WITH LARGE AMPLIFICATION DIFFERENCE

As one reason for the rarity of detectable BSL events, Dominik (1998) pointed out that if the difference in the impact parameters between the two source stars \( \delta \beta = |\beta_1 - \beta_2| \) is too large, the amplification of one star completely dominates that of the other. As a result, the light curve of the BSL event appears to be that of a blended SSL event, i.e. \( A_{\text{BSL}} \sim F_j A(u_j) + (1 - F_j) \), where \( j \) represents the source star with higher amplification. The probability that a BSL event has a large \( \delta \beta \) increases as the separation between source stars \( \ell \) increases, and thus BSL events are misidentified more frequently in cases of wide source star separations. Therefore, if most binary source stars are widely separated compared with the typical size of the Einstein ring, a significant fraction of BSL events will be indistinguishable from SSL events.

We now show, however, that the very low detection rate for BSL events cannot be explained by large values of \( \delta \beta \) alone. To determine the fraction of actual BSL events that are misidentified as SSL events because of large \( \delta \beta \), we compute the distribution of BSL events with \( \delta \beta \) less than a limiting value \( \delta \beta_{\text{lim}} \), as a function of binary source separation, \( f(\delta \beta_{\text{lim}}, \ell) \). This distribution is obtained by convolving the distribution of BSL separations \( f(\ell) \) with the mean probability \( P(\delta \beta_{\text{lim}}, \ell) \) for each BSL event with \( \ell \) to have \( \delta \beta \leq \delta \beta_{\text{lim}} \), i.e. \( f(\delta \beta_{\text{lim}}, \ell) = f(\ell) \otimes P(\delta \beta_{\text{lim}}, \ell) \), where the notation ‘\( \otimes \)’ represents convolution.

For \( f(\ell) \) we adopt the distribution found by Duquennoy & Mayor (1991), which is based on the orbital periods of 164 G dwarf samples. They found that the distribution of the logarithmic value of orbital periods appeared remarkably symmetric and could be approximated by a Gaussian with a mean and standard deviation given by \( \langle \log P \rangle \sim 4.8 \) and \( \sigma_{\log P} \sim 2.3 \), when \( P \) is represented in units of days. When the typical mass of a binary system is assumed to be \( \sim 1 \, M_\odot \), the distribution of binary source star separations also has a Gaussian form with the mean and standard deviation given by \( \langle \log \ell \rangle \sim 1.5 \) and \( \sigma_{\log \ell} \sim 1.5 \) in units of au. This form of \( f(\ell) \) is shown in the top panel of Fig. 1.

To compute \( f(\delta \beta_{\text{lim}}, \ell) \), we carried out a simulation in which we produced a set of binaries, the component stars of which are separated according to \( f(\ell) \). For each binary, we assign the impact parameter for the first event, which is uniformly distributed over the range \( 0 \leq \beta_1 \leq 1 \). Once \( \beta_1 \) is assigned, the impact parameter of the second star is assigned to be \( \beta_2 = |\beta_1 + \ell \sin \theta| \) and \( \delta \beta \) is computed as \( \delta \beta = |\beta_1 - \beta_2| \). Here the position angle \( \theta \) is randomly distributed in the range \( 0 \leq \theta \leq 2\pi \). Unlike \( \beta_1 \), we allow \( \beta_2 \) to have any value. Therefore, according to our definition of a BSL event, both stars in the binary do not necessarily pass inside the Einstein ring as long as at least one of the two stars does.

Finally, the probability \( P(\delta \beta_{\text{lim}}, \ell) \) is obtained by computing the fraction of all events yielding \( \delta \beta \leq \delta \beta_{\text{lim}} \). In the middle and lower panels of Fig. 1, we present \( P(\delta \beta_{\text{lim}}, \ell) \) and the corresponding distributions of \( f(\delta \beta_{\text{lim}}, \ell) \) for the two cases \( \delta \beta_{\text{lim}} = 0.1 \) and 1.0. Here we have assumed \( r_0 = 1 \, \text{au} \), which is the typical Einstein ring radius for Galactic bulge events, with \( M \sim 0.25 \, M_\odot \), \( D_{\text{E}} \sim 5 \, \text{kpc} \), and \( D_{\odot} \sim 8 \, \text{kpc} \).

From the distribution \( f(\delta \beta_{\text{lim}}, \ell) \) we find that the fraction of BSL events with similar source star impact parameters is substantial. For example, the fraction of BSL events with \( \delta \beta \leq \delta \beta_{\text{lim}} = 0.1 \) comprises \( \sim 8.2 \) per cent of the total (represented by the dark shaded region in the lower panel of Fig. 1). Assuming a stellar duplicity rate of \( \sim 50 \) per cent (Abt & Levy 1976), if large \( \delta \beta \) were the only reason for the low rate of BSL event detections, among the total of \( \sim 300 \) microlensing events one would expect to find \( \sim 12 \) BSL events, far exceeding the single detection to date. Therefore, additional reasons are required to explain the rarity of BSL events.

4 BSL EVENTS WITH SIMILAR AMPLIFICATIONS

In the previous section we showed that the very low detection rate of BSL events cannot be explained solely by large differences in amplification and so additional reasons are required. To find these reasons, we carry out realistic simulations of BSL events, the source
star amplifications of which are similar. In order to match the observational conditions of the current lensing experiments, in the simulation we assume observations are made using a 1.27-m telescope with a dichroic beam splitter for simultaneous imaging. The CCD camera can detect 25 photons s\(^{-1}\) in two bands, following the observing facilities of the MACHO group. The simulation we assume observations are made using a 1.27-m telescope.

The most important type of Galactic bulge source stars is turn-off stars, and thus we assume a magnitude of \(V = 19.5\) for the primary star, and that the difference between the primary and secondary stars follows the distribution \(f(\delta m)\). The distribution \(f(\delta m)\) is adopted from that of G dwarfs which is determined by Duquennoy & Mayor (1991). Note that our \(f(\delta m)\) is identical to those adopted by Griest & Hu (1992) to determine the frequency of various types of BSL events. The distribution of separation between binary stars follows the Gaussian Duquennoy & Mayor (1991) model as mentioned in Section 3. The second important type of Galactic bulge stars is clump giants. However, the expected BSL event rate for clump giants would be very low because as the radius of the giant expands, the close binaries (\(\ell \approx 0.3\) au), which have the most probable candidates for BSL event detection, are eliminated. According to \(f(\delta \beta_{\text{lim}})\) the probability for binary source stars with \(\ell \geq 0.3\) au to have impact parameter differences less than \(\delta \beta_{\text{lim}} = 0.1\) is highly unlikely. Therefore, we concentrate primarily on turn-off stars not only because they comprise the majority of bulge source stars, but also because they have a relatively higher possibility of producing detectable BSL events.

Once both source stars are selected, we produce BSL events according to equations (3) and (4), in which the difference in impact parameters is restricted to be less than 0.1. In our example, events are assumed to have \(t_E = 15\) d, which is the most common value observed for Galactic bulge events. The observations are assumed to be carried out once each night during the period \(-5t_E \leq t \leq 5t_E\) with the high photometric precision of 1 per cent. Then the light curve of each BSL event is fitted with a SSL event light curve as given in equation (1) and the resulting \(\chi^2\) is obtained by

\[
\chi^2 = \sum_{i=1}^{N_p} \frac{[N_{\text{SSL}}(t_i) - N_{\text{BSL}}(t_i)]^2}{pN_{\text{SSL}}(t_i)},
\]

where \(N_p\) is the number of data points, \(p = 1\) per cent is the photometric precision, \(N_{\text{SSL}}(t)\) is the photon count of the theoretical SSL event light curve and \(N_{\text{BSL}}(t)\) represents the counts predicted for the simulated BSL event. We define 'detectable BSL events' to be the BSL events, the light curves of which can be distinguished from those of SSL events with a confidence level greater than 3\(\sigma\).

In Table 1, we list the mean probability \(P_{3\sigma}(\delta m)\) of detecting a BSL event with \(\delta m\), averaged over the entire ranges of \(\ell\) and \(\beta\). We also list the distribution of BSL events that can be distinguished from SSL events at a high confidence level as a function of source brightness difference, which is obtained by \(f_{3\sigma}(\delta m) = P_{3\sigma}(\delta m)/f(\delta m)\). From the table one finds the following trends. First, the probability of BSL events, the light curves of which can be distinguished from SSL events, is very low.
detecting BSL events is low. We find increases. However, even for these events, the probability of...

$P_{3a}(\delta m) = \int f(\delta m')d\delta m' = 3.8$ per cent even with similar source star amplifications and high-precision photometry. The probability is especially low for events with large brightness differences between component stars. For example, detecting events with $\delta m \geq 4.8$ is highly unlikely, but the number of these events comprises $\sim 41$ per cent of the total BS events. Secondly, as the brightnesses of the source stars become similar, the probability $P_{3a}$ increases. However, even for these events, the probability of detecting BSL events is low. We find $P_{3a}(\delta m \sim 2) \sim 8.3$ per cent and $P_{3a}(\delta m \sim 1) \sim 10.2$ per cent. This is because most binary source stars with very small separations (log $\ell \leq -1.0$) behave as if they were single source stars, making them difficult to distinguish from SSL events; those events with small $\delta \ell$ comprise $\sim 75$ per cent of the total number of BSL events with $\delta \ell \leq 0.1$. Additionally, the light curves of some fraction of BSL events with medium size separations (log $\ell \sim -0.5$) mimic those of SSL events with lensing parameters adjusted to longer time-scales and larger impact parameters. Consequently, the fraction of detectable BSL events is very small ($\leq 4$ per cent), even among events with similar amplifications.

## 5 SUMMARY

The detection rate of BSL events is very low relative to the detection rate of BLL events despite similar duplicities of lenses and source stars. The scarcity of BSL event detections results from a combination of reasons. First, if the difference in impact parameters between individual components of a BSL event is very large, the light curve with lower amplification has little effect on that of the high-amplification event, making the observed BSL event light curve difficult to distinguish from a SSL event one. However, we find that the fraction of BSL events with similar source star amplifications is still substantial ($\sim 8$ per cent for $\delta \ell \leq 0.1$), and thus the very low detection rate of BSL events cannot be explained by this reason alone. We find that the light curves of an important fraction of BSL events are confused with SSL events for various other reasons. These reasons include the large brightness differences between source stars, small source star separations and the imitation by BSL events of SSL events with longer time-scales and larger impact parameters.

## ACKNOWLEDGMENTS

We thank A. Gould for making helpful comments. We also thank M. Everett for careful reading of the manuscript. This research is supported by a Korean Science and Engineering Foundation (KOSEF) grant 981-0203-010-1.

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