BLENDING IN FUTURE SPACE-BASED MICROLENSING SURVEYS

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ABSTRACT

We investigate the effect of blending in future gravitational microlensing surveys by carrying out simulations of Galactic bulge microlensing events to be detected by a proposed space-based lensing survey. From this simulation, we find that the contribution of the flux from background stars to the total blended flux would be equivalent to that from the lens itself despite the greatly improved resolution of space-based observations, implying that characterizing lenses from the analysis of the blended flux would not be easy. As a method to isolate events for which most of the blended flux can be attributed to the lens, we propose using astrometric information of source star image centroid motion. For the sample of events obtained by imposing a criterion that the centroid shift should be less than 3 times the astrometric uncertainty among the events for which blending is noticed with blended light fractions $f_B > 0.2$, we estimate that the contamination of the blended flux by background stars would be less than 20% for most ($\sim 90\%$) of the sample events. The expected rate of these events is $>700$ events yr$^{-1}$, which is large enough for the statistical analysis of the lens populations.

Subject heading: gravitational lensing

1. INTRODUCTION

Observational experiments to detect light variations in stars induced by gravitational microlensing have been carried out for more than a decade (Udalski et al. 1993; Alcock et al. 1993; Aubourg et al. 1993; Bond et al. 2001). Originally, the experiments were initiated for the purpose of searching for dark matter in the Galactic halo (Paczynski 1986). However, microlensing developed many applications in various aspects of Galactic, stellar, and planetary astrophysics such as probing the structure of the inner Galaxy (Kiraga & Paczynski 1994; Evans 1994; Han & Gould 1995b; Zhao et al. 1995), resolving the photospheres of distant stars (Witt 1995; Albrow et al. 1999; Abe et al. 2003; Field et al. 2003), and detecting extrasolar planets (Mao & Paczynski 1991; Gould & Loeb 1992; Bond et al. 2004; Udalski et al. 2005; Beaulieu et al. 2006; Gould et al. 2006). Current experiments routinely detect more than 500 events each season, and the total number of detected events is now reaching 3000.

The probability of a star being gravitationally lensed is very low (of the order of $10^{-13}$). As events are very rare, lensing searches are conducted toward very crowded star fields such as the Galactic bulge in order to monitor as many stars as possible within a single frame. For observations in such a dense field, blending of stellar images is inevitable (Di Stefano & Esin 1995; Wozniak & Paczynski 1997). The light curve of a blending-affected event is expressed as

$$F_{\text{obs}} = AF_0 + FB, \quad A = \frac{u^2 + 2}{u(u^2 + 4)},$$

where $F_0$ is the baseline flux of the lensed source star, $F_B$ is the amount of the blended flux, $A$ is the magnification induced by the lensing, and $u$ is the lens-source separation normalized by the Einstein ring radius $\theta_E$. The normalized lens-source separation is related to the lensing parameters by

$$u = \left(\frac{t - t_0}{t_E} - u_0^2\right)^{1/2},$$

where $t_0$ is the Einstein timescale, $t_0$ is the time of the closest lens-source approach, and $u_0$ is the separation at that moment (impact parameter). Among the lensing parameters, the Einstein timescale is related to the mass and location of the lens and relative lens-source transverse speed, and thus it can provide a constraint on the lens system. However, the constraint is weak because the timescale results from the combination of the physical parameters. Blending aggravates the photometric precision because of the increased noise from the blended flux. In addition, blending makes accurate determinations of the lensing parameters difficult because of the poorly known baseline flux of the source star. As a result, the constraint on the lens system becomes even weaker.

At present, next-generation microlensing experiments based in space are being seriously discussed. The Gravitational Exoplanet Survey Telescope (GEST) mission (Bennett & Rhie 2002), is a space mission proposed to NASA’s Discovery Program with the main goal of searching for a large sample of extrasolar planets using the gravitational lensing method (Bennett et al. 2004). By conducting observations in space, it is possible to minimize blending effects thanks to the improved resolution.

Another important advantage of space-based observation is that one could directly detect and characterize the lens based on the observed flux. This is possible when a light-emitting star is responsible for a lensing event and the flux from the lens contributes a substantial fraction of the observed flux. It is believed that the majority of events detected toward the Galactic bulge are caused by stars (Han & Gould 2003). In addition, the GEST mission plans to monitor faint main-sequence stars in order to optimize detections of low-mass planets by minimizing the finite-source effect. Therefore, the light from the lens would not be negligible...
for a significant fraction of the event sample, and thus the existence of the lens could be revealed by the excess flux from the lens. By conducting multiband observations, it would be possible to determine the spectral type of the lens, which would provide a much tighter constraint on the lens.

However, this new method of constraining lenses can be applicable under the condition that most events are free from blending caused by background stars. If an unrelated background star is located within the resolution disk of the lensed source star, the blended flux comes not only from the lens but also from the background star. This causes complexity in the analysis of the observed blended light, making it difficult to uniquely characterize the lens. Han (2005, hereafter Paper I) warned of the possible contamination of the blended flux by background stars. As a method to resolve the contamination, he suggested using the astrometric information of the source star image centroid shift. If an event is affected by background stellar blending, the centroid will shift from the apparent position of the combined image of the source plus blended stars toward the lensed star during the event (Goldberg 1998).

In this paper, we further investigate the blending problem in future space-based lensing surveys following Paper I and probe the feasibility of sorting out events whose blended flux is mostly attributable to the lenses by using the additional astrometric information of the centroid shift. For this, we carry out simulations of Galactic bulge microlensing events expected to be detected by the proposed MPF survey by imposing realistic observational conditions and detection criteria. Based on this simulation, we investigate the expected pattern of blending and the seriousness of the contamination by background stars. We also estimate the fraction of events that can be identified to be free from background stellar blending by using the proposed astrometric method.

2. SIMULATION

The basic scheme of the simulation of lensing events is similar to that in Paper I. The locations of the lenses and source stars are allocated based on the Han & Gould (1995a) Galactic mass distribution model, which is composed of a double-exponential disk and a barred bulge. The velocity distribution of the bulge is deduced from the tensor virial theorem, while the disk velocity distribution is modeled to have a flat rotation speed of 30 km s\(^{-1}\) along and normal to the disk plane of \(\sigma_{\|} = 30 \text{ km s}^{-1}\) and \(\sigma_{\perp} = 20 \text{ km s}^{-1}\), respectively. The brightnesses of the bulge stars are assigned on the basis of a combined luminosity function constructed based on those of Holtzman et al. (1998) and Gould et al. (1997) considering extinction and distance modulus. The lens masses are assigned based on the mass function of Gould (2000), which is composed of stars and stellar remnants. The mass function model is constructed under the assumption that bulge stars are initially formed according to a double power-law distribution of \(dN/dM = k(M/0.7 \, M_{\odot})^{-\gamma}\), where \(\gamma = -2.0\) for \(M \geq 0.7 \, M_{\odot}\) and \(\gamma = -1.3\) for \(M < 0.7 \, M_{\odot}\). Based on this initial mass function, remnants are modeled by assuming that stars with initial masses \(1 \, M_{\odot} < M < 8 \, M_{\odot}\) have evolved into white dwarfs (with a mean mass \(M = 0.6 \, M_{\odot}\)), with \(8 \, M_{\odot} < M < 40 \, M_{\odot}\) into neutron stars \((M = 1.35 \, M_{\odot})\), and with \(M > 40 \, M_{\odot}\) into black holes \((M = 5 \, M_{\odot})\). For events caused by stellar lenses, the lens brightness is determined based on the lens mass by using a mass-luminosity relation. For events caused by remnant lenses, the lens is assumed to be dark.

However, the main focus of Paper I was investigating possible contamination of blended flux in general, and thus it did not concentrate on a specific survey. As a result, there are several major differences between the simulations in Paper I and in this work. The differences are described below.

1. Since no specific instrument was defined, the analysis in Paper I was based on all possible events regardless of their detectability. In this work, analyses are based only on events that could be detected by the MPF survey. The detectability of an event is subject to the conditions and strategy of the observation. For the observation field, we assume that the future survey will monitor a field centered at \((l, b) \sim (12^\circ, -24^\circ)\) with a field of view of \((\Delta l, \Delta b) \sim (0^\circ 93, 2^\circ 8)\). For the sampling frequency, we assume that the survey will continuously observe the target field with an interval of 15 minutes during 9 months of a year. For each interval, we assume that a 10 minute exposure image is acquired with a photon count rate of 13 photons s\(^{-1}\) for an \(I = 22\) star.

2. Another factor that determines the event detectability is the selection criteria. We judge the detectability of an event based on the uncertainties of the lensing parameters recovered from the light curve. We determine the uncertainties by computing the curvature matrix of the \(\chi^2\) surface of the lensing parameters for each event produced by the simulation. For the case of a lensing light curve, the curvature matrix is defined as

\[
b_{ij} = \sum_{k} \frac{\partial F_{\text{obs}, k}}{\partial p_{i}} \frac{\partial F_{\text{obs}, k}}{\partial p_{j}} \frac{1}{\sigma_{k}^{2}},
\]

where \(N_{\text{obs}}\) is the number of observations, \(\sigma_{k} = \sqrt{\chi_{\text{obs}}^{2}}\) is the photometric precision of each measurement, and \(p_{i} = (F_{0}, F_{B}, u_{0}, t_{0}, t_{E})\) are the five lensing parameters required to fit the light curve of a standard point-source single-lens event. Then the uncertainties of the individual lensing parameters correspond to the diagonal components of the inverse curvature matrix (covariance matrix), i.e.,

\[
\sigma_{p_{i}} = \sqrt{c_{ii}}, \quad c \equiv b^{-1}.
\]

With the determined uncertainties, we set the detection criteria of events such that the fractional uncertainties of the timescale and blended flux should be less than \(20\%\), i.e., \(\sigma_{t_{0}}/t_{E} \leq 0.2\) and \(\sigma_{F_{B}}/F_{\text{obs}} \leq 0.2\). Under this definition of event detectability, we note that events could be detected even if the source star trajectory does not enter the Einstein ring of the lens. This can be seen in Figure 1 (top left), where we present the distribution of impact parameters of events. From the distribution, one finds that a fraction of events have impact parameters larger than unity, especially for events involving relatively bright source stars \((l_{0} \leq 22)\). In Paper I, detectable events were limited only to those with source trajectories entering the Einstein ring, i.e., \(u_{0} < 1.0\).

3. Another major difference is the brightness range of source stars. In Paper I, we considered only stars with \(I\)-band baseline brightness of \(I_{0} \leq 23\). With the implementation of the detection criteria described above, we found that events associated with much fainter stars could be detected. Therefore, in this work we do not set the limit of source star brightness as long as the event meets the detection criteria. With the new criteria, we find that events could be detected with source brightness down to \(I_{0} \sim 27\), as shown in Figure 1 (bottom), where the distribution of \(I\)-band baseline source star brightness is presented. With this new range of the source star brightness, the baseline flux of the source star decreases on average, while the blended flux remains similar to the previous estimate. As a result, the average value of the blended light fraction, \(f_{B} = F_{B}(F_{0} + F_{B})\), is smaller than the value in Paper I.
4. The last major change is the definition of the resolution angle \( \theta_{\text{res}} \). In Paper I, we assume that two stars cannot be resolved if the separation between them is less than a fixed value of the diffraction limit (DL) regardless of the flux ratio between the two stars. To describe the experiment more realistically by considering the variation of the resolution angle depending on the relative flux, we set the resolution angle as

\[
\theta_{\text{res}} = \begin{cases} 
0.5 \text{FWHM} & \text{if } \frac{F_2}{F_1} \leq 0.1, \\
(-0.44 \frac{F_2}{F_1} + 0.54) \text{FWHM} & \text{otherwise,}
\end{cases}
\]

where \( F_1 \) and \( F_2 \) are the fluxes of the brighter and fainter stars, respectively, and FWHM \( \sim 2 \text{DL} \sim 0.04 \) corresponds to the diameter of the resolution disk. Then the resolution angle for two equally bright stars is \( \theta_{\text{res}} = 0.1 \text{FWHM} \sim 0.004 \). With the adoption of the new definition of the resolution angle, the average blended light fraction further decreases compared to that in Paper I.

Based on the simulation, we estimate that the total event rate of the MPF survey would be \( \Gamma_{\text{tot}} \sim 3500 \text{ events yr}^{-1} \), among which bulge self-lensing and disk-bulge events comprise \( \sim 64\% \) and \( \sim 36\% \), respectively. The ratio of the events caused by stellar to those caused by remnant lenses is \( \Gamma_\star : \Gamma_\text{rem} = 73.5 : 26.5 \). We summarize the event rates in Table 1.

| Event Category         | Rate (yr\(^{-1}\)) | Percent (%) |
|-----------------------|---------------------|-------------|
| Bulge self-lensing    | 2192                | 64.2        |
| Disk-bulge            | 1223                | 35.8        |
| Stellar lens          | 2510                | 73.5        |
| Remnant               | 905                 | 26.5        |
| Total event rate      | 3415                | ...         |

Note.—Detection rate of microlensing events from the MPF survey.

3. RESULTS

Figure 2 (top) shows the distribution of events expected to be detected by the MPF survey in the parameter space of the Einstein timescale and blended light fraction. We compare the distribution with those of events expected when the only blending source is the lens (middle) and background stars (bottom). In each panel, the light and dark gray points represent events caused by stellar and remnant lenses, respectively.

In the case in which the dominant source of blending is the lens itself, the distribution has the following distinctive features. First, the region with very little blended light fraction \( f_B \leq 0.05 \) is densely populated by events caused by remnant lenses, which are dark and thus do not contribute to the blended flux. Second, except for those caused by remnants, events are distributed smoothly...
over the entire range of the blended light fraction. Third, there exists a correlation between the timescale and the blending fraction. This correlation arises because heavier lenses tend to be brighter, and thus events with longer timescales are more likely to be affected by a larger amount of blended flux. We find that the mean timescale is $\langle t_e \rangle \approx 20$ days for stellar-lens events with $f_B \leq 0.1$, while it is $\langle t_e \rangle \approx 35$ days for events with $f_B \geq 0.9$. However, this correlation is not very strong due to the large dispersions of the Einstein timescale and lens brightness.

On the other hand, in the case in which most of the blended flux comes from background stars, the distribution has very different features from those described above. First, the distribution is not smooth but divided into two groups of heavily and lightly blended events. The two groups are roughly divided by $f_B \approx 0.5$. This kind of distribution occurs when the number of blended stars is small ($n < 1$), and in this case, most events will be distributed in the region of high (low) blended light fraction. We find that the average number of blended stars is $n \approx 0.42$. Another noticeable feature is that events caused by both stellar and remnant lenses have similar distributions. This is because there is no contribution of the flux from the lens to the total blended flux.

Considering the characteristics of the distributions in the regimes dominated by stellar and lens blending, we find that the distribution of MPF events has features of both types of blending. For example, although most remnant events are located in the very small $f_B$ region, a considerable fraction of these events are smoothly distributed in a wide range of blended light fraction. In addition, although events can still be divided into two groups of heavily and lightly blended events, the distinction between the two groups is less clear. These characteristics imply that both types of blending would have a significant effect on events detected by the MPF survey. This can also be seen in Figure 3, where we plot the distribution of the blended light fraction in the figure, one sees that both types of blending are nearly equally important.

4. ADDITIONAL ASTROMETRIC INFORMATION

When a source star blended with background stars is gravitationally magnified, the apparent position of the blended image centroid moves toward the source position during the event. The amount of the centroid shift is

$$\Delta r = |\vec{r} - \vec{r}_0| = D|\vec{r}_S - \vec{r}_0|,
D = \frac{(1 - f_B)(A - 1)}{(1 - f_B)(A - 1) + 1},$$

where $\vec{r}_S$ is the position of the source, and $\vec{r}_0$ and $\vec{r}$ are the positions of the image centroids before and in the middle of lensing magnification, respectively.

The centroid shift can be measured in another way. Han (2000) and Gould & An (2002) pointed out that the position of the lensed source star, $r_S$, instead of the centroid position of the combined image of the source and blend, $\vec{r}$, can be directly measured on an image obtained by using difference imaging. Difference imaging is an image-subtraction technique that provides accurate photometry and astrometry of variable stars in crowded fields (Tomaney & Crotts 1996; Alard & Lupton 1998). In this technique, one first forms a high-quality “template” image. For each of the other images (“current” image), one convolves the template image to the same seeing as the current image, translates it so that the two images are geometrically aligned, and linearly rescales its flux so that the two images are photometrically aligned as well. Then, the convolved template image is subtracted from the current image, which are point spread functions (PSFs) at the locations of stars that experienced light variation. Then by transforming the coordinates of the source position measured on the subtracted image to the template image, one can measure the positional difference between $r_S$ and $\vec{r}_0$. The centroid shift
measured in this way is related to the shift measured directly on two regular images by

$$\Delta r_{\text{DI}} = |r_S - \bar{r}_0|.$$  

(7)

We note that the centroid shift measured in this way is always larger than the shift in equation (6) because $D < 1.0$.

Astrometric information of the centroid shift may be important in distinguishing events blended by the lens and background stars. This is because the typical separation between the source and blended background star, which is of the order of $10^{-2}\text{r}_S$, is much larger than the separation between the source and lens, which is of the order of $10^{-4}\text{r}_S$. Thus, if blending is noticed from the light curve, but no centroid shift is detected within the astrometric precision of the centroid shift measurement, then the chance that the lens is the blending source is very high. Figure 4 shows the distribution of the centroid shifts for events detectable by the MPF survey.

We investigate the usefulness of the astrometric information in sorting out events in which most of the blended flux can be attributed to the lens. For this, we calculate the fraction of blended flux from background stars, $F_\ast$, out of the total blended flux for events in which blending is noticed with $F_B \geq 0.2$ but no centroid shift is detected within the astrometric uncertainty. The astrometric uncertainty of the centroid shift measurement is

$$\sigma_{\text{ast}} \sim \frac{\text{FWHM}}{N_p^{1/2}},$$

(8)

where $N_p$ is the photon count. We assume that the centroid shift is measured from difference imaging, i.e., $\Delta r_l = |r_S - \bar{r}_0|$. Despite the absence of atmosphere, difference imaging on a space-based observation may not be simple due to variations in the PSF profile from image to image caused by temporal variations in the thermal load on the spacecraft (Gilliland et al. 2000). Furthermore, the MPF images may suffer from undersampling of the PSF due to relatively large pixel size compared to the PSF. This may further complicate the geometric alignment procedure that involves interpolation of undersampled PSFs. To account for these possible additional sources of uncertainty in the astrometric measurement, we consider only centroid shifts with $\Delta r_{\text{DI}} > 3\sigma_{\text{ast}}$ as firmly detected.

In Figure 5, we present the resulting distributions of the fraction $F_\ast/F_B$. The dotted curve shows the distribution for events with blended light fractions $F_B \geq 0.2$, and the solid curve shows the distribution for events that are further filtered out with astrometric information under the condition that the measured centroid shift is $\Delta r_{\text{DI}} \leq 3\sigma_{\text{ast}}$. We note that the blended flux from background stars works as a contaminant to the flux from the lens, and thus a small ratio of $F_\ast/F_B$ implies that the blended flux is mostly from the lens. From the distributions, we find that blended flux of nearly half (49%) of all events with $F_B \geq 0.2$ is contaminated by the flux from background stars by more than $F_\ast/F_B = 20\%$. However, for the sample of events filtered out by using the additional astrometric information, it is found that only a minor fraction ($\sim10\%$) of events are contaminated by background stellar blending. We also find that this sample of events comprises $\sim22\%$ of all MPF lensing events. Considering the total event rate of $\sim3500$ events yr$^{-1}$ of the survey, the rate of these uncontaminated events is $\geq700$ events yr$^{-1}$, which is large enough for the statistical analysis of the lens populations.

5. CONCLUSION

We investigate the effect of blending in future gravitational microlensing surveys using a 1 m class space telescope. For this, we carried out a simulation of Galactic bulge microlensing events to be detected by the proposed MPF lensing survey by imposing realistic observational conditions and detection criteria. From this simulation, we found that the contribution of the flux from blended background stars to the total blended flux is equivalent to that of the lens itself, implying that characterizing lenses from the analysis of the blended flux would not be easy. However, with the additional astrometric information of the source star image centroid shift, we found that it would be possible to isolate events for which most of the blended flux is attributable to the lens. We estimate that the contamination of the blended flux by background stars would be less than 20% for most ($\sim90\%$) of the sample events obtained by imposing a criterion that the centroid shift should be less than 3 times the astrometric uncertainty among the events for which blending was noticed with blended light fractions $F_B > 0.2$. The expected rate of these events is $\geq700$ events yr$^{-1}$, which is large enough for the statistical analysis of the lens populations.

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