DETECTION OF M31 BINARIES VIA HIGH-CADENCE PIXEL-LENSING SURVEYS

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ABSTRACT

The Angstrom Project is using a distributed network of 2 m class telescopes to conduct a high-cadence pixel-lensing survey of the bulge of the Andromeda galaxy (M31). In this paper we estimate the detection rate of binary-lens events expected from high-cadence pixel-lensing surveys toward M31 such as the Angstrom Project based on detailed simulation of events and application of realistic observational conditions. Under the conservative detection criteria that only high signal-to-noise ratio caustic-crossing events with long enough durations between caustic crossings can be firmly identified as binary-lens events, we estimate that the rate would be $\Gamma_x \sim (7 - 15) f_b (N/50)$ per season, where $f_b$ is the fraction of binaries with projected separations of $10^{-3} \text{ AU} < d < 10^3 \text{ AU}$ out of all lenses and $N$ is the rate of stellar pixel-lensing events. We find that detected binaries would have mass ratios distributed over a wide range down to $q \geq 0.1$ but with separations populated within a narrow range of $1 \text{ AU} \leq \tilde{d} \leq 5 \text{ AU}$. Implementation of an alert system and subsequent follow-up observations would be important not only for the increase of the binary-lens event rate but also for the characterization of the lens matter.

Subject headings: galaxies: individual (M31) — gravitational lensing

1. INTRODUCTION

Surveys to detect transient variations of stellar brightness caused by gravitational microlensing have been and are being conducted toward various star fields. These fields include the Magellanic Clouds (MACHO, Alcock et al. 2000; EROS, Afonso et al. 2003), Galactic bulge (MACHO, Alcock et al. 2001; EROS, Hamadache et al. 2006; OGLE, Sumi et al. 2006; MOA, Bond et al. 2001), M31 (AGAPE, Ansari et al. 1999; POINT-AGAPE, Calchi Novati et al. 2005; VATT-Colombia, Uglesich et al. 2004; MEGA, de Jong et al. 2004; WeCAPP, Riffeser et al. 2003), and even to M87 (Baltz et al. 2004). The number of lensing events detected so far from these surveys is about 3000. Most of these events were detected toward the Galactic bulge field, and the events detected toward the Magellanic Cloud and M31 fields, which are several dozens toward the individual fields, have meager contributions to the total number of events. Toward the Magellanic Cloud field, the line of sight passes mainly through the halo of our Galaxy and thus the low detection rate could be attributed to the scarcity of massive compact halo objects that can work as lenses (Alcock et al. 2000; Tisserand et al. 2007). On the other hand, the line of sight toward M31 passes through the dense stellar region of M31 and thus the small number of detected events is mainly due to the low detection efficiency of the surveys.

With the expansion of the global telescope network, however, the detection efficiency of M31 lensing surveys is expected to greatly improve. For example, a new M31 pixel-lensing survey, the Andromeda Galaxy Stellar Robotic Microlensing (Angstrom) Project,9 will be able to achieve a monitoring frequency of approximately five observations per 24 hr period by using a network of telescopes, including the robotic 2 m Liverpool Telescope at La Palma, Faulkes Telescope North in Hawaii, the 1.8 m telescope at the Bohyunsan Observatory in Korea, the 2.4 m Hiltner Telescope at the MDM Observatory in Arizona, and the 1.5 m telescope at the Maidanak Observatory in Uzbekistan. Intensive monitoring programs such as Angstrom are expected to detect events with a rate of up to ~100 per season (Kerins et al. 2006). Among them, a considerable fraction would be caused by binaries. Baltz & Gondolo (2001) pointed out that the rate of binary events relative to single-lens events is higher in pixel lensing because many of the binary events involve caustic crossings during which the magnification is high and thus more detectable. In this work, we estimate the detection rate of binary-lens events expected from a high-cadence pixel-lensing survey toward M31 based on detailed simulation of events and application of realistic observational conditions.

The paper is organized as follows. In § 2 we describe the basics of binary lensing. In § 3 we investigate the dependency of the detection efficiency on the binary-lens parameters. We then estimate the event rate based on the simulation of M31 pixel-lensing events. We describe the details of the simulation and the criteria applied for the selection of binary events. We also investigate the characteristics of the binaries detectable from the survey. We end with a brief summary of the results and discussion in § 4.

2. BASICS OF BINARY LENSING

General relativity predicts that a light ray passing by a stellar object is deflected. If a source star is gravitationally lensed by a
binary lens, the equation of lens mapping from the lens plane to
the source plane is expressed as
\[ \zeta = z - \sum_{j=1}^{2} \frac{m_j/M}{2 - z - z_{L,j}}, \]
(1)
where \( \zeta = \xi + i\eta, z_{L,j} = x_{L,j} + iy_{L,j}, \) and \( z = x + iy \) are the com-
plex notations of the source, lens, and image positions, respec-
tively, \( \bar{z} \) denotes the complex conjugate of \( z, m_j \) are the masses of
the individual lens components, and \( M = m_1 + m_2 \) is the total
mass of the system (Witt 1990). Here all lengths are normalized
to the radius of the Einstein ring of the total mass of the system.
The Einstein radius is related to the physical parameters of the
lens system by
\[ \theta_{\text{E}} = \left( \frac{4GM}{c^2} \right)^{1/2} \left( \frac{1}{D_L} - \frac{1}{D_S} \right)^{1/2}, \]
(2)
where \( D_L \) and \( D_S \) are the distances to the lens and source, respec-
tively. Due to lensing, the source star image is split into several
segments. For binary lensing, the number of images, \( N_I \), is either
3 or 5 depending on the source position with respect to the lens
position. The lensing process conserves the source surface bright-
ness and thus the magnifications \( A_i \) of the individual images cor-
crespond to the ratios between the areas of the images and
source. For an infinitesimally small source element, the mag-
nification is
\[ A_i = \left| 1 - \frac{\partial \zeta}{\partial \bar{z}} \right|^{-1}. \]
(3)
Then, the total magnification corresponds to the sum over all im-
age, \( A = \sum_{i=1}^{N_I} A_i \).
The main new feature of binary lensing compared to single
lensing is the formation of caustics. Caustics are the set of positions
in the source plane on which the magnification of a point-source
event is infinite. The set of caustics form closed curves, which are
composed of multiple concave line segments (fold) that meet at
points (cusp). When the source enters the caustic curve, two new
points (cusp). When the source enters the caustic curve, two new
images appear and the number of images changes from 3 to 5. Due
to the divergent nature of the magnification near a caustic, the light
curve during the caustic crossing of a binary-lens event is char-
acterized by a sharp spike. Since the caustic curve is closed, the
number of caustic crossings is a multiple of 2. The light curve
between a set of two caustic crossings is characterized by its dis-
tinctive “U” shape.
The number and shape of caustics vary depending on the sepa-
ration, \( s \) (normalized by \( \theta_{\text{E}} \)), and mass ratio, \( q \), between the two
lens components. If the separation is substantially smaller than
the Einstein radius, \( s \ll 1 \), there exist three sets of caustics. One
big caustic is located close to the center of mass of the binary, and
the other two tiny ones are located away from the center of mass
on the heavier lens side. If the separation is substantially larger
than the Einstein radius, \( s \gg 1 \), on the other hand, there exist two
sets of caustics. They are located close to the positions of the
individual lens components but slightly shifted toward the lens
component of the other side. The amount of the shift is
\[ \Delta z_{L,i} = \text{sgn}(z_{L,j} - z_{L,i}) \frac{m_j/M}{s}, \]
(4)
where \( z_{L,i} \) is the position of the lens component on the same side
of each set of caustics while \( m_j/M \) and \( z_{L,j} \) represent the mass
fraction and position of the other lens component located on the
opposite side, respectively (Di Stefano & Mao 1996). If the bi-
ary separation is equivalent to the Einstein ring, \( s \sim 1.0 \), the
caucitic curve forms a single large closed figure with its center
roughly at the center of mass of the binary. In Figure 1 we present
the caustic pattern for various binary lenses with different sep-
arations. The dependence of the caustic size on the mass ratio is
weak. As a result, the caustic size is not negligible even for an ex-
treme case of a star-planet binary-lens pair with \( q \lesssim 10^{-3} \). This
makes microlensing an efficient method for planet searches
(Mao & Paczyński 1991).

3. BINARY-LENS EVENT RATE

We estimate the rate of M31 binary pixel-lensing events ac-

1. We first produce a large number of single-lens events caused
by the primaries, the heavier component of the binary, and com-
pute the detection probability of the individual events considering
distributions of the physical parameters related to the lens and
source and observational condition.
2. We then produce binary-lens events by introducing a com-
panion to the lens of each single-lens event, where the mass and
separation of the companion are derived from model distributions.
3. For each binary event, we check the detectability of binary
signal in the lens light curve. Finally, we estimate the binary-lens
event rate as the sum of the probabilities of events for which bi-
nary signal is detected.

We describe the details of the procedure in the subsequent
subsections.

3.1. Single-Lens Events

The production of single-lens events and the computation of
their detection probabilities are based on the simulation conducted
by Kerins et al. (2006). Such a simulation requires modeling of not
only the distributions of the physical parameters related to the lens
and source, such as the spatial, velocity, and mass distributions of
matter, luminosity distribution of source stars, and background
surface brightness, but also the observational condition such as the
monitoring frequency, exposure, and instrument. It also requires
definition of the detection criterion.

In the simulation, the M31 mass density distribution is modeled
by a standard double-exponential disk plus a barred bulge under
the assumption that the M31 halo is not significantly populated
with MACHOs. The double-exponential disk is represented analyti-
cally by
\[ \rho_d = \rho_{d,0} \exp \left[ -\left( \frac{R}{h_R} + \frac{|z|}{h_z} \right) \right], \]
(5)
where \( \rho_{d,0} = 0.3 \ M_\odot \ pc^{-3} \) is the central density and \( h_R = 5.8 \ kpc \) and
\( h_z = 0.4 \ kpc \) are the radial and vertical scale heights of the
density distribution, respectively. The bulge model is expressed as
\[ \rho_b = \rho_{b,0} \exp \left\{ - \left( \frac{x}{a} \right)^2 - \left( \frac{y}{b} \right)^2 - \left( \frac{z}{c} \right)^2 \right\}, \]
(6)
where \( a \) and \( b \) are the bar scale lengths along the long and short
axes, respectively, and the coordinates \((x, y, z)\) are aligned with
the bar principal axis where \( z \) is normal to the disk plane. The central density is chosen to be \( \rho_b = \frac{12}{12^{1/2}} \frac{M}{L_R} \frac{pc}{c} \) so that the total bulge mass is \( 3.6 \times 10^{10} M_\odot \). The choice of \( a = 1 \) kpc, \( b = 0.6 \) kpc, and \( \gamma = 0.75 \) combined with a mass-to-light ratio of \( M/L_R = 7 \) provides a good fit to the surface brightness observed by Walterbos & Kennicutt (1987). The velocity is modeled by an isotropic Maxwellian distribution, which is represented by

\[
f(v) = \frac{\rho}{(2\pi)^{3/2}\sigma^3} \exp\left( -\frac{v_\parallel^2 + v_\perp^2}{2\sigma^2} \right),
\]

where \( \rho = \rho_d + \rho_b \), \( \sigma = 90 \) km s\(^{-1}\) is the velocity dispersion, and \( v_\parallel \) and \( v_\perp \) are the velocity components that are normal to and parallel with the line of sight, respectively. The brightness distribution of source stars is constructed by using synthetic color-magnitude data based on the theoretical stellar isochrones of the Padova group (Girardi & Salaris 2001). The mass functions of lenses are modeled by a broken power law represented by

\[
\Phi(m) = \begin{cases} 
\kappa \left( \frac{m}{0.5 M_\odot} \right)^{-1.4}, & 0.08 M_\odot \leq m < 0.5 M_\odot, \\
\kappa \left( \frac{m}{0.5 M_\odot} \right)^{-2.35}, & 0.5 M_\odot \leq m < 1.0 M_\odot,
\end{cases}
\]

where \( \kappa \) is a proportional constant.

For the photometry, we assume that the instrument can detect 1 photon s\(^{-1}\) for an \( I = 24.2 \) star following the specification of the Liverpool Telescope. The observation is assumed to be carried out such that small-exposure images are combined to make a \( t_{\text{exp}} = 30 \) minute exposure image to obtain a high signal-to-noise ratio while preventing saturation in the central bulge region. We assume that five such combined images are obtained per 24 hr.
PIXEL-LENSING DETECTIONS OF M31 BINARIES

3.2. Binary-Lens Events

Based on the single-lens events produced in the previous subsection, we then produce binary-lens events under the assumption that a fraction of events are caused by binaries. We did this by introducing a companion to the lens of a single-lens event.

We introduce a companion by assigning its separation from the primary under the assumption that binary separations are uniformly distributed in a logarithmic distance scale (Abt 1983). The mass of the companion is assigned based on a mass ratio distribution. For the mass ratio distribution, we test three models. The first model is based on the assumption that the two masses of the binary components are drawn independently from the same mass function as that of single stars. This model is the natural result of the binary formation process, where binaries are formed through interactions between protostellar disks (Pringle 1989) or some other form of capture. We refer to this model as the “capture” model. Other possible mechanisms of binary formation are fission of a single star and fragmentation of a collapsing object. Numerical calculations suggest that the former process results in a mass ratio distribution peaking at around $q = 0.2$ (Lucy 1977), while the latter results in more equal masses (Norman & Wilson 1978). We refer to these models as the “fission” and “fragmentation” models, respectively. We model the mass ratio distribution in the fission model as

$$f(q) = \begin{cases} 5q, & q \leq 0.2, \\ -1.25q + 1.25, & q > 0.2. \end{cases}$$

The distribution of the fragmentation model is modeled as

$$f(q) = q.$$ 

In the capture and fragmentation models, the mass of the primary is drawn from the single-lens mass function in equation (8) and the mass of the companion is determined based on the mass ratio derived from the mass ratio distribution. In the fission model, on the other hand, we set the total mass of the binary to be the same as that of a single lens because a single mass is split into two components of a binary in this model. As a result, the average mass of the binary lenses in the fission model is smaller than those in the capture and fragmentation models. In Figure 3 we present the mass ratio distributions of the three tested models.

For a single-lens event, the source trajectory is defined with respect to the position of the lens. However, there exist two lens components for a binary-lens event, and thus a new definition of the reference position is required. For this, we introduce an effective single-lens position, which is defined as the location of a single lens at which the resulting single-lens light curve best describes the light curve of a binary-lens event. For example, the light curve of an event caused by a close binary with $s \ll 1.0$ is well described by that of a single-lens event caused by a mass equal to the total mass of the binary located at the center of mass of the binary. In this case, the effective single-lens position is the center of mass of the binary. For the case of a wide separation binary with $s \gg 1.0$, on the other hand, the individual lens components behave as if they are two independent single lenses located at the centers of the individual sets of caustics. In this case, there are two effective lens positions located at the center of the individual caustics. For an intermediate-separation binary where the separation is equivalent to the Einstein ring radius ($s \sim 1.0$), the resulting lensing behavior substantially deviates from that of a single-lens events. In this case, we classify the binary as wide or close depending on whether the caustic is divided...
into two pieces or not. In Figure 1 we present effective lens positions for various cases of binary-lens systems.

For many of the M31 pixel-lensing events, the involved source stars would be giants, for which the source size relative to the Einstein radius is not negligible. The finite-source effect is especially important to high-magnification and caustic-crossing events, which correspond to the majority of the M31 pixel-lensing events. Therefore, we take the finite-source effect into consideration in producing light curves. The magnification of a finite source corresponds to the intensity-weighted magnification averaged over the source star surface, i.e.,

$$A(z) = \frac{\int_{S} I(z') A_{pt}(z' + z') dz'}{\int_{S} I(z') dz'},$$

where $A_{pt}$ represents the magnification of the corresponding point source, $z'$ is the vector position of the center of the source, $z''$ is the displacement vector of a point on the source star surface with respect to the source star’s center, and $\int_{S} \cdots dz'$ denotes the surface integral over the source star surface. The normalized radius of the source star is computed by $R_s = \theta_s/\theta_E$, where the angular source radius $\theta_s$ is determined from the synthetic stellar isochrone data and the Einstein radius is determined from the lens mass and distances to the lens and source produced by the simulation. To save computation time, we assume that the source star has uniform surface brightness and reduce the two-dimensional integral into a one-dimensional one by using the general Stoke’s theorem (Gould & Gaucherel 1997).

3.3. Binary Signals

Once light curves of binary-lens events are produced, we check the detectability of binary signal. The light curves of binary events exhibit diverse patterns. In many cases, it is difficult to firmly distinguish them from those caused by single lenses or other types of source variability. Fortunately, a fraction of binary-lens events involve caustic crossings, and the characteristic features (e.g., spikes during caustic crossings and a U-shape curve between caustic crossings) in the resulting light curves can be used to securely identify not only the lensing-induced variability but also the binary nature of the lens. Therefore, we restrict detectable binary events only to caustic-crossing events. For the confirmation of caustic crossings, we require events to have at least five data points with $S/N > 3$: on the part of the light curve between caustic crossings. Considering that the assumed observation frequency of the Ångstrom survey is 5 times per day, this requirement means that the source star should stay in the caustic at least for a day. We note that the data points with $S/N > 3$ do not have to be consecutive.

In the right panels of Figure 1 we present example light curves of binary-lens events for which binary signal is detected. In each light curve, the dark-tone filled circles represent data points satisfying the requirements that the source is within the caustic and the signal-to-noise ratio is higher than a threshold value of $(S/N)_{th} = 3.0$.

3.4. Results

In Table 1 we present the expected rates of binary-lens events under three different models of binary mass ratio distributions. We
note that the event rate is normalized so that it becomes 50 events per season if all lenses are composed of a single component following the estimation of Kerins et al. (2006). We find that the rate of binary-lens events is $f_b \sim 10^{-3} \text{AU} < d < 10^3 \text{AU}$ out of all lenses. By adopting a value of $f_b = 0.5$ and considering the 7 month duration of the M31 observation season (from August to February), this rate roughly corresponds to $\sim 0.7$ events per month.

In Figure 4 we plot the distributions of mass ratios and separations between the lens components of binary-lens events. The three different histograms in each panel represent the distributions under the three different models of binary mass ratio distributions. From the mass ratio distribution, we find that detectable binaries will have mass ratios distributed over a wide range of mass ratio down to $q \sim 0.1$. We also find that the dependence of the detection rate on the binary mass ratio distribution is such that the rate increases as more companions are populated in a higher mass ratio region. As a result, the rate becomes bigger in the order of the fission, capture, and fragmentation models. From the separation distributions, we find that most events have binary separations located within a narrow range of $1 \text{AU} \leq d \leq 5 \text{AU}$.

4. DISCUSSION AND CONCLUSIONS

We estimated the detection rate of binary-lens events expected from high-cadence pixel-lensing surveys toward M31 such as the Angstrom Project based on detailed simulation of events and application of realistic observational conditions. Under the conservative detection criteria that only high signal-to-noise ratio caustic-crossing events with large separations as binaries-lens events, we estimated that the rate would be $f_b \sim (7 - 15)f_b(N/50)$ per season, where $N$ is the rate of stellar pixel-lensing events. We found that detected binaries would have mass ratios distributed over a wide range down to $q \gtrsim 0.1$ but with separations populated within a narrow range of $1 \text{AU} \leq d \leq 5 \text{AU}$.

The Angstrom survey is currently commissioning operation with a real-time data processing pipeline and a Web-based transient and microlensing alert system (Darnley et al. 2007). Realization of the alert system and subsequent follow-up observations would greatly increase the observation frequency and thus overall event rate. Considering that a significant fraction of caustic crossing events are missed from detection due to the short duration between caustic crossings, increasing the monitoring frequency from follow-up observations would be able to dramatically increase the binary event rate.

Follow-up observation of binary-lens events would be important not only for the increase of the event rate but also for the characterization of lens matter. The majority of M31 pixel-lensing events are associated with giant stars with large angular radii. The large source size allows resolution of caustic crossings because the duration of the caustic crossing is proportional to the source radius, i.e.,

$$\Delta t_{cc} = 2\left(\frac{\rho_{\star}}{\sin \alpha}\right)t_{E},$$

where $t_E$ is the Einstein timescale and $\alpha$ is the incidence angle of the source trajectory with respect to the caustic curve. For a typical M31 pixel-lensing event with $\rho_{\star} \sim 0.03$ and $t_E \sim 10$ days, the caustic-crossing duration is $\Delta t_{cc} \approx 14$ hr. Then, if events can be followed up with a frequency higher than once every hour, the caustic crossing can be resolved. Once the caustic is resolved and the value of $\rho_{\star}$ is known from the analysis of the light curve, one can estimate the Einstein radius with additional information of the source radius by $\rho_{\star} = \theta_E/\rho_{\star}$. Since the Einstein radius is related to the physical parameters of the lens by the relation in equation (2), one can better constrain the nature of the lens.

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