NEAR-FIELD MICROLENSING FROM WIDE-FIELD SURVEYS

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ABSTRACT

We estimate the rate of near-field microlensing events expected from all-sky surveys and investigate the properties of the events. Under the assumption that lenses are composed of stars, our estimation of the event rate ranges from \( \Gamma_{\text{tot}} \sim 0.1 \text{ yr}^{-1} \) for a survey with a magnitude limit of \( V_{\text{lim}} = 12 \) to \( \Gamma_{\text{tot}} \sim 23 \text{ yr}^{-1} \) for a survey with \( V_{\text{lim}} = 18 \). We find that the average distances to the source star and lens vary considerably depending on the magnitude limit, while the dependencies of the event timescale and lens-source transverse speed are weak. We also find that the average lens-source proper motion of events expected from a survey with \( V_{\text{lim}} = 18 \) would be \( \langle \mu \rangle \sim 40 \text{ mas yr}^{-1} \), and the value further increases as the magnitude limit becomes lower, implying that the source and lens of a significant fraction of near-field events can be resolved from high-resolution follow-up observations conducted several years after the lensing magnification. From the investigation of the variation of the event characteristics depending on the position of the sky, we find that the average distances to source stars and lenses become shorter, the lens-source transverse speed increases, and the timescale of events increases as the Galactic latitude of the field increases. Because of the concentration of events near the Galactic plane, we find that \( \geq 50\% \) of events would be detected in the field with \( b \leq 30^\circ \).

Subject heading: gravitational lensing

1. INTRODUCTION

The concept of one star gravitationally amplifying the light from another background star was first considered by Einstein (1936), although he concluded that the chance to observe the phenomenon (gravitational microlensing) would be very low. With the advance in technology, however, detections of microlensing events became feasible from systematic searches. The first detections were reported in the early 1990s (Alcock et al. 1993; Aubourg et al. 1993; Udalski et al. 1993). To date, lensing events are routinely detected with a rate of \( \geq 500 \) events per season, and the total number of detections now exceeds 3000. To maximize the number of detections, these searches have been and are being conducted toward very dense star fields of nearby galaxies, such as the Magellanic Clouds (Alcock et al. 2000; Afonso et al. 2003) and M31 (Ansari et al. 1999; Riflesser et al. 2003; Uguagli et al. 2004; de Jong et al. 2004; Calchi Novati et al. 2005; Kerins et al. 2006), and the Galactic center (Alcock et al. 2001; Hamadache et al. 2006; Sumi et al. 2006; Bond et al. 2001).

Recently, a detection of a lensing event that occurred on a nearby star was reported by Gaudi et al. (2008) and Fukui et al. (2007). The lensed star (GSC 3656–1328) is located about 1 kpc from the Sun in the disk of the Milky Way. This detection along with the advent of transient surveys capable of covering a very wide field with high cadence such as ASAS (Szczygieł & Fabrycky 2007), ROTSE (Akerlof et al. 2003), TAROT and ARAGO (Boër 2001), and Pan-Starrs (Hodapp et al. 2004) have drawn the attention of many researchers in the microlensing community on the feasibility of near-field microlensing surveys. If near-field events could be detected from such surveys, they would be able to provide precious information about the matter distribution around the Sun, including dark objects. In addition, these surveys might enable detections of close planets with the microlensing technique that has demonstrated its capability in detecting distant planets (Bond et al. 2004; Udalski et al. 2005; Beaulieu et al. 2006; Gould et al. 2006).

The probability of lensing occurring on nearby stars has been estimated by Colley & Gott (1995) and Nemiroff (1998). The estimation of Colley & Gott (1995) focused on events that could be observable with naked eyes, i.e., with a magnitude limit \( V_{\text{lim}} \sim 6 \). Nemiroff (1998) estimated the lensing probability expected from surveys with various magnitude limits. However, he estimated the probability in terms of the average number of stars undergoing lensing magnification at a moment, not in terms of events per year, by using the combination of the star count information and optical depth to lensing. The optical depth to lensing represents the probability that any given star is microlensed with a magnification \( A \geq 1.34 \) at any given time. This optical depth is dependent on the spatial mass distribution, but it is independent of the mass of the individual lensing objects. Therefore, the probability based on the optical depth does not provide detailed information about the physical parameters of lens systems, such as the lens mass, locations of the lens and source, and their relative transverse speed, and the observables of events, such as the event timescale and source brightness. For this information, additional modeling of the mass function and velocity distribution of Galactic matter is required. Di Stefano (2005) discussed the event rate due to nearby lenses, but the events were against crowded fields.

In this paper we extend the works of Colley & Gott (1995) and Nemiroff (1998) to estimate the rate of lensing events in terms of events per year and to obtain the distributions of the physical parameters and observables of events expected from all-sky lensing surveys with various magnitude limits. For this, we conduct a Bayesian simulation of near-field lensing events.

The paper is organized as follows. In § 2 we describe the details of the simulation. In § 3 we present the resulting event rate and distributions of the physical parameters of lens systems and observables of lensing events. We also investigate the variation of the event characteristics and the lensing probability depending on the position of the sky. We analyze the tendencies found in the distribution and explain the reasons for these tendencies. We summarize the result and conclude in § 4.
2. LENSSING SIMULATION

To investigate the rate and properties of near-field lensing events, we conduct a Bayesian simulation of these events. The basic scheme of the simulation is as follows.

1. We first produce source stars on the sky that can be seen from a survey with a given magnitude limit. We assign the locations on the sky and the distances to the stars based on a spatial mass distribution model of the Galaxy. The stellar brightness is assigned based on a model luminosity function considering distances to stars and extinction.

2. Once source stars are produced, we then produce lenses. We assign the lens masses based on a model mass function. The distances to the lenses are allocated from the same spatial mass distribution model as that of the source star.

3. The lens-source transverse speed of each event is computed from the velocities of the lens and source, which are assigned based on a dynamic model of the Galactic disk.

4. With all the lens parameters, we then produce events and estimate the event rate by weighting the individual events with an appropriate lensing probability.

The details of the simulation are described in the following subsections.

2.1. Stellar Distribution

We model the mass distribution in the solar neighborhood as a double-exponential disk of the form

\[ \rho(R, z) \propto \exp \left[ -\left( \frac{R - R_0}{h_R} + \frac{|z|}{h_z} \right) \right], \]  

where \( R_0 \) is the galactocentric distance of the Sun and \( h_R \) and \( h_z \) are the radial and vertical scale heights, respectively (Bahcall 1986). We adopt \( R_0 = 8 \) kpc. For the radial scale height, we adopt a fixed value of \( h_R = 3.5 \) kpc. For the vertical scale heights, on the other hand, we adopt varying values depending on the stellar brightness such that \( h_z = 90 \) pc for \( M_V \leq 3.0 \), 200 pc for \( M_V = 4.0 \), 325 pc for \( M_V = 5.0 \), 455 pc for \( M_V = 6.0 \), 585 pc for \( M_V = 7.0 \), and 600 pc for \( M_V > 7.0 \). There exist stars with luminosity types other than main-sequence stars. In addition, a fraction of stars may belong to other Galactic structures such as the thick disk and halo. We do not consider these stars under the assumption that these stars comprise a small fraction of the total stars.

We model the luminosity function of stars by adopting that of stars in the solar neighborhood presented in Binney & Merrifield (1998). This luminosity function is constructed by combining the data published in Allen (1973) for \( M_V \leq 0 \) and in Jahreiss & Wielen (1983) and Kroupa et al. (1990) for \( M_V > 0 \).

Extinction is modeled such that the stellar flux decreases exponentially with the increase of the dust column density, i.e.,

\[ A_V = -2.5 \log \left| \exp \left( -k \Sigma_d \right) \right|, \]

where \( \Sigma_d \) is the dust column density and \( k \) is a proportional constant. The dust column density is computed on the basis of an exponential dust distribution model, i.e.,

\[ \Sigma_d = \int_0^{D_{\text{d}}} \rho_d(\ell) d\ell, \quad \rho_d \propto \exp \left( -\frac{|z|}{h_{d,z}} \right), \]

where the integral is along the line of sight toward the source star and \( h_{d,z} \) is the vertical scale height of the dust distribution. We adopt \( h_{d,z} = 150 \) pc (Drimmel & Spergel 2001).

2.2. Lens Distribution and Mass Function

In our simulation we assume that only stars are responsible for lensing events and no MACHOs or stellar remnants are taken into consideration. For the mass function of lens matter, we adopt the model of Kroupa et al. (1993), which is based on the initial mass function of stars in the solar neighborhood. The model has a triple power-law distribution of the form

\[ \frac{dN}{dM} \propto \begin{cases} 0.035(M/M_\odot)^{-13}, & 0.08 \leq M/M_\odot < 0.5, \\ 0.019(M/M_\odot)^{-2.2}, & 0.5 \leq M/M_\odot < 1.0, \\ 0.019(M/M_\odot)^{-2.7}, & 1.0 \leq M/M_\odot. \end{cases} \]  

The distances to the individual lenses are assigned from the same spatial mass distribution model as that of source stars in equation (1). Since the scale height varies depending on the brightness, it is needed to determine the lens brightness. We deduce the lens brightness from its mass by using the \( M_V \)-mass relation of stars presented in Cox (1999). Based on the absolute magnitude of the lens, we choose the corresponding scale height and then assign the lens location. We note that in most cases the lens is much fainter than the source star, and thus, the contribution of the lens to the observed flux is negligible.

2.3. Velocity Distribution

We model the velocity distribution as Gaussian, i.e.,

\[ f(v) \propto \exp \left( \frac{(v - \bar{v})^2}{2\sigma^2} \right). \]

The adopted means and standard deviations of the distributions of the individual velocity components in the galactocentric cylindrical coordinates are \( \bar{v}_R, \bar{v}_\phi, \bar{v}_z = (0, 220, 0) \text{ km s}^{-1} \) and \( \sigma_R, \sigma_\phi, \sigma_z = (38, 25, 20) \text{ km s}^{-1} \), respectively, i.e., a flat rotating disk with Gaussian velocity dispersion. For lensing, the projected velocity, \( v_{\perp} \), as seen from the observer is related to lensing events. Then, it is required to convert the velocity components into those in the spherical coordinates that are centered at the position of the Sun. This conversion is done by the relation

\[ \begin{pmatrix} v_r \\ v_\phi \\ v_z \end{pmatrix} = \begin{pmatrix} \cos b & 0 & \sin b \\ 0 & 1 & 0 \\ -\sin b & 0 & \cos b \end{pmatrix} \times \begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_R \\ v_\phi \\ v_z \end{pmatrix}, \]

where \( b \) is the Galactic latitude of the star and \( \alpha \) is the angle between the two lines connecting the Sun, the projected position of the star on the Galactic plane, and the Galactic center (see Fig. 2).
Fig. 1.—Stellar number density as a function of Galactic latitude. The curves are based on our models of the spatial mass distribution, luminosity function, and extinction, while the data points are from the observations presented in Cox (1999). The lack of stars with $V \leq 17$ at low Galactic latitudes is because our model spatial mass distribution does not include bulge stars.
The angle $\alpha$ is related to the Galactic longitude of the star, $l$, the galactocentric distance of the Sun, $R_0$, and the projected distance to the star on the Galactic plane from the Sun, $d$, by

$$\alpha = \sin^{-1} \left( \frac{R_0 \sin l}{\tilde{R}} \right), \quad \tilde{R} = (R_0^2 + \tilde{d}^2 - 2R_0 \tilde{d} \cos l)^{1/2},$$

where $\tilde{R}$ is the projected distance to the star from the Galactic center (see Fig. 2). Then, the projected velocity of a star depends not only on the Galactic coordinates $(l, b)$ but also on the distance to the star $d = \tilde{d}$ sec $b$. With the projected velocities of the lens, $v_L = v_\perp(D_L)$, and source, $v_L = v_\perp(D_S)$, the relative lens-source transverse velocity is computed by

$$v_t = v_L - \left[ v_S \left( \frac{D_L}{D_S} \right) + v_\Omega \left( \frac{D_S - D_L}{D_S} \right) \right],$$

where $v_\Omega$ represents the projected velocity of the observer and $D_L$ and $D_S$ are the distances to the lens and source, respectively.

We note that the observer, lens, and source are all in rotation with the same rotation speed, and thus, the contribution of the rotation to the transverse speed is negligible. Then, the lens-source transverse motion is mostly caused by the dispersion of the rotation-subtracted residual velocity.

2.4. Event Rate

Once the source, lens, and their relative speed are chosen, their contribution to the event rate is computed by

$$\Gamma \propto n(l, b, D_S)n(l, b, D_L)D_\Sigma^2 \sigma v_t,$$

where $n(l, b, d)$ represents the number density of stars at the position $(l, b, d)$ and $\sigma$ is the cross section of the lens-source encounter. Here, the factor $D_\Sigma^2$ is included to account for the increase of the number of source stars with the increase of the distance. Under the definition of a lensing event as the approach of the source star within the Einstein ring of the lens (equivalently, source...
flux is magnified with a magnification $A \geq 1.34$), the lensing cross section is set as $\sigma = 2r_E^2$, where $r_E$ is the physical Einstein ring radius. The Einstein radius is related to the physical parameters of the lens system by

$$r_E = \left(\frac{4GM}{c^2}\right)^{1/2} \sqrt{\frac{D_L(D_S - D_L)}{D_S}},$$  \hspace{1cm} (10)$$

where $M$ is the mass of the lens. We assume that the survey is conducted all through the year$^2$ and events are detected with 100% efficiency.

### 3. RESULTS

In Table 1 we list the total event rate, $\Gamma_{\text{tot}}$, expected from surveys with various magnitude limits. Also listed in the table are the total number of stars that can be monitored from the surveys, $N_{\text{tot}}$, and the average optical depth to lensing, $\langle \tau \rangle$. The optical depth is determined from the mass distribution model by

$$\tau(l, b) = \int_0^\infty dD_S n(l, b, D_S; V \leq V_{\text{lim}}) \frac{D_S^2}{D_L} \frac{dD_L}{D_L} n(l, b, D_L) r_E^2,$$

$$\int_0^\infty dD_S n(l, b, D_S; V \leq V_{\text{lim}}) D_S,$$  \hspace{1cm} (11)$$

where the factor $\int_0^\infty dD_S n(l, b, D_S; V \leq V_{\text{lim}}) D_S^2$ corresponds to the number of stars brighter than the magnitude limit toward the observation field, $N_\star$, and the other factor $\int_0^\infty dD_S n(l, b, D_S) r_E^2$ is the accumulation of the area occupied by the Einstein rings of the individual lenses along the line of sight toward the source star. We note that although there exists a limitation in the brightness of source stars ($V \leq V_{\text{lim}}$), there is no restriction in the lens brightness. The presented values in Table 1 are the mean optical depth averaged over the whole sky, i.e., $\langle \tau \rangle = (4\pi)^{-1} \int_{-180}^{180} d\ell \int_{-90}^{90} \tau(l, b) \sin b \, db$, and the total number of stars over the entire sky, i.e., $N_{\text{tot}} = \int_{-180}^{180} d\ell \int_{-90}^{90} N_\star(l, b) \sin b \, db$. We find that our estimation of the optical depth well matches the estimation of Nemiroff (1998). The multiplication $N_{\text{tot}} \langle \tau \rangle$ represents the number of stars undergoing lensing magnification at a given moment, which was presented in Nemiroff (1998). We also find a good match between his and our estimations. The estimated event rate ranges from $\Gamma_{\text{tot}} \sim 0.1$ yr$^{-1}$ for a survey with a magnitude limit of $V_{\text{lim}} = 12$ to $\Gamma_{\text{tot}} \sim 25$ yr$^{-1}$ for a survey with $V_{\text{lim}} = 18$, confirming the result of Nemiroff (1998) that the lensing probability rapidly increases with the increase of the magnitude limit. Two factors contribute to the increase of the event rate with the increase of the magnitude limit. The first factor is the increase of the number of source stars, and the other factor is the extension of the line of sight toward source stars and thus the increase of the optical depth. We find that the former factor is more important.

In Figure 3 we present the distributions of lens parameters and the observables of events including the distributions of the source star brightness, distances to source stars and lenses, lens masses, lens-source transverse speed, event timescale, and lens-source relative proper motion. The event timescale is determined by the Einstein timescale, which is required for the source to transit the Einstein radius of the lens, i.e., $t_E = r_E/c$. The proper motion corresponds to $\mu = \theta_E/t_E$, where $\theta_E = r_E/D_L$ is the angular Einstein radius. In Table 2 we also present the average values of the lens parameters. From Figure 2 and Tables 1 and 2 we find the following tendencies.

1. The distributions of $D_S$ and $D_L$ vary considerably depending on the observation field, $N_\star$, and the other factor $\int_0^\infty dD_S n(l, b, D_S) r_E^2$, which was presented in Nemiroff (1998). We also find a good match between his and our estimation at a given moment, which was presented in Nemiroff (1998).

2. On the other hand, the dependency of the distribution of the lens mass, event timescale, and transverse speed on the magnitude limit is weak. The mean value of the lens mass is $\langle M \rangle \sim 0.2 M_\odot$, implying that the majority of events will be caused by low-mass stars.

3. With the increase of the magnitude limit, the distance to the lens increases while the transverse speed remains nearly the same. As a result, the average proper motion $\mu = \theta_E/t_E = v_i/D_L$, of events decreases as the magnitude limit increases. However, we note that even for surveys with $V_{\text{lim}} = 18$, the mean proper motion of events is $\langle \mu \rangle \approx 40$ mas yr$^{-1}$, which is much larger than the typical value of 5 mas yr$^{-1}$ of Galactic bulge events. Then, the lens and source of a significant fraction of near-field events can be resolved from follow-up observations by using high-resolution instruments such as the Hubble Space Telescope conducted several years after the peak of the magnification. Resolving of the lens and source not only enables the measurement of the proper motion but also helps to identify the lens.

### Table 1

| $V_{\text{lim}}$ | $N_{\text{tot}}$ | $\langle \tau \rangle$ | $\Gamma_{\text{tot}}$ (yr$^{-1}$) |
|------------------|-------------------|------------------------|-------------------------------|
| 12               | $0.10 \times 10^7$ | $0.12 \times 10^{-8}$  | 0.08                          |
| 14               | $0.47 \times 10^7$ | $0.25 \times 10^{-8}$  | 0.57                          |
| 16               | $2.0 \times 10^7$  | $0.52 \times 10^{-8}$  | 3.8                           |
| 18               | $7.5 \times 10^7$  | $0.92 \times 10^{-8}$  | 23.0                          |

**Notes**: Rates of near-field microlensing events, $\Gamma_{\text{tot}}$, expected from all-sky surveys with various magnitude limits, $V_{\text{lim}}$. Also listed are the total number of stars that can be monitored from the surveys, $N_{\text{tot}}$, and the average optical depth to lensing, $\langle \tau \rangle$.

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$^2$ This requires a network of wide-field telescopes distributed over the Earth.
Fig. 3.—Distributions of lens parameters and observables of near-field microlensing events expected from all-sky surveys with various magnitude limits, $V_{\text{lim}}$. Down from the left top panel and then down from the right top panel, the individual panels represent the distributions of the source star brightness ($V$), distances to the source star ($D_s$) and lens ($D_L$), lens masses, transverse speeds ($v_t$), event timescales ($t_E$), and lens-source relative proper motions ($\mu$). The mean values of the parameters and observables are listed in Table 2.
timescales for events that occurred on stars located at a lower latitude.

3. With the increase of the stellar number density combined with the increase of the optical depth, the event rate increases rapidly toward the Galactic plane. We find that the fraction of the event rate from the fields with $|b| ≤ 30^\circ$ are 70%, 67%, 54%, and 48% for surveys with $V_{\text{lim}} = 12, 14, 16,$ and 18, respectively.

4. CONCLUSION

Instigated by the recent discovery of an event that occurred on a nearby star, we estimated the rate of near-field lensing events expected from all-sky surveys with various magnitude limits. Under the assumption that all lenses are composed of stars, our estimation of the event rate ranges from $\Gamma_{\text{tot}} \sim 0.1 \, \text{yr}^{-1}$ for a survey with a magnitude limit of $V_{\text{lim}} = 12$ to $\Gamma_{\text{tot}} \sim 23 \, \text{yr}^{-1}$ for a survey with $V_{\text{lim}} = 18$, confirming the previous result that lensing probability rapidly increases with the increase of the magnitude limit. The increase of the rate is due to two factors, which are the extension of the line of the sight toward source stars and the increase of the number of source stars. We found that the latter factor is more important. We also investigated the distributions of the physical parameters of lens systems and the observables of these events. From this, we found that although the average distances to source stars and lenses vary considerably depending on the magnitude limit, the dependencies of the lens mass, event timescale, and lens-source transverse speed are weak. We also found that the average lens-source proper motion of events expected from a survey with $V_{\text{lim}} = 18$ would be

### Table 2: Average Values of Lens Parameters

| $V_{\text{lim}}$ (mag) | $(D_S)$ (kpc) | $(D_L)$ (kpc) | $(M_L)$ ($M_\odot$) | $(v_t)$ (km s$^{-1}$) | $(t_E)$ (days) | $(\mu)$ (mas yr$^{-1}$) |
|------------------------|----------------|----------------|---------------------|---------------------|----------------|-----------------------|
| 12                     | 0.36           | 0.18           | 0.18                | 54.7                | 13.4           | 73.7                  |
| 14                     | 0.49           | 0.25           | 0.18                | 55.5                | 15.4           | 60.7                  |
| 16                     | 0.72           | 0.35           | 0.18                | 56.6                | 17.4           | 49.3                  |
| 18                     | 1.03           | 0.46           | 0.18                | 57.4                | 19.9           | 41.7                  |

Note.—Average values of the lens parameters and observables of near-field microlensing events expected from wide-field surveys with various magnitude limits, $V_{\text{lim}}$. 

![Fig. 4.—Variation of the characteristics and probability of near-field microlensing events depending on the position of the sky. From the top, the panels in each row represent the distributions of the average distances to source star ($D_S$) and lens ($D_L$), lens-source transverse speed ($v_t$), event timescale ($t_E$), average number density of stars in the field ($N_\circ$), optical depth ($\tau$), and the event rate per unit angular area ($\Gamma$). The panels in each column represent the distributions for different magnitude limits. The map is centered at the Galactic center, i.e., ($l, b$) = (0°, 0°).](image-url)
(µ) ≳ 40 mas yr\(^{-1}\), and the value further increases as the magnitude limit becomes lower. This implies that the source and lens of a typical near-field lensing event can be resolved from high-resolution follow-up observations conducted several years after the peak of the lensing magnification. From the investigation of the variation of the event characteristics depending on the position of the sky, we found that the average distances to source stars and lenses become shorter, the lens-source transverse speed increases, and the timescale becomes shorter as the Galactic latitude of the field increases. Because of the concentration of events near the Galactic plane, we found that ≳50% of events would be detected in the field with \( b \leq 30^\circ \).

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