EXPANSION OF PLANET DETECTION METHODS IN NEXT-GENERATION MICROLENSING SURVEYS

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ABSTRACT

We classify various types of planetary lensing signals and the methods for detecting them. We estimate the relative frequencies of planet detections by various methods, with special emphasis on new methods to be provided by future lensing experiments that will continuously survey wide fields at high cadence using very large format imaging cameras. From this investigation, we find that the fraction of wide-separation planets that would be discovered through the new methods of detecting planetary signals as independent and repeating events would be substantial. We estimate that the fraction of planets detectable through the new methods would comprise \( \sim 15\% - 30\% \) of all planets, depending on the models of planetary separation distribution and the mass ratios of the planets. Considering that a significant fraction of planets might exist as free-floating planets, the frequency of detections through the new methods would be even higher. With the addition of the new methods, future lensing surveys will greatly expand the range of planets that can be detected.

Subject headings: gravitational lensing — planets and satellites: general

1. INTRODUCTION

Microlensing is one of the important techniques that can detect and characterize extrasolar planets. The technique is especially important in the detection of low-mass planets, and can detect Earth-mass planets from ground-based observations. The capability of the microlensing technique has been demonstrated by the recent detections of four planets (Bond et al. 2004; Udalski et al. 2005; Beaulieu et al. 2006; Gould et al. 2006), including one (OGLE-2005-BLG-390Lb) that is the lowest mass planet ever detected among those orbiting normal stars.

Planetary lensing signals last a short period of time: several days for a Jupiter-mass planet and several hours for an Earth-mass planet. To achieve the observational frequency required for the detection of a short-lived planetary signal, current microlensing planet search experiments are being operated in an observational setup, in which survey observations (e.g., OGLE, Udalski 2003; MOA, Bond et al. 2002a) issue alerts of ongoing events, and subsequent follow-up observations (e.g., PLANET, Algbrow et al. 2001; MicroFUN, Dong et al. 2006) intensively monitor the alerted events. With this strategy, however, only those planetary signals that occur during the lensing magnification of the source star can be effectively monitored. These signals are produced by planets that have projected separations from the star similar to the Einstein radius of the primary star. As a result, only planets located in a narrow region of separation from the host star can be effectively detected by current planetary lensing searches.

The range of planets detectable with the microlensing technique will be expanded with next-generation lensing experiments that will continuously survey wide fields at high cadence using very large format imaging cameras. Several such surveys both in space and on the ground are being seriously considered. The Micro-lensing Planet Finder (MPF), which succeeds the original concept of the Galactic Exoplanet Survey Telescope (GEST; 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 technique (Bennett 2004). The “Earth Hunter” project is a ground-based microlensing survey that plans to achieve \( \sim 10 \) minute sampling by using a distributed network of multiple wide-field (\( \sim 2^\circ \times 2^\circ \)) telescopes (A. Gould 2007, private communication). Recently, the MOA group began observing a fraction of their fields very frequently, using a recently upgraded 1.8 m telescope with a 2.2 deg\(^2\) field of view. These surveys dispense with the alert/follow-up mode of searching for planets, and instead simultaneously obtain densely and continuously sampled light curves of all microlensing events in the field of view. With these surveys, the efficiency of planet detection will greatly improve, thanks to their enhanced monitoring frequency and continuous sampling. In addition, future lensing experiments will be able to open new channels for detecting planets, because source stars are monitored regardless of their magnifications. In this paper, we classify various methods of detecting planetary lensing signals, and estimate the relative frequencies of planet detections probable with the individual methods, with special emphasis on the new methods that will be provided by future lensing surveys.

The format of the paper is as follows. In § 2, we describe the basics of planetary microlensing. In § 3, we present various types of planetary lensing perturbations, and classify the methods for detecting them. In § 4, we estimate the relative frequency of planet detection using the various methods. We discuss the importance of the new planet detection channels to be provided by future lensing surveys. We summarize the results and conclude in § 5.

2. BASICS OF PLANETARY MICROLENSING

Because of the existence of a planetary companion, a description of planetary lensing behavior requires modeling binary lensing (Witt 1990; Witt & Mao 1995). Because of the small mass ratio of the planet, the light curve of a planetary lensing event is well described by that of a single lens of the primary star for most of the event duration. However, a short-duration perturbation can occur when the source star passes the region around the caustics. The caustics are important features of binary lensing, representing the set of source positions at which the magnification of a point source becomes infinite. The caustics of binary lensing form a single or multiple set of closed curves, each of which is composed of concave curves (fold caustics) that meet at points (cusps). For
a planetary case, there exist two sets of disconnected caustics, the central and planetary caustics.

The single central caustic is located close to the host star. It has a wedge shape with four cusps, with two located on the star-planet axis, and the other two located off the axis. The size of the central caustic as measured by the separation between the on-axis cusps is represented by (Chung et al. 2006)

$$\Delta s_{\text{cc}} \sim \frac{4q}{(s-s^{-1})^2},$$

(1)

where $q$ is the planet/star mass ratio and $s$ is the star-planet separation normalized by the Einstein radius of the planetary lens system, $\theta_E$. The caustic size becomes maximum when $s \sim 1.0$. In the limiting case of a very wide-separation planet ($s \gg 1.0$) and a close-in planet ($s \ll 1.0$), the caustic size decreases, respectively, as

$$\Delta s_{\text{cc}} \propto \begin{cases} s^{-2} & \text{for } s \gg 1.0, \\ s^2 & \text{for } s \ll 1.0. \end{cases}$$

(2)

For a given mass ratio, a pair of central caustics with separations $s$ and $s^{-1}$ are identical to the first order of an approximation in which the planet-induced anomalies are treated as a perturbation (Dominik 1999; Griest & Safizadeh 1998; An 2005). The central caustic is always smaller than the planetary caustic. Since the central caustic is located close to the primary lens, the perturbation induced by the central caustic always occurs near the peak of high-magnification events.

The planetary caustic is located away from the host star. The center of the planetary caustic is located on the star-planet axis, and the position vector to the center of the planetary caustic from the primary lens position is related to the lens-source separation vector $s$ by

$$r_{\text{pc}} = s \left( 1 - \frac{1}{s^2} \right).$$

(3)

The planetary caustic is located on the planet side, i.e., $\text{sign}(r_{\text{pc}}) = \text{sign}(s)$, when $s > 1.0$, and on the opposite side, i.e., $\text{sign}(r_{\text{pc}}) = -\text{sign}(s)$, when $s < 1.0$. When $s > 1.0$, there exists a single planetary caustic, with a diamond shape with four cusps. When $s < 1.0$, there are two caustics, each with a triangular shape with three cusps. The size of the planetary caustic is related to the planet parameters by

$$\Delta s_{\text{pc}} \propto \begin{cases} q^{1/2} \left[ s(s^2-1)^{1/2} \right]^{-1} & \text{for } s > 1.0, \\ q^{1/2} \left( \kappa_0 - \kappa_0^{-1} + \kappa_0 s^{-2} \right) \cos \theta_0 & \text{for } s < 1.0, \end{cases}$$

(4)

where

$$\kappa(\theta) = \left\{ \frac{\cos 2\theta \pm (s^4 - \sin^2 2\theta)^{1/2}}{s^2 - s^{-2}} \right\}^{1/2},$$

$$\theta_0 = \frac{\pi \pm \sin^{-1}(s^2 \sqrt{3}/2)}{2},$$

$$\kappa_0 = \kappa(\theta_0).$$

(Han 2006). We note that the dependence of the planetary caustic size on the mass ratio is $\Delta s_{\text{pc}} \propto q^{-2}$, while the dependence of the central caustic size is $\Delta s_{\text{cc}} \propto q$. Therefore, the decay rate of the planetary caustic with the decrease of the planet mass is slower than that of the central caustic. The planetary caustic is located within the Einstein ring of the primary star when the planet is located in the range of separation $0.6 \leq s \leq 1.6$ from the star. The size of the caustic is maximized when the planet is located in this range, and thus this range is called the "lensing zone" (Gould & Loeb 1992; Griest & Safizadeh 1998). In the limiting cases of planetary separation, the size of the planetary caustic decreases as

$$\Delta s_{\text{pc}} \propto \begin{cases} s^{-2} & \text{for } s \gg 1.0, \\ s^2 & \text{for } s \ll 1.0. \end{cases}$$

(5)

In the limiting case of $s \ll 1.0$, the two lens components work as if they were a single lens. In the limiting case of $s \gg 1.0$, on the other hand, the star and planet work as two independent lenses.

3. CLASSIFICATION OF PLANET DETECTION METHODS

Planetary lensing signals take various forms depending on the characteristics of the planetary system—especially on the star-planet separation—and the source trajectory with respect to the positions of the star and planet. In this section, we classify various types of planetary lensing signals and the methods for detecting them.

A type I perturbation shows up as a perturbation to the smooth light curve of the primary-induced lensing event (see the top curve in Fig. 1). This type of perturbation is produced by planets with projected star-planet separations similar to the Einstein radius of the primary star, i.e., $s \sim 1.0$. As a result, we refer to the method of detecting planets through a type I perturbation as the "resonant channel". The resonant channel is the primary method of detecting planets in current planetary lensing searches, which are based on the survey/follow-up mode. Depending on whether the perturbation is induced by the planetary or central caustic, the perturbation takes place to the side of or near the peak of the light curve.

A type II perturbation is produced by a planet with a projected separation from its primary star that is substantially larger than the Einstein radius of the primary star ($s \gg 1.0$), and it occurs when the source trajectory passes the effective magnification regions of both the primary star and the planet. The planetary signal is the planet-induced lensing light curve that is well separated from the light curve of the primary (see the second curve in Fig. 1). Since two successive events are produced by the star and planet, we refer to this method of planet detection as the "repeating channel" (Di Stefano & Scalzo 1999). The planetary signal occurs long after or before the event induced by the primary star, and thus a type II perturbation is difficult to detect with current planetary lensing searches, which only monitor the time of primary-induced lensing magnification.

A type III perturbation is also produced by a wide-separation planet, but it occurs when the source trajectory only passes the effective magnification region of the planet. In that case, the planetary signal is the independent lensing light curve produced by the planet itself (see the third curve in Fig. 1). We refer to this method of planet detection as the "independent channel." Type III perturbations are also difficult to detect with current planetary lensing searches.

Wide-separation planets can also be detected by another method. A type IV perturbation is produced by a wide-separation planet, and it occurs when the source trajectory passes very close to the primary star. The planetary signal is then a brief perturbation near
the peak of the high-magnification lensing light curve produced by the primary star (see the fourth curve in Fig. 1). We refer to this method as the "wide central channel." High-magnification events are of highest priority in the current microlensing follow-up observations because of their high sensitivity to planets (Griest & Safizadeh 1998; Albris et al. 2000; Bond et al. 2002b; Rattenbury et al. 2002; Abe et al. 2004; Yoo et al. 2004; Dong et al. 2006), and thus type IV perturbation can be detected from current follow-up observations.

A type V perturbation is produced by a planet with a star-planet separation substantially smaller than the Einstein radius of the primary star, and it occurs when the source trajectory passes very close to the primary star. The planetary signal is very similar to the type IV perturbation (see the fourth curve in Fig. 1) due to the $s \rightarrow s^{-1}$ symmetry of the central caustic (Dominik 1999; An 2005). As a result, distinguishing the two types of perturbation is often difficult, especially for perturbations induced by low-mass planets with mass ratios $q \lesssim 10^{-4}$ (Chung et al. 2006).

4. FREQUENCY OF THE INDIVIDUAL METHODS

In the previous section, we presented various types of planetary perturbations and the methods for detecting them. Now we ask, what would be the relative frequencies of detecting planets through the various methods in future lensing surveys?

The rate of planet detection is proportional to the cross section of the planetary perturbation region, $\sigma$. We therefore estimate the relative frequencies by computing the cross sections of the planetary perturbation regions for each type. We carry out our computation according to the following procedure.

1. First, we make maps of perturbation induced by planets with various separations and mass ratios.
2. Second, we classify the types of perturbation based on the planetary separation and the locations of the perturbation regions. We then estimate the average cross sections of the perturbation regions in each category based on the constructed perturbation maps.
3. Finally, we compute the relative frequencies of planet detection through the individual methods by convolving the cross sections with the model distributions of planetary separation.

The details of the individual processes are described in the following subsections.

4.1. Maps of Planetary Signal Detectability

The map of planetary perturbation represents the region of planet-induced lensing perturbations as a function of source position. The quantity that has often been used to represent the perturbation region is the fractional deviation of the planetary lensing light curve from that of the single lensing event of the primary star, i.e.,

$$\epsilon = \frac{A - A_0}{A_0}, \quad (6)$$

where $A$ and $A_0$ represent the lensing magnifications with and without the planet, respectively. With this quantity, however, one cannot consider the variation of the photometric precision, which depends on the lensing magnification and source brightness. To consider this, we construct the map of perturbation with the quantity defined as the ratio of the fractional deviation, $\epsilon$, to the photometric precision, $\sigma_v$, i.e.,

$$D = \frac{|\epsilon|}{\sigma_v}; \quad \sigma_v = \frac{(AF_{\nu,S} + F_{\nu,B})^{1/2}}{(A - 1)F_{\nu,S}}, \quad (7)$$

where $F_{\nu,S}$ and $F_{\nu,B}$ represent the photon counts from the source star and blended background stars, respectively. Under this definition of the planetary perturbation, $D = 1$ implies that the planetary signal is equivalent to the photometric precision. Hereafter, we refer to the quantity $D$ as the "detectability".

To construct the map of detectability, we choose a representative Galactic bulge event. Following the result of simulations of Galactic bulge events (e.g., Han & Gould 2003, 2005), we choose as a representative event the one produced by a lens with a primary lens mass of $m = 0.3 M_\odot$, and distances to the lens and source of $D_L = 6$ kpc and $D_S = 8$ kpc, respectively. For the observational condition, we use the space-based lensing survey MPF as a reference. The prime target source stars monitored by the MPF survey are main-sequence stars, and thus we choose a main-sequence source star with an $I$-band absolute magnitude of $M_I = 4.8$, which corresponds to a K0 star. With an assumed amount of extinction toward the Galactic bulge field of $A_I = 1.0$, this corresponds to an apparent magnitude of $I = 20.3$. Following the specification of the MPF mission, we assume that the photon acquisition rate is 13 photons s$^{-1}$ for an $I = 22$ star, and that photometry is done on each combined image with an exposure time $t_{exp} = 10$ minutes. We assume that blending is not important due to high resolution from space-based observation. The finite size of the source star might affect the planet detectability (Bennett & Rhie 1996).

However, the populations of planets that interest us are the ones to be detected through the new methods (i.e., the repeating and...
independent channels), and most of them would have to be giant planets because of their larger cross sections. Considering that the angular size of the source star is a few percent of the angular Einstein radius of a giant planet, the finite size of the source star has little effect on the planet detectability. We therefore do not consider finite-source effect in our analysis.

Figure 2 shows constructed maps of detectability for some example planetary systems. The maps are centered at the position of the primary lens star, and the planet is located on the left. The gray and white contours are drawn at the level of $D = 1, 2, \text{and} 3$. The solid white circle arcs centered at the primary star in each map represent the Einstein ring. The closed figures drawn by red curves are the caustics. All lengths are in units of the Einstein radius of the planetary system, and $\xi$ and $\eta$ represent the coordinates that are parallel and normal to the star-planet axis, respectively. Each planetary perturbation region is approximated by an elliptical region, and the green curve represents its boundary. The planetary lens system has a common planet/star mass ratio of $q = 3 \times 10^{-3}$.

4.2. Cross Section of Perturbation

With the constructed maps of perturbation, we then estimate the average cross sections of the perturbation regions of the individual types. For this, we classify the types of perturbation based on the planetary separation and the location of the perturbation region.

The following are the criteria for the classification. First, we classify all perturbations induced by planets located in the lensing zone ($0.6 \leq s \leq 1.6$) as type I. If a perturbation is induced by a wide-separation ($s > 1.6$) planet, the perturbation region is divided into two parts: one around the planetary caustic and the other around the central caustic. If the perturbation is caused by the central caustic, it is classified as a type IV perturbation. From those perturbations caused by the planetary caustics of wide-separation planets, the fraction classified as type II perturbations is geometrically estimated as $\sin \left(\frac{2}{\pi} \sin^{-1}\left(\frac{\eta}{s}\right)\right)$, where
\( u_0 \) is the radius of the effective lensing magnification region of the primary star. We adopt \( u_{0b} = 1.5 \). The rest of the perturbations induced by the planetary caustics of wide-separation planets are then classified as type III. Finally, perturbations induced by planets with separations \( s < 0.6 \) are classified as type V.

Once the types of the individual perturbation regions are determined, we then estimate the average cross sections of the perturbation regions. A straightforward approach to estimating the cross section would be first to draw many light curves resulting from source trajectories with various combinations of the distance to the trajectory from the center of the perturbation region and orientation angles, to check the detectability of the planet-induced perturbations for the individual light curves, and finally to estimate the cross section as an angle-averaged value. However, this requires a large amount of computation time. Fortunately, the perturbation region is confined around caustics, and its boundary is approximated by an ellipse. We therefore estimate the cross section by approximating the perturbation region as an elliptical region.

With this approximation, the cross section of the perturbation region is estimated as the angle-averaged cross section of the ellipse, i.e.

\[
\langle \sigma \rangle = \frac{1}{\pi} \int_0^{\pi} \left( a_p^2 \sin^2 \theta + b_p^2 \cos^2 \theta \right)^{1/2} d\theta = \frac{2}{\pi} a_p E(e), \tag{8}
\]

where \( a_p \) and \( b_p \) are the semimajor and semiminor axes of the elliptical boundary of the perturbation region, \( e = (1 - b_p^2/a_p^2)^{1/2} \) is the eccentricity of the ellipse, and \( E \) is the complete elliptical integral of the second kind. We define the semimajor and semiminor axes of the ellipse as the widths of the perturbation region enclosed by the detectability contour with a level of \( D = 3 \) along and normal to the star-planet axis, respectively. If the perturbation region is composed of multiple segments, we approximate the individual segments with different ellipses. In Figure 2, we present the elliptical boundaries of perturbation regions (green ellipses) on top of the detectability map.

Figure 3 shows the determined cross section of the planetary perturbation region as a function of the normalized star-planet separation. The segments marked by different shades of gray under the curve represent the types of the related planetary perturbations.

\[
\sigma = \alpha_0 + \beta_0 s^2 + \gamma_0 s^4 + \delta_0 s^6 + \epsilon_0 s^8 + \zeta_0 s^{10},
\]

where \( \alpha \) is the semimajor axis of the planet orbit. There is little consensus about the power of the distribution. From the analysis of observed extrasolar planets detected by radial velocity surveys, Tabachnik & Tremaine (2002) claimed that \( \alpha \approx 1 \). On the other hand, Hayashi (1995) claimed that the surface density distribution of the minimum-mass solar nebula is well described with \( \alpha \approx 1.5 \).

We therefore test two different powers of \( \alpha: 1.0 \) and 1.5. We note that the larger absolute value of the power implies that planets are populated in the inner region, and that the fraction of planetary events detectable through the type I perturbation increases, while the fractions through the type II, III, and IV decrease. We assume that planets are distributed up to a distance of 100 AU as an independent lens, and the cross section converges into the value corresponding to the cross section of the effective magnification region of the planet.

### 4.3. Relative Frequencies

Once the average cross sections of the individual types of perturbation have been computed, we estimate the relative frequencies of planet detection by the individual methods of planet detections. This is done by convolving the cross section with model distributions of planetary separation.

We model the distribution of star-planet separation as a power-law function of the form

\[
\frac{dN}{da} \propto a^{-\alpha}, \tag{9}
\]

where \( \varphi \) is the inclination angle of the orbital plane and \( \varphi \) is the phase of the planet on the orbital plane.

In Table 1, we present the relative frequencies of planet detection through the various methods. From the table, we find that the frequency of detecting planets through the new methods to be provided by future lensing surveys would be substantial. We estimate that the fraction of planets detectable through the independent and repeating channels would comprise \( \sim 15\% \)–30\% of all planets, depending on the models of the planetary separation distribution and mass ratios of the planets. Considering that the total number of planets expected to be detected from 5 year lensing surveys in space would be several thousand (Bennett 2004), the number of planets detectable through the new methods would be...
of the order of 100, and could reach up to 1000. We note that
the estimation in Table 1 is based only on planets bound to primary
stars.

The new methods to be provided by future lensing surveys are
important for a better understanding of planet formation and evo-
lution processes. Planets located \( k = 5 \) AU from host stars cannot
be detected by any of the methods currently being used for planet
searches. Therefore, since it is able to detect planets in this range,
the microlensing method would provide a complete sample of
planets. Another population of planets that can be detected through
the new methods are free-floating planets (Bennett & Rhie 2002;
Han 2004). It is believed that a good fraction of planets were
ejected from their planetary systems during or after the epoch of
planet formation (Zinnecker 2001). Another possible origin of
these planets would be the accretion of gas, similar to the star for-
mation process (Boss 2001). Since these planets were not in-
cluded in our analysis, the relative frequency of planet detection
through the new methods would be even larger if these planets
are common.

5. CONCLUSION

We classified various types of planetary lensing signals and the
methods for detecting them. We estimated the relative frequencies
of planet detections through the individual methods, with special
emphasis on the new additional methods that will be provided by
future lensing surveys. From this investigation, we found that the
fraction of wide-separation planets that would be discovered
through the new methods for detecting planetary signals as in-
dependent and repeating events would be substantial. We esti-
mated that the fraction of planets detectable through the new
methods would comprise \( \frac{1}{4} \) to \( \frac{1}{3} \) of all planets, depend-
ing on the models of planetary separation distribution and mass ra-
tios of the planets. Considering that a significant fraction of planets
might exist in the form of free-floating planets, the frequency of
planets to be detected through the new methods could be even
higher. We therefore demonstrate that future lensing surveys will
greatly expand the range of planets that can be detected.

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