REEVALUATING THE FEASIBILITY OF GROUND-BASED EARTH-MASS MICROLENSING PLANET DETECTIONS

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ABSTRACT

An important strength of the microlensing method to detect extrasolar planets is its high sensitivity to low-mass planets. However, many believe that microlensing detections of Earth-mass planets from ground-based observation would be difficult because of limits set by finite-source effects. This view comes from the previous estimation of planet detection probability based on the fractional deviation of planetary signals; however, a proper probability estimation is required when considering the source brightness, which is directly related to the photometric precision. In this paper, we reevaluate the feasibility of low-mass planet detections by considering photometric precision for different populations of source stars. From this, we find that the contribution of improved photometric precision to the planetary signal of a giant-source event is large enough to compensate for the decrease in magnification excess caused by finite-source effects. As a result, we conclude that giant-source events are suitable targets for Earth-mass planet detections with significantly higher detection probability than events involved with source stars of smaller radii, and we predict that Earth-mass planets could be detected by prospective high-cadence surveys.

Key words: gravitational lensing: micro – planetary systems

Online-only material: color figures

1. INTRODUCTION

Searches for extrasolar planets by using the microlensing method are being conducted toward the Galactic bulge field (OGLE: Udalski 2003; MOA: Bond et al. 2001; WISE: Shvartzvald & Maoz 2012). Because of the high sensitivity to planets that are difficult to detect via other methods, this method is particularly important for the comprehensive understanding of the formation and evolution of planets in various types of stars (Mao & Paczyński 1991; Gould & Loeb 1992; Gaudi 2012).

An important strength of the microlensing method is that it is sensitive to low-mass planets. This is because the amplitude of a microlensing planetary signal does not depend on the planet mass for a point source, although the duration of the signal becomes shorter as the planet mass decreases. In practice, the low-mass limit of a microlensing planet is set by finite-source effects that diminish planetary signals. For giant-source stars, the size of the caustic induced by an Earth-mass planet is equivalent to the angular size of the source star; thus, the planetary signal is significantly weakened due to severe finite-source effects. On the other hand, for events associated with a main-sequence (MS) star, the attenuation of the planetary signal is mild, but poor photometric precision caused by the source faintness limits secure detections from ground-based observation. As a result, many believe that detecting Earth-mass planets from ground-based observation would be difficult.

The difficulty of detecting Earth-mass planets from ground-based microlensing observation was first pointed out by Bennett & Rhie (1996). This result is based on their estimation of planet detection probability using simulations of planetary lensing events with various types of source stars. In their simulation, they computed the fractional deviation of the lensing magnification, \((A - A_0)/A_0\), and estimated the detection probability by imposing a threshold deviation. Here, \(A\) and \(A_0\) represent the lensing magnifications with and without the presence of the planet, respectively. With this criteria, the planet detectability is mostly decided by the severity of finite-source effects. As a result, they reached the conclusion that the detection probability of giant-source events would be significantly lower than the probability of events associated with faint source stars with smaller radii. Based on this result, Bennett & Rhie (2002) proposed a space-based microlensing experiment to search for Earth-mass planets by resolving faint MS stars.

However, proper estimation of the planet detection probability requires us additionally to consider the source brightness. This is because the strength of planetary signal \(\Delta \chi^2 = \sum_i (F_i - F_{0,i})^2/\sigma_i^2\) not only depends on the amplitude of the planetary deviation, \(F - F_0\), but also on the photometric uncertainty, \(\sigma\), which is directly related to the source brightness. Here, \(F\) and \(F_0\) represent the observed source fluxes with and without the planet, respectively. In addition to decreased photon noise directly relating to increased photon count, photometric precision also depends on the source brightness because bright-source events are less likely to be affected by blending.

In this paper, we reevaluate the feasibility of ground-based detections of Earth-mass planets by considering the dependence of photometric precision and blending on the source type. In Section 2, we describe the simulation of planetary lensing events conducted for the probability estimation. In Section 3, we present results from the analysis. In Section 4, we summarize and discuss the results.

2. SIMULATION

In order to evaluate the feasibility of ground-based Earth-mass planet detections, we conduct simulations of Galactic microlensing events. The simulations are based on representative lensing events following current and/or prospective Galactic microlensing surveys.

For the lens, we assume that the mass of the primary lens is \(0.3 M_\odot\) by adopting the mass of the most common lens population of low-mass stars (Han & Gould 1995). Then, the mass ratio of an Earth-mass planet to the lens is \(q \sim 10^{-3}\). We adopt an Einstein timescale of \(\tau_E \approx 20\) days and assume that events are observed with a 10 minute cadence following the observational strategy of the prospective ground-based survey.
of the Korean Microlensing Telescope Network (KMTNet; Kim et al. 2010). Following OGLE, we assume that images are taken in the $I$ band.

For the source, we test three representative stellar populations of Galactic bulge stars, including MS, subgiant, and giant stars. For the source radii of $\theta_\ast$, normalized by the Einstein radius of $\theta_E$, we adopt $\rho_\ast = \theta_\ast / \theta_E = 0.001, 0.003, \text{ and } 0.010$ for the individual source stars, which roughly correspond to the physical source radii of $1R_\odot, 3R_\odot$, and $10R_\odot$, respectively. Considering the stellar types and distance to the Galactic bulge, as well as using an average extinction of $A_I = 1.0$ (Nataf et al. 2013), we assume that the unlensed, unblended, apparent $I$-band magnitudes of the individual source stars are $I_0 = 19.5, 18.0$, and $16.5$, respectively. In Table 1, we summarize the characteristics of the individual source stars.

For realistic simulations of lensing light curves, photometric errors are estimated by using the relation between the photometric uncertainty and the source brightness, which is obtained based on actual lensing events observed by the OGLE survey. For this, we choose multiple events with wide spans of lensing magnification and take an average value as a representative uncertainty for a given source brightness. We note that systematics of photometry are taken into consideration because the estimated magnitude–error relation is not based on theoretical assumptions of systematics, but on actual data resulting from systematics. Figure 1 shows the magnitude–uncertainty relation. At faint magnitudes, photometry is limited by photon count, resulting in a rapid decrease of error as a star becomes brighter. At very bright magnitudes, on the other hand, photometry is dominated by non-photon noise, e.g., read-out noise, dark current, etc.; therefore, photometry does not improve for $I \leq 14$. In the region $I \geq 16$, the uncertainty decreases rapidly as the source becomes brighter. For example, sub-milli-magnitude level photometry is possible for a giant star, while the uncertainty for an MS star is $\sigma \sim 0.1$ mag. We assume that photometry follows Gaussian distribution.

Photometric precision in lensing observation not only depends on the source brightness, but also on the blended light from unlensed neighboring stars. Considering that faint stars are more strongly affected by blending, we adopt blend to source flux ratios of $F_b/F_\ast = 4.0, 1.0$, and $0.25$ for the individual source populations. With these ratios, the source brightness of a lensing event varies as

$$I(t) = I_{\text{base}} - \Delta I(t),$$

where $I_{\text{base}} = I_0 - 2.5\log(1 + F_b/F_\ast)$ is the blended baseline source brightness, $\Delta I(t) = 2.5\log A_{\text{obs}}(t)$ is the apparent brightening of the source, and $A_{\text{obs}}(t) = [A(t) + F_b/F_\ast]/(1 + F_b/F_\ast)$ is the apparent lensing magnification (Han 1999).

To produce light curves affected by finite-source effects, we use the ray-shooting method (Kayser et al. 1986; Schneider & Weiss 1987). With this method, uniform rays shoot from the observer to the lens plane, the deflection angle is calculated from the individual lens components, and rays are collected in the source plane. The deflection angle is computed by the lens equation

$$\zeta = \varepsilon_1 \left( \frac{z - z_{L,1}}{z - z_{L,2}} \right) - \varepsilon_2 \frac{z - z_{L,1}}{z - z_{L,2}},$$

where $\varepsilon_i$ is the mass fraction of each lens component; $\zeta$, $z_{L,i}$, and $z$ represent the complex notations of the source, lens, and image positions, respectively; and $\zeta$ denotes the complex conjugate of $z$ (Witt 1990). Finite-source magnifications are computed as the ratio of the number density of rays on the surface of the source star to the density on the observer plane. In computing finite-source magnifications, we also consider the variation of the source surface brightness caused by limb-darkening effects. For this, we model the surface brightness profile as

$$S_I \propto 1 - \Gamma_I \left( 1 - \frac{3}{2} \cos \phi \right),$$

where $\Gamma_I$ is the linear limb-darkening coefficient and $\phi$ is the angle between the line of sight toward the source star and the normal to the source surface (Albrow et al. 2001). The adopted values of the limb-darkening coefficients are listed in Table 1.

In Figure 2, we present example lensing light curves produced by simulation. Two typical cases of planetary perturbations produced by close (top panels) and wide (bottom panels) planets are shown. Here, the terms “close” and “wide” denote the cases where the projected planet–star separation is smaller and larger than the Einstein radius, respectively. For each set of panels, we present three light curves associated with giant (top), subgiant (middle), and MS (bottom) source stars. The lensing magnifications of the individual light curves are identical, but the light curves appear to be different due to the differences in the source brightness and the blend to source flux ratio. The three small middle panels show the enlarged view of the perturbation regions (shaded region in the left panel) presented as “magnitude.” Also presented in the right panels are the light curves of the perturbations in terms of the lensing “magnification.”
3. DETECTION PROBABILITY

With light curves produced from simulation, we estimate the planet detection probability. The probability is estimated as the ratio of the number of events with noticeable planetary signals to the total number of tested events, assuming that source trajectories are randomly oriented with respect to the star–planet axis.

In order to estimate the detection probability, it is required to produce a large number of finite-source light curves that demand heavy computation. For efficient estimation of the probability, we use the map-making method (Dong et al. 2006). With this method, a pixel map of rays covering a large area on the source plane is stored in the buffer memory of a computer, and light curves are produced from rays in the pixels of the map located along the source trajectory. This method is useful for producing numerous light curves from different source trajectories without needing to shoot rays for each light curve.

In our probability estimation, we consider events with impact parameters (normalized by $\theta_\text{E}$) of the lens-source approach $u_0 < 1$, i.e., events produced by the source approach within the Einstein ring of the primary lens. Microlensing planets can be detected for events with $u_0 > 1$, where the planetary signal stands on the weak or no-base lensing magnification of the primary event (Han et al. 2005; Sumi et al. 2011; Bennett et al. 2012), but we do not consider these cases in this work.

We estimate the probability by setting a threshold value of $\Delta \chi^2_{\text{th}}$ as a criterion for the detectability of planetary signals. Gould et al. (2010) extensively discussed the choice of $\Delta \chi^2_{\text{th}}$ and pointed out that $\Delta \chi^2_{\text{th}}$ should be high enough to avoid false-positive signals arising from systematics in the data. Therefore, we adopt a conservative value of $\Delta \chi^2_{\text{th}} = 500$. We note that the trends of probability dependence on the source type and the planetary separation for different values of $\Delta \chi^2_{\text{th}}$ are consistent regardless of the choice of threshold values within $300 \leq \Delta \chi^2_{\text{th}} \leq 700$.

Intrinsic source variability, especially for giant stars, can induce short-term variation in lensing light curves (Gould et al. 2013). However, in general, resulting deviations have

Figure 2. Example light curves of microlensing events produced by simulation. The top and bottom panels show light curves produced by planets with projected separations of $s = 0.83$ and 1.20, respectively. The three light curves in each set of panels represent those of events occurring on (top) giant-source, (middle) subgiant-source, and (bottom) MS-source stars. The shaded region of each light curve represents the planetary perturbation region, and the enlarged view is presented in the middle and right panels, marked by the corresponding number. The dotted curve for each light curve represents the light curve without the planet.

(A color version of this figure is available in the online journal.)
different forms from those induced by planets. Thus, they can easily be distinguished with follow-up photometric and spectroscopic observation. Therefore, we do not consider contamination of planetary lensing signals by source variability.

In Figure 3, we present the estimated detection probability as a function of the projected planet separation normalized by the Einstein radius, $s$, for three different populations of source stars. From the distributions, we find that the probability is substantially higher for giant-source events than for events with source stars of smaller radii throughout the planetary separations, except for a narrow region around $s = 1$. The result is contradictory to that of Bennett & Rhie (1996), who found a smaller probability for a larger source size.

The cause of the opposite results between our and Bennett & Rhie’s analyses is found from the comparison of the planetary perturbations presented in the brightness (magnitude) and magnification, which are shown in the middle and right panels of Figure 2. As pointed out by Bennett & Rhie (1996), magnification excess of a planetary deviation caused by finite-source effects decreases with the increase of the source size. However, a source star becomes brighter as its size increases, and the contribution of the improved photometric precision to the planetary signal is great enough to compensate for the decrease of magnification excess and to result in stronger planetary signals. For example, we find that the planetary signal $\Delta \chi^2 = 2878$ of the giant-source event marked by (1) is much stronger than the signal $\Delta \chi^2 = 322$ of the MS-source event marked by (3), despite that the former event suffers from more severe finite-source effects.

4. SUMMARY AND DISCUSSION

In order to verify the previous result indicating the difficulty in detecting Earth-mass planets from ground-based observation, we reevaluated the detection feasibility by considering the dependence of photometric precision on source populations. From the analysis based on realistic simulation of lensing events, we found that the probability of detecting Earth-mass planets for giant-source events was higher than the probability for events involved with source stars of smaller radii. This result was in opposition to the previous one. It was found that the main reason for the higher probability for giant-source events was that the contribution of the improved photometric precision to the planetary signal of a giant-source event was big enough to compensate for the decrease of magnification excess caused by finite-source effects.

Although no Earth-mass planet has yet been detected, the competing effects of extended source and source brightness are well illustrated by microlensing planets detected through the channel of high-magnification events. A good example is the planetary event MOA-2007-BLG-400 (Dong et al. 2009). Even though the mass of the planet ($\sim 0.5–1.3 M_{\text{Jup}}$) discovered in the event is much greater than that of the Earth, the event is similar to a giant-source Earth-mass planetary event in the sense that the caustic was substantially smaller than the source and the planetary deviation occurred when the source was bright. Despite that, the planetary deviation was greatly attenuated by severe finite-source effects, the signal was detected with the large significance of $\Delta \chi^2 = 1070$, and the planetary deviation was unambiguously ascertained. As the detection was possible because of the high photometric precision of the bright source, giant-source events would be suitable targets for the detection of low-mass planets. Therefore, we predict that Earth-mass planets would be detected from future ground-based high-cadence lensing surveys.

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