THE POSSIBILITY OF DETECTING PLANETS IN THE ANDROMEDA GALAXY

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and

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ABSTRACT

The Angstrom project is using a global network of 2 m class telescopes to conduct a high-cadence pixel microlensing survey of the bulge of the Andromeda galaxy (M31), with the primary aim of constraining its underlying bulge mass distribution and stellar mass function. Here we investigate the feasibility of using such a survey to detect planets in M31. We estimate the efficiency of detecting signals produced by planets with various masses and separations from the host star. We find that for a ~5MJ planet that is located within the lensing zone (~1–3 AU), detection is possible above 3σ with detection efficiency ~6%. This corresponds to the yearly detection rate of ~3fLZ planets, where fLZ is the probability that a planet exists in the lensing zone. It is expected that most events with detectable planets are associated with giant source stars, and thus source size will have a significant effect on the planet detection efficiency. We also find that the planetary perturbations will be in nearly all cases caused by central caustics, and thus observational strategies focusing on these central perturbations would maximize planet detections. A dramatic improvement in the efficiency of ~30%–50% is expected if follow-up observations on an 8 m telescope are made possible by a real-time alert system.

Subject headings: galaxies: individual (M31) — gravitational lensing — planets and satellites: general

1. INTRODUCTION

Various techniques are being used to search for extrasolar planets, including the radial velocity technique (Mayor & Queloz 1995; Marcy & Butler 1996), the transit method (Struve 1952), direct imaging (Angel 1994; Stahl & Sandler 1995), pulsar timing (Wolszczan & Frail 1992), and microlensing (Mao & Paczynski 1991; Gould & Loeb 1992). See the reviews of Perryman (2000) and Perryman et al. (2005). The microlensing signal of a planetary companion to microlens stars is a short-duration perturbation to the smooth standard light curve of the primary-induced lensing event occurring on a background source star. Once the signal is detected and analyzed, it is possible to determine the planet/star mass ratio, q, and the projected planet-star separation, r (normalized by the angular Einstein ring radius θE). Recently, four robust microlensing detections of exoplanets were reported by Bond et al. (2004), Udalski et al. (2005), Beaulieu et al. (2006), and Gould et al. (2006).

The microlensing technique has various advantages over other methods. First, microlensing is more sensitive to lower mass planets than most other methods, and it is possible, in principle, to detect Earth-mass planets from ground-based observations (Gould et al. 2004). Second, the microlensing technique is the only proposed method that could detect and characterize free-floating planets (Bennett & Rhee 2002; Han et al. 2005). Third, the biases in the search technique are less severe and can be quantified more easily than for other methods (Gaudi et al. 2002). Therefore, the microlensing technique will be able to provide the best statistics of the Galactic population of planets.

In addition to the advantages mentioned above, the microlensing technique is distinguished from other techniques in the sense that the planets to which it is sensitive are much more distant than those found with other techniques. With the advent of photometry techniques such as difference imaging (Alard & Lupton 1998) and the pixel method (Melchior et al. 1999), microlensing searches are not restricted to the field within the Galaxy and can be extended to unresolved star fields of nearby galaxies such as M31. Therefore, microlensing is the only feasible technique that could detect planets located in other galaxies.

Microlensing searches toward M31 have been and are being carried out by various collaborations including the POINT-AGAPE (Aurière et al. 2001; Paulin-Hendriksen et al. 2002, 2003; An et al. 2004; Belokurov et al. 2005; Calchi Novati et al. 2005), AGAPE (Ansari et al. 1997, 1999), VATT/Columbia (Crots & Tomaney 1996; Uglesich et al. 2004), MEGA (de Jong et al. 2004; Ingrasso et al. 2006), and WeCAPP (Riffeser et al. 2001, 2003) collaborations, as well as the MDM (Calchi Novati et al. 2003), McGraw-Hill (Calchi Novati et al. 2002), and Nainital (Joshi et al. 2003, 2005) surveys. The monitoring frequencies of these experiments are typically ~3 observations per week, too low to detect planetary signals. However, with the expansion of the global telescope network, the monitoring frequency of such surveys is rapidly increasing. For example, a new M31 microlensing survey, the Andromeda Galaxy Stellar Robotic Microlensing (Angstrom) project is expected to achieve a monitoring frequency of ~5 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, 1.8 m telescope at the Bohyunsan Observatory in Korea, and the 2.4 m Hiltner Telescope at the MDM Observatory in Arizona (Kerins et al. 2006).

The possibility of detecting planetary microlensing events caused by a lens located in M31 was discussed by Baltz & Gondolo

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(2001). However, the main focus of their paper was evaluating the detectability of events caused by binary lenses in general, and the comment about planetary lensing was brief, treating the planetary system as a special case of binary lenses. In addition, their detection rate estimate of the M31 planetary lensing events was based only on events that exhibit caustic crossings, while a significant fraction of events with detectable planetary signals might be non-caustic-crossing events. Moreover, the aim of their work was the rough evaluation of feasibility, and thus it was not based on a specific observational setup and instruments. Similarly, the work of Covone et al. (2000) was also based on an arbitrary observational setup.

In this paper, we explore the feasibility of detecting planets in M31 from a high-cadence pixel-lensing survey using a global network of 2 m class telescopes. The paper is organized as follows. In §2, we briefly describe the basics of planetary lensing. In §3, we estimate the efficiency of detecting planetary signals produced by planets with various masses and separations from the primary star. From this, we investigate the type of planets that produced by planets with various masses and separations from the primary star. From this, we investigate the type of planets that would be detectable from the survey and the characteristics of the events. In §4, we discuss methods to improve the planet detection efficiency. We summarize the results and conclude in §5.

2. BASICS OF PLANETARY LENSING

Planetary lensing is described by the formalism of a binary lens with a very low mass companion. Because of the very small mass ratio, the planetary lensing behavior 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 near a caustic, which represents 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 closed figures, where each figure is composed of locally concave curves (fold caustics) that meet at points (cusp caustics). For the planetary caustic, there exist two sets of disconnected caustics. One, the “central caustic,” is located close to the host star. The other, the “planetary caustic,” is located away from the host star, and there could be one or two of them depending on whether the planet lies outside (s > 1) or inside (s < 1) the Einstein ring. The size of the caustic, which is directly proportional to the planet detection efficiency, is maximized when the planet is located in the “lensing zone,” which represents the range of the star-planet separation of 0.6 ≤ s ≤ 1.6 (Gould & Loeb 1992).

The planetary perturbation induced by the central caustic is of special interest for M31 pixel-lensing events. While the perturbation induced by the planetary caustic can occur at any part of the light curve of any event, even those of low magnification, the perturbation induced by the central caustic always occurs near the peak of the light curve of a high-magnification event. Thus, the chance for the M31 pixel-lensing events to be perturbed by the central caustic could be high because these events tend to have high magnifications. In addition, the chance of detecting planetary signals for these events becomes even higher due to the improved photometric precision thanks to the enhanced brightness of the lensed source star during the time of perturbation.

3. DETECTION EFFICIENCY

To estimate the efficiency of detecting planetary signals of M31 events, we compute the “detectability” defined as the ratio of the planetary signal, \( \epsilon \), to the photometric precision, \( \sigma_{ph} \), i.e.,

\[
D = \frac{|\epsilon|}{\sigma_{ph}}.
\]

The planetary signal is the deviation of the lensing light curve from that of the single-lensing event of the primary lens star, and thus it is defined as

\[
\epsilon = \frac{A - A_0}{A_0},
\]

where \( A \) is the magnification of the planetary lensing and \( A_0 \) is the single-lensing magnification caused by the host star alone. For an M31 pixel-lensing event, the lensing signal is the flux variation measured on the subtracted image, while the noise is dominated by the background flux. Thus, the photometric precision is approximated as

\[
\sigma_{ph} = \frac{\sqrt{F_B}}{F_S (A - 1)},
\]

where \( F_S \) and \( F_B \) are the baseline flux of the lensed source star and the blended background flux, respectively. Under this definition of the detectability, \( D = 1 \) implies that the planetary signal is equivalent to the photometric precision.

We estimate the detection efficiency for a representative M31 event that is most probable under the assumption that the M31 halo is not significantly populated with MACHOs. We select the representative event based on the simulation of M31 pixel-lensing events carried out by Kerins et al. (2006) but using an updated synthetic stellar bulge population from the BaSTI population synthesis program (Pietrinferni et al. 2004). Figure 1 shows the distributions of the physical parameters involved with the events. Here \( m \) represents the mass of the lens, \( D_{LS} \) is the lens-source separation, \( I_S \) is the \( J \)-band source star brightness, \( \theta_I \) is the Einstein timescale, and \( \mu \) is the background surface brightness. In each panel, there are two sets of distributions, where that drawn in light gray is for all events detectable with 3 \( \sigma \) threshold, while that drawn in dark gray is for events with \( \theta_I \geq 3 \) days, where \( \theta_I \) is the half of the duration that the event can be seen with a signal greater than 3 \( \sigma \) (visibility timescale). Considering that the monitoring frequency of the Angstrom survey is \( \sim 5 \) times day\(^{-1} \), the latter distribution corresponds to that of events detectable by the Angstrom survey. According to the simulation, the total number of events expected to be detected by the Angstrom survey with \( \theta_I \geq 3 \) is \( \sim 52 \) events per year over an area of \( 11 \times 11 \) arcmin\(^2\). Based on these distributions, we choose a representative event as that caused by a lens with a primary star mass of \( m = 0.4 \) \( M_\odot \) and distance to the source star and lens of \( D_S = 780 \) kpc and \( D_L = 780 - 0.8 \) kpc, respectively. Then the corresponding physical and angular Einstein ring radii are \( R_{E} = 1.6 \) AU and \( \theta_E = 2.1 \) \( \mu \)as, respectively. For a representative value of the Einstein timescale, we adopt \( \theta_I = 10 \) days. The most likely source star is a giant with \( I \sim 24.4 \). We assume that the source has a radius of \( R_s = 10.0 \) \( R_\odot \). Then the source size normalized by the Einstein radius is \( \rho_s = \theta_s/\theta_E = (R_s/D_S)/\theta_E = 0.03 \). We note that this source size is comparable to the caustic size. In this case, the planetary signal can be significantly diminished due to the finite-source effect (Bennett & Rhie 1996). We therefore take the finite-source effect into consideration in our efficiency computation. For the background surface brightness, we adopt \( \mu = 17.6 \) mag arcsec\(^{-2} \), but we test the variation of the efficiency depending on the surface brightness later.

Observations and photometry are assumed to be carried out as follows. Following the specification of the Liverpool Telescope, we assume that the instrument can detect 1 photon s\(^{-1} \) for an \( I = 24.2 \) star. We also assume that the average seeing is \( \theta_{see} = 1^\prime 0 \) and that the observation is carried out such that
small-exposure images are combined to make a 30 minute exposure image to obtain a high signal-to-noise ratio while preventing saturation in the central bulge region. The photometry is done such that the flux variation is measured at an aperture that maximizes the signal-to-noise ratio of the measured flux variation. In the background-dominated regime such as the M31 field, the noise is proportional to the aperture radius \( r_{\text{ap}} \), i.e., \( F_B / \sigma_{\text{psf}}^2 \) \( r_{\text{ap}} \) \( 2 \). On the other hand, assuming a Gaussian point-spread function (PSF), the measured source flux variation scales as 
\[
F = F_S (\theta_{\text{ap}} \ll \theta_{\text{psf}}) \exp \left( -\theta^2 / 2 \sigma_{\text{psf}}^2 \right) \theta_{\text{ap}} \equiv 0.673 \theta_{\text{ap}}^2.
\]
Thus, the optimal aperture that maximizes the signal-to-noise ratio is \( \theta_{\text{ap}} = 0.673 \theta_{\text{ap}}^2 \). With the adoption of this aperture, the fraction of the source flux within the aperture is \( F(\theta \leq \theta_{\text{ap}}) / F_{\text{tot}} = 0.715 \), where \( F_{\text{tot}} \) is the flux measured at \( \theta_{\text{ap}} \equiv 0.673 \theta_{\text{ap}}^2 \).

In Figure 2, we present the contour maps of the detectability of the planetary lensing signal as a function of the source star position \((\xi, \eta)\) for events caused by planetary systems with various values of the projected star-planet separation, \( r_s = s \theta_{\text{E}} \), and planet mass, \( m_p = q m \), where \( m \) is the mass of the primary lensing star. The contours are drawn at the levels of \( D = 1.0 \) (white contours), \( 2.0 \) (yellow contours), and \( 3.0 \) (brown contours), respectively. We assume that the planetary signal is firmly detectable if \( D \geq 3.0 \). In the map, we present only the region around the “visibility zone,” which represents the region of the source star position where the magnification is higher than a threshold magnification required for the event detection, \( A_{\text{th}} \). The threshold magnification is defined by 
\[
(A_{\text{th}} - 1) F_S = 3 (F_B)^{1/2}, \text{i.e., 3 \sigma detection of the event. If we define} u_{0,\text{th}} \text{ as the threshold lens-source impact parameter corresponding to} A_{\text{th}}, \text{everything of interest is contained within the circle with the radius} u_{0,\text{th}} \text{(white dotted circle). We therefore use} u_{0,\text{th}} \text{ as a scale length instead of the Einstein radius.}
\]
Once the maps of the detectability are constructed, we produce a large number of light curves of lensing events resulting from source trajectories with random orientations and impact parameters with \( u_0 \leq u_{0,\text{th}} \) (see an example light curve in Fig. 3). Then we estimate the detection efficiency as the ratio of the number of events with detectable planetary signals to the total number of tested events. We assume that on average five combined images with a 30 minute exposure are obtained daily following the current Angstrom survey. By applying a conservative criterion for the detection of the planetary signal, we assume that the planet is detected if the signal with \( D \geq 3 \) is detected at least 3 times during
Since the monitoring frequency is $f = 5$ times day$^{-1}$, this implies that the planetary signal should last at least 0.6 days for detection. In actual lensing observations, the value of the single-lensing magnification $A_0$ is unknown. Thus, the measured planetary signal is not the deviation from the single-lensing light curve of the primary but the deviation from the best-fitting curve to the observed one. We therefore compute $D$ based on the deviation from the best-fitting light curve. The lensing parameters of the best-fitting light curve are obtained by a $\chi^2$ minimization method.

In Figure 4, we present the estimated detection efficiency as a function of the projected star-planet separation and planet mass for different surface brightness levels. From the figure, we find the following results.

1. It is expected that massive giant planets are detectable with the Angstrom survey. Although the efficiency varies considerably depending on the star-planet separation, the efficiencies averaged over the lensing zone of $1.0 < r < 2.6$ AU are $\sim 8.4\%$, $6.1\%$, and $2.4\%$ for planets with masses of $m_p = 7.0M_J$, $5.0M_J$, and $3.0M_J$, respectively. Considering that the number of events detectable over an 11$'$ field is $\sim 52$ yr$^{-1}$ for a survey such as Angstrom, these efficiencies correspond to yearly planet detection rates of $4.3f_{LZ}$, $3.9f_{LZ}$, and $1.2f_{LZ}$ detections, respectively, where $f_{LZ}$ is the probability that a planet exists in the lensing zone. However, it is expected that detecting Saturn-mass planets ($m_p \sim 0.3M_J$) would be difficult. The drastic decrease of the efficiency for lower mass planets is caused by the rapid decrease of the perturbation region combined with the increased finite-source effect.

As a result, the values of the detectability in the maps of Fig. 2 differ from those we used in our estimate of the planet detection efficiency. However, we leave the maps as they are because they show the pattern of deviation.
In all tested cases, the planetary perturbations of M31 pixel-lensing events are caused by central caustics. This is because the visibility region is confined to a narrow region around the primary star, and thus the planetary caustics, in most cases, are located outside the visibility region. Therefore, an observational strategy of focusing on the central perturbations would maximize the detections of M31 planets. An alert system based on real-time survey observations combined with prompt follow-up observations would do this.

The source size has a significant effect on the planet detection efficiency. The normalized size of the central caustic as measured by the horizontal width along the star-planet axis is related to the planetary separation and mass ratio by (Chung et al.

\[
\frac{\Delta_x^{\text{cc}}}{\Delta_x^{\text{cc}}} = \frac{4q}{(s - 1/s)^2}. \tag{4}
\]

Thus, the caustic size of a planet with \( s = 1.2 \) (\( r_\perp \sim 1.9 \text{ AU} \)) and \( q = 3 \times 10^{-3} \) (\( m_p \sim 1.0M_J \)) is \( \Delta_x^{\text{cc}} = 0.03 \), which is equivalent to the source size. Therefore, even for a Jupiter-mass planet located in the lensing zone, the finite-source effect is considerable. The effect would be smaller for events associated with main-sequence stars, but such events are rare (see Fig. 1, bottom left).

The surface brightness has some effect on the planet detection efficiency. The effect is twofold: aggravating the photometric precision and shrinking the perturbation region; both contribute to the decrease of the detection efficiency. The efficiency is higher in low surface brightness regions, but the number of planet detections would be low due to the lack of events in these regions (see Fig. 1, bottom right).

### 4. IMPROVING PLANET DETECTION EFFICIENCY

Considering that planetary perturbations, in many cases, are missed from detection due to short durations, a significant improvement in the planet detection efficiency is expected with the increase of the monitoring frequency. One way to do this is to use more telescope time or employ more telescopes ("strategy II"). The other way is to conduct follow-up observations for events detected in the early phase by the survey experiment ("strategy III"). In this section, we estimate the efficiencies expected under these improved observational strategies. We designate the observational condition of the current pixel-lensing survey (with \( f = 5 \times \text{day}^{-1} \)) as "strategy I." We simulate the observations under strategy II by doubling the monitoring frequency of the current Angstrom experiment, i.e., \( f = 10 \times \text{day}^{-1} \). For strategy III, we assume survey-mode observations with \( f = 5 \times \text{day}^{-1} \) and follow-up observations with \( f = 20 \times \text{day}^{-1} \) by using a single 8 m class telescope. Follow-up observations are assumed to start 4 hr after the first detection of the lensing signal from the survey observation. Since a single telescope is employed, follow-up observations can be done only during the night (8 hr day\(^{-1}\)) and thus for 24 minutes per each observation. Assuming 20 minutes per exposure (to allow ~4 minutes for readout), the photometric uncertainty of the follow-up observation is \( \sigma_{m}^{\text{eff}} \sim (30 \text{ minutes}/20 \text{ minutes})^{1/2}(2 \text{ m}/8 \text{ m}) \sim 31\% \) of the survey observation.

In Figure 5, we present the efficiency expected under the two improved observational strategies. In Table 1, we also present the average detection efficiencies of detecting planets located in the lensing zone. From the figure and table, we find that significant
improvement in efficiency is expected, especially from the adoption of the follow-up observation strategy. The improvement is more significant for perturbations produced by lower mass planets because the short-duration perturbations are readily detectable with the increased monitoring frequency.

5. CONCLUSION

We explore the feasibility of detecting planets in M31 from a high-cadence pixel-lensing survey using a global network of 2 m class telescopes. From this investigation, we found that massive giant planets with several Jupiter masses could be detectable with nonnegligible efficiency. We found that most events with detectable planets are associated with giant source stars, and thus source size would have a significant effect on the planet detection efficiency. We also found that the planetary perturbations would be in nearly all cases caused by central caustics, and thus observational strategies focusing on these central perturbations would maximize the planet detections. Follow-up observations triggered by an alert system from a real-time data reduction pipeline would help not only to increase the efficiency but also to detect lower mass planets.

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TABLE 1
DETECTION EFFICIENCIES UNDER VARIOUS STRATEGIES

| PLANET MASS | DETECTION EFFICIENCY (%) |
|-------------|--------------------------|
|             | Strategy I | Strategy II | Strategy III |
| 1.0M\textsubscript{\textodot} | 0.0 | 0.1 | 9.4 |
| 3.0M\textsubscript{\textodot} | 2.4 | 3.8 | 32.8 |
| 5.0M\textsubscript{\textodot} | 6.1 | 10.1 | 45.5 |
| 7.0M\textsubscript{\textodot} | 8.4 | 15.6 | 52.7 |

Notes.—Average detection efficiencies of planets located in the lensing zone under three different observational strategies. The individual strategies imply a survey mode with a monitoring frequency of \( f = 5 \) times day\(^{-1} \) (strategy I), a survey mode with \( f = 10 \) times day\(^{-1} \) (strategy II), and a survey mode with \( f = 5 \) times day\(^{-1} \) plus follow-up observations by employing a single 8 m telescope (strategy III).