Discovering habitable Earths, hot Jupiters and other close planets with microlensing

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ABSTRACT

Searches for planets via gravitational lensing have focused on cases in which the projected separation, $a$, between planet and star is comparable to the Ein-stein radius, $R_E$. This paper considers smaller orbital separations and demon-strates that evidence of close-orbit planets can be found in the low-magnification portion of the light curves generated by the central star. We develop a protocol to discover hot Jupiters as well as Neptune-mass and Earth-mass planets in the stellar habitable zone. When planets are not discovered, our method can be used to quantify the probability that the lens star does not have planets within specified ranges of the orbital separation and mass ratio. Nearby close-orbit planets discovered by lensing can be subject to follow-up observations to study the newly-discovered planets or to discover other planets orbiting the same star. Careful study of the low-magnification portions of lensing light curves should produce, in addition to the discoveries of close-orbit planets, definite detections of wide-orbit planets through the discovery of “repeating” lensing events. We show that events exhibiting extremely high magnification can effectively be probed for planets in close, intermediate, and wide distance regimes simply by adding several-time-per-night monitoring in the low-magnification wings, possibly leading to gravitational lensing discoveries of multiple planets occupying a broad range of orbits, from close to wide, in a single planetary system.

1. Introduction

Microlensing planet searches have been directed toward discovering planets in orbits whose size is comparable to the size of the Einstein radius, $R_E$, of the central star. Here we study the detectability of planets in much closer orbits. This is necessary, because we now know that many planets are in such close orbits. We demonstrate that ground based surveys for lensing events can detect a wide range of close-orbit planets, including “hot Jupiters” orbiting sun-like stars, and even Earth-mass planets in the habitable zones of M dwarfs. We also discuss the role of space missions.

We were led to the study of close-orbit planets by work to determine whether or not planets in the habitable zones of nearby stars could produce detectable lensing signatures (Di Stefano & Night 2008). The standard planetary-lensing scenario is most sensitive to planets with $\alpha = a/R_E$ in the range $0.5 - 2$, where $a$ is the orbital separation (Mao & Paczyński 1991; Gould & Loeb 1992). In many cases, this corresponds to the region

\footnote{http://exoplanet.eu/catalog.php}
beyond the snowline (e.g., Sumi et al. 2010), while the habitable zone is closer to the star. We found that lensing observations would be able to detect planets orbiting within the habitable zones of nearby M dwarfs (Di Stefano & Night 2008). Here, we demonstrate the importance of lensing by close-orbit planets for a broader range of systems: the planets may be in the habitable zone, closer in, or farther out. The planetary systems may be within a few tens of pc or much farther away. The host stars may be M dwarfs, brown dwarfs, or much more massive stars.

In §2 we study the incidence of close planets. In §3 we study the expected signatures. We sketch the steps needed to mount successful programs to discover these planets in §4. This paper provides a guide to the discovery and analysis of lensing light curves generated by close-orbit planets.

2. Evidence for Close-Orbit Planets

As this text is being written, 696 planets are listed in the Interactive Extra-solar Planets Catalog. Most of these planets (~ 645) have been detected by radial velocity (RV) studies of the host star. The second-largest group (~ 185) have been detected through planetary transits. There is some overlap between these two groups. Twenty six planets have been detected by imaging, and 12 have been discovered through planet-lens signatures detected during gravitational lensing events in which the host star serves as the primary lens.

Searches for planet-lens events have focused on the case in which the orbital separation at the time of the event, \( a \), is comparable in size to the Einstein radius, \( R_E \), of the central star: \( 0.5 < \alpha < 2 \), with \( \alpha = a/R_E \). To determine the effect this has on planet discovery, we treat each exoplanet central star as a potential lens, and determine the value of \( \alpha \) for each of the discovered planets. To do this calculation, we need to compute the value of \( R_E \) for each central star.

\[
R_E = 1.01 \text{ AU} \left[ \left( \frac{M_*}{1 M_\odot} \right) \left( \frac{D_L}{125 \text{ pc}} \right) \left( 1 - \frac{D_L}{D_S} \right) \right]^{\frac{1}{2}},
\]

(1)

To compute \( R_E \), we need the star’s mass, \( M_* \), and its distance \( D_L \) from us. The value of \( R_E \) also depends on the distance, \( D_S \), to the source that would be lensed. Because most of the central stars do not have a bright source located directly behind them, the value of \( D_S \) is not determined. To compute \( R_E \) we must therefore make some assumptions about the ratio \( D_L/D_S \). Here we first consider lenses for which \( D_L/D_S << 1 \); this allows us to ignore the last factor in Equation 1. The physical meaning of this assumption is that we are focusing on nearby planetary systems or on planetary systems with source stars located much farther from us. We will mention a second case in §4, with \( (D_S - D_L)/D_S << 1 \), generally corresponding to lens stars very close to the lensed source.

Making these assumptions, we can compute \( \alpha = a/R_E \), for each known exoplanet whose semimajor axes \( a \) has been measured. Figure 1 shows the results for all

\(^2\)http://exoplanet.eu/catalog.php
planets for which we have estimates of $a, M_*, M_{pl}, D_L$, and the orbital period, $P$. We have defined $q = M_{pl}/M_*$. The two dashed lines in each panel enclose the region $0.5 < \alpha < 2$. This is the region for which microlensing planet searches have been primarily directed. Only about $1/3$ of the known planets fall in this region. Even among systems with $\alpha$ in this range, planets will be discovered for only a small fraction. This is because the path of the source behind the lens must be favorable for planet discovery and also because the sensitivity and sampling cadence must be well suited to planet discovery.

It is therefore advantageous to extend lensing planet searches to both smaller and larger values of $\alpha$. Larger values have been considered in some detail (DiStefano & Scalzo 1999a, 1999b; Han 2009). We will discuss them briefly in §4. The major part of this paper is devoted to studying planet detection of smaller values of $\alpha$.

From Figure 1, we see that, judging by the planetary systems already known, smaller values of $\alpha$ are expected for a wide range of stellar masses, planet masses, and distances $D_L$. One variable that displays a trend with $\alpha$ is the orbital period, $P$.

$$P = 71.3 \text{ days} \left(\frac{\alpha}{\frac{1}{3}}\right)^\frac{1}{2} \left(\frac{M_*}{M_\odot}\right)^\frac{1}{2} \left(\frac{D_L}{125 \text{ pc}}\right) \left(1 - \frac{D_L}{D_S}\right)^{-\frac{1}{2}} $$

Thus, smaller values of $\alpha$ are associated with shorter orbital periods. In the next section we will study the geometry of the isomagnification contours of close-orbit planetary systems, and will find that there is a small region exhibiting deviations from the point-lens form at large distances ($u > 1 R_E$) from the center of mass. This region rotates around the center of mass at the orbital period. The region of deviation can therefore rotate into the path of the source track, increasing the probability of detection.

If $v$ is the relative transverse motion, the proper motion is

$$\mu = 0.0338'' \text{ yr}^{-1} \left(\frac{v}{20 \text{ km s}^{-1}}\right) \left(\frac{125 \text{ pc}}{D_L}\right)$$

The Einstein angle is

$$\theta_E = 0.0081'' \left[\left(\frac{M_*}{1 M_\odot}\right) \left(\frac{125 \text{ pc}}{D_L}\right) \left(1 - \frac{D_L}{D_S}\right)\right]^{\frac{1}{2}}, $$

Define $\tau_{E,1}$ to be the time taken for the source-lens separation to change by an angle equal to the Einstein angle. For nearby lenses, $\tau_{E,1} \approx \theta_E/\mu$, and its value can be comparable to the value of $P$, when $\alpha$ is small. For, example, a solar mass lens at 125 pc will have $\tau_{E,1} \approx 88$ days if $v = 20$ km s$^{-1}$. If the detection limit is 2%, the event may be detectable during the time taken to cross through $6 R_E$. For a range of lens masses and distances, several orbits may occur during a lensing event.

3. Close-Planet Magnification Geometry and Light Curves

3.1. The Role of $\alpha$

When the projected distance between planet and star is significantly smaller than $R_E$, then at distances larger than $R_E$, the system is well approximated by a point-lens of total
mass equal to the sum of the stellar and planet masses. Nevertheless, there are small deviations from the point-lens form. To study these deviations we consider lenses with planets, each planet characterized by the mass ratio $q = M_{pl}/M_*$, and the separation $\alpha$.

We begin by considering the magnification geometry for a fixed value of $q$ by computing the magnification around each of a sequence of concentric rings, centered on the center of mass. If the system were a point mass, we would expect that each ring of radius $r$ would have a single magnification, $A(r)$, whose value would be equal to $(r^2 + 2)/(r \sqrt{r^2 + 4})$. For each ring, we computed the difference, $\Delta$, between the maximum and minimum value of the magnification. Deviations from symmetry are associated with values of $\Delta$ that differ from zero. The top panel of Figure 2 shows $\Delta$ as a function of $r$ for a lens with $q = 0.001$. The most striking feature of this panel is the sequence of 9 peaks. Each corresponds to a single value of $\alpha$, and the peak occurs at $r = R_\alpha = \frac{1}{\alpha} - \alpha$. The black peak on the right corresponds to $\alpha = 0.1$. The value of $\alpha$ increases by 0.05 for each peak toward the left, to $\alpha = 0.5$ for the left-most peak. For values of $\alpha$ near or above 0.5, lensing by planetary systems has been well studied; the black curve ($\alpha = 0.5$) shows that there are deviations from the point-lens form larger than 1% over a wide range of values of $r$. For smaller $\alpha$, however, the deviations in the region $r > 1$ are small, except in the peaks, where they can be as large as several tens of percent. We would derive a similar pattern for other values of $q$. In fact, the locations of the peaks would be identical. The width of the peaks would be larger (smaller) for larger (smaller) values of $q$.

To see why non-linear effects become evident at the star-planet separation $r = R_\alpha = \frac{1}{\alpha} - \alpha > 1$, consider the image geometry for the simplified case of a point source, located a distance $R_\alpha$ from a point lens. If the $x$ axis connects the lens and source, then at a value of $x$ equal to $-\alpha$, there will be a negative parity image of the source. When a planet happens to lie near this point, its influence on the total magnification will be enhanced.

Now consider a planetary system with the center of mass at the origin and the planet at $x = -\alpha$. There are two tiny caustics located along the circle of radius $R_\alpha$; one appears at a positive value of $y$ and one appears at a negative values of $y$. The caustics themselves are too small to play a significant role, but they serve as a convenient way to locate the regions in the lens plane within which the magnification deviates from the point-lens form. When the source happens to lie behind one of these “perturbed” regions, the light curve will exhibit features that signal the presence of the planet.

### 3.2. The role of the mass ratio, $q$

As shown in §3.1, the value of $\alpha$ determines the distance from the center of mass of the region with isomagnification perturbations. In this subsection we show that the size of these perturbed regions is determined by the mass ratio, $q$. The alterations in the isomagnification contours are shown in the bottom-right panels of Figures 3, 4, and 5. With $\alpha = 1/3$ in all three cases, these panels differ from each other only in the value of $q$, which is $1.25 \times 10^{-3}$, $2.0 \times 10^{-4}$, and $1.2 \times 10^{-5}$ in Figures 3, 4, and 5, respectively. These figures demonstrate that the size of the perturbed regions is smaller for smaller values of $q$.

The figures for the two smallest values of $q$ correspond to a Neptune-mass planet
and an Earth-mass planet, respectively, orbiting a star with 0.25 \( M_\odot \). In each case, the lower-right panel zooms in on the perturbed region, to reveal that, in a small region of the annulus around \( R_\alpha \), isomagnification contours from larger values of \( r \) are pulled in to smaller values of \( r \), with the contours from smaller \( r \) pushed out on either side. When a source with larger transverse than radial speed passes behind this region, the magnification will deviate upward from the point lens form, then downward and up again before descending back to the point-lens value. As shown in the top panel of all three figures and in the portion of the light curve shown in the lower left-hand panel of each figure, this characteristic “up-down-up-down” form of the light curve is exhibited when both \( \alpha \) and \( q \) are small.

The isomagnification contours in the lower-right-hand panels for the Neptune-mass and Earth-mass planets exhibit small closed curves, which enclose caustics. The caustics are tiny and their positions are not marked here; in fact, the caustics do not play an important role in the light curve deviations. The light curve deviations are dominated instead by the more subtle affects associated with the perturbations of the low-magnification isomagnification contours. Nevertheless, the positions of the caustics, which can be vanishingly small, provide a convenient way to measure the size of the perturbed region.

We define \( \Delta y_c \) to be the straight-line distance between the tiny caustics discussed above, expressed in units of \( R_E \). We compute a normalized separation, \( \Delta Y_{\text{norm}} \), by dividing \( \Delta y_c \) by \( C_\alpha = 2\pi R_\alpha \), the circumference of a circle of radius \( R_\alpha \). Consider the bottom panel of Figure 2. The variable along the vertical axis is the logarithm of the normalized separation, \( \Delta Y_{\text{norm}} \); it is plotted against \( \log_{10}(q) \). There are 5 colored curves for values of \( \alpha \) ranging from 0.10 to 0.33; these curves are almost indistinguishable. Moving to wider orbits, the green curve for \( \alpha = 0.40 \) can be distinguished from the others, but it is close to them. All in all, there is very little alpha dependence, indicating that the linear dimensions of the perturbed area depend primarily on the value of \( q \). The curves for small \( \alpha \) and small \( q \) are well approximated by the equation: \( \log_{10}(\Delta Y_{\text{norm}}) = 0.5 \log_{10}(q) - 0.2 \). Thus, the physical separation, expressed in units of \( R_E \), can be expressed as a product of a factor that depends only on \( \alpha \) and one that depends only on \( q \): \( \Delta y_c = 2\pi R_\alpha \Delta Y_{\text{norm}}(q) \).

Figures 4 and 5 clearly show that the perturbed region is larger than the distance between the centers of the closed curves, which is an approximate measure of the separation \( \Delta y_c \) between caustics. Let \( L(\alpha, q) \) represent the linear dimensions of the perturbed region, expressed in units of \( R_E \). On an empirical level, the size of the region is determined by the size of the smallest deviations that can be reliably detected for any given observational scheme. If deviations like those shown in the light curves in the top panels of Figures 3 through 5\(^3\) are detectable, then we find, empirically, that \( L(\alpha, q) \approx 2.5 \Delta y_c \).

For the three cases shown in Figures 3, 4, and 5, the linear dimensions, \( L(\alpha, q) \), are approximately 0.93 \( R_E \), 0.37 \( R_E \), and 0.09 \( R_E \), respectively. In the absence of orbital rotation, the event rate would be proportional to these linear dimensions. The event durations would be equal to the time taken for the relative lens and source positions to

\(^3\) We note that, in order to generate these particular light curves, we used face-on circular orbits. The general theory applies to orbits of all orientations and eccentricity; the value of \( \alpha \) and the geometry of the isomagnification contours are then time dependent. Nevertheless, if the time duration of the deviations from the point-lens form is primarily determined by the value of the orbital period, the basic shape of individual deviations will have the same characteristics as shown here.
change by $L(\alpha, q)$. Let this time be denoted by $T_{\text{transverse}}$.

$$T_{\text{transverse}} = 21.6 \text{ days} \left(\frac{L(\alpha, q)}{0.25}\right) \left(\frac{R_E}{1 \text{ AU}}\right) \left(\frac{20 \text{ km/s}}{v}\right)$$

(5)

In most cases, however, the events will be significantly shorter, because orbital motion plays an important role. In addition, orbital motion increases the likelihood that a detectable event will occur. In the case in which $T_{\text{transverse}} > P$, the probability that a detectable event will occur is unity.

3.3. Event Probabilities and the Role of Orbital Motion

Particularly in cases with $\alpha < 0.5$, the orbital period can be comparable to or even shorter than $T_{\text{traverse}}$, the time taken for the source to traverse a distance $L(\alpha, q)$. In such cases, the orbital motion is very likely to rotate the perturbed region in front of the source. The probability is $T_{\text{traverse}}(q)/P_{\text{orb}}$ when $T_{\text{traverse}}(q) < P_{\text{orb}}$ and is unity otherwise. When the probability is larger than unity, deviations repeat on a time scale roughly equal to $P_{\text{orb}}$. If we are monitoring the system frequently enough to catch a deviation in progress, our chance of seeing the deviation can be 100% if the planet exists.

The time duration of a deviation from the point-lens form is

$$T_{\text{dev}} = \frac{L(\alpha, q)}{2 \pi R_\alpha} P_{\text{orb}} = 2.5 P_{\text{orb}} 10^{0.5 \log_{10}(q) - 0.2}$$

(6)

In the cases shown in Figures 3, 4, and 5, this produces deviations of durations 1.1 days, 0.56 days, and 0.14 days, which compare well with values of $T_{\text{dev}}$ shown in the bottom-left panels of each figure.

3.4. Hot Jupiters

The first exoplanet to be discovered orbiting a sun-like star was 51 Peg b (Mayor & Queloz 1995), a planet with $m \sin(i) \approx 0.5 M_J$ in a 4-day orbit. At present, there are 155 known exoplanets with semimajor axis smaller than 0.5 AU and with $m \sin(i)$ between 0.5 $M_J$ and 10 $M_J$. These planets are generally referred to as “hot Jupiters”. The value of $m \sin(i)$ is larger than $(1 M_J, 2 M_J, 3 M_J)$ in $(96, 57, 31)$ cases, respectively.

The planet corresponding to Figure 3 is a hot Jupiter. Its mass is equal to that of Jupiter, and it orbits a star of $0.8 M_\odot$; $\alpha = 1/3$. With $D_L = 25$ pc; $D_S = 8$ kpc, we find $R_E = 0.4$ AU. Thus, the semimajor axis is $a = \alpha R_E = 0.13$ AU, and the orbital period is 20 days. With a transverse speed of 20 km/s, the time taken to cross $R_E$ is $\tau_{E,1} = 35$ days. The duration of the deviations is just over a day, and the deviations repeat. This example demonstrates that hot Jupiters can be found through their influence on the low-magnification portion of lensing light curves. Note that if, for the same lens star and orbit, the planet had a mass of $(3 M_J, 6 M_J, 10 M_J)$, then $T_{\text{dev}}$ would be (1.9 days, 2.7 days, 3.5 days).

Lensing provides a potentially important complement to the radial-velocity and transit studies that have already been discovering hot Jupiters. It allows planet discovery even if
the central star is too dim for detailed spectral studies, and for all orbital inclinations, in contrast to transit studies. Furthermore, lensing provides a direct measure of the lens mass, at least in cases in which the mass of the central star can be determined. Furthermore, as we show below, lensing searches for hot Jupiters can be effective for nearby stars, allowing detailed follow-up studies, and also for distant stars.

An important issue is whether the discovery of hot Jupiters, or placing reliable limits on their presence around lens stars, can be accomplished on a regular basis. To answer this, we consider a condition sometimes used to define the boundary between hot Jupiters and planets farther out: $a < 0.5$ AU.

$$\alpha R_E < 0.5 \text{AU} \quad (7)$$

Consider background sources located in the Galactic Bulge ($D_S = 8$ kpc). If the central star is a low-mass dwarf, with $M_* \sim 0.1 M_\odot$, then the condition above holds for all values of $D_L$. For stars of $0.25 M_\odot, 0.5 M_\odot, 0.75 M_\odot, 1.0 M_\odot$, the condition holds for $D_L < 1.4 \text{kpc}$, $600 \text{pc}$, $400 \text{pc}$, and $300 \text{pc}$, respectively, and also for $D_L > 6.6 \text{kpc}$, $7.4 \text{kpc}$, $7.6 \text{kpc}$, and $7.7 \text{kpc}$, respectively. Since a large fraction of the lenses are located in the Bulge itself or else within a kpc of Earth (DiStefano 2008a, 2008b), searches for hot Jupiters in the low-magnification portion of lensing light curves are feasible.

### 3.5. Neptunes and Earths in the Habitable Zone

In both Figures 4 and 5, the central mass is $0.25 M_\odot$, and $D_L$ is 50 pc. This yields, $R_E \sim 0.32$ AU. As in Figure 3, $\alpha = 1/3$. The separation between planet and star is $\sim 0.1$ AU. The flux incident on the planets associated with both figures is, therefore, about 78% the flux received by Earth from the Sun, and these planets are in or near the habitable zone. The orbital periods are about 25 days, and the transverse speed was 15 km s$^{-1}$.

Figures 4 and 5 show the light curve, the characteristic form of the deviations from the point-lens case, and the perturbations of the isomagnification contours for the Neptune-mass and Earth-mass planets, respectively. The shorter duration of the deviations for the lower mass planets means that higher-cadence sampling would be required to fully resolve them. Nevertheless, the general up-down-up-down form is clear in all three cases. Furthermore, the light curves shown in the top panels of both figures indicate that the orbital period may be recoverable in cases such as these.

If planets are not uncommon in the habitable zones of their stars, then studying the low-magnification portions of lensing light curves for evidence of planets in $\alpha < 0.5$ orbits is an effective way to discover them, both for nearby and distant planetary systems. DiStefano & Night (2008) computed the range of stellar-lens masses and distances for which a planet with a given value of $\alpha$ would be in the habitable zone. Their results indicate that close-orbit planets in the habitable zone could be detected for a wide range of values of $D_L$. For example, $\alpha$ is smaller than 0.5 for planets in the habitable zone of a $\sim 1.5 M_\odot$ star, with 800 pc < $D_L$ < 7200 pc.
4. Successful Observing and Analysis Strategies

Lensing associated with close orbit planets is a new frontier. Fortunately, the ongoing monitoring programs can allow us to begin exploring this frontier in the immediate future. Below we summarize the relevant features of lensing associated with close-orbit planets.

1. Every light curve can be used to either discover close-orbit planets or else to place quantifiable limits on the presence of planets orbiting the lens in close orbits. This is because the region in which the deviations occur are low-magnification regions, and every detectable lensing event exhibits low magnification, whatever peak magnification it achieves.

2. When the magnification is $A = 1 + \delta$, the corresponding value of $\alpha$ is

$$\alpha = 0.84 \delta^2$$  \hspace{1cm} (8)

Thus, every interval of the low-magnification part of every light curve can be studied to either discover or place limits on planets at a specific projected separation $\alpha$. The higher the precision of the photometric measurements, the smaller the values of $\alpha$ we can probe.

3. For each value of $\alpha$, the value of $q$ determines the size of the region over which perturbations of a given magnitude are detectable.

$$L(\alpha, q) = 2.5 \xi \left[ 2 \pi \left( \frac{1}{\alpha} - \alpha \right) \right] 10^{[0.5 \log_{10}(q) - 0.2]}$$  \hspace{1cm} (9)

$L(\alpha, q)$ is expressed in units of the Einstein radius, and the value of $\xi$ depends on the photometric sensitivity and frequency of sampling. The value of $L(\alpha, q)$ can be fairly large. For example, for $\alpha = 0.25$ and $q = 0.001$, $L(\alpha, q) = 0.19$. This is the radius of the annulus around $R_\alpha$ within which the perturbations are potentially detectable. The source must pass through this annulus both on the way in toward higher magnifications and as it emerges from the higher-magnification region.

4. Orbital motion increases the probability of detection. In the case considered in point 3 (just above), the total time spent in this annulus would be $\sim 0.38 \tau_{E,1}$. If, e.g., the Einstein radius crossing time is 30 days, the source would spend more than 10 days crossing the annulus. We would have a very good chance of detecting deviations for hot Jupiters with orbital periods smaller than 10 days, because the perturbed region would rotate into the path of the source one or more times.

5. The deviations from the point-lens form will have a magnitude that can be easily computed by using the formula for $L(\alpha, q)$. The point-lens magnification will be that for $u = R_\alpha = \frac{1}{\alpha} - \alpha$. The upward and downward deviations will have magnitudes approximately corresponding to the point lens magnifications at $R_\alpha \pm \frac{1}{2} L(\alpha, q)$. Thus, for each $\alpha$, we can compute the range of magnifications expected during a deviation for each $q$, and determine how large $q$ would have to be in order for a planet to produce detectable deviations, given the quality of the observations. Alternatively one can decide whether more sensitive photometric observations should be taken, in order to be able to detect a planet with a particular value of $q$, hence planetary mass.

6. For each value of $\alpha$, the value of $q$ determines the duration of the deviation. If we
assume that orbital motion dominates, then.

$$T_{\text{dev}} = \frac{L(\alpha, q)}{2\pi R_\alpha} P_{\text{orb}} = 2.5\xi P_{\text{orb}} 10^{0.5 \log_{10}(q) - 0.2}$$

(10)

In fact, for close orbit planets, orbital motion is likely to dominate for all but stars with exceptionally large proper motion. Consider a solar-mass star at 125 pc. Equation 4 tells us that, if the lensed source is in the Bulge, $\theta_E \approx 8$ mas. If $R_\alpha$ is approximately equal to 3, and if the orbital period is $\sim 70$ days, then the orbital angular speed of the deviation is $\sim 0.7''$ yr$^{-1}$, larger than the angular speeds of all but a handful of stars.

6. Nearby Lenses: If the lens star lies within a kpc or so, it is likely to be detectable. It may be catalogued, perhaps even by the monitoring programs that search for evidence of lensing. We have found, e.g., that $\sim 8\%$ of all lensing event candidates have 2MASS counterparts, many likely to correspond to the lens (McCandlish & DiStefano 2011), while $>10\%$ of the lenses producing the events detected by the monitoring programs are predicted to lie within about a kpc (DiStefano 2008a, 2008b). Thus, we may know the spectral type of the lens and be able to estimate its mass and distance from us. We may even know its proper motion. This information, combined with the Einstein angle crossing time, allows us to determine the total lens mass and distance. The wide range of other information potentially derivable from fits to the lensing light curve, may allow us to also determine the planet’s mass and key features of its orbit. Thus, if we do find a planet, we can learn a great deal about it, including its gravitational mass, from the lensing observation. In addition, because it is nearby, follow up studies to learn more about this planet and to search for others orbiting the same star may be possible. On the other hand, if we do not find evidence of a planet, we can place quantifiable limits on the presence of planets with a well-defined range of properties orbiting a star of known type.

Given the importance of what we can learn about planets orbiting nearby stars, it is important to identify those events with counterparts that may be nearby stars. Thus, in addition to conducting automated searches through catalogs for possible counterparts to lensing events, we can employ Virtual Observatory (VO) capabilities to scan existing images of the area within which the lensing event occurs. By identifying nearby lens stars, we can direct resources toward that subset of events whose study is most likely to be productive through planet discovery or, alternatively, through providing opportunities to place meaningful limits on the presence of planets.

7. Distant Lenses: Events associated with close-orbit planets may also be produced when $D_L$ is large, particularly when $(D_S - D_L)/D_S < 1$. In such cases, we may not be able to detect the central star. We therefore may not have any specific information about its mass or distance from us. The value of $\tau_{E,1}$, fit from the light curve, provides a relation connecting $M, D_L, D_S,$ and the transverse speed. Beyond this, we may have to resort to statistical arguments based on the distribution of stars in the Galaxy, to provide further constraints. The deviations may exhibit periodicity, allowing us to estimate the orbital period, or the fits to the deviations, combined with other light curve information, may otherwise allow us to determine approximate values of $\alpha$ and $q$.

For large $D_L$, the Einstein angle can be small, comparable in size to the magnification features associated with deviations. This means that finite-source-size effects can be
important. Finite source size can play a negative role by softening and diminishing the short-duration deviations associated with the presence of planets. Thus, finite-source-size effects may make it more difficult to identify the effects of close-orbit planets orbiting distant stars. If, however, the deviations remain detectable, then the alteration in their shape produced by finite-source-size may allow us to derive the value of $\theta_E$. While this will not entirely break the degeneracy, it does give an extra relation connecting $M$ and $D_L$ (assuming that $D_S$ is known, at least approximately). It is therefore important to include, in the fits to deviations in the low-magnification portions of the light curve, finite-source-size effects.

8. Blending: When the source star contributes only a fraction of the baseline light, then the measured magnification (i.e., the ratio between the light received portion of the event and the baseline light) during the low-magnification portion of the event is actually $A_{\text{measured}} = 1 + f \delta$. If, therefore, we are not aware of the blending, we will underestimate the value of $\delta$, hence $\alpha$. It is therefore important to include the effects of blending in the light curve fits (Di Stefano & Esin 1995). If the event is studied to search for planets as it occurs, then it is worthwhile observing it in several filters as it occurs, to determine the amount of baseline light that is lensed, as a function of wavelength.

4.1. General Procedure

The simple points listed above lead to an important conclusion: every light curve can be used to either place limits on the presence of possible close-orbit planets or else to discover them. Furthermore, a relatively straightforward procedure can be employed to achieve these goals. We begin by discussing the case of catalogued events and then consider what can be learned from ongoing events.

4.1.1. Catalogued Events

Many of the more than 8500 candidate events already discovered\footnote{See, for example, \url{http://ogle.astrouw.edu.pl/}; \url{http://www.phys.canterbury.ac.nz/moa/microlensing_alerts.html}} are well-enough sampled at low magnification to provide fertile hunting grounds for close-orbit planets. Not all of the candidate events correspond to lensing events, but those with acceptable lens-model fits should be considered as strong candidates. The fit provides an estimate of $\tau_{E,1}$, which relates the total lens mass to $D_L$, $D_S$, and $v$. The fit also provides a value for the blending parameter, $f$, the fraction of the baseline light provided by the lensed source. Although multiple values of $f$ can be consistent with the data, the degeneracy can be lifted if the peak magnification is higher than about 3 (Wozniak & Paczynski 1997). The degeneracy is also broken if the event is observed in a variety of wavebands, even just a few times, or if we have information about other sources of light along the direction to the event, such as the lens itself.

To search for close-orbit planets, we must search the low-magnification portions of the light curve for any upward or downward deviations from the point-lens form. The value
of $\delta$ in the region containing the deviation provides an estimate of $\alpha$. If there are several points per deviation, a model fit can provide an estimate of $q$. Whatever the numbers of points per deviation, we search for signs of periodicity in the wings of the light curves. Repeating signatures of close-planet lensing are not exactly periodic (Di Stefano & Esin 2011), but it is possible to introduce a correction to extract the correct period (Gao et al. 2011). An interesting feature of the near-periodicity, is that it is a transient phenomenon, occurring in the wings of a light curve. That is, if it is due to a close-orbit planet, it is not a long-term property of the baseline, nor is it necessarily exhibited throughout the event. An orbital period for the portion of the light curve corresponding to a particular value of $\alpha$ (hence the projected angular separation), connects the systems mass with true separation.

The combination of these tests provides a great deal of information about the mass of the lens system, the mass of the planet, and the size and orientation of the planetary orbit. These quantities are all expressed in terms of $D_L$, $D_S$, and $v$. The value of $D_S$ is usually known approximately, because the source is likely to be located in the dense stellar field being monitored, often the Bulge, but sometimes the Magellanic Clouds or M31. Galactic models can be used to construct a probability distribution for the values of $D_L$ and $v$. If, however, the lens is a catalogued star, then estimates of the values of $D_L$, $v$, and $M$ may already be known. Alternatively, observations taken several years after the event can resolve the separation between lens and source, especially in those cases in which the lens happens to be nearby. This type of study has already been done for the event MACHO-LMC-5, for which an HST image taken 6 years after the event was able to provide a photometric parallax and measure the proper motion, allowing the gravitational mass of the lens to be determined (Alcock et al. 2001a).

When there is no sign of deviations or of deviations that repeat, then it is possible to place limits on the orbital period and the value of $q$ of any planet that might be in close orbit with the lens star. This is because it is possible to estimate the length of time the magnification is close to $\delta$. This tells us the duration $T_{\text{transverse}}$ of the interval when deviations caused by a planet with $\alpha = 0.84 \delta^{1/4}$ would have been detectable. For orbital periods shorter than $T_{\text{transverse}}$, there would be a chance to detect deviations caused by the planet at least once. Thus, by studying the frequency of sampling during this time, we can determine the duration $T_{\text{dev,min}}$ of the shortest deviation to which we would have been sensitive. This allows us to compute the smallest value of $q$ to which the observations would be sensitive. To quantify limits on the presence of planets, we can run a Monte Carlo simulation in which we model the planetary system, generate large numbers of light curves, and compute the fraction of all planets within some range of masses, orbital separations, orientations, and eccentricities would have been discovered, given the frequency and sensitivity of the observations.

4.1.2. Newly Discovered Events

The present discovery rate of candidate lensing events is roughly 1500 per year. The sensitivity to low-magnification is good, as witnessed by the fact that events with estimated peak magnification smaller than 10% are regularly identified. Whereas for events that have already finished, we must rely on whatever data has already been collected, for ongoing
events we have opportunities to collect as much data as would be needed to discover any close orbit planets. Fortunately, significant improvements in detection efficiency can be achieved with relatively modest changes in the observing plan.

The key improvement would be to ensure regular sampling of the baseline. If, e.g., we want to be able to catch any up-down-up-down deviation that lasts for at least $12 - 24$ hours, we could form a team with telescopes spanning $\sim 4 - 6$ time zones, with $2 - 3$ observations per night in each. The work already carried out by the monitoring teams would constitute a significant part of the monitoring we propose, so that only modest additional resources would be needed. Ideally, each telescope would be able to reliably identify changes in magnification at the level of a tenth of a percent. To ensure that the blending parameter can be measured, we might arrange that at several times during the underlying event, $2 - 3$ different filters are employed.

Note that, although this pattern of monitoring increases the coverage normally provided by the OGLE and MOA teams, the increase is relatively modest compared with the kind of intensive, almost continuous monitoring that takes place over about a night to find planets with $0.5 R_E < \alpha < 1.5 R_E$. We will therefore refer to the procedure we suggest as a moderate increase in monitoring. Nevertheless, with more than 100 events occurring at any given time, it is unrealistic to think that this type of program can be carried out for each. This means that we must select events for special attention. Criteria that could be useful include the following.

1. **High peak magnification:** After a handful of points have been collected as the event rises from the baseline, it is possible to begin to predict the peak magnification, $A_{peak}$. Values of $A_{peak}$ greater than about 3 make it easier to reliably determine the blending parameter from the light curve fit. Since this is important to determining the value of $\delta$ in the low-magnification wings, it makes sense to devote special attention to events with predicted high values of the magnification. Moderate monitoring, like that described above, can be started while the light curve is still on the rise, after the first $5 - 10$ points above baseline have been obtained. It is especially important that the modest increase in monitoring frequency continue during the decline to baseline to ensure that, at least on one side of the light curve, we have ideal time coverage. Note that extreme high-magnification events are already selected for intensive monitoring near peak (Griest & Safizadeh 1998). We suggest that these events receive, in addition, monitoring that is not so intensive but which supplements what is normally done at present, to ensure that deviations near baseline would be detected.

2. **Transient periodicity in the wings:** A nearly periodic signal that becomes detectable as the light curve begins to depart from baseline may be a signature of close-orbit planets. To identify such light curves, checks for periodicity could be made in a sliding window. Windows with a range of sizes should be considered, since the characteristic size $L(\alpha, q)$ of the region within which perturbations can be detected is not known a priori.

3. **Counterpart that could be the lens or lensed source:** If there is a counterpart in a catalog, or else if images of the region reveal evidence for a possible counterpart, it could be that the counterpart is the lens or the lensed source. It is necessary to check that the association between the position of the event and the possible counterpart is likely to be real, which can be accomplished with a Monte Carlo simulation (McCandlish &
Determining whether the counterpart is the lens (making it possible to search for nearby planets) or the lensed source (possibly making it easier to measure the magnification, especially if the baseline is bright) can be accomplished through measuring the blending parameter.

4. **Bright baseline:** Whether or not there is an identified counterpart, a bright baseline may signal that either the lensed source or else the lens itself is bright. In the first case is ideal for the detection of deviations, and smaller telescopes may be able to play an important role in monitoring the event. In the latter case, we may have an opportunity to test for the presence of nearby planets.

4.2. **Close-Orbit Planets, Wide-Orbit Planets and Planets in the “Resonant Zone”**

Figure 1 demonstrates that planetary systems exhibit a wide range of separations. From the perspective of gravitational lensing, they range from “close” to “wide”. The intermediate range, bounded by the dashed lines, is sometimes called the “resonant zone”. It is in this range that planet-lens light curves sometimes exhibit caustic crossings, and this is the range that on which most lensing-event searches have concentrated. The work we have done in this paper can significantly help with the discovery of just over 1/3 of the close-orbit planets, roughly corresponding to those in orbits with $\alpha > 0.15$.

The wide-orbit planets populate the upper portion of Figure 1. Di Stefano & Scalzo (1999b), showed that the probability that an event would “repeat”, with one portion due to lensing by the star, and another short-duration portion showing evidence of the planet, could be as high as a few percent to about 10%. The type of moderately intensive monitoring we have suggested for the wings of the light curve to discover close-orbit planets is also ideally suited to the discovery and study of repeating events. The type of monitoring we suggest therefore provides opportunities to discover planets in two orbital ranges. Furthermore, because many wide-orbit planets are likely to be massive enough to produce events that last a day or more, failure to detect planets is meaningful. If, for example, the Einstein-crossing time for a solar-mass planet is 30 days, then a $>2\%$ deviation will typically take 180 days; a $>2\%$ deviation for a Neptune-mass planet would take about 1.3 days and would be easily detected by any program designed to discover close-orbit planets.

Multiple planets orbiting a single star appear to be common, and one such has already been discovered via lensing (Gaudi & al. 2008). In that case, both planets were located in what we have called the zone for resonant lensing. It is certainly possible that we could use lensing to discover planetary systems containing both close-orbit and wide-orbit planets. Should this happen, the signatures of both could appear together in one of the wings of the light curve, making it important to include both effects when modeling the light curve.

It seems likely that many planetary systems have planets in all three zones. This suggests an interesting possibility. At present, the search for planets in the resonant zone focuses on events with extremely high values of the magnification. The great advantage of these events is that intensive, nearly continuous monitoring near peak will either discover planets or place limits on the existence of planets in the resonant zone. We suggest that all
such high-magnification events should be targeted for continued monitoring at the moderate intensity required for close-orbit planets. We will thereby either discover close-orbit planets or else place quantifiable limits on their existence as well. Furthermore, this search has the ability to discover wide-orbit planets as well. If this plan is followed it will almost certainly lead to the discovery of interesting systems containing planets in all three zones, and a better understanding of planetary systems in general.

4.3. Prospects

Searches for close-orbit planets can begin with studies of existing data. The study of the archived light curves can provide evidence for planets. Whether or not such evidence is found, these studies can place limits on the existence of such planets. Although the limits might only extend across a limited range of values of \( \alpha \) and \( q \), they will be new and interesting.

As new data is taken, searches for close-orbit planets can be incorporated without making major changes. The few changes that will be useful are to conduct searches for transient periodicity, and to select some events for the moderate increases in monitoring near baseline that can improve the chances for discovering or placing limits on close-orbit planets.

Ongoing monitoring has already established that events can be identified, and that binary and planet-events can be found. If there is a new technical challenge in the study of close-orbit planets, it is posed by the importance of the low-magnification portion of the light curves. For close orbit planets we want to measure the value of \( \delta = A - 1 \). Unidentified blending can interfere with these measurements. Yet, it is very interesting to consider cases in which blending may occur, because nearby stars which serve as lenses may contribute light to the baseline. Measurements of the blending parameter are therefore crucial. It is also important to be aware of low-level variability in light from the stars along the line of sight, including the source and, possibly, the lens. Stellar variability is, however, unlikely to exhibit the form seen in the lower-left panels of Figures 3, 4, and 5.

The search for close-orbit and wide-orbit planets can proceed simultaneously, using the same observing strategy and data. Fits must make sure to model planets in both types of orbit. Of particular importance are extreme-magnification events. As pointed out above, we can use these events to search for evidence of close-orbit, resonant-orbit, and wide-orbit planets occupying the same planetary system.

Interestingly enough, there are other near-term opportunities to search for evidence of close-orbit planets. One of them is provided by a predicted close passage between the high-proper-motion dwarf star VB 10 and a background star. This event, slated to occur during the winter of 2011/2012, was predicted by Lepine & Di Stefano (2011). The signatures of any planets that may be orbiting VB 10 are presented in Di Stefano et al. (2011). The form of the prediction is a probability distribution of possible times and distances of closest approach between VB 10 and the background star. For those cases in which the distance of closest approach is smaller than approximately 60 mas, close-orbit planets could be detected. For example, at 60 mas, a planet with an orbital separation of 0.012 AU and an orbital period of 1.7 days would produce distinctive signatures, similar to those shown in
In addition, it is likely that the \textit{Kepler} space mission will either discover or place limits on the existence of close-orbit planets. \textit{Kepler} samples the light from each of its target stars every 30 minutes. (Light from a small subset of the targets are sampled every minute.) \textit{Kepler} can detect photometric changes of roughly 50 parts per million for a star of twelfth magnitude. This means that \textit{Kepler} can detect low-magnification events and can probe the low-magnification portion of all events. We have shown that there is a high probability that \textit{Kepler} will observe a dozen low-magnification events when either a low-mass object passes in front of one of the 150,000 target stars monitored by the mission, or when a target star passes in front of a background source. In fact, target stars with the highest probability of participating in lensing events are presently being monitored (PI: Di Stefano).

In the future, studies like those needed to discover close-orbit planets will be conducted as part of ongoing monitoring programs. Planned programs, such as KNET, will be ideally suited to the discovery of close-orbit planets. KNET is an ambitious monitoring program approved for funding from the South Korean government. Observing from locations at several positions in the Southern Hemisphere, KNET will provide continuous coverage of a large patch of sky, sampling each region with a cadence of 10 minutes.

Gravitational lensing is becoming an effective tool for planet discovery. The work presented here shows that some simple modifications in the way we monitor events have the potential to increase the discovery rate by extending the range of our searches. The procedures we suggest are ideally suited to the discovery of close-orbit planets, and will also discover wide-orbit planets. Undoubtedly, there will be challenges in implementing these ideas, as there have been with every method of planet discovery. Within several years however, it should be possible to regularly discover close-orbit planets both near and far.
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Fig. 1.— Each point corresponds to a known planetary orbit. In each panel, the value of $\alpha$ is shown along with a second quantity. From left to right, the second quantity is the planet’s mass, the stellar mass, the orbital period, the mass ratio $M_{pl}/M_*$, and the distance to the lens. Planets in orbits with values of $\alpha$ in between the two dashed lines are in the “resonant zone” and can be found by methods already employed. The systems below the lower dashed lines are the close-orbit planets we focus on in this paper. Those above the upper dashed line are wide-orbit systems. These can produce repeating events that will automatically be discovered by searches for close-orbit planets.
Fig. 2.— Top panel: $\log_{10}(\Delta)$ vs $\log_{10}(r)$ for a set of planetary systems with $q = 0.001$ and different values of $\alpha$. $\alpha = 0.10$ for the right-most curve and increases by 0.05 for each curve to the left. $r$ is the distance from the center of mass; $\Delta$ is the difference between the maximum and minimum magnification around the ring of radius $r$. For a point lens, $\Delta = 0$. Bottom panel: Normalized distance between small caustic vs $log_{10}(q)$. The curve is multicolored, with each color corresponding to a different value of $\alpha$: 0.10 (blue); 0.15 (red); 0.20 (cyan); 0.25 (black); 0.33 (yellow); 0.40 (green). The fact that it is difficult to resolve these curves shows that there is little dependence on $\alpha$. 
Fig. 3.— Jupiter-mass planet in orbit with a star of $0.8 \, M_\odot$, $\alpha = 1/3$. Top panel: light curves. Each light curve corresponds to a different value of the distance of closest approach: $b = 2/3$ in the top curve and increases by $2/3$ in each subsequent curve. Bottom left: Zoomed-in image of a single deviation. Bottom right: Isomagnification contours associated with the light curves in the top panel.
Fig. 4.— Neptune-mass planet in orbit with a star of $0.25 M_\odot$, $\alpha = 1/3$. Top panel: light curves. Each light curve corresponds to a different value of the distance of closest approach: $b = 2.5$ in the top curve and increases by 0.05 in each subsequent curve. Bottom left: Zoomed-in image of a single deviation. Bottom right: Isomagnification contours associated with the light curves in the top panel.
Fig. 5.— Earth-mass planet in orbit with a star of $0.25 M_\odot, \alpha = 1/3$. Top panel: light curves. Each light curve corresponds to a different value of the distance of closest approach: $b = 2.5$ in the top curve and increases by 0.05 in each subsequent curve. Bottom left: Zoomed-in image of a single deviation. Bottom right: Isomagnification contours associated with the light curves in the top panel.