Searching for Planets During Predicted Mesolensing Events: II. PLAN-IT: An Observing Program and its Application to VB 10

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ABSTRACT

The successful prediction of lensing events is a new and exciting enterprise that provides opportunities to discover and study planetary systems. The companion paper investigates the underlying theory. This paper is devoted to outlining the components of observing programs that can discover planets orbiting stars predicted to make a close approach to a background star. If the time and distance of closest approach can be well predicted, then the system can be targeted for individual study. In most cases, however, the predictions will be imprecise, yielding only a set of probable paths of approach and event times. We must monitor an ensemble of such systems to ensure discovery, a strategy possible with observing programs similar to a number of current surveys, including PTF and Pan-STARRS; nova searches, including those conducted by amateurs; ongoing lensing programs such as MOA and OGLE; as well as MEarth, \textit{Kepler} and other transit studies. If well designed, the monitoring programs will be guaranteed to either discover planets in orbits with semi-major axes smaller than about two Einstein radii, or else to rule out their presence. Planets on wider orbits may not all be discovered, but if they are common, will be found among the events generated by ensembles of potential lenses. We consider the implications for VB 10, the first star to make a predicted approach to a background star that is close enough to allow planets to be discovered. VB 10 is not an ideal case, but it is well worth studying. A more concise summary of this work, and information for observers can be found at https://www.cfa.harvard.edu/~jmatthews/vb10.html.

1. Introduction
1.1. A Brief History of Prediction

When Einstein was first convinced to publish a paper on the generation of gravitational lensing events, he expressed doubt that the effect would be observed (Einstein 1936). The
probability of an event occurring is very low. In addition, detection can be made challenging through the “dazzling by the light of the much nearer star”, the lens. Einstein’s doubts have not deterred astronomers, with their familiarity of the universe of possible lenses and background sources, from predicting specific lensing events.

In 1966, Feibelman suggested that the star 40 Eridani-a, a member of a triple which also contains a white dwarf, would pass close enough to a background star in 1988 to produce detectable lensing effects. Given its mass of $0.84 M_\odot$ and its distance of only 5 pc, 40 Eridani-a has an Einstein angle, $\theta_E$, of about 37 milliarcseconds (mas) when it lenses a star at much larger distances from us. Unfortunately, though, studies of the motion during the following 20 years found that the distance of closest approach would be approximately 3″, about $81 \theta_E$ (Feibelman 1986), too distant for observations at that time to detect the effects of lensing. In addition, the closest approach between 40 Eridani-a and the background star was predicted to occur in June, when Eridani, a winter constellation, would have been unobservable. Any plans to monitor the region were abandoned.

In 2001, Paczyński suggested that the isolated neutron star RX J185635-3754 would pass close enough to a background star (within about 0.3″) that its action as a gravitational lens would produce an astrometric shift that could be detected with HST. As reported by Neuhäuser et al. 2011, the Ph.D. thesis of Eisenbeiss finds that there is no star close enough to the paths of any of the seven isolated neutron stars known as the Magnificent Seven (Haberl 2007) to produce detectable lensing through the rest of the 21st century.

Recently, our group predicted a very close approach between the high-proper-motion dwarf star VB 10, and a dim background star (Lépine & Di Stefano 2011). With two HST images of the region, and the results of previous of astrometric studies of VB 10, we thought at first that we could predict the distance of closest approach to within several mas, and also the approximate date of closest approach. Taking into account the uncertainties, including the uncertainty in the motion of the background star, however, we realized that existing observations are consistent with a bundle of paths, each characterized by a date and distance of closest approach. The most likely date was during December of 2011, when VB 10 is a twilight star, very close to the Sun. Nevertheless, the predicted approach is very close: the probability is $\sim 65\%$ that the distance of closest approach will lie in the range from less than an Einstein angle to $15 \theta_E$. The time of closest approach could be during the spring of 2012, even though the most likely dates are earlier. Faced with these uncertainties, and also with the fact that the background star is dim, we set out to assess the value of an observing campaign. To explore the possibilities in detail, we asked whether, if VB 10 has planets, they could enhance the lensing signature or even produce detectable events at different times. The answer to both questions is yes, and the details are reported in the companion paper (Di Stefano et al. 2012a, hereafter Paper I).

### 1.2. Possible Observing Programs

In spite of the difficulty of predicting individual events, Paczyński (1986) found a way to transform the study of lensing events into an observational enterprise. He overcame Einstein’s concern about low probability by pointing out that, fifty years later, computers had made it possible to track the light curves of many millions of stars per night, guaranteeing
the detection of some events if large, dense stellar fields could be monitored. He countered
the possibility that dazzling by the lens could prevent the detection of lensing by focusing
on the possibility of lensing by compact dark matter objects. Within a few years, several
monitoring programs were each monitoring large portions of the Magellanic Clouds and
the Galactic bulge to find evidence of microlensing. The challenge that the first generation
of microlensing observing programs faced was to prove that they could extract from the
haystack of ubiquitous stellar variability, the signal of a relatively small number of lensing
events (Udalski et al. 1993, Alcock et al. 1993, Aubourg et al. 1993).

They succeeded, and the present generation of lensing monitoring teams are discover-
ing more than 1500 events per year. By demonstrating that long-term, high-cadence
monitoring can reveal variability of many types, producing a high science yield, these
projects have inspired many other astronomical time domain studies. These include the
Palomar Transient Factory (PTF; Rau et al. 2009, Law et al. 2009), the Panoramic Survey
Telescope & Rapid Response System (Pan-STARRS; Kaiser et al. 2002), and the Large
Synoptic Survey Telescope (LSST; Tyson 2002).

One particularly innovative approach has been designed to search for evidence of
transits of Earth-like planets around M dwarfs. The MEarth Project is a survey to photo-
metrically monitor approximately 2000 nearby M dwarfs, searching for transits by planets
that could be habitable Super-Earths (Irwin et al. 2009a). The project has had some
success in the detection of Super-Earths (Charbonneau et al. 2009) and also in discovering
a number of eclipsing binary systems (Irwin et al. 2009b; Irwin et al. 2010). The unique
feature that we will find potentially important in monitoring the sites of predicted lensing
events (§5) is that MEarth monitors many directions per night, because their target stars
are spread over a large portion of the sky. The same will be true for predicted lensing
events.

1.3. Plan of the Paper

We develop an observational strategy to systematically study predicted lensing events
with the goal of learning about the planetary system of the lens star. The companion
paper (Di Stefano et al. 2012) presents the theory. Here we focus on observations. In
Sections 2 and 3 we describe what we can learn by monitoring the site of a predicted
event during the months and years prior to and after the event, as well as during the
time of closest approach. Section 2 is devoted to planning observations for a specific case
meant to represent an ideal situation. Section 3 is devoted to planning a real observing
campaign for the star VB 10, which is generating the first predicted event about which
we can hope to derive observational constraints. In Section 4 we address the issue of how
many events are likely to be predicted each year. Since the majority of predictions will not
be precise, with the time and distance of closest approach not known in detail, we turn in
Section 5 to observational programs designed to monitor the sites of thousands of predicted
events. By monitoring a large enough number of events, we can be guaranteed to detect the
lensing signatures of some foreground stars and their planetary retinues. The prospects for

\[\text{ogle.astrouw.edu.pl/}; \text{www.phys.canterbury.ac.nz/moa/}\]
successful observing programs are discussed in Section 6. In addition to predicted lensing events, there are at least two connections to ongoing observing programs: The first is to current surveys for lensing events; the second connection is to transit studies.

2. Monitoring Individual Predicted Events

2.1. Events to target

Multiple precise measurements of the relative positions of source and lens can, in some cases, allow the time and distance of closest approach to be computed with modest uncertainty limits. If the probability is high that the closest approach will lie within \( \theta_E \) of the lens, and that the source star will be observable near the time of closest approach, then monitoring the source star during the lensing event can measure the mass of the lens, determine if it has a planetary system, discover planets in a wide variety of orbits and with a broad range of masses, and place limits on the presence of various types of planets (see Paper I for details). In an ideal case, the source is brighter than the lens in some waveband, bright enough that large telescopes are not needed to detect changes of a few percent in the amount of received light. This circumstance can allow amateurs to play significant roles in the monitoring program, strengthening the results.

To make the discussion in this section concrete, we will consider the prediction of an event by a specific star, PMI18537+4929. This is a star with an estimated mass of \( 0.46 M_\odot \). PMI18537+4929 is 44.8 pc away and has a proper motion \( \mu = 0.137'' \text{yr}^{-1} \). These parameters allow us to compute the value of the Einstein angle, \( \theta_E = 9.1 \text{mas} \). We also have the Einstein-diameter crossing time, \( \tau_E = 49 \text{days} \). This star falls into the general category of stars expected to produce events at a rate of just under one per century.

The orbital period of a planet with semi-major axis \( a = R_E \) is approximately 140 days. If observations are able to detect deviations of 1% in the amount of light received from the source star, then a deviation from baseline is potentially detectable for a maximum of \( 3.5 \tau_E \sim 172 \text{days} \). Thus, rotation could play a role in increasing the detectability of planets in similar orbits. Rotation is less likely to be significant in events caused by wide-orbit planets. On the other hand, deviations caused by close-orbit planets will, in many cases, repeat. (The orbital period for a planet with \( a = 0.25 R_E \) is about 18 days.)

For the purposes of the lensing signatures, the important separation is the projected separation between the lens star and its planet. To simplify this discussion we consider circular face-on orbits. The value of \( a \) is constant, and it we define \( \alpha = a/R_E \). In Paper I we have shown that it is convenient to consider three classes of orbital separation: wide-orbits (\( \alpha > 2 \)); orbits in the zone for resonant lensing (\( 0.5 < \alpha < 2 \)), and close-orbit planets (\( \alpha < 0.5 \)). Events generated by planets in each of these ranges exhibit distinctive characteristics, suggesting that the observing strategy should evolve with time, as orbits
with different values of $\alpha$ become detectable.\footnote{Note that, although this classification is very useful, the values for the boundaries given above are somewhat arbitrary, because event characteristics depend on the mass ratio $q = m_p/M_*$, where $m_p$ is the mass of the planet and $M_*$ is the mass of the star.}

An important parameter in determining what we can learn from a specific predicted event is the angle of closest approach, $b$, between the foreground and background stars. With $\beta = b/\theta_E$, three ranges of values determine which types of planets can be detected. The wide regime covers the entire lens plane; wide-orbit planets can be detected throughout the wide regime, as long as $\alpha > \beta$. In addition to wide-orbit planets, close-orbit planets can be detected if $\beta < \eta$, where the value of $\eta$ depends on the photometric sensitivity and is typically larger than 3 but smaller than 10. In addition to wide-orbit and close-orbit planets, planets in the zone for resonant lensing can be detected in the resonant regime, ($\beta < 2$). More details are presented in Paper I.

Because the goal of this section is to determine the best day-by-day monitoring strategy, we have chosen a star that is more typical than VB 10 of what we can expect in the future. We do, however, assume that the observing conditions will be better than those expected for VB 10. First, we assume that the closest approach occurs when the lens and source are observable: that is, they appear in the night sky, close to neither the Sun nor Moon. Second, we assume that the source star is bright enough that changes in the light we receive from it of about a percent can be detected. Third, we assume a distance of closest approach smaller than $\theta_E$. We chose a close approach because it allows us to explore the full range of behavior which is potentially detectable.

### 2.2. Detection as a function of time

We considered the possibility that PMI18537+4929 has a Jupiter-mass planet in a face-on, circular orbit. To study detectability, we conducted a simulation in which we generated 20,000 orbits with values of $\alpha$ ranging from 0.1 to 20. For each value of $\alpha$, we also generated a random starting value for the orbital phase. We then followed the path of both the star and its planet as the center of mass executes a straight-line path making a closest approach of $\beta = 0.5$ to a bright background star at time $t = t_0$. We computed the magnification, $A_{pl}(t)$, caused by the planetary system at each time, and compared it with the magnification, $A_{pt}(t)$ expected if PMI18537+4929 alone had been traveling along the line followed by the planetary system’s center of mass. At each time, we asked whether the value of $A_{pl}(t) - A_{pt}(t)$ had reached an extremum with a value greater than 0.01. If so, we stored the value of $\alpha$ and $(t - t_0)$. In order to display the structures in the densest regions, within about 40 days of $t_0$, we did not plot all of the points. Nevertheless, the relative density of points in a given region roughly corresponds to the probability that a planetary system with a specific value of $\alpha$ will produce a light curve with significant deviations at time $t$. Points in orange correspond to caustic crossings. The magenta curves that start in the upper right and upper left of the figure were calculated with the analytic formula given in Equation 3 of Paper I, which applies to planets in wide orbits. The cyan curves that start in the lower right and lower left of the figure were calculated with the
analytic formula given in Equation 6 of Paper I, which applies to close-orbit planets. The black points, from our simulation, generally follow these curves, especially for the widest and closest orbits; the curves therefore provide good guides to the positions that would be occupied by low-probability events.

To determine what type of event will be detected as time goes on, we consider a ruler, with its straight edge coincident with the vertical axis. As time goes on, the ruler moves to the right. The points and/or curves it intersects at each time show the types of events that can be detected at that time.

2.2.1. Early times and late times

Approximately 500 days before the closest approach between the nearby star and the foreground source, a planet with $\alpha = 20$ could make a very close approach to the background star, producing detectable lensing effects. The radius of the Einstein ring of the planet is

$$\theta_{E,pl} = \sqrt{\frac{m_p}{M_\star}} \theta_E = 0.42 \text{ mas} \sqrt{\frac{m_p}{m_J}}. \quad (1)$$

The Einstein diameter crossing time, $\tau_{E,pl}$, is approximately $2.3 \sqrt{\frac{m_p}{m_J}}$ days. If 1% deviations from baseline are detectable, the planet-induced event could last as long as $\sim 8$ days. The peak magnification induced in the source star will be large if the distance of closest approach between the planet and background star is small.

One goal of an observing program would be to discover any lensing events generated by wide-orbit planets. In addition, by measuring the magnification as any discovered planet-lens events progress, we can gather enough data to perform a model fit and to extract the gravitational mass of the planet. Furthermore, should any of the planets themselves be binaries, this could affect the lensing signature in a distinctive way.

These goals can be achieved in a two-stage process. The first step is monitoring designed to discover evidence of lensing. The second step occurs only if it appears that a lensing event is in progress; in this case, the observing plan can be made more intensive for a limited time interval in order to track the progress of the event.

(1) Monitoring to discover wide planet-lens events: It is important to make this stage as easy as possible, because there is a long time (in this case years) during which there is a low but significant probability of detecting wide-orbit planets, should they exist. Fortunately, the fact that it takes so long for the lens star to travel $\sim 20 \theta_E$ means that it can take a few days for a planet-lens event to go from start to finish. Monitoring several times a day is therefore adequate. Ideally, there should not be gaps in coverage; this favors developing a team that can conduct observations across longitudes. If a large enough number of telescopes are involved, each can take observations several times a week. With such infrequent observations by individual teams, it becomes important that the data be quickly communicated to one group for each event, in order to identify trends as they occur for the purposes of calling alerts when needed.

An advantage of a long baseline of observations is the opportunity it provides to characterize the intrinsic variability of both the lens star and the source to be lensed. We will
discuss this more for the specific case of VB 10 in the next section; VB 10 provides a clear lesson that it can be advantageous to understand the variability in different wavebands.

(2) Tracking an event: Once an event is detected, it is important to obtain enough data to provide a model fit. If an event can be identified as such before the magnification has risen by about $\sim 34\%$, then more intensive monitoring will be able to catch the event during the interval in which it is most variable. During this interval, a total rate of observations on the order of every few hours would be adequate for a Jupiter-mass planet. An alert can encourage more observers to join in, providing even more frequent coverage over an interval of a few days. This could prove helpful if the planet happens to be less massive than Jupiter.

The teams observing predicted events have a number of decisions to make as they design a program to monitor a specific predicted event. For example, what is the minimum mass to which they would like to be sensitive? Because the time duration scales as the square root of the mass, the complementary question is: What is an appropriate investment of resources? To decide the answers to such question it can be helpful to consider the evolution of the event probability with time. The probability is $\sim 1\%$ to detect a planet with $\alpha = 20$ (see Table 1), at $|t - t_0| \sim 500$ days. As time goes on, lensing by planets with smaller values of $\alpha$ becomes detectable, and the probability increases. For example, at $|t - t_0| \sim 35$ days we there is a probability of $\sim 11\%$ of detecting a planet with $\alpha = 2$.

| $\alpha$ | $|t - t_0|$ | $P(A > 1.06)$ | $P(A > 1.01)$ |
|---------|-----------|--------------|--------------|
| 2       | $\sim 35$ | 0.11         | 0.18         |
| 3       | $\sim 80$ | 0.07         | 0.12         |
| 5       | $\sim 115$| 0.03         | 0.05         |
| 10      | $\sim 250$| 0.01         | 0.02         |
| 20      | $\sim 500$| 0.01         | 0.01         |

Table 1: Probability of an event with $A > 1.06, 1.01$ produced by a Jupiter mass planetary companion to PM18537+492, for a range of orbital separations, $\alpha$, as predicted by Equation (4) of Paper I. This is for a circular face-on orbit; different eccentricities and orientations will produce different probability distributions.

2.2.2. Intermediate times

In the interval within about 80 days of the closest passage, a greater variety of events can be detected\(^3\). Detection of planets in certain types of orbits is all but guaranteed, should they exist. A well-designed monitoring program will therefore either make discoveries or place strong limits of the presence of planets with orbits characterized by $\alpha < 2$.

\(^3\)We define “intermediate times” to refer to the interval which starts when close-orbit planets can be detected. In principle, this interval can start earlier, if highly sensitive photometric observations are possible. To be conservative, here we take the interval to begin about 80 days prior to closest approach, when close binaries with $\alpha = 3$ produce a strong signal.
By the time the stellar lens has come within about $3\theta_E$ of the background source, four things, summarized below, have changed.

1. The probability of events generated by wide-orbit planets has increased. The increase in probability is shown in Table 1 and can be seen in Figure 1: as time goes on and the ruler discussed in the introduction of §2.2 moves to the right, the density of points lining the magenta curve increases. The increase in probability is partly due to the smaller size of the orbit (see Equation 4 of Paper I) and is partly due to the somewhat larger size of the isomagnification contours associated with detectable events. Furthermore, with a larger event probability, every day a planet is not discovered translates into a significant probability that a planet with a given value of $\alpha$ doesn’t exist.

2. Events caused by wide-orbit planets are more likely to exhibit binary effects. This is because the stretching of the isomagnification contours is accompanied by other distortions, making the characteristics of wide-planet-lens events more likely to exhibit deviations from the pure point-lens form. One enhanced binary effect is that the caustic structures are larger. An example of a wide-orbit-planet light curve exhibiting binary effects is shown in the red light curve ($\alpha = 2.73$) on the lower-left of Figure 2. The deviation of this light curve from the underlying green light curve is caused by a close approach of the Jupiter-mass planet to the background star. Although it is difficult to see on this scale, this event actually exhibits a caustic crossing.

3. The magnification due to the stellar lens has increased. At $\alpha = 3$, the magnification is about 1.7%, potentially detectable. It is convenient to define $\delta = (A - 1)$. From the time the value of $\delta > 0$ becomes measurable, the exact distance between the lens star and the background star is known, in units of $\theta_E$. Each measurement of the magnification can now be used not only to discover planets, but also to measure the mass of the lens.

4. It has become possible to detect close-orbit planets. In the top panel of Figure 2, the green deviation in the light curve at about 390 days ($\sim 25$ days after closest approach) is caused by a close-orbit planet. A larger set of such deviations is shown in the bottom panel. More light curves for close-orbit planets are shown in Paper I. The key point to take away from these images is that the phases chosen to generate the light curves were random, yet every light curve exhibits deviations. For the case of Jupiter-mass planets orbiting low-mass dwarfs like PMI18537+492 and VB 10, with $\alpha$ approximately equal to $1/3$, these deviations can be easily detected. Furthermore, the values of the orbital separation and mass ratio can be determined. Below we summarize results presented in Di Stefano (2011).

For each value of $\delta$, observations are sensitive to planets with $\alpha = 0.84\delta^{0.25}$. If such a planet exists, it will produce a deviation in the light curve like those that shown in Figure 2, for $\log_{10}(A - 1) = \log_{10}(0.25) = -1.6$. The relatively short orbital period of about 26 days, means that the deviations will be repetitive, although their size is maximized in the region just mentioned above. If $P_{\text{orb}}$ the planet’s orbital period then the time duration of a deviation from the point-lens form is

$$T_{\text{dev}} \approx 2.5 P_{\text{orb}} 10^{(0.5 \log_{10}(q) - 0.2)}$$

This predicts a deviation duration of about 2 days for a Jupiter-mass planet in an orbit with $\alpha = 3$; this is reflected in the light curves of Figure 2.

Thus, by deciding on a sampling frequency and the depth of the observations for each measured value of $\delta$, observers are certain to either detect lensing signatures of close-orbit
planets, or else to be able to determine with certainty that certain orbital separations and mass ratios can be ruled out.

(1) Monitoring: Once $\delta$ is larger than about 0.017, the monitoring program designed to allow event alerts should be stepped up. This is because the probability of detecting certain close-orbit planets, if they exist, approaches unity. Therefore, at this point in the program it will be productive to increase the numbers of telescopes in use, and to attempt observations two times per night with each, if possible. Fast and efficient calls of alerts are needed, because the deviations from the underlying point-lens light curve associated with lensing by the high-proper-motion star, may exhibit more structure than the planet-lens events expected at early and late times.

(2) Tracking an event: The basic principle is the same as for tracking events that occur at early or late times. But, because the light curves will tend to exhibit structure on short time scales, more frequent observations after the alert would be fruitful. This portion of the observing plan would be very similar to plans carried out to discover planets in present-day microlensing programs.

### 2.2.3. Times near the time of closest approach

Once the the stellar lens passes within about $2\theta_E$ of the background source (within $\sim 35$ days of closest approach) we can start to see features of planets in the zone for resonant lensing, in addition to continuing to find evidence for close-orbit and wide-orbit planets. During the interval from 35 days prior to closest approach until 35 days after closest approach we are almost certain to discover evidence of planets in the zone for resonant lensing, if they exist. Sensitivity to close-orbit planets continues during this time as well.

**Monitoring and Tracking:** The program for monitoring to discover events and tracking the evolution of any events discovered should be the same as described above for close-orbit planets. During the time around closest approach, however, it is especially important to have frequent, deep monitoring: (a) close-orbit planets can cause deviations in the magnification as the lens star wobbles in its orbit on short time scales (Figure 4 of Paper I); (b) wide-orbit planets cause subtle deviations from the point-lens form in the magnification produced by the central star, also associated with stellar wobble (Figure 5 of Paper I).

### 3. Monitoring VB 10

#### 3.1. VB 10 as an example of a nearby lens

VB 10 is a nearby high proper motion M dwarf, whose upcoming predicted close approach with a background star was discussed in detail in Lépine & DiStefano 2011 and in Paper I. VB 10 has an estimated mass of $0.075 M_\odot$, at a distance from us of 5.82 pc, with a proper motion of about $1.5''$ yr$^{-1}$. These parameters allow us to compute the value of the Einstein angle, $\theta_E \approx 10$ mas, and the Einstein diameter crossing time, $\tau_E \approx 5$ days.

As we did for PM18537+4929, we conducted simulations considering a hypothetical
Jupiter-mass planet orbiting VB 10 in a face-on, circular orbit. For VB 10 we selected a physical path compatible with astrometric measurements of the system, specifically, the path with $\beta = 0.5$ (5 mas), shown in Figure 1 of Paper I. The resulting pattern of points in the plane of $\alpha - (t - t_0)$ is shown in Figure 3. The most obvious difference from PMI18537+4929 as shown in Figure 1, is the significantly shorter timescale of the event.

The reason the time scale for VB 10’s approach is almost ten times shorter than that of PMI18537+4929, is VB 10’s relatively high angular speed. To quantify the comparison with other nearby stars, we considered $\sim 7500$ stars that happen to lie in the Kepler field and which have measured proper motion. Setting the value of $D_L/D_S$ to zero, we computed the distributions of the values of both $\theta_E$ and $\tau_E$. Figure 4 shows that both PMI18537+4929 and VB 10 have large Einstein rings, but that neither is among the largest for nearby stars. Yet, while the value of $\tau_E$ for PMI18537+4929 is fairly typical of values for other nearby stars, the value of $\tau_E$ for VB 10 is smaller than for any star in the sample. This is because it is nearby and also because its transverse speed of about 40 km s$^{-1}$ is also fairly large.

3.2. Observing the first Predicted Mesolensing Event

The relative brightness of VB 10 at long wavelengths and its variability (Cutri et al. 2003; Berger et al. 2008; West et al. 2008; Hilton et al. 2010) pose challenges. VB 10 is an active M dwarf and is known to exhibit flares. It is important to be able to distinguish lensing signatures from possible flare activity. For this we must rely on multi-waveband observations and on the pattern of time variability. Flares have a characteristic fast rise and exponential decay. Although rotation effects can alter the light curve (Berger et al. 2008), it should be rare for a flare to mimic a lensing event. Furthermore, the time scale of most flares is shorter than that of the lensing events we have considered. Thus, should we detect evidence of lensing, we expect to be able to distinguish it from flare activity; this is why we emphasize the need for good time coverage and mutiband observations. In fact, during late November we were able to compare MEarth I-band light curves with a small number of 7-band observations with GROND. This showed that, even when significant I-band variability of VB 10 was exhibited, the variability was less evident or not evident at shorter wavelengths.

The primary challenge we face in designing a program to monitor VB 10 is that the date and distance of closest approach are uncertain (Lépine & Di Stefano 2011; Paper I). Despite the difficulties, we can still learn from the VB 10 lensing event, but what we learn depends on the time of closest approach. It is important to note that, although we do not know at the time this text is being written what the distance and time of closest approach was or will be, future high-resolution images will allow us to determine the relative path of VB 10 and [VB 10]-PMLS-1 with small uncertainties.

(1) If the closest approach has already occurred, then we may be able to discover lensing signatures from the time of closest approach in existing data, such as the combination of MEarth and GROND data mentioned above. Since, however, dense monitoring has not yet begun, and VB 10 is still near the Sun, we are not likely to detect
lensing signatures associated with the closest approach. This means that we will not measure the mass of VB 10, nor will we be sensitive to signatures from planets in the resonant zone. The signature most likely to be detected, however, is that due to wide-orbit planets. Monitoring that starts now and continues for a few months will either detect or place weak limits on the presence of wide-orbit planets. On every day from now onward, the detection or failure to detect a planet-lens signature either discovers or places a weak limit on the presence of a planet with a well defined value of $\alpha$.

In analogy to the work described in §2.2, we can estimate the probability, $P$, that an event with $A > 1.06$ will be produced by a Jupiter-mass planet on a wide orbit. While simulations like those that produced the probability plots of Paper I can provide better estimates, Equation 4 of Paper I provides a reasonable guide to the $\alpha$ dependence of $P$, especially for small $\beta$. The probability is $\sim 1\%$ to detect a planet with $\alpha = 20$ at $|t - t_0| \sim 46$ days. As time goes on, lensing by planets with smaller values of $\alpha$ becomes detectable, and the probability increases. For example, at $|t - t_0| \sim 5$ days we have a $\sim 27\%$ chance of detecting a planet with $\alpha = 2$. The increased probabilities compared to PMI18537+4729 reflect the higher mass ratio for a Jupiter-mass planet orbiting VB 10.

$$
\begin{align*}
\alpha & |t - t_0| (\text{days}) & P(A > 1.06) & P(A > 1.01) \\
2 & \sim 5 & 0.27 & 0.47 \\
3 & \sim 7 & 0.16 & 0.28 \\
5 & \sim 11 & 0.08 & 0.14 \\
10 & \sim 23 & 0.02 & 0.03 \\
20 & \sim 46 & 0.01 & 0.01 \\
\end{align*}
$$

Table 2: Probability of an event produced by a Jupiter mass companion to VB 10. with $A > 1.06$, 1.01 for a range of orbital separations, $\alpha$, as predicted by Equation (4) of Paper I.

(2) If the approach occurs in the near future, we are unlikely to have ideal monitoring during the event. Nevertheless, if VB 10 is orbited by a planet in the zone for resonant lensing, and if the distance of closest approach lies within about 20 mas, we have a good chance of detecting evidence of the planet. This is because the magnification of the [VB 10]-PMLS-1 will be high enough that we will receive roughly as much light from it in B band as we receive from VB 10 itself. If VB 10 is orbited by a close-orbit planet, we may be able to detect evidence of it, but only when observing conditions become more favorable, because close-orbit planets will produce deviations that are typically small and, for VB 10, short-lived as well. The main channel of detection will be in the wide regime. Fortunately, since we will have continuous monitoring from the time of the event, Table 2 shows that we will be able to place meaningful limits for modest values of $\alpha$, since the probability that such planets produce events is high.

(3) If the event occurs in late winter or early spring, we will be able to learn a good deal. It is therefore important to take high-resolution images as soon as possible, to refine the prediction, as in this case, we should enlist a large number of observers. Close-orbit planets: The orbital period can be very short. For example, with $\alpha = 1/3$, $P_{\text{orb}} = 3.6$ days, so that orbital motion can increase the detection probability to nearly unity. Equation 2 shows that the deviation duration would be $\sim 0.65$ days for a Jupiter-mass planet orbiting VB 10 with $\alpha = 1/3$. The fractional deviation due to the magnification
of the dim background star is small, so that deep observations are required. *Planets in the zone for resonant lensing:* Orbital motion is still important enough to significantly increase the probability of detection (see Figure 3 of Paper I). The magnification tends to be large, making it easier to identify the magnification of the dim background star. As is the case for close-orbit planets, frequent observations will either discover planets in the zone for resonant lensing, or else will place strong limits on their existence. *Wide-orbit planets:* There is a high probability of discovering wide-orbit planets during an interval of weeks from the closest approach.

**Observing Strategy:** While intensive monitoring of a system in which the distance and time of approach is uncertain cannot be justified, a discovery would be important. We therefore propose a compromise between the scientific potential and the uncertainty associated with the event. First we consider the questions of detectability in more detail. If telescopes at approximately ten locations around the globe can each observe the source star 2–5 times per night, a reasonably densely sampled light curve can be developed. Because the background star is so dim, the signal-to-noise ratios required to reliably measure the magnification may require meter-class telescopes. The exception would be for high-magnification.

**Analysis:** For each value of \( \alpha \), a set of orbits are possible. This set includes face-on orbits in either direction, inclined orbits, and eccentric orbits. For each type of orbit, and for a wide range of possible planetary masses, we compute the light curves, specifically computing the value of the magnification at each time an observation occurs. This will identify the cases in which we would have had a high or low probability of planet detection, and may even lead to the discovery of a planet.

Due to the proximity in time of the VB 10 event, we have not yet conducted a full analysis of orbits in the general case—i.e., including eccentricity and inclination effects. Throughout this paper and Part I we have considered circular face-on orbits, and will conduct a full general treatment shortly.

### 4. Will event prediction be common?

Feibelman’s identification of the possible 40-Eridani event was almost certainly serendipitous, as was our discovery that VB 10 would make such a close approach to a background star. The relative ease of these predictions suggests that lensing event prediction should not be too difficult. It is therefore important to make a quantitative estimate.

This was first done by Paczyński (1995), who calculated the area of the region swept out per year within \( \theta_E \) of a typical nearby lens within \( D_L = 10 \) pc. He found that, if the background source density is 0.3 per sq. arcsecond, then each nearby dwarf should produce, on average, slightly fewer than one event per century. Thus, by monitoring a few hundred of the nearest stars, one can expect that a few of them per year will produce events in which the background star is magnified by \( \sim 34\% \) or more. Paczyński (1996) later went on to consider events displaying the astrometric effects of lensing, for which the distance of closest approach can be larger, leading to a higher event rate.

Here we include for the first time, lensing by possible planetary companions to nearby stars. Every time a nearby star produces an event, there is an opportunity to discover
planets in the zone for resonant lensing as well as close-orbit planets. In addition, the stellar-lens light curve may be distorted by the fact that the lens star is wobbling in response to an orbiting wide-orbit planet. In addition to possibly being discovered through their influence on the motion of the star they orbit, when it serves as a lens, wide-orbit planets can be discovered by producing independent events that may or may not be preceded or followed by a detectable stellar-lens event. If a population of \( N \) nearby stars is being monitored, and each produces events at a rate \( \mathcal{R}_j \), where \( j \) labels the star, then the rate of independent wide-planet-lens events is

\[
\mathcal{R}_{\text{wide}}^{\text{ind}} = \sum_{j=1}^{N} \mathcal{R}_j \sum_{i=1}^{n(j)} \sqrt{\frac{m_{p,i}}{M_{*j}}},
\]

where \( i \) labels the planets associated with an individual star, and \( n(j) \) is the number of planets orbiting the \( j \)th star. The rate of separate planet-lens events can be a significant fraction, as much as several tenths, of the rate at which nearby stars produce events, depending on the number of planets per star and the mass distribution of the planets.

We also extend the reach of these studies by considering lensing by somewhat more distant stars. While the proper motion of stars more than \( \sim 10 \) pc away is generally smaller, producing a smaller event rate per star, there are nevertheless a large number of stars within a hundred parsecs or so that have proper motions larger than 0.15 arcseconds per year.

First we consider the rate at which nearby stars produce events, then turn to the enterprise of prediction. To determine the event rate, we have considered approximately 7500 stars with measured proper motion that happen to lie in the field observed by the Kepler space mission. For each of these stars we have estimates of the mass and distance, in addition to the proper motion. This allows us to compute the size of the Einstein ring of each star and the area covered by the Einstein ring per year. We find that, in total, the Einstein rings of these stars cover approximately 3.6 arcseconds per year. Events can be detectable even when the angle of closest approach is larger than \( \theta_E \). For example, deviations of 6\% or more are likely to be detectable, so that the angle of closest approach need only be smaller than 2\( \theta_E \). Thus, the lensing region of nearby stars in the Kepler field covers about 7.2 sq. arcseconds per year. Over the whole sky (which has about 400 times the area of the Kepler field) the lensing regions of nearby stars cover approximately 3000 sq. arcseconds per year. If the background stellar density is 0.3 per sq. arcsecond, then we expect roughly 1000 events across the sky caused by nearby lenses.

These events will be generated by over \( 2 \times 10^6 \) stars, most of which have already been identified. The question then becomes, how do we make predictions? There are two types of answers to this. The first is to simply develop an ensemble of possible lenses and to arrange to monitor enough of them that we are guaranteed to detect several events per year. We will know which specific monitored stars produce the events only after the events begin. Wide-field surveys that are more-or-less automated can simply keep track of any changes in the amount of light received from the positions around all high-proper-motion (HPM) stars.

Surveys that must select a limited number of directions to monitor must know which of the high-proper-motion stars are most likely to produce events. This can be discovered
by computing, for each HPM star, the area it covers in the sky. Those that cover the largest area are generally the best candidates to produce events. By studying the sample of stars in the *Kepler* field, we find that a small fraction of the HPM stars have a very high probability of producing lensing events: 0.6% of all of the possible lenses will likely produce 10% of the events. The most likely lenses tend to lie within about 100 pc. Thus, subsets of high-probability lenses can easily be selected; in fact we have already done this for the *Kepler* field (Di Stefano et al. 2012b).

These numbers make it clear that it is possible to identify ensembles of nearby stars, each of which has a high probability of producing a lensing event sometime during the next year. In fact, the total probability is so large that, by monitoring these stars, we are guaranteed to discover dozens of event per year. The reason these events are special is that each can yield the gravitational mass of the lens star and can explore its planetary system in detail, potentially discovering several planets per star and measuring the mass and orbital separation of each. It is clear that, if we focus attention on predicted events, we will have a tool that can be continuously employed to study nearby planetary systems.

It is not necessary to rely on only statistical probabilities. We can identify potential lens-source pairs by using catalogs of nearby stars with measured proper motion, and by cross correlating them with catalogs of nearby background stars. In fact catalog matches were suggested by Feibelman,5 and implemented by Salim & Gould (2000), who used catalogs to identify pairs of nearby stars that could induce astrometric shifts in more distant stars. The idea was to use the then-proposed Space Interferometry Mission (SIM) to observe these events, due to its excellent astrometric precision of $\sim 4\mu$ arcsec.

This discussion leads us to develop a hierarchy of prediction. **Level 1:** At the lowest level are the stars with measured proper motion, such as those in the LSPM catalog (Lépine 2005; Lépine & Shara 2005; Lépine et al. 2002, 2003). Large-scale semi-automated surveys like PTF and Pan-STARRS can keep track of the light curves of each such star in their fields. **Level 2:** In order to select the best stars to monitor for smaller or less automated surveys, or to decide on a set of fields that might receive highest priority in large surveys, it is important to know which stars have the highest probability of producing lensing events. To identify them, we must be able to estimate the masses of the stars with measured proper motion, and the distances to them. Using this information, we can identify those whose Einstein rings cut the largest swath across the sky. If, for example, it is feasible to monitor 2000 stars, we may decide to select the top 2000 stars from this list. **Level 3:** At level 3, we consider the background stellar density. Stars that cut a smaller swath across the sky may nevertheless have a higher probability of producing events if the density of stars behind them is larger. Thus, level 3 is simply a reordering of the systems in level 2, based on a more realistic estimate of the event rate per star. **Level 4:** We consider all of the stars in level 1 and identify those for which there are high-resolution images of the background extending over time. For this set of systems, we can compute the path of the potential lens and identify stars that lie close to it. In cases in which a full astrometric solution is

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5Feibelman wrote (1986) “It is hoped that this 20-year exercise in frustration will encourage others to conduct systematic searches, perhaps by means of computer-based data banks, for stars with large proper motions that eventually may eclipse a background star and give rise to the elusive gravitational lens effect.”
possible, we can predict the approximate distance and time of closest approach. If there are too many images to analyze, we can choose to start with the potential lenses at the top of the level 3 list, since they have the highest probabilities of creating lensing events.

At the end of this process we should be able to predict a set of specific events. Because the number of such events per year depends not just on the properties of nearby stars and the stellar fields in front of which they travel, but also on the availability of data, it is not possible to predict how many individual events can be predicted each year. It seems likely that at least a handful of individual photometric events will be predicted each year. The ability to detect astrometric events with a mission such as Gaia, should lead to a larger rate of successful event predictions. Since the elements of day-by-day monitoring for individual events were covered in sections 2 and 3, we turn below to the issue of monitoring ensembles of predicted events.

5. Monitoring Ensembles of Sites of Predicted Events

Once an ensemble of potential future lensing events is identified, monitoring to detect evidence of lensing can begin. The ideal approach is a partnership among several groups. This minimizes gaps in coverage, while reducing the telescope time needed from any single group. It is important to have a central clearinghouse that receives data soon after each observation, so that photometric changes can be detected quickly enough to call an alert when lensing events start.

At present, alerts are called by lensing monitoring teams so that almost continuous coverage of a lensed star can be achieved during a period when the magnification is changing rapidly due to planet-lens effects (see e.g, Janczak et al. 2010; Miyake et al. 2011). The need for continuous observations will be rare for nearby lenses, since effects caused by nearby planets tend to be longer-lived because of the relatively large sizes of the Einstein rings (Figure 4). Instead, an alert will be designed to encourage more observers to join in to achieve monitoring as frequent as a few times per hour (i.e., a few times per day per team) over an interval of several days. With this type of observational plan in mind, the discussion below explores how different observing teams can begin the search for lensing by an ensemble of stars, each having a high probability of causing lensing events in the near future.

5.1. Wide-Field Surveys

With 100 – 1000 nearby-lens events per year, and a detection efficiency likely to be smaller than unity, it is important to survey large regions. Fortunately, wide-field surveys are already being conducted. Some of the teams conducting wide-field monitoring are large professional programs. These include PTF and Pan-STARRS. Others are programs of long-standing run by amateurs. These surveys differ from each other in the photometric

For example, an amateur program that surveys 4500 sq. degrees every two nights to find novae was the first to discover a mesolensing event in the field. The Tago event, named for its discoverer, involved a nearby lens that passed in front of an A0 star 1 kpc away (Fukui et al. 2007; Gaudi et al. 2008a).
sensitivities they achieve and in the observing cadences they employ. None of the wide-field surveys currently operating are searching for lensing across the sky. The quarry considered most exciting by these teams are explosive transients. Lensing is one of many other types of less dramatic variability, and the existing teams have limited resources for research outside their main purview.

Event prediction will allow the teams to sidestep the difficult task of characterizing variability and identifying lensing events among the much larger set of all variables. Simply by supplying these teams with the coordinates of the stars likely to cause events within the next few years, we can make it possible for them to begin identifying event candidates immediately. Such a list is now relatively straightforward to develop. Indeed, our group has already identified several hundred high-priority sites to monitor for the Kepler space mission (§5.5; Di Stefano et al. 2012b). We also plan to publish an all-sky table of the sites of predicted events, prioritized according to levels 2 and 3.

The light curves from these locations should be carefully checked with each observation to assess the probability that variability at the site of a predicted event is due to lensing. Because observations by the wide-field monitoring surveys are taken regularly during an interval of years, they have the advantage of developing a long baseline. Information collected over the this timescale can help to determine if variability at the site of a predicted event is unusual in terms of its magnitude, color, or temporal pattern.

One caveat is that most fields covered by these surveys are observed at intervals of several days, which is too infrequent. Since, however, several surveys may be observing the same sites of predicted events, a clearinghouse can compile a composite light curve that can be used to identify lensing-like signatures on a shorter time scale. Once a system is determined to be possibly experiencing lensing, additional observations are needed. These can test the lensing hypothesis and measure the mass of the lens star and/or of its planets. We address the issue of follow-up in §5.4.

5.2. Ongoing Lensing Monitoring Programs

Ongoing lensing teams are of course the best equipped surveys to discover and identify lensing events. At present, however, it is difficult to predict specific events for two reasons, both related to the fact that these programs monitor dense stellar fields. First, it is difficult to measure the proper motion of stars traveling across regions with a high surface density of stars, and values found in catalogs are often not reliable. This problem can be overcome by the monitoring teams themselves: with a long baseline, they can measure the proper motion of nearby stars against the background of distant stars. This has so far only been carried out for part of the data (Alcock. et al. 2011; Rattenbury et al. 2008). Second, the background stars are highly blended, making it difficult to know which specific star might serve as a lensed source.

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7Pan-STARRS has a sub-program Pandromeda that has identified lensing candidates in M31.

8In a preliminary study that checked images against the published proper motion of stars near lensing events, we found that the images could fail to confirm the result, presumably because variability in a dense stellar field can mimic stellar motion (McCandlish et al. 2010; McCandlish et al. 2012).
Nevertheless, we know that some of the lensing events discovered by the monitoring programs are generated by nearby lenses. At present, lensing teams like OGLE and MOA are monitoring large regions of the sky, on the order of 200 sq. degrees, or \( \sim 0.005 \) of the sky. If, therefore, there are 1000 events per year generated by stars within about 100 pc, roughly 5 per year of them occur in the fields monitored for evidence of lensing. Although these events may not have been predicted in advance, they are ideal for the types of study outlined for individual predicted events in §2 and §3, because we know that \( \beta \) is small and that the background star is bright enough to render the rest of the event detectable. In particular, the proximity of the lens means that \( R_E \) is likely to be small, and planets in orbits with small values of \( \alpha \), even with \( \alpha \) near unity, will have short orbital periods. This means that, if we conduct frequent enough monitoring, and if we can detect small changes in the amount of light received from the lensed source, we will either discover planets or else will know that there are no planets within about \( 2 \theta_E \) of the lens star. There is also a significant probability of discovering wide-orbit planets, if they exist, with a day-by-day monitoring program either finding wide-orbit planets, or placing limits on the existence of planets in well-defined orbits. In addition, the value of \( \theta_E \) will be large enough to minimize or eliminate finite-source-size effects.

If therefore an event posted online in real time by the monitoring teams\(^9\) can be identified as being due to a nearby lens, we can immediately start additional observations which can test for close-orbit planets and planets in the zone for resonant lensing. We can also ensure that these observations continue to supplement those of the lensing teams after the event, to search for evidence of wide-orbit planets. (Please see §5.4.) It is important to note that some of the light-curve features associated with close-orbit planets and/or with planets in the zone for resonant lensing, may make the light curve seem different from a typical lensing light curve. This is because the effects of rotation are to distort the features familiar from the more common static case. It is important that the lensing monitoring teams identify these possibly-unusual-looking events as good lensing candidates, so that they will be targeted for further study.

In addition to the handful of events per year generated in the lensing fields by stars within about 100 pc, a much larger number of events are generated by stars within about a kpc (Di Stefano 2008a, 2008b). In fact, as many as 10% of the \( \sim 1500 \) events they post per year, may be caused by stars within a kpc. While these lenses will have somewhat larger values of \( R_E \), close-orbit planets and wide-orbit planets can be found in the manner outlined in §2 and §3. The search for planets in the resonant zone can be conducted with existing protocols. This has been demonstrated by the discovery, through a lensing event that exhibited evidence of orbital motion, of a system with 2 planets in the zone for resonant lensing, only 1 kpc away (Gaudi et al. 2008b).

The key issue is selecting, from among the lens candidates identified by the monitoring teams, those specific events which happen to have been caused by nearby lenses. This can be accomplished using searches through existing catalogs. In fact our group has already studied catalog matches to all of the events discovered that, over a 15 year interval roughly \( \sim 8\% \) of the lensing event candidates have matches to catalogued stars that could corre-

\(^9\)http://ogle.astrouw.edu.pl/; http://www.phys.canterbury.ac.nz/moa/
spond to nearby lenses (McCandlish et al. 2010; McCandlish et al. 2012). We are refining the assessment procedure. Ideally, data from the monitoring teams can also be used to determine if there is evidence of a high proper motion star along the line of sight to each event.

5.3. MEarth

5.3.1. The MEarth Concept

As described in §1.2, MEarth monitors 2000 stars across the sky (Irwin et al. 2009a). This all-sky coverage is ideal for a survey of predicted lensing events since the sites of predicted events are scattered across the sky. MEarth consists of a bank of small telescopes which switch from field to field during the course of a night. Because the goal is to discover planets transiting M dwarfs, MEarth monitors in I band. If a MEarth target star happens to lens a background star, then MEarth could discover lensing events in the data it collects. This is most likely to happen if the background star also happens to be luminous in I band. As we see with the VB 10 event, however, the lensed star could provide only a tiny fraction of the light received in I band, rendering a lensing event essentially invisible.

5.3.2. Additions to MEarth

While the basic design of MEarth is well suited to the study of the sites of thousands of predicted lensing events spread across the sky, some alterations would make a MEarth-like project better suited to monitoring lensing events. If MEarth, or a follow-up project of similar design were to make the discovery of lensing events by M dwarfs one of its scientific goals, it could take several steps to increase the discovery rate.

First, the set of stars to monitor could be chosen with the idea of maximizing the area of the sky covered by the Einstein rings of the targets. In fact, the stars already selected are high-proper-motion stars like VB 10, well suited to lensing studies. As additional stars are selected for study, the likelihood that each will produce detectable lensing in the near future could provide an additional selection criterion. Useful information for this purpose would include not only the size and speed of the dwarf star’s Einstein ring, but also information about the background stellar field. Higher priority could be assigned to potential targets whose travels are likely to bring them in front of stars that can be detectably lensed.

Second, because the background star to be lensed may not be bright in I band, multi-waveband observations are necessary. These could be taken by a new MEarth-like project, if two or more filters can be utilized. They could also be taken by independent telescope participating in the program with the idea of supplementing the basic MEarth coverage to improve the detection efficiency for lensing events.

Finally, the analysis of the data should include fits for lensing models. If software suitable to this purpose is applied to existing MEarth data, it may find evidence of past lensing events. If a typical MEarth target has \( \theta_E = 10 \) mas, and \( \mu = 0.15'' \, \text{yr}^{-1} \), then over a 5-year period, the total region producing magnifications of 6% covers a significant portion of the sky, about 60''. Although not every star is observed at all times, the area
covered by the targets during MEarth observations is almost certainly large enough that some events occurred.

5.4. Collaborative Observation: Before, During, and After

The idea of “follow-up” is that no single observing program can collect all of the data needed to discover and study planets around nearby stars. It is therefore important to build a team that works together and that can also call occasional alerts as needed to enlist even more observers.

Follow-up has been an important part of lensing searches for planets. During certain events deemed as good candidates for planet searches, alerts are called to start intensive world-wide monitoring. Observations that are almost continuous during an interval that is typically longer than several hours and shorter than a few days are taken by different groups, using telescopes across longitudes. The data are combined to provide exquisitely detailed model fits.

For predicted lensing events, the concept of follow-up must be generalized. When a specific event, like the VB 10 event, is anticipated, monitoring must begin before lensing is expected, and continue after the time of closest approach. This is needed to discover planets with a range of orbital periods. Monitoring need not be very frequent: a few times per night for each of several teams spread across longitudes will be sufficient. Once evidence of lensing is detected, more frequent coverage may be called for, depending on the situation. In most cases, a total of a few observations per hour, conducted by a combination of teams, will be able to resolve the lensing light curves enough to determine if there are planets and even to discover multiple planets. In some cases, evidence that a short-lived deviation is occurring may trigger intensive monitoring during a limited time interval, similar to what is required in other planet-lens searches. Monitoring in different wavebands is more likely to avoid the “dazzling” effect of the lens. When an ensemble of high-probability events is being monitored, the same considerations apply.

Networks of observers have already been set up and have successfully studies a number of different individual systems, including planetary lenses. These projects have engaged a broad range of participants, including the Las Cumbres Observatory Global Telescope Network (LCOGT\textsuperscript{10}), the AAVSO\textsuperscript{11} and others. A network for predicted events is presently being formed\textsuperscript{12}.

5.5. Kepler

The Kepler mission monitors approximately 150,000 stars, with the goal of identifying transits by Earth-sized planets. It was not designed to identify lensing events, but we have conducted calculations showing that in the Kepler field there are a large number of possible

\textsuperscript{10}http://lcogt.net/

\textsuperscript{11}http://www.aavso.org/

\textsuperscript{12}https://www.cfa.harvard.edu/~jmatthews/vb10.html
lensing candidates (see Figure 4). The excellent photometry from Kepler means that small perturbations can be reliably detected. Such perturbations could be associated with distant approaches by the lens star, possibly including deviations by planets in very close orbits.

By conducting a study of the high-proper-motion stars in the Kepler field, we have identified a set of about 700 stars that have the highest probabilities of producing lensing events. We have created a program to make sure that these stars are included among the Kepler targets. It is almost certain that one of these stars, or even some of the other stars already targeted, will produce low-magnification events during the expected 3.5-year duration of the Kepler mission (DiStefano et al. 2012b)

5.6. Transits and Lensing: A symbiotic connection

The observations needed to monitor predicted lensing events are well suited to discovering planetary transits. In fact transit-search programs such as MEarth and Kepler are sensitive to lensing events by the target star and/or its planets (DiStefano et al. 2012b), while the lensing monitoring teams find evidence of transits (Dreizler et al. 2003; Konacki et al. 2005). The observations we propose will test each nearby potential lens for both effects.

The probability that the orbital inclination is favorable for transits is $R_*/a$. For a $0.25M_\odot$ star with a planet in an orbit of 0.13 AU, corresponding roughly to the center of the habitable zone (DiStefano & Night 2008), this probability is roughly equal to 0.009. The number, $N_L$, of lensing events caused by nearby a high-proper motion star is

$$N_L = 0.0018 \text{yr}^{-1} \left( \frac{\theta_E}{10 \text{ mas}} \right) \left( \frac{\mu}{0.15 \text{ arcsec yr}^{-1}} \right) \left( \frac{\sigma}{0.3 \text{ arcsec}^{-2}} \right)$$

where $\sigma$ is the density of background stars on the sky. Depending on the time scale of the observations, the probability of detecting lensing can be comparable to the probability associated with transits described above. Every time we conduct monitoring for a predicted lensing event, there is an opportunity to look for planets through both their possible lensing and transit signatures.

6. PLAN-IT: Prospects

The idea of PLAN-IT is to plan observations of nearby stars likely to serve as lenses. This strategy is different from the now common approach of monitoring many stars in a dense field in hope that an unknown mass will happen to lens a more distant star. By focusing on nearby stars that are potential lenses, we are likely to know the proper motion and distance to the lens, so that the light curve fit, which provides an estimate of the Einstein-diameter crossing time, immediately provides an estimate of the gravitational mass of the nearby star. In addition, we have shown that planets orbiting the nearby star can produce lensing signatures, whether or not lensing by the star is detected. When, however, lensing by the star is detected, tests for planets in all orbital ranges can be carried out. It is even possible that the astrometric effects of lensing will be detected in some cases.
The nearby dwarf star VB 10 is the first test case. This text is being completed in mid-February 2012. If the closest approach between VB 10 and the background star [VB 10]-PMLS-1 has not yet occurred, and if the approach between VB 10 and the background star [VB 10]-PMLS-1 is within about two $\theta_E$, then the upcoming event will measure the gravitational mass of VB 10, determine with certainty whether it has planets orbiting within about two $\theta_E$, and quantify the probability that VB 10 has planets in wider orbits. Even if the closest approach has already occurred, and even if the closest approach is (or was) more distant, we can still either discover wide-orbit planets or derive constraints on their presence. These constraints will be very weak, but they nevertheless represent the exercise of a new capability.

Enhanced monitoring of the region around VB 10 should begin immediately. To balance the excitement of a potential discovery with the uncertainty that detectable lensing will occur, we propose a modest program: observations from 10 or more locations across longitudes, about twice each night from each location. The observations should be combined as they are taken to identify trends so that an alert can be called if there is evidence of deviations which may be short-lived. Frequent I-band observations of VB 10 with MEarth will soon resume, as will observations with GROND. GROND, a 2-m telescope, provides 7-band coverage that has a good chance to detect the lensing of the dim blue background star, [VB 10]-PMLS-1. When new telescopes join in, observations in wavebands blueward of I will be useful.

The significance of the observing program extends beyond the VB 10 event. Whether or not a discovery is made, the VB 10 event calls our attention to the fact that prediction programs can now be started, and provides a test case about which to organize the first observing campaign. A modest investment of a few observations per telescope per night, spread out across longitudes will allow us to not only check for lensing events but also to test an observing network that can be called into action for future events.

We expect future events worthy of monitoring to be identified regularly, by a process that proceeds systematically by starting with catalogs of high-proper-motion stars. Groups of such stars with the highest probability of producing events can be identified and monitored by programs that observe large regions of the sky. These programs will range from those run by amateur astronomers who hunt for novae, to large semi-automated programs like PTF and Pan-STARRS, to programs like MEarth that systematically target interesting systems spread across the sky.

The stars with the highest probability of producing events in the near future can be identified through studies of their proper motion that incorporate cross-correlation with catalogs of possible background stars and analysis of any existing high-resolution images. This process will lead to the identification of individual events that can be monitored to learn about both the high proper motion star and any planetary system it harbors (§2 and §3).

It is worth noting that the sets of observations designed to search for lensing by nearby stars are also ideally suited to the search for transits by planets that may orbit these stars in edge-on orientations. Thus, lensing searches and transit searches are automatically carried out for each star studied. In fact, the ongoing MEarth program could find lensing using its current strategy. This is most likely to happen if the lensed background star happens
to have a color similar to that of the M dwarfs that they are targeting for a transit search.

Beyond the serendipitous circumstance of being able to search for planets in two ways at once, lensing searches for planets around nearby stars are intimately connected to other planet-search techniques. This is simply because these lensing studies will discover planets orbiting nearby stars or will place quantifiable limits on the masses and orbital separations. These studies can therefore complement and inform radial velocity and direct imaging studies.

In summary, we have proposed a monitoring strategy for VB 10. Analogous considerations for other individual predicted events will shape future programs to optimize what we learn about the ’planetary systems of nearby stars predicted to produce lensing events. In addition to the monitoring of individual systems, ensembles of future events can be monitored by a variety of surveys. This type of program will produce guaranteed results in the form of discoveries of planets of a variety of masses and with a range of orbital separations orbiting specific nearby stars that can be targeted for complementary observations.

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Fig. 1.— The logarithm of $\alpha$, the orbital separation in units of $R_E$, versus $(t - t_0)$, where $t_0$ is the time of closest approach. For each point shown, $t$ is the time of a peak in the photometric deviation $|A_{pl} - A_{pt}|$ from the single lens; we consider only those peaks with $|A_{pl} - A_{pt}| > 0.01$. The lens is PM118537+4729 (see §2), orbited by a hypothetical Jupiter-mass planet in a circular face-on orbit. The distance of closest approach is $\beta = 0.5$. The smooth magenta curves that start in the upper corners of the plot show the analytic prediction for events produced by wide-orbit planets. Similarly, the smooth cyan curves that start in the lower corners show the analytic prediction for events produced by close-orbit planets. The orange points show the times of events associated with caustic crossings.
Fig. 2.— Light curves for hypothetical planets orbiting PMI18537+4729. *Top Panel:* Light curves exhibiting caustic crossings for three different values of $\alpha$; in each case, $\beta = 0.5$. *Bottom Panel:* Light curves for $\alpha = 1/3$ for a variety of different distances of closest approach between PMI18537+4729 and a background star. In this case the planet’s mass is $3 M_J$. The orange dashed curve corresponds to $\beta = 0.5$, as in Figure 1. The other curves form a sequence of increasing distance of closest approach, with the highest peak having $\beta = 1/3$ and $\beta$ increasing in increments of $1/3$ for each subsequent light curve with lower peak magnification.
Fig. 3.— The logarithm of $\alpha$, the orbital separation in units of $R_E$, versus $t-t_0$, where $t_0$ is the time of closest approach. For each point shown, $t$ is the time of a peak in the photometric deviation $|A_{pl} - A_{pt}|$ from the single lens; we consider only those peaks with $|A_{pl} - A_{pt}| > 0.01$. The lens is VB 10 (see §3), orbited by a hypothetical Jupiter-mass planet in a circular face-on orbit. The distance of closest approach is $\beta = 0.5$. The smooth magenta curves that start in the upper corners of the plot show the analytic prediction for events produced by wide-orbit planets. Similarly, the smooth cyan curves that start in the lower corners show the analytic prediction for events produced by close-orbit planets. The orange points show the times of events associated with caustic crossings.
Fig. 4.— Top panel: A histogram showing the distribution of Einstein angles across the whole sky of stars with proper motions $> 0.04 \, \text{"yr}^{-1}$, extrapolated from a sample of 7474 stars across 100 square degrees in the Kepler field of view. The values for VB 10 and PMI18537+4729 are marked with green and red lines respectively; the bin size is 0.5 mas. These nearby stars are mesolenses, having Einstein rings significantly larger than typical microlenses, which have values of $\theta_E$ often less than a mas. They have high probabilities of serving as lenses and may produce detectable astrometric shifts in the positions of the stars they lens. Bottom Panel: A histogram showing the distribution of Einstein diameter crossing times in days, for the same stars. The values for VB 10 and PMI18537+4729 are again marked with green and red lines.