ON THE DETECTABILITY OF A PREDICTED MESOLENSING EVENT ASSOCIATED WITH THE HIGH PROPER MOTION STAR VB 10∗

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ABSTRACT

Extrapolation of the astrometric motion of the nearby low-mass star VB 10 indicates that sometime in late 2011 December or during the first 2–3 months of 2012, the star will make a close approach to a background point source. Based on astrometric uncertainties, we estimate a 1 in 2 chance that the distance of closest approach ρmin will be less than 100 mas, a 1 in 5 chance that ρmin < 50 mas, and a 1 in 10 chance that ρmin < 20 mas. The last would result in a microlensing event with a 6% magnification in the light from the background source and an astrometric shift of 3.3 mas. The lensing signal will however be significantly diluted by the light from VB 10, which is 1.5 mag brighter than the background source in B band, 5 mag brighter in I band, and 10 mag brighter in K band, making the event undetectable in all but the bluer optical bands. However, we show that if VB 10 happens to harbor a ∼1 MJ planet on a moderately wide (∼0.18 AU−0.84 AU) orbit, there is a chance (1% to more than 10%, depending on the distance of closest approach and orbital period and inclination) that a passage of the planet closer to the background source will result in a secondary event of higher magnification. The detection of secondary events could be made possible with a several-times-per-night multi-site monitoring campaign.

Key words: astrometry – gravitational lensing: micro – planetary systems – stars: low-mass

1. INTRODUCTION

Microlensing monitoring programs have been operating since the early 1990s (Paczynski 1995; Udalski et al. 1997; Palanque-Delabrouille et al. 1998; Alcock et al. 2000; Bond et al. 2001). These programs monitor large areas of the sky in the hope that a planetary or a stellar mass object will pass close enough to the position of a more distant “source” star to cause a detectable lensing event. More than 8000 lensing event candidates have now been identified. Among all possible gravitational lenses, nearby masses (d ≲ 1 kpc) hold a special place (Di Stefano 2008a, 2008b). Their Einstein radii (θE) are larger than they would be were they to be as distant as the typical microlenses (several kiloparsecs away along directions to the bulge and several tens of kiloparsecs away along directions to the Magellanic Clouds), and their angular motions are significantly faster. The combination of a large Einstein ring and angular speed means that nearby stars have a larger probability of producing a detectable lensing event. Furthermore, because nearby stars are independently detected, the degeneracy inherent in lensing light curves can be overcome, allowing us to determine their gravitational mass. Because many nearby stars already have their positions and proper motions known to some accuracy, we can predict and plan for the monitoring of specific events (Paczynski 1995; Gould 2000; Salim & Gould 2000; Di Stefano 2008a, 2008b). Very nearby stars moving against the backdrop of the Milky Way (Lépine et al. 2002; Lépine 2005, 2008; Rattenbury & Mao 2008) make promising targets in this regard because the high field densities provide more opportunities for chance alignments.

Lensing events can also be used to search for stellar or substellar companions. Because the shape of the lensing light curve is sensitive to the mass distribution of the lens system (Mao & Paczynski 1991; Gould & Loeb 1992; Di Stefano & Scalzo 1999a, 1999b), orbiting planets can produce significant, short-lasting deviations from the standard microlensing profile. To detect a planet in a lensing light curve, moderate-cadence monitoring must be supplemented by high-cadence observations (Gould & Loeb 1992; Griest & Safizadeh 1998; Di Stefano & Scalzo 1999a, 1999b), triggered when a deviation to the single-mass microlensing light curve is detected. Several exoplanets have already been detected using this method, which holds strong potential to provide a wealth of statistical data on planetary masses and orbital distributions, especially in the wide separation range. Unfortunately, most planetary systems detected through microlensing are relatively far from the Sun, and their host stars are much dimmer than the background source (e.g., Janczk et al. 2010; Sumi et al. 2010; Miyake et al. 2011). This seriously limits the possibilities for follow-up observations, making it nearly impossible to confirm the presence of the planet by other means (spectroscopic, photometric, astrometric) and limiting the information one can obtain about the host star. Most exoplanet detections through microlensing light curves are essentially “one shot deals.”

Microlensing by a nearby star, also called “mesolensing,” would have all the potential for detecting exoplanets through microlensing, with the added bonus that the lens system would be much more amenable to follow-up observations. The presence of the planet could potentially be confirmed using secondary detection methods, and the properties of the host star could be easily determined, if not already known.

In this Letter, we predict a future event associated with the low-mass star VB 10, based on precise astrometric measurements made with the Hubble Space Telescope (HST). We investigate the detectability of the event itself and of any secondary
event that might be produced by a hypothetical planet in orbit around the star.

2. HUBBLE SPACE TELESCOPE ARCHIVAL

DATA ON VB 10

The low-mass star VB 10 (≈ V 1298 Aql), discovered by Van Biesbroeck (1961), is a common proper motion companion to the high proper motion star Ross 652 (≈ V 1428 Aql). The pair is separated by ≈74′, share a proper motion μ ≈1.5 yr⁻¹, and is located at a distance d = 5.8 pc. The distance and angular separation correspond to a projected physical separation ≈429 AU in plane of sky. The two stars are currently moving against a rich Milky Way background at a Galactic latitude b = +7.86. The proper motion and parallax of VB 10 have recently been measured to a high level of accuracy by Pravdo & Shacklan (2009). Their claimed detection of a 6 Mₑ exoplanet orbiting VB 10 has however not been confirmed by subsequent studies (Bean et al. 2009; Lazorenko et al. 2011). Radial velocity measurements of VB 10 to a precision of 150 m s⁻¹ have shown no evidence for a companion (Anglada-Escudé et al. 2010). Combined with the astrometry from Pravdo & Shacklan (2009), these radial velocity measurements set an upper limit of 2.5 Mₑ for a planet orbiting VB 10 with an orbital period <1 year.

VB 10 was imaged by HST on two occasions with the Near Infrared Camera and Multi-Object Spectrograph (NICMOS). Exposures in the F113N filter were obtained on 1999 November 19, and in the F187N filter on 1998 June 19. The images are available from the Hubble Legacy Archive (HLA), where they have been combined into a single cleaned image with the drizzle routine, which also performs astrometric corrections for field distortions. A section of the resulting F187N image is shown in Figure 1.

VB 10 was also imaged with the Wide Field and Planetary Camera 2 (WFPC2) on 1999 October 2. Exposures were obtained in the F439W, F555W, F775W, and F814W filters. The images are also available from the HLA, where they too have been combined with drizzle. A section of the composite F814W image is shown in Figure 1. All the NICMOS and WFPC2 images in the HLA have been remapped on a grid with angular scale 0.′1 pixel⁻¹, and with the X-axis oriented along right ascension and the Y-axis along declination.

The proper motion of VB 10 is apparent from a comparison of the NICMOS and WFPC2 frames, obtained two years apart. The location of VB 10 is noted in Figure 1 (circles) and a pair of dashed lines running parallel to its proper motion are overlaid. A close examination of the F187N and F814W images reveals a faint source lying along the projected path of VB 10. That source is identified by a box. The source is detected in the F439W, F555W, and F775W frames as well, but fell outside the field of view of the NICMOS F113W exposures. We name the source [VB 10]-PMLS-1, for VB 10 Predicted Mesolensing Source number 1.

Photon counts show that the source is 1.5 mag fainter than VB 10 in F439W (equivalent to B band), 5.4 mag fainter in F814W (I band), and ≈7 mag fainter in F187N (close to infrared H band). VB 10 has visual magnitudes V = 17.2 and I = 12.8 (Casagrande et al. 2008), and the Two Micron All Sky Survey catalog lists the star with infrared magnitude H = 9.23. The blue magnitude is estimated at B = 19.5 from the WFPC2 images. This puts [VB 10]-PMLS-1, the background source, at B ≈ 21.0, I ≈ 18.2, and H ≈ 16. Data on VB 10 and the background source are summarized in Table 1.

Limits can be placed on the relative proper motion of [VB 10]-PMLS-1 by comparing the position of the source on the NICMOS and WFPC2 images. We find that the position in the WFPC2 and NICMOS epochs agree to within 26 mas, which indicates a proper motion <14 mas yr⁻¹. Random field stars tend to have proper motions smaller than this, however, with typical values in the 5–10 mas yr⁻¹ range. A search of the Sloan Digital Sky Survey catalog (Abazajian et al. 2009) for example, turns up five times as many r < 20 stars with proper
motions $\mu < 10$ mas yr$^{-1}$ than stars with $\mu > 10$ mas yr$^{-1}$. If [VB 10]-PMLS-1 has any net proper motion, it is more likely to be in the 5–10 mas yr$^{-1}$ range.

### 3. PREDICTED PRIMARY MESOLENSING EVENT

To calculate the time and distance of closest approach to the background source, we extrapolate the parallax and proper motion of VB 10 based on the astrometric solution of Pravdo & Shacklan (2009). We use the drizzled WFPC2 images to calculate the position of VB 10 in the reference frame of [VB 10]-PMLS-1 at the epoch of the 1999 HST visit.

To account for astrometric errors and uncertainties in the proper motion of [VB 10]-PMLS-1, we perform Monte Carlo simulations to generate $10^3$ possible paths for VB 10, with variations in its parallax and proper motion within the range of astrometric uncertainties, and with the assignment of random components of proper motion [VB 10]-PMLS-1 with mean values $(\mu_{\alpha} \cdot \mu_{\delta}) = (0,0)$ mas yr$^{-1}$ and dispersions $(\sigma_{\mu_{\alpha}}, \sigma_{\mu_{\delta}}) = (10,10)$ mas yr$^{-1}$. Results are illustrated in Figure 2, where the point density is proportional to the probability of a path passing by that location. Statistics show that encounters with distance at closest approach $\rho_{\text{min}} < 100$ mas occur in 44% of trajectories, encounters with $\rho_{\text{min}} < 50$ mas in 22% of trajectories, whereas encounters with $\rho_{\text{min}} < 20$ mas occur 9% of the time. Three trajectories with $\rho_{\text{min}} \approx (20,50,100)$ mas are shown in Figure 2 as examples.

To investigate the effects of a smaller proper motion for [VB 10]-PMLS-1, we generate an additional set of paths using $(\sigma_{\mu_{\alpha}}, \sigma_{\mu_{\delta}}) = (5,5)$ mas yr$^{-1}$. We then find trajectories with $\rho_{\text{min}} < 100$ mas occurring 51% of the time, which trajectories with $\rho_{\text{min}} < 50$ mas 22% of the time, and trajectories with $\rho_{\text{min}} < 20$ mas 8% of the time. Given the similar results, we conclude that under the assumption that [VB 10]-PMLS-1 has a proper motion in the 5–10 mas yr$^{-1}$ range, there is a roughly 1 in 2 chance that an alignment will occur with separation of 100 mas or less, a 1 in 5 chance for an alignment with separation of 50 mas, and a 1 in 10 chance of an alignment with separation 20 mas or less. The time of closest approach varies depending on the relative path of VB 10 to the background sources. The median value is 2011 December 21, with a dispersion of ±30 days.

From the projected trajectory of VB 10, and assuming the M8.0V dwarf to have a mass of 0.08 $M_\odot$ (Baraffe & Chabrier 1996), it is possible to predict the magnification and astrometric shift of [VB 10]-PMLS-1 due to gravitational lensing. The angular radius of the Einstein ring ($\Theta_e$) of VB 10 is approximately equal to 10 mas. As discussed above, trajectories consistent with the astrometric measurements produce distances of closest approach from $\rho_{\text{min}} \approx 2\Theta_e$ (20 mas) to $\rho_{\text{min}} \geq 10\Theta_e$ (>100 mas). At 20 mas, the total magnification of the background star is 6%. The magnification at 50 mas is 0.3%, while it is $\sim 0.02\%$ at 100 mas. The decline is steep, because the magnification falls as $\rho^{-4}$. The centroid shift falls off more slowly with distance ($\sim \rho^{-1}$), and the astrometric shift would be approximately (3.3,1.9,1.0) mas, for distances of closest approaches of (20,50,100) mas, respectively.

There are complications to observing this predicted mesolensing event. First, VB 10 is brighter than [VB 10]-PMLS-1. The magnification light curve will thus be significantly diluted, and the astrometric shift reduced. In the infrared ($J$) the $>600$ dilution factor will reduce the amplitude of a 6% event to less than 1 part in $10^4$. In the blue ($B$), however, the light from [VB 10]-PMLS-1 is diluted by a factor of $\sim 5$, which would reduce the amplitude of the event to $\approx 1\%$ of the integrated flux. In addition, VB 10 will be close to the Sun in December and January, making ground observations challenging and space observations impossible when the source falls, e.g., within the solar avoidance zone of HST (Figure 2, bottom panel).

### 4. SECONDARY LENSING EVENT FROM A PLANETARY COMPANION

If VB 10 has a dark companion, the effects of lensing can be enhanced. Lazorenko et al. (2011) measurements exclude a 3.2 $M_J$ planet with period of 270 days, and the Anglada-Escudé

#### Ancillary Data

| Datum          | Value     | Source               |
|----------------|-----------|----------------------|
| R.A. (ICRS)    | 19 16 57.622 | Cutri et al. (2003)   |
| Decl. (ICRS)   | +05 09 02.18 | Cutri et al. (2003)   |
| Epoch$^a$      | 1999.58   | Cutri et al. (2003)   |
| $\mu_{\alpha}$ | 589.01 ± 0.2 mas yr$^{-1}$ | Pravdo & Shacklan (2009) |
| $\mu_{\delta}$ | −1361.12 ± 0.3 mas yr$^{-1}$ | Pravdo & Shacklan (2009) |
| $\pi_{\text{trig}}$ | 171.6 ± 1.4 mas | Pravdo & Shacklan (2009) |
| $B$            | 19.5 mag  | This paper           |
| $V$            | 17.2 mag  | Casagrande et al. (2008) |
| $I$            | 12.8 mag  | Casagrande et al. (2008) |
| $J$            | 9.90 mag  | Cutri et al. (2003)   |
| $H$            | 9.23 mag  | Cutri et al. (2003)   |
| $K$            | 8.76 mag  | Cutri et al. (2003)   |
| [VB 10]-PMLS-1 (lensed source) |           |                      |
| R.A. (ICRS)    | 19 16 57.136 | This paper           |
| Decl. (ICRS)   | +05 08 45.34 | This paper           |
| $B$            | 21.0 mag  | This paper           |
| $I$            | 18.2 mag  | This paper           |
| $H$            | 16 mag    | This paper           |

Note. $^a$ Epoch of the R.A. and decl. measurements.
et al. (2010) radial velocity measurements exclude most planets with masses $>2.5 \, M_J$. However, planets with a range of masses and orbits are still possible.

The type of secondary effect expected in the microlensing light curve depends on the orbital separation between the planet and VB 10, but also on the orientation of the orbital plane, and on the orbital phase. We generate sets of microlensing light curves for one of three possible trajectories for VB 10, with distances of closest approach $\rho_{\text{min}} = 20 \, \text{mas}$, 50 mas, and 100 mas; these are the trajectories shown in Figure 2. For each path, we calculate circular face-on planetary orbits in which a Jupiter-mass planet orbits VB 10. We consider three separate orbital periods of 100 days, 271 days, and 1000 days. We compute light curves for each of several thousand choices of the initial orbital phase, chosen uniformly between 0 and $2 \pi$. This allows us to compute the fraction of the time the peak magnification is larger than some arbitrary value (e.g., 30%).

We find a small fraction of events in which the planet makes a significantly closer approach to the source star than does VB 10 itself, resulting in a large magnification (Figure 3). For the $\rho_{\text{min}} = 20 \, \text{mas}$ path, events of all three orbital periods are found to generate some high magnification peaks. For $\rho_{\text{min}} = 50 \, \text{mas}$ trajectories, only the planets on 271-day and 1000-day orbits generate high magnification events, while for $\rho_{\text{min}} = 100 \, \text{mas}$, only the 1000-day orbit produces significant magnification events.

Figure 2. Top: predicted range of trajectories of the star VB 10 in the reference frame of the target mesolensing source [VB 10]-PMLS-1. The point density is proportional to the probability of a path passing by that location, given the uncertainties in the astrometric solution for the motion of VB 10 and proper motion of the background source. Three possible trajectories are shown, with distances of closest approach $\approx 100 \, \text{mas}$, 50 mas, and 20 mas; these are used for the simulations shown in Figures 3 and 4. Bottom: angular distance to the Sun of VB 10 around the predicted time of the mesolensing event. The star is likely to be too close to the Sun to be observed with HST and will be challenging even for ground-based observations. The vertical dotted lines show the most likely range for the peak of the primary lensing event. (Secondary, planet-lens events may occur earlier or later.)

(A color version of this figure is available in the online journal.)

Figure 3. Magnification curves for three of the best case scenarios from our simulations, where a planet orbiting VB 10 causes a significant secondary microlensing event. The same three orbiting planets are shown for different possible trajectories of VB 10 relative to the source, yielding different distances of closest approaches (20 mas, 50 mas, and 100 mas, top to bottom.) Each colored light curve corresponds to a system hosting a hypothetical 1 $M_J$ planet with an orbit of 1000 days (red), 271 days (green), and 100 days (blue). Planets on shorter orbits only produce notable magnifications in short-distance encounters, while planets with larger orbital separations can produce significant magnifications even when the distance of closest approach between VB 10 and the background source is large.

(A color version of this figure is available in the online journal.)
100 mas trajectories, only planets on a 1000-day orbit generate events with significant magnification. For planets on a 1000-day orbit, we found the probability of a >30% magnification event to be \( \approx 0.7\% \) for all three values of \( \rho_{\text{min}} \). Planets on a 271-day orbit had a \( \approx 2\% \) probability of generating >30% magnification events in both \( \rho_{\text{min}} = 20 \) mas and \( \rho_{\text{min}} = 50 \) mas models (no such events are generated in the \( \rho_{\text{min}} = 100 \) mas case). The direction of orbital motion influences the event probability for planets with shorter orbital periods. For example, a planet on a 100-day orbit (which can generate events for \( \rho_{\text{min}} \) less than or equal to about 20 mas) has a 12% chance of generating events with >30% magnifications with one orbital direction and a 5% chance if the orbital direction is reversed, giving an average of 8.5%.

In addition, we find that secondary events can occur up to 3 months before or after the primary event, depending on the period and orbital phase of the companion. Predicted composite light curves for the magnification events shown in Figure 3 are displayed in Figure 4, and show the apparent magnitude of the unresolved source and lens accounting for the dilution from the light of VB 10. The secondary events retain symmetrical profiles, but blending reduces the timescale of the peak to \(<1\) day.

5. DISCUSSION AND CONCLUSIONS

This prediction of a microlensing event associated with the very low-mass star VB 10 constitutes a unique opportunity for observational astronomy. Detection of the primary event presents severe challenges. The lensed source is a faint background star, which means that the event will suffer significant dilution from VB 10. The event will also occur at an inopportune time, because VB 10 will be close to the Sun near the time of the event, making it an evening star at unfavorable airmass. Proximity to the Sun will also prevent observations from HST and other space telescopes, which have solar avoidance angles of \( \sim 50^\circ \). In the red or infrared, the large dilution from the VB 10 light will make the event undetectable using existing facilities. At best, the light curve for the unresolved source and lens may reach an amplitude \( \sim 1\% \) in the blue, for a source with magnitude \( B = 19.5 \). The detection of such a weak event would be difficult if not impractical.

However, our simulations show that intensive monitoring of the event in the months before and after the primary event could potentially yield the microlensing detection of a planet orbiting VB 10, if the proper alignment conditions are met. Evidence has now been accumulating that low-mass stars can hold planetary retinues. Indeed, the 0.3 \( M_{\odot} \) M dwarf GJ 581 is now the system with the largest number of confirmed planets (Mayor et al. 2010), and several other low-mass M dwarfs have been found to have planetary companions. A massive planet was also recently discovered orbiting an M dwarf through microlensing (Batista et al. 2011). It is thus a definite possibility that VB 10 might have associated planets. If the proper alignment conditions are met, then secondary microlensing events could reach high enough magnifications to be detected. If an event yields a total magnification of the source+lens light by 30% or more, then a signal-to-noise ratio \( S/N > 10 \) would be sufficient for a 3\( \sigma \) detection achievable in minutes of exposure on a 1 m class telescope.

Simulations show that high magnification events due to orbiting planets would have timescales of several hours. A monitoring campaign on VB 10 to detect them would thus require intensive monitoring from multiple sites of various.

![Figure 4](image-url)
longitudes. These events could occur at any time up to a few months before and after the peak of the primary event, which means that they could be occurring at anytime through winter 2012 or even later.

Intrinsic variability in VB 10 might however complicate the detection of a planetary microlensing event. VB 10 is a known flare star (Berger et al. 2008), and the activity and flaring rate for a red dwarf with very late spectral type (M8) is expected to be high (West et al. 2008; Hilton et al. 2010). Flares, however, typically show a rapid rise on timescales of minutes, followed by an exponential decay lasting < 1 hr (Welsh et al. 2007). This is in contrast to the symmetric light curve with a timescale of several hours expected of a hypothetical planetary microlensing event (see Figure 4). It will be critical to characterize the base variability level and intrinsic variability patterns in VB 10, which will be possible when the system is no longer susceptible to microlensing.

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