WFIRST PLANET MASSES FROM MICROLENS PARALLAX

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ABSTRACT

I present a method using only a few ground-based observations of magnified microlensing events to routinely measure the parallaxes of WFIRST events if WFIRST is in an L2 orbit. This could be achieved for all events with \( A_{\text{max}} > 30 \) using target-of-opportunity observations of select WFIRST events, or with a complementary, ground-based survey of the WFIRST field, which can push beyond this magnification limit. When combined with a measurement of the angular size of the Einstein ring, which is almost always measured in planetary events, these parallax measurements will routinely give measurements of the lens masses and hence the absolute masses of the planets. They can also lead to mass measurements for dark, isolated objects such as brown dwarfs, free-floating planets, and stellar remnants if the size of the Einstein ring is measured.

Key words: gravitational lensing: micro – planets and satellites: general

1. INTRODUCTION

The microlensing portion of the WFIRST mission will complete the census of planets by finding large populations of planets beyond the snow line with masses as small as Mars (Green et al. 2012). If the masses of the planets and their hosts are measured, this will permit a direct comparison to planet formation theories. However, the primary observables in microlensing events are the mass ratio and projected separation (scaled to the Einstein ring) between the planet and its host star. A measurement of the lens mass is necessary to transform these to physical quantities.

If the lens is bright enough, WFIRST will be able to estimate its mass based on a measurement of the lens flux. However, there will be many cases for which the lens light will be too faint to be measured. Such cases will most likely be lenses at the bottom of the stellar mass function, but could also include brown dwarfs, free-floating planets, or stellar remnants. For these events, with only an upper limit on the lens flux, the conclusions that can be drawn about the nature of the planet are limited. In addition, the WFIRST measurement of the lens flux will be a measurement of the total flux of the lens system, including any companions to the lens, which may or may not participate in the lensing event. Typically, companions within 10 AU will produce a measurable microlens perturbation and companions at more than 5 mas (~40 AU) will be identifiable from a shift in the centroid relative to the lensing event. However, companions at intermediate separations are not easily identified. Hence, the WFIRST mass estimate will necessarily be an upper limit for any given system.

Fortunately, the lens masses can be measured if microlens parallax and finite source effects are observed. Microlens parallax is a vector quantity whose magnitude is the ratio of Earth’s orbit to the size of the Einstein ring projected onto the observer plane, \( \pi_E \):

\[
\pi_E \equiv \frac{\text{AU}}{r_E}. \tag{1}
\]

If \( \pi_E \) is measured, the mass of the lens, \( M \), can be obtained with a measurement of the angular size of the Einstein ring, \( \theta_E \):

\[
M = \left( \frac{\theta_E}{\pi_E} \right) \left( \frac{c^2 \text{AU}}{4G} \right). \tag{2}
\]

For any event in which the size of the source is resolved in time, i.e., it passes over a caustic or near a cusp, \( \theta_E \) is measurable. Such finite source effects are almost always measured in events with planets because detection of a planetary companion to the lens almost always requires a caustic interaction. Hence, if the microlens parallax can be measured, the planet masses are known. Finite source effects can also be measured in any event for which the source crosses the position of the lens.

In this Letter, I discuss a means to routinely measure the lens masses using microlens parallax if WFIRST is in an L2 orbit.\(^1\) Because the WFIRST light curve will be measured so precisely, the orbital parallax effect will be routinely detected at high significance, effectively giving one extremely well-measured component of the parallax (Gould 2013). I show that only a few ground-based observations of each event are needed to complement the WFIRST observations and yield a complete parallax measurement for a large fraction of events.

2. MEASURING \( \pi_{E,\perp} \)

2.1. Simplified Case

The microlens parallax vector can be written

\[
\pi_E = (\pi_{E,\parallel}, \pi_{E,\perp}) = (\pi_E \cos \theta, \pi_E \sin \theta), \tag{3}
\]

where \( \theta \) is the angle between the lens trajectory and the projection of the Sun–Earth line on the plane of the sky, measured counter-clockwise. Because WFIRST will be in orbit about the Sun, there will be a measurable asymmetry in the light curve due to the orbital parallax effect (Gould 1992; Gould et al. 1994). This gives strong constraints on the component of the parallax parallel to the projected position of the Sun relative to the event, \( \pi_{E,\parallel} \), but usually only very weak constraints on the other component, \( \pi_{E,\perp} \) (e.g., Gould 2013).

I will show that if WFIRST is at L2, as few as two observations of a microlensing event from Earth can be used to measure \( \pi_{E,\perp} \), leading to a measurement of \( \pi_E \). I begin with a simplified case to illustrate the problem. In the following section, I will present the full derivation and expression for \( \pi_{E,\perp} \) and show that it reduces to what is derived here.

\(^1\) See Gould (2013) for a discussion of WFIRST parallax measurements for a geocentric orbit.
Figure 1. Left panel: basic geometry of a microlensing event projected onto the observer plane. Right panel: expanded view around the projected positions of Earth and WFIRST ("E" and "W," respectively). The x-axis is parallel to the projection of the Sun–Earth–WFIRST line. The dotted line ab shows the lens trajectory. The value of $\pi_{E,\perp}^{-1} = \sin \theta_\perp/D = \Delta u/D$ can be derived from the observables $\Delta u$ and $D$, while $\pi_{E,\parallel} = \cos \theta/\tilde{r}_E$ can be measured by WFIRST alone.

Consider the projection of the microlensing event onto the observer plane (Figure 1). For illustration purposes, I assume that the size of Einstein ring projected onto this plane is $\tilde{r}_E = 10$ AU, $u_0 = 0.05$, and that the observations are taken close to the equinox (the anticipated midpoint of WFIRST observations) so that the projection of the Earth–WFIRST line onto the sky, $D$, is equal to the true separation, i.e., $D = 0.01$ AU. The exact values for these quantities are irrelevant to the derivation; I will discuss their practical implications below. Finally, note that WFIRST at L2 puts it in line with Earth and the Sun, so the projection of the Earth–WFIRST line on the sky is parallel to the projection of the Sun’s position.

The WFIRST light curve will be extremely well measured, giving $\pi_{E,\perp}$ and the basic microlens parameters: the time of the peak, the source-lens impact parameter scaled to the Einstein ring, and the Einstein crossing time ($t_0, u_0$, and $\tilde{r}_E$, respectively). Hence, the value of $u_0\tilde{r}_E(\cos \theta)^{-1}$ is also known. This fixes point “a” on the lens trajectory projected onto the observer plane. Assume the event is observed from Earth when it is at the peak as seen from WFIRST (i.e., when the lens is at point “b”). Then, the fractional difference in the magnification is

$$\frac{\Delta A}{A} = \frac{A - A_\parallel}{A} \approx \frac{\Delta u}{u_0}, \quad (4)$$

where $A$ is the magnification as seen from WFIRST, $A_\parallel$ is the magnification as seen from Earth, and I assume that the magnification is given by $A \simeq u_0^{-1}$ (which applies in the limit $u_0 \ll 1$) and that the difference between the impact parameter as seen from Earth and from WFIRST is $\Delta u \ll u_0$. As illustrated in Figure 1, in the regime where $u_0\tilde{r}_E \gg D$, $(\Delta u)/\tilde{r}_E \simeq D \sin \theta$ meaning that with some manipulation $\pi_{E,\perp}$ can be written:

$$\pi_{E,\perp} = u_0 \left( \frac{\Delta A}{A} \right) \left( \frac{A}{D} \right). \quad (5)$$

Note that all the variables in the right-hand side of the equation are known or measurable.

From the geometry in Figure 1, there is one degeneracy in Equation (5). It is possible to change the sign of $u_0$, i.e., reflect the figure over the x-axis, which changes the sign of $\pi_{E,\perp}$. This leads to a degeneracy in the direction of $\pi_E$, but not in its magnitude, which is the relevant quantity for calculating masses. Out of the eight possible configurations one might consider as potentially degenerate with the geometry shown, only the $u_0 \rightarrow -u_0$ degeneracy described here is permitted by the observables.

2.2. Exact Expression for $\pi_{E,\perp}$

I now derive a general expression for $\pi_{E,\perp}$ that applies to an Earth-based measurement of the magnification at any time. In practice, this is the expression that will be used to calculate $\pi_{E,\perp}$ from the observables.

Figure 2 shows the generalized geometry with all quantities scaled to $\tilde{r}_E$. Consider an observation from Earth is taken at time $t$, i.e., when the lens is at point “c.” The lens position is given by $u_0$ and $r = (t - t_0)\tilde{r}_E^{-1}$. The measured magnification is related to the separation of the lens, $u$, by

$$A(u) = \frac{u^2 + u^2}{u \sqrt{u^2 + 4}}. \quad (6)$$

where $u$ is measured as a fraction of the Einstein ring. Thus, from the measured magnifications as seen from Earth and WFIRST,
the lens separation from their projected positions is known, $u_E$ and $u_W$, respectively. I can write

$$u^2_E = (x_W + D/r_E)^2 + y^2_W,$$

where $x_W$ and $y_W$ are the projections of $u_W$ onto the $x$- and $y$-axes. Equation (7) can be rewritten as

$$u^2_E - u^2_W = \frac{2D}{r_E^3} (u_0 \sin \theta + \tau \cos \theta) + \frac{D^2}{r_E^6}. \quad (8)$$

Recognizing that $(\Delta u, \pi E, \perp) = (\cos \theta, \sin \theta)(AU) r_E^{-1}$ (Equations (1) and (3)), I evaluate

$$\pi_{E, \perp} = \left[ \Delta u (2u_W + \Delta u) - \frac{D^2}{r_E^3} \right] \left( \frac{AU}{2Du_0} \right) - \frac{\pi_{E, \parallel}}{u_0}, \quad (9)$$

where $\Delta u = u_E - u_W$. Since $\tilde{r}_E^{-2} = (\pi_{E, \perp}^2 + \pi_{E, \parallel}^2)/(AU)^2$, this can be rewritten as a quadratic equation for $\pi_{E, \perp}$ with the solutions:

$$\pi_{E, \perp, \pm} = u_0 (\frac{AU}{r_E}) \pm \sqrt{1 - \frac{1}{u_0^2} \left( \frac{D}{AU} \right)^2 \pi_{E, \parallel}^2 + 2 \left( \frac{D}{AU} \right) \frac{\pi_{E, \parallel}}{u_0}(\Delta u (2u_W + \Delta u))}.$$

Although there are formally two solutions for $\pi_{E, \perp}$, these can readily be distinguished. The solution $\pi_{E, \perp, -}$ corresponds to the case in which the lens passes between the projected positions of Earth and WFIRST. This scenario is expected to be very rare, but it can be definitively excluded with additional observations of the event from Earth.

If $\pi_{E}$ is large, then the full expression must be evaluated. However, this Letter is primarily focused on cases for which $\pi_{E}$ is small because those are the cases in which the WFIRST light curve will constrain only one component of the parallax well. In that case, Equation (10) is well represented by the first term in the Taylor expansion:

$$\pi_{E, \perp, +} = \frac{1}{2u_0^2} \left[ \Delta u (2u_W + \Delta u) - 2 \left( \frac{D}{AU} \right) \tau \pi_{E, \parallel} \right] + \left( \frac{D}{AU} \right)^2 \pi_{E, \parallel}^2. \quad (11)$$

Furthermore, the last term can generally be ignored because it is second order. Finally, if the event is observed at peak ($\tau \to 0$ and $u_W \to u_0$) and we assume that $|\Delta u| \ll |u_0|$, then

$$\pi_{E, \perp} \to \Delta u \left( \frac{AU}{D} \right). \quad (12)$$

which is equivalent to Equation (5).

2.3. Constraints on $\pi_{E, \perp}$

The uncertainties from the WFIRST light curve are negligible compared to the uncertainties from the ground-based photometry, so the largest uncertainty in $\pi_{E, \perp}$ comes from the measurement of $(\Delta A/A)^{-1}$. The actual observables from Earth are the magnified flux, $f_{\text{mag,} \oplus}$, and flux of the event at the baseline, $f_{\text{base,} \oplus}$, such that

$$A_{\oplus} = \frac{f_{\text{mag,} \oplus} - f_{\text{base,} \oplus}}{f_{S, \oplus}} + 1, \quad (13)$$

where $f_{S, \oplus}$ is the source flux as seen from Earth. To solve for $A_{\oplus}$, the unknown source flux must be estimated by calibrating the ground-based photometry to the WFIRST photometry using comparison stars. This situation is equivalent to the problem of measuring $\Delta u$. Gould (1995), Bouteux & Gould (1996), and Gaudi & Gould (1997) showed that $\Delta u$ is poorly constrained because $u_0$ is correlated with $f_E$ and $f_{\oplus}$, where $f_{\oplus} = f_{\text{base,} \oplus} - f_S$ is the blended (non-varying) component of the flux. However, most of the information about $f_{\oplus}$ comes from the wings of the event (Yee et al. 2012), which will not be well measured from the ground because the sky background is so high. Hence, flux calibration is necessary to find $f_{\oplus}$ constrain $f_S$, and improve the precision of the measurement of $A_{\oplus}$ or equivalently $\pi_{E, \perp}$.

If only one or two observations are taken of the magnified event, the flux calibration ultimately sets the limit on the precision of $\pi_{E, \perp}$. Based on previous experience (e.g., Yee et al. 2012), the uncertainty in this calibration is limited by systematics to a precision of about 1%. This sets the fundamental noise floor on the measurement of $(\Delta A/A)^{-1}$. Given that by definition, $|\langle \Delta u \rangle r_E^{-1} \leqslant D$, the limit in the flux precision means that a 3σ measurement of $\pi_{E, \perp}$ is possible for

$$u_0 \leqslant 0.03 \left( \frac{D}{0.01 \text{AU}} \right) \left( \frac{\tilde{r}_E}{10 \text{AU}} \right)^{-1} \left( \frac{\sigma_{\Delta A/A}}{0.01} \right)^{-1}, \quad (14)$$

where I again make the assumption that $u_0 \ll 1$, i.e., $A \simeq u_0^{-1}$.

In contrast, if there are many magnified points that can be seen above the baseline from the ground, the peak of the event will be resolved allowing a measurement of the effective timescale, $t_{\text{eff}} = u_0 f_{\oplus}$. Yee et al. (2012) showed that this quantity is invariant to uncertainties in $f_{\oplus}$, so flux calibration is unnecessary. Because the velocity offset between WFIRST at L2 and Earth are quite small (0.3 km s$^{-1}$), $f_{\oplus}$ is approximately the same for the WFIRST and ground-based light curves. Then, the uncertainty in $\Delta u$ is:

$$\sigma_{\Delta u} \simeq \sigma_{u_0, \oplus} \sqrt{\left( \frac{\sigma_{t_{\text{eff,} \oplus}}}{t_{\text{eff,} \oplus}} \right)^2 + \left( \frac{\sigma_{\tilde{r}_E}}{\tilde{r}_E} \right)^2}, \quad (15)$$

where $u_{0, \oplus}$ is the impact parameter of the event as seen from Earth and I assume that $u_{0, \oplus}$ is known essentially perfectly. Hence, the method can be applied to events with $u_0 > 0.03$ by reducing the uncertainty in $t_{\text{eff,} \oplus}$ using additional observations.

Finally, I note that even if $\pi_{E, \perp}$ is less well measured than $\pi_{E, \parallel}$, this does not mean that the value of $\pi_{E}$ is not well measured. So long as $\pi_{E, \parallel} \gtrsim 3\sigma_{\pi_{E, \parallel}}$, the constraints on $\pi_E$ will be useful. This will be true for a large fraction of cases, depending on how well the lens trajectory aligns with the projection of the Sun–Earth–WFIRST line, which is primarily a random effect.

3. DISCUSSION

For pure satellite parallax measurements, the Earth–L2 baseline is not ideal because it is only a small fraction of $r_E$ (0.01 AU versus ~10 AU), limiting the precision of the measurement that can be made. However, here I take advantage of several consequences of this special geometry that had not been previously considered for a microlensing satellite at L2 (Gould et al. 2003; Han et al. 2004) and the precision of the WFIRST light curve, which will allow the $\pi_{E, \parallel}$ component of the parallax to be measured extremely well. The short baseline actually resolves the magnitude degeneracy described in Gould (1994) because it is extremely unlikely that the lens will pass in between the two observatories, and if such a case occurred, the parallax would
be so large as to be easily measured from the \textit{WFIRST} light curve alone. In addition, \textit{L2} is in line with the projected position of the Sun, which, when combined with the measurement of $\pi_{E,1}$, greatly simplifies the geometry (Figures 1 and 2). Finally, because \textit{L2} is moving with Earth, the relative velocity offset between Earth and the satellite can be neglected relative to stellar motions (0.3 km s$^{-1}$ versus 300 km s$^{-1}$). This means that $\epsilon_f$ is essentially the same for the ground-based and space-based observations and the degeneracies discussed in Gould (1999); Dong et al. (2007) are avoided.

I have shown that for an event discovered by \textit{WFIRST} at \textit{L2}, a measurement of the event magnification as seen from Earth yields a measurement of the component of the parallax perpendicular to the projection of Earth’s orbit, $\pi_{E,\perp}$. Although the basic calculation was done assuming the event was observed from the ground at the peak as seen from \textit{WFIRST}, I showed that, in principle, the Earth measurement can be made at any time. However, it is best to make the measurement as close to the peak of the event as possible, since the fractional difference in magnification will be largest at the peak, allowing for the best measurement of the parallax.

Measuring the magnification of the event as seen from Earth requires at least two observations: one when it is magnified and one at baseline. A third, magnified, observation would be beneficial in case the source is passing over a caustic at the time of the observations and to distinguish between the two possible solutions for $\pi_{E,\perp}$ given in Equation (10). These ground-based observations can be made either with target-of-opportunity (ToO) observations of \textit{WFIRST} events announced in real time or with a simultaneous, ground-based survey of the \textit{WFIRST} microlensing fields.

If there are only a few observations, as would likely be the case with ToO, $\pi_{E,\perp}$ is measurable in all events with $u_0/E < 0.3$ AU, i.e., $u_0 < 0.03$ or peak magnification $A_{\max} < 30$. This limit is set by systematics in the flux calibration between the ground-based data and the \textit{WFIRST} data, which experience shows is limited to a precision of 1%. If only a few events can be observed from the ground, it is best to focus on the highest magnification events. In practice many of the \textit{WFIRST} sources will be quite faint, so while 1% precision will be possible for the brighter sources, the limits on $u_0$ are probably more stringent for the majority of events. This leads to a preference for higher magnification events. However, it is precisely these events for which parallax measurements are most desirable because these events are the most likely to have planetary signals (Griest & Safizadeh 1998). Furthermore, for point lens events, the higher the magnification, the more likely it is that finite source effects will be observed, allowing mass measurements for these lenses. These isolated objects could include stellar remnants, isolated stellar mass black holes, brown dwarfs, or the population of free-floating planets found by Sumi et al. (2011). Gould & Yee (2013) also proposed a means to measure the mass of free-floating planets using terrestrial parallax. However, because the baseline for terrestrial parallax measurements is $\sim R_0$, parallaxes are only measurable for the closest objects. Here, parallax measurements are possible for much more distant lenses (and hence, a larger volume and larger number of events) because of the larger Earth–\textit{WFIRST} baseline. Hence, targeted observations for measuring parallaxes should focus on the higher magnification events.

A NIR, ground-based survey simultaneous with \textit{WFIRST} has the distinct advantage over ToO that it would not require real-time information. In half of all events with planets, the planetary signal will occur after peak, so the opportunity to measure the parallax with ToO will be missed. In addition, a survey would take multiple points throughout the light curve. At the very least, this will improve the precision of the ground-based flux measurement, allowing the limit of 1% precision to be reached for more events. However, the peaks of the events may also be resolved, leading to a measurement of $l_{\max}$ and allowing $\pi_{E,\perp}$ to be measured for events with $A_{\max} < 30$. Such a survey could be carried out with existing facilities such as the UKIRT or VISTA telescopes or a purpose-built facility. Either way, it would cost a fraction of the \textit{WFIRST} mission cost and yield substantial scientific benefit.

There is value in carrying out both a survey and a ToO program. The brighter events would be covered by the survey, but ToO with a larger telescope equipped with adaptive optics could reach fainter events. Combining the two approaches would maximize the number of events for which parallax observations can be made while minimizing the cost.

Although the method for obtaining parallaxes described here is observationally intensive, the potential scientific impact makes such observations invaluable. The core accretion theory of planet formation predicts that giant planets should be rare around M dwarfs (Laughlin et al. 2004; Ida & Lin 2005), which are typical microlensing hosts. Hence, measuring the masses of the lens stars and planets allows a direct comparison to the theory, which is otherwise very difficult if only mass ratios are known. Furthermore, when the lens mass is measured, solving:

\begin{equation}
\tilde{r}_E = \frac{\text{AU}}{\pi_E} = \sqrt{\frac{4GM}{c^2}} \frac{D_L D_S}{D_S - D_L},
\end{equation}

yields a measurement of its distance, $D_L$ (where the source distance, $D_S$, is assumed to be in the bulge). Such measurements would allow a comparison of the planet populations in the bulge and disk. Given that the stars (and planets) in the bulge formed in a dense region of rapid star formation, one might expect a dearth of giant planets there (Thompson 2013). In addition, although \textit{WFIRST} will measure the lens system fluxes for many events, whether the light comes from the lens itself or a stellar companion will be unknown. Systematic measurements of the microlens parallax can be used to measure the fraction of events for which the lens light is contaminated by the presence of a companion not involved in the microlensing event. Finally, if microlens parallax is measured for many events, including ones with lens mass estimates from \textit{WFIRST}, this will allow the first systematic test of the parallax effect.

Although this Letter has been written from the perspective of the \textit{WFIRST} mission, it is broadly applicable to any microlensing satellite at \textit{L2}. Thus, if a microlensing survey is included in the \textit{Euclid} mission (cf. Penny et al. 2013; Beaulieu et al. 2013), it would also benefit from complementary ground-based observations. In fact, for \textit{Euclid} a ground-based parallax campaign is even more important for measuring the lens mass because its NIR resolution will make it more difficult to accurately measure the lens system fluxes. I thank Matthew Penny, Ondrej Pejcha, and especially Andrew Gould for helpful conversations. I thank the anonymous referee for helpful comments. This work was supported by NASA grant NNX12AB99G.

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