Microlens Mass Measurement using Triple-Peak Events

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ABSTRACT

We show that one can measure the effects of microlens parallax for binary microlensing events with three well-measured peaks – two caustic crossings plus a cusp approach, and hence derive the projected Einstein radius \( \tilde{r}_E \).

\begin{equation}
\theta_E = \frac{\theta_{E}}{\mu_{\text{rel}}}, \quad \theta_{E} \equiv \sqrt{\frac{2R_{\text{Sch}}}{D_{\text{rel}}}}. \tag{1}
\end{equation}

Here \( D_{\text{rel}} = \frac{AU}{\pi_{\text{rel}}} \), \( \pi_{\text{rel}} \) is the lens-source relative trigonometric parallax, \( \mu_{\text{rel}} \) is the relative proper motion, \( \theta_E \) is the angular Einstein radius, and \( R_{\text{Sch}} \) is the Schwarzschild radius of the lens mass. Rather, it would be necessary to interpret the results statistically, to infer an average mass scale of the lenses from the mean timescale of the observed events together with statistical estimates of \( \pi_{\text{rel}} \) and \( \mu_{\text{rel}} \). Note that \( D_{\text{rel}}^{-1} = D_L^{-1} - D_S^{-1} \), where \( D_L \) and \( D_S \) are the distances to the lens and the source.

Gould (1992) showed that it was possible to extract the individual lens mass \( M \) if one could measure two “observables”: the angular Einstein radius \( \theta_{E} \), and the projected Einstein radius \( \tilde{r}_E \):

\begin{equation}
\tilde{r}_E \equiv \theta_{E}D_{\text{rel}} = \sqrt{2R_{\text{Sch}}D_{\text{rel}}}, \tag{2}
\end{equation}

\begin{equation}
M = \frac{c^2}{4G} \tilde{r}_E \theta_{E}. \tag{3}
\end{equation}

The microlens parallax \( \pi_{E} \) re-expresses \( \tilde{r}_E \) in a convenient way. It is a two-dimensional vector whose magnitude is given by

\begin{equation}
|\pi_{E}| = \frac{\pi_{\text{rel}}}{\theta_{E}} = \frac{AU}{\tilde{r}_E}, \tag{4}
\end{equation}

and whose direction is that of the lens-source relative proper motion. Measurement of \( \theta_{E} \) requires that the Einstein ring be compared with some “angular ruler” on the plane of the sky, while to measure \( \tilde{r}_E \), one must compare the Einstein ring with some “physical ruler” in the observer plane.

The only angular ruler to be used for this purpose to date is the angular radius of the source \( \theta_\ast \) which can be estimated from its de-reddened color and magnitude, and the empirical color/surface-brightness relation (eg. van Belle 1999). When the source passes very close to or directly over a caustic (zone of formally infinite magnification) in the lens magnification pattern, the finite size of the source affects the microlensing light curve. By analyzing this finite-source affected light curve, one can measure \( \rho_\ast \equiv \theta_\ast/\theta_{E} \), and thus \( \theta_{E} \) as well. While this idea was originally proposed for point-mass lenses, which have point-like caustics.
Typically $\tilde{r}_E$ is of order several AU, and so the natural scale of the physical ruler must be $\sim 1$ AU. This is the case for the two main methods proposed to measure $\tilde{r}_E$. First, a satellite in solar orbit would see a substantially different event from the one observed on Earth, and from the difference, one can determine $\tilde{r}_E$ (Refsdal 1966; Gould 1995). Second, the reflex of the Earth’s orbital motion induces a wobbling of the source’s passage through the Einstein ring, which in turn perturbs the light curve, and $\tilde{r}_E$ can be determined from this perturbation (Gould 1992). To date, this latter method is the only one by which $\tilde{r}_E$ has been measured (Alcock et al. 1995; Mao 1999; Sozioński et al. 2001; Bond et al. 2001; Smith, Mao, & Woźniak 2001; Mao et al. 2001; Bennett et al. 2001). Unfortunately, this method requires that the event be rather long, $t_E \gtrsim 90$ days. To the extent that the Earth’s motion can be approximated as rectilinear, it is not possible even in principle to detect this effect. Over the relatively short timescales of typical events $t_E \sim 20$ days, on the other hand the Earth’s motion can be approximated as uniform acceleration which can lead to a potentially detectable asymmetry in the light curve (Gould, Mirala-Escudé, & Bahcall 1994). However, this would yield a measurement of only the projection of $\pi_E$, along the direction of the Earth’s acceleration vector at the peak of the event. Hence, even if this asymmetry were detected, it would give only an upper limit on $\tilde{r}_E$. To measure both components of $\pi_E$ requires that the event last long enough for the Earth’s acceleration vector to change substantially while the source lies within the Einstein ring.

However, it is possible to make parallax measurements using much shorter baselines. During a caustic crossing of a binary lens, the flux can change by several magnitudes as the caustic transits the star. The source radius projected onto the observer plane $\theta_s D_{rel}$ can be of order $\sim 100 R_\odot$ for a main-sequence star. Hence, observers on two continents could see fluxes differing by a few percent. This would again yield only one projection of $\pi_E$, but by repeating this procedure for the two caustic crossings of a single event, or by observing one crossing from three continents, one could obtain a full measurement of parallax (Hardy & Walker 1995; Gould & Andronov 1999). An important feature of this approach is that it also allows to measure $\theta_E$, which can be obtained from any caustic crossing. Hence, if this method were ever applied, it would yield the mass through equation (3). Unfortunately, the method requires extraordinary cooperation from the event itself, from the observatory directors, and from the weather. Consequently, it has not to date been successfully carried out.

It is expected that the use of the high-precision interferometric astrometry, most notably the Space Interferometry Mission (SIM) will be the best way to measure the individual lens mass (Paczyński 1998; Boden, Shao, & van Buren 1998). With 10-$\mu$as level astrometry of SIM, one can directly measure $\pi_E$. Furthermore, by monitoring the displacements in the light centroid caused by microlensing, $\theta_E$ can be also directly measured (Høg, Novikov, & Polanarev 1995; Miyamoto & Yoshii 1995; Walker 1995). Unlike most techniques mentioned earlier, neither of these measurements requires the event to be of a special class such as long time-scale or caustic-crossing events. That is, individual lens masses can be measured for common point-source/point-lens events.

Here, we propose a new method to measure parallax for a subclass of caustic crossing binaries. The method requires the event to have at least three separate well-defined photometric peaks so that the source position can be precisely located relative to the lens geometry at three distinct times. Two of the peaks should be caused by caustic crossings: an entrance and an exit. It would be best for the third peak to be a cuspy-caustic crossing, but the chance of two fold-caustic crossing accompanied by an additional cusp crossing is low. In the following, we investigate events where the third peak is due either to a cusp crossing or to a generic cusp approach.

2. Overview

If the event has two well-observed caustic crossings, plus a well-observed “cusp approach”, these features then provide nine “empirical parameters” – parameters that can be measured directly from the light curve, without appealing to a model that depends upon a global lens geometry. They are the maximum flux $F_{\max}$, the half-duration $\Delta t$, and the time at the maximum $t_{\max}$ of each of the three peaks. The uncertainties in the measurements of these quantities are approximately

$$\frac{\sigma(F_{\max})}{F_{\max}} \sim \frac{\sigma(t_{\max})}{\Delta t} \sim \frac{\sigma(\Delta t)}{\Delta t} \sim \frac{\sigma_{ph}}{\sqrt{N}} = 10^{-3} \left( \frac{N}{100} \right)^{-1/2} \frac{\sigma_{ph}}{1\%}, \quad (5)$$
where \( \sigma_{ph} \) is the mean fractional error of each of the \( N \) photometric measurements taken over the bump. Since \( \Delta t \) is generally of order a day, the errors in \( \Delta t \) and \( t_{max} \) measurements can easily be of order a minute or smaller. The fact that six independent times can be measured with such precision, typically four or five orders of magnitude smaller than the characteristic timescale of the event \( t_E \), is what makes the parallax measurement feasible.

In principle, any localizable feature found in the light curve may provide similar empirical parameters. What then makes peaks more significant as information posts than other features such as minima or points of inflection? The answer to this question is that the high precision measurements attainable for peaks can rarely be achieved for empirical parameters associated with the other localizable features, so that their merit as signature beacons is much weaker than for peaks. For instance, minima question is that the high precision measurements attainable for peaks can rarely be achieved for empirical parameters associated with other localizable features, so that their merit as signature beacons is much weaker than for peaks. For instance, minima in microlensing light curves typically have widths that are ten times greater than peaks do (and by definition less flux as well). From equation (5), \( \sigma(t) \propto \sqrt{\Delta t/F} \), so that it is substantially more difficult to localize minima than peaks. Here, we assume Poisson noise (\( \sigma_{ph} = \sqrt{F} / F \)), and the same sampling frequency (i.e. \( N \propto \Delta t \)). Points of inflection are even more difficult to localize than minima.

Ordinarily, under the approximation that the lens-source relative motion is rectilinear, to specify a binary-lens light curve requires seven global (or geometric) parameters: \( d \), the binary separation in units of \( \theta_E \); \( q \), the binary mass ratio; \( \alpha \), the angle of the source-lens relative motion relative to the binary axis; \( t_E \), the Einstein timescale; \( u_0 \), the minimum angular separation between the source and the binary center in units of \( \theta_E \); \( t_0 \), the time at this minimum; \( \rho_s \), the source size in units of \( \theta_E \). (In addition, to transform the magnification curve to the specific photometric system of the observations, one also needs limb-darkening parameters for each wave band of observations; plus the source flux \( F_s \) and background flux \( F_b \), for each telescope and wave band.) However, since the actual motion is not rectilinear, these seven parameters will not be adequate to describe the event for very high precisions, and in particular, subtle inconsistencies will be introduced among the nine precisely measured quantities mentioned earlier. We now show how these inconsistencies can lead to a parallax measurement.

### 3. Measurement of Parallax

In practice, the parallax will be measured by multi-dimensional fitting and subsequent \( \chi^2 \) minimization. However, it is instructive for two reasons to identify in a systematic way the features of the event that permit \( \pi_E \) to be measured. First, this enables one to predict when an event will have a measurable \( \pi_E \). Second, there are technical difficulties associated with \( \chi^2 \) minimization, and these can be ameliorated if the model parameterization is modified to reflect the underlying physics (Albrow et al. 1999b).

To understand how \( \pi_E \) is measured, we first show how some of the nine empirical parameters are related to one another in the absence of parallax, i.e., \( \pi_E = 0 \). We will initially assume that the lens geometry \((d, q)\) and the fluxes \( F_s \) and \( F_b \) are known a priori. Then, at the peak of the cusp approach \( t_{max,ca} \), the source position within the Einstein ring \( u_{ca} \) can be determined very precisely from the precise measurements of \( t_{max,ca} \) and \( F_{max,ca} \). That is, at this time \( t_{max,ca} \), the source must be somewhere along the cusp-approach ridge line and its position on that line is determined from the inferred magnification \( A = (F_{max,ca} - F_b) / F_s \).

Now consider the angles at which the source crosses each caustic line, \( \phi_1 \) and \( \phi_2 \). The half-duration of a caustic crossing is given by \( \Delta t_{cc} = t_E \rho_s \csc\phi \). If this motion is assumed to be rectilinear, then \( t_E \) becomes a well-defined quantity over the whole duration of the event, and thus,

\[
\frac{\csc\phi_2}{\csc\phi_1} = \frac{\Delta t_{cc,2}}{\Delta t_{cc,1}}. \tag{6}
\]

The source trajectory is then the straight line that passes through \( u_{ca} \) and has caustic-crossing angles that satisfy equation (6). From that equation, this angle can be determined with a precision of

\[
\sigma(\alpha) = \left| \cot\phi_2 - \cot\phi_1 \right| \left\{ \left( \frac{\sigma(\Delta t_{cc,2})}{\Delta t_{cc,2}} \right)^2 + \left[ \frac{\sigma(\Delta t_{cc,1})}{\Delta t_{cc,1}} \right]^2 \right\}^{1/2}, \tag{7}
\]

which can be estimated using equation (5).

Next, we turn to the times of the two caustic crossings \( t_{0,cc,1} \) and \( t_{0,cc,2} \), at which the center of the source lies on the caustic lines. These are not the same as the times of peak flux \( t_{max,cc,1} \) and \( t_{max,cc,2} \), but they can be determined to the same precision (see eq. [5]) and are more convenient to work with. Let \( u_{cc,1} \) and \( u_{cc,2} \) be the positions in the Einstein ring of the two caustic
crossings. For rectilinear motion, these satisfy the vector equation,

\[
\frac{\mathbf{u}_{cc,2} - \mathbf{u}_{cc,1}}{t_{0,cc,2} - t_{0,cc,1}} = \frac{\mathbf{u}_{ca} - \mathbf{u}_{cc,1}}{t_{\text{max,ca}} - t_{0,cc,1}} \quad (= |\mu_E|) .
\]  

Here, \(|\mu_E| = t_E^{-1}\). However, if the acceleration due to the Earth’s orbital motion is not negligible, equation (8) will not in general be satisfied. This can be quantified in terms of \(\delta t_2\), the difference between the measured value of \(t_{0,cc,2}\) and the one that would be predicted from the other measured parameters on the basis of equation (8),

\[
\delta t_2 \equiv \frac{t_{0,cc,2} - t_{0,cc,1}}{- |\mu_E|} (t_{\text{max,ca}} - t_{0,cc,1}) .
\]

To evaluate the relation between \(\delta t_2\) and \(\pi_E\), we make the approximation that the Earth’s acceleration vector projected on the sky \(\mathbf{a}_{\parallel,\perp}\) is constant for the duration of the caustic crossings and cusp approach. We first note that the magnitude of this acceleration is related to the parallax by

\[
|\mathbf{a}_{\parallel,\perp}| = \pi_E \sin \psi \left( \frac{\Omega_\parallel}{r_E/\text{AU}} \right)^2,
\]

where \(\psi\) is the angle between the lines of sight towards the Sun and the event from the Earth \(r_E\) is the distance between the Sun and the Earth, during the caustic crossings, and \(\Omega_\parallel = 2\pi \text{ yr}^{-1}\). Then, after some algebra, we find

\[
\frac{\delta t_2}{t_3 - t_2} = \frac{\sin \psi |t_E|}{2} \left( \frac{\Omega_\parallel}{r_E/\text{AU}} \right)^2 \left\{ -\pi_{E,\parallel} (t_2 - t_1) + \pi_{E,\perp} [(t_3 - t_2) \cot \phi_2 - (t_3 - t_1) \cot \phi_1] \right\} ,
\]

where \((\pi_{E,\parallel}, \pi_{E,\perp})\) are the components of \(\pi_E\) parallel and perpendicular to \(\mathbf{a}_{\parallel,\perp}\), and where we have used the simplified notations, \(t_{0,cc,i} \to t_i\) and \(t_{\text{max,ca}} \to t_3\). Hence, by measuring \(\delta t_2\) one can determine a particular projection of \(\pi_E\) whose components are given by equation (11).

However, since \(\pi_E\) is a two-dimensional vector, measurements of two independent components are required for its complete determination. A second constraint is available from the width of the cusp approach \(\Delta t_{ca}\). We define \(\delta \ln \Delta t_{ca}\) in analogy to \(\delta t_2\) and after some more algebra we find,

\[
\delta \ln \Delta t_{ca} = \frac{|\sin \psi| |t_E|}{\cot \phi_2 - \cot \phi_1} \left( \frac{\Omega_\parallel}{r_E/\text{AU}} \right)^2 \left\{ \pi_{E,\parallel} [(t_3 - t_2) \cot \phi_1 + (t_2 - t_1) \cot \phi_3 - (t_3 - t_1) \cot \phi_2] \\
+ \pi_{E,\perp} [(t_3 - t_1) \cot \phi_3 \cot \phi_1 - (t_3 - t_2) \cot \phi_3 \cot \phi_2 - (t_2 - t_1) \cot \phi_2 \cot \phi_1] \right\} .
\]

Measurement of \(\delta \ln \Delta t_{ca}\) therefore gives another projection of \(\pi_E\). Furthermore, it is possible to obtain a third constraint on \(\pi_E\) from the behavior of the light curve after the source has left the caustic but while it still remains within the Einstein ring. For rectilinear motion, the Einstein time scale is well determined (cf. eq. [8]). If the late-time light curve drops off faster or slower than indicated by this timescale, it implies that the Earth’s acceleration vector has a component aligned with the direction of lens-source relative motion. The effect is similar to the one identified by Gould et al. (1994) but can be measured more easily because both \(t_E\) and \(t_0\) are determined very precisely from the light curve around the caustic-crossing region. The relative orientation of these three constraints depends on the details of the lens geometry. In principle, they could all be roughly parallel, but this is unlikely; in general, it should be possible to combine the three projections to measure both components of \(\pi_E\). If the event is sufficiently long (typically \(t_E \gtrsim 60\) days), so that the Earth moves \(\gtrsim 1\) radian during an Einstein timescale then the late time behavior of the light curve will give information about both components of \(\pi_E\). In this case there would be the fourth constraint.

The exact expression for the errors in the components of \(\pi_E\) obtained from the first two constraints can be derived from equations (11) and (12), but these are extremely complicated and for that reason not very interesting. However, reasonable estimates of these errors can be made as follows. First, we note that the error from applying the \(\delta t_2\) constraint is dominated by the problem of determining the change in \(\alpha\) from the parallax to the non-parallax case. The error in the measurement of \(\alpha\) is given by equation (7). On the other hand, the change in \(\alpha\) (chosen for definiteness to be the angle at the time of the cusp approach) is given by

\[
(cot \phi_2 - cot \phi_1) \delta \alpha = \frac{2\delta t_2}{t_3 - t_2} .
\]

Hence the fractional error in \(\pi_{E,\delta t_2}\), the projection of \(\pi_E\) measured by this constraint, is of the order of

\[
\frac{\sigma(\pi_{E,\delta t_2})}{\pi_{E,\delta t_2}} \sim \frac{\sigma(\alpha)}{\delta \alpha} \sim \frac{N^{-1/2} \sigma_{ph}}{|\sin \psi| \Omega_\parallel (t_2 - t_1) t_E / \pi_E} .
\]
where we have made use of equations (5) and (7). For typical bulge parameters, $|\sin \psi| \sim 0.2$ and $\pi_E \sim 0.1$, and with good photometric coverage of the caustic crossings, $N^{-1/2} \sigma_{\text{ph}} \sim 10^{-3}$, the fractional error is $\sim 0.17 \times (t_E/50 \text{ days})^{-1} \times [(t_2 - t_1)/20 \text{ days}]^{-1}$ and hence $\pi_{E, \delta t_2}$ should plausibly be measurable. For the other constraint one finds similar expressions.

We now relax our assumption that $d$, $q$, $F_s$, and $F_b$ are known a priori. Actually, if $d$ and $q$ are known, $F_s$ and $F_b$ can be easily determined from, for example, the baseline flux $F_s + F_b$, and the minimum flux observed inside the caustic $A_{\min} F_s + F_b$. Here $A_{\min}$ is the magnification at minimum which, for fixed $(d, q)$, is virtually independent of the minor adjustments to the trajectory due to parallax. However, it is still necessary to relax the assumption that $d$ and $q$ are known. In fact, these must be determined simultaneously with the parallax because changes in $(d, q)$ can have effects on the relative times of the caustic and cusp crossing and on the crossing angles, just as parallax can. Nevertheless, there are numerous other constraints on $(d, q)$ coming from the overall light curve, and so while $(d, q)$ and $\pi_E$ can be expected to be correlated, they should not be completely degenerate. Hence, even allowing for degradation of the signal-to-noise ratio for the $\pi_E$ measurement due to the correlations between the projections of $\pi_E$ and $(d, q)$, it should be possible to measure $\pi_E$ with reasonable precision for events with two well-covered caustic crossings and a well-covered cusp approach.

4. Effect of Binary Rotation

The measurement of the parallax discussed in the previous sections essentially relies upon the failure of the rectilinear approximation of the lens-source relative motion when the trajectory is over-constrained by available observations. For a relatively short time scale, what is actually measured from this is an instantaneous acceleration on the source trajectory and this acceleration may contain significant contributions by other effects, a notable example of which is the binary rotation around its center of mass. The rotational motion of the binary lens projected onto the plane of the sky is observable in terms of a contraction or expansion of the binary separation $d$, and the lateral rotation of the binary axis with respect to the fixed direction on the sky $\omega$. The apparent observable result of the latter effect may heuristically be understood as a centripetal acceleration $\sim u_c \omega^2$ on the source motion relative to the (static) lens system, where $u_c$ is the angular extent of the caustic in units of the Einstein ring. For a face-on circular binary orbit observed at the ecliptic pole, the ratio of the Earth’s acceleration to the projected acceleration due to the binary orbit is then

\[ \frac{a_{\oplus}}{a_{\text{bin}}} = \frac{\pi_E}{u_c} \left( \frac{P}{\text{yr}} \right)^2. \]

Thus, depending on these parameters, either parallax or binary rotation could dominate. In addition, for the general case, both the Earth and binary acceleration would be reduced by possibly very different projection factors (while the projection factor for the binary rotation is from the orbital inclination of the binary, the parallactic projection is due to the angle between the direction to the ecliptic pole and the line of sight to the event). Although the effect of $d$ is in general not expressible analytically, one can expect it to be of similar order of magnitude to the one of $\omega$.

Unambiguous determination of the parallax therefore requires the measurement of the acceleration at least at two different times, or not less than four independent constraints on the projection of the acceleration at different times. We argued above that there are generically at least three constraints for the types of events under discussion and that there is a fourth constraint for sufficiently long events. In this latter case, parallax can be unambiguously discriminated from rotation. But even when the event is short, so that there are only three constraints, it may still be feasible to measure the parallax. We first note that the rotation cannot significantly affect the late-time light curve – i.e., $t_E$ is not influenced by rotation – for it does not affect separations between the source and the binary center of masses. Hence, if one component of $\pi_E$ is measured from the late-time light curve, it may be possible using equation (15) and Kepler’s Third Law, to show that parallax is more important than rotation, in which case the caustic crossings can be used to determine the full parallax $\pi_E$.

In brief, there is good reason to hope that events with three well-defined bumps can yield parallax measurements, and hence mass measurements. Whether this will be possible for any particular such event can only be determined by detailed modeling.

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