Constraining Physical Properties of a Microlens

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Angles!

\[ \pi = \frac{AU}{D} \]

\[ \mu = \frac{v_{proj}}{D} \]
\[ \pi = \frac{AU}{D} \]

\[ \mu = \frac{v_{\text{proj}}}{D} \]

\[ t_E = \frac{\theta_E}{\mu_{\text{rel}}} \]

\[ \theta_E = \sqrt{\kappa M_L \pi_{\text{rel}}} \]

where, \( \kappa = 8.14 \frac{\text{mas}}{M_{\text{sun}}} \), \( \pi_{\text{rel}} = \frac{AU}{D_L} - \frac{AU}{D_S} \)
What can be directly learned about the planet from the light curve?

Key scale: Einstein radius

Mass ratio $q = \left(\frac{\theta_{E,P}}{\theta_E}\right)^2$

Projected separation $s$ in $\theta_E$

Trajectory angle $\alpha$
How do we get host/planet mass and distance?

Need to know lens mass $M$ and physical size of Einstein radius $r_E$. 

$q, s$ $ightarrow$ $M_p, r_{proj}$ in AU
Ruler 1: Source Star Angular Size

- Angular size of the star can be derived from its de-reddened color and magnitude (Albrow et al., 1999; Yoo et al., 2004)

Source (radius $\rho = \theta_E / \theta_E$)

Lens

$\theta_E$
Finite-source: Angular Einstein Radius (High-mag)

\[ u_0 = 0.002 \]
\[ \rho = 0.0045 \]
\[ \theta_\ast = 2.20 \pm 0.06 \, \mu\text{as} \]
\[ \theta_E = \frac{\theta_\ast}{\rho} = 0.48 \pm 0.01 \, \text{mas} \]
\[ = \frac{\theta_\ast}{t_\ast t_E} \]

Finite-source: Angular Einstein Radius (Binary/Planetary)

\[ \theta_\star = 5.2 \pm 0.2 \, \mu\text{as}. \]

\[ \theta_E = 0.98 \pm 0.04 \, \text{mas} \]

Ruler No. 2 on the observer plane

- Microlens parallax:

Ruler No. 2 on the observer plane

- Microlens Orbital parallax:
  Earth orbit as the ruler:
  Measuring Projected Einstein radius on the observer plane

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\[
\theta_E \bar{r}_E = \alpha r_E = \frac{4GM}{c^2}
\]

\[
\theta_E = \alpha - \psi = \frac{\bar{r}_E}{D_I} - \frac{\bar{r}_E}{D_s} = \frac{\bar{r}_E}{D_{rel}}
\]

\[
\pi_E \theta_E = \pi_{rel}, \quad \pi_E = \frac{AU}{\bar{r}_E}
\]

Parallax + Finite Source

Muraki et al., 2011, accepted
MicroFUN

From Jennie McCormick, Farm Cove, New Zealand
Fun with multi-site observations

Credit: Grant Christie
Terrestrial Parallax

Earth altitude: 19110.4734 km
OGLE-2007-BLG-224, An old thick-disk brown dwarf

M = 0.056 +/- 0.004 Msun; D = 525 +/- 40 pc

Old Thick-disk Brown dwarf?

Expected: H ~ 25.7 mag

Space-based Microlens Parallax


WFIRST will be at L2, suitable for measuring microlens parallax for Earth-mass planet:

\[ d_{\text{sat}} \sim \sqrt{\frac{4GM_\oplus \text{AU}}{c^2 \pi_{\text{rel}}}} = 0.025 \text{AU} \left( \frac{\pi_{\text{rel}}}{40 \mu\text{as}} \right)^{-1/2} \]

Seeing the lens with high-res imaging

- **Flux** = $F_{\text{source}} \times A + F_{\text{blend}}$
  - $F_{\text{blend}}$: Lens + Other stars in the PSF (~1") <-> Bulge Field is very crowded!
  - High-res imaging is needed
    - Hubble Space Telescope
    - Adaptive Optics in IR from the ground (Keck, VLT)

- Constrain brightness (and color) of the lens
- $\theta_E$ or $\pi_E$ yields a mass-distance constraint
OGLE-2005-BLG-071Lb

Ground v.s. Space
Even marginal astrometry signal!
The most massive M-dwarf planet?

- V, I-band photometry
- Microlens Parallax
- Constraint on Finite-source effects
- Astrometry

M ~ 0.46 M☉  D$_{\text{lens}}$ ~ 3.2 kpc
Mp ~ 3.8 M$_J$ at 3.6 AU

Too massive to form easily for M-dwarfs in core-accretion (Laughlin 2004; Kennedy & Kenyon 2008)
\[ q = (3.3 \pm 0.3) \times 10^{-4} \]
\[ \theta_* = 0.76 \pm 0.05 \, \mu \text{as}, \]
\[ \rho = 0.0049 \]
\[ \theta_E = 0.155 \pm 0.011 \, \text{mas} \]

• $\theta_E = 0.14$ mas, $\pi_{\text{rel}} = 1/D_{\text{Lens}} - 1/D_{\text{Source}} = 2.4$ uas $(M/M_{\text{Sun}})^{-1}$

• A planet in the bulge? $VLT: M_L \sim 0.67 \ M_{\text{Sun}}$
Many years after the event

Microlensing Event MACHO-LMC-5

Mt. Stromlo
Feb. 1993

Hubble Space Telescope • ACS

HST ACS/HRC
July 11, 2002

NASA, ESA and D. Bennett (University of Notre Dame)
Summary

• Extra information (finite-source, microlens parallax, high-res imaging, etc.) is needed to constrain mass and distance of the lens (and the planetary companion)
• Angular Einstein radius is usually measured for planetary event
• High-res imaging can constrain the lens flux as well as proper motion
  – See Jay Anderson, Justin Crepp & J.P. Beaulieu’s talks
Gould (2010) High-mag sample

<table>
<thead>
<tr>
<th>Name</th>
<th>$A_{\text{max}}$</th>
<th>$t_0$ (HJD)</th>
<th>$t_E$</th>
<th>$M/M_\odot$</th>
<th>Method</th>
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<tbody>
<tr>
<td>OGLE-2007-BLG-224</td>
<td>2424</td>
<td>4233.7</td>
<td>7</td>
<td>0.056 ± 0.004</td>
<td>$M = \theta_E/\kappa\pi_E$</td>
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<td>0.49$^{+0.23}_{-0.29}$</td>
<td>$GM\oplus\theta_E \oplus t_E$</td>
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<td>$GM\oplus\theta_E \oplus t_E$</td>
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