Microlensing At 5 AU

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How Microlensing Finds Planets
5. OBSERVATIONAL REQUIREMENTS

Two distinct steps are required to observe a planetary system by microlensing. First, one must single out a disk star which happens to be microlensing a bulge star. Second, one must observe this star often enough to catch the deviation in the light curve due to the planet. The first step involves the observation of millions of bulge stars on the order of once per day. The second step involves the observation of a handful of stars many times per day. In the following we give a rough outline of what is required for each of these steps.

While observations from one site would be useful, there are advantages to be gained by observing from several sites. First, two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out two observations per night. During the near-December season,
OGLE-2005-BLG-390

“Classical-Followup” Planetary Caustic

Beaulieu et al. 2006, Nature, 439, 437
First “High-Magnification” Planet

OGLE-2005-BLG-169: Second Cold Neptune
OGLE-2006-BLG-109: Without Followup Observations
OGLE-2006-BLG-109
Parallax+Finite-Source+Rotation+Blend

Gaudi et al. 2008, Science, 319, 927
Five Lightcurve Features

$1+2+3+5 = \text{Saturn} \quad 4 = \text{Jupiter}$
OGLE-2007-BLG-349: Saturn Mass-Ratio Planet +

Dong et al. 2010, in prep
MOA-2007-BLG-400

“Buried” Jovian-Mass Planet
Microlensing vs. Other Methods

Exoplanet Discoveries: M vs. a

Mass (Earth masses)

semi-major axis (AU)

Doppler
Kepler
microlensing

UN
S
V E

M
M
Microlensing and the “Snow Line”
Relation of **Mass** and **Distance** to **Lensing Observables**

\[
\alpha/\tilde{r}_E = \frac{\theta_E}{r_E}
\]

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

\[
\theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_L} - \frac{\tilde{r}_E}{D_S} = \frac{\tilde{r}_E}{D_{\text{rel}}}
\]

\[
\tilde{r}_E = \sqrt{\frac{4GM D_{\text{rel}}}{c^2}} \quad \theta_E = \sqrt{\frac{4GM}{D_{\text{rel}} c^2}}
\]
To measure angular Einstein radius:

Standard Sky-Plane Rulers
To measure parallax:

Standard Observer-Plane Rulers
Another Crackpot Idea:
Terrestrial Microlens Parallaxes

PHOTON STATISTICS LIMITS FOR EARTH-BASED PARALLAX MEASUREMENTS OF MACHO EVENTS

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ABSTRACT

We analyze the limitations imposed by photon-counting statistics on extracting useful information about MACHOs from Earth-based parallax observations of microlensing events. We find that if one or more large (say 2.5 m) telescopes are dedicated to observing a MACHO event for several nights near maximum amplification, then it is possible, in principle, to measure the velocity of the MACHO well.

We thank Andrew Gould for pointing out an error in the original version of this manuscript. This research was
Terrestrial Parallax:
Simultaneous Observations on Earth
Space-Based Parallaxes & Einstein Radii: SIM

\[ \tilde{r}_e \Delta u = d_{\text{SIM}} \]

\[ \tilde{r}_e = \frac{d_{\text{SIM}}}{\Delta u} \]

\[ \tilde{r}_e \]
... or, more immediately: Spitzer
OGLE-2005-SMC-001

CMD

Photometry

SMC128.5 and OGLE-2005-SMC-001

2005-SMC-1

OGLE I
OGLE V
CTIO I
Auckland
CTIO V

Spitzer Obs
Microlens Parallax

OGLE-2005-SMC-001

- Ground-Based
- Spitzer

Magnitude


Ground

Spitzer
Well-covered events: fair sample (A_{max}>200)

Well-Covered  All Events
Planet Sensitivity Vs. Detections
Solar System is Richer than Average...

... But Not Dramatically So
Planet Sensitivity Vs. Mass Ratio

![Graph showing sensitivity vs. mass ratio with various data points and a line indicating $\eta=0.32$.](image)
RV & Microlensing

Inside vs Outside Snow Line

![Graph showing distribution of dN/dlogq vs loga with markers for different mass-ratios and semimajor axes](image)
MOA-2008-BLG-310
A Verifiable Bulge Planet?

Why 5 AU?

\[
\tilde{r}_E = \frac{\text{AU}}{\pi_E}; \quad \pi_E = \sqrt{\frac{\pi_{\text{rel}}}{\kappa M}}; \quad \kappa = \frac{4G}{\text{AU} c^2} = 8.1 \frac{\text{mas}}{M_\odot}
\]

“Typical” disk lens

\[
\tilde{r}_E = 5.7 \text{AU} \left( \frac{M}{0.5 M_\odot} \right)^{1/2} \left( \frac{\pi_{\text{rel}}}{125 \mu\text{as}} \right)^{-1/2}
\]

“Typical” bulge lens

\[
\tilde{r}_E = 16 \text{AU} \left( \frac{M}{0.5 M_\odot} \right)^{1/2} \left( \frac{\pi_{\text{rel}}}{16 \mu\text{as}} \right)^{-1/2}
\]

“Extreme” bulge lens

\[
\tilde{r}_E = 30 \text{AU} \left( \frac{M}{0.5 M_\odot} \right)^{1/2} \left( \frac{\pi_{\text{rel}}}{4.5 \mu\text{as}} \right)^{-1/2}
\]
NextGen Microlensing Planet Search Simulations by Scott Gaudi

- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics down to systematics limit
Simulation Ingredients (abridged)
Target Fields

- Four Fields
  - (l,b)=(1,-3)
    - ~2900 Events/yr
  - (l,b)=(3,-3)
    - ~2300 Events/yr
  - (l,b)=(1,-5)
    - ~900 Events/yr
  - (l,b)=(3,-5)
    - ~800 Events/yr
Baseline Results

- **Simulate:**
  - **Mass:**
    \[
    \log(M/M_\oplus) = -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0
    \]
  - **Semimajor Axis:**
    \[
    \log(a/AU) = -0.35, -0.10, 0.15, 0.40, 0.65, 0.90, 1.15
    \]

- **Average over \(a\)**
  - \(-0.35 < \log(a/AU) < 1.15\)
  - Two planets per star

- **Scaling with Mass:**
  - \(N \propto M\) for \(M < 3M_\oplus\)
  - \(N \propto M^{0.6}\) for \(M > 3M_\oplus\)
## Summary of Baseline Results

<table>
<thead>
<tr>
<th>log(a/AU)</th>
<th>-0.35</th>
<th>-0.10</th>
<th>0.15</th>
<th>0.40</th>
<th>0.65</th>
<th>0.90</th>
<th>1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Γ (yr⁻¹)</td>
<td>0.4±0.4</td>
<td>3.8±1.2</td>
<td>12.5±3.1</td>
<td>10.9±1.7</td>
<td>8.8±1.9</td>
<td>4.3±1.2</td>
<td>1.0±0.7</td>
</tr>
</tbody>
</table>

Every MS star has one Earth-mass planet

<table>
<thead>
<tr>
<th>log(a/AU)</th>
<th>-0.35</th>
<th>-0.10</th>
<th>0.15</th>
<th>0.40</th>
<th>0.65</th>
<th>0.90</th>
<th>1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Γ (yr⁻¹)</td>
<td>0</td>
<td>0.6±0.3</td>
<td>0.6±0.4</td>
<td>3.1±0.9</td>
<td>3.9±1.2</td>
<td>1.8±0.9</td>
<td>0.2±0.2</td>
</tr>
</tbody>
</table>

Every MS star has one Earth mass ratio planet

<table>
<thead>
<tr>
<th>log(M/M₉)</th>
<th>-1.0</th>
<th>-0.5</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Γ (yr⁻¹)</td>
<td>1.5±0.3</td>
<td>3.7±0.5</td>
<td>12±1</td>
<td>30±3</td>
<td>78±8</td>
<td>150±10</td>
<td>350±20</td>
<td>590±30</td>
<td>1012±40</td>
</tr>
</tbody>
</table>

2 planets per star, uniformly distributed in log a in the range 0.4-20 AU
Initiatives

- **MOA**: 1.8m tel, 2.2 sq.deg camera already exists (New Zealand)
- **OGLE**: 1.3m tel already exists, currently being upgraded to 1.6 sq.deg. (Chile)
- **KOREA**: KASI entered national competition. Dec 2008: Korean Congress approved US$30M for three 2m tels, with 4 sq.deg cameras (Africa South America, Australia) [KMTNet]
Conclusions

• μlensing planets now found “routinely”
  – Now 3 per year

• Some planet distances are measured
  – Contrary to initial expectations

• Bulge lens IDs require satellite at 5 AU
  – Expected to contain MOST planets

• NextGen experiments will increase 10-fold
  – MOA/OGLE/KMTNet