Microlensing Planets: Probing the Extremes of Parameter Space
From Einstein’s Putdown to Modern Surveys
Andy Gould (OSU)
Generation 1

- Liebes 1964, Phys Rev, 133, B835
  - Many practical examples, including planets
  - Mass measurement of Isolated Star
  - Space-Based Parallaxes
  - Proposed First Practical Experiment
Generation 0

- Eddington 1920, Space, Time, and Gravitation
- Chwolson 1924, Astron. Nachr. 221, 329
- Einstein 1936a, Science, 84, 506
  
  “Some time ago R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request .... there is no great chance of observing this phenomenon.”

- Einstein 1936b (private letter to Science editor)
  
  “Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy.”
Generation -1: Einstein (1912)

[Renn, Sauer, Stachel 1997, Science 275, 184]
1136 Events (1st half of 2011)
the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.
DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

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Received 1991 December 26; accepted 1992 March 9

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,
How Microlensing Finds Planets
1995 PLANET Pilot Season

- Albrow et al. 1998
OGLE-2005-BLG-390

“Classical-Followup” Planetary Caustic

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

Amateurs + Professionals

Grant, Ian, Jennie, Phil
Amateurs + Professionals

"It just shows that you can be a mother, you can work full-time, and you can still go out there and find planets."

Jennie McCormick
(Amateur Astronomer, Auckland, New Zealand)
<table>
<thead>
<tr>
<th>Station</th>
<th>Country/Location</th>
<th>Lead Scientist(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+12 Auckland</td>
<td>NZ (Grant Christie)</td>
<td></td>
</tr>
<tr>
<td>+12 Farmcove</td>
<td>NZ (Jennie McCormick)</td>
<td></td>
</tr>
<tr>
<td>+12 Auckland</td>
<td>NZ (David Moorhouse &amp; Guy Thornley)</td>
<td></td>
</tr>
<tr>
<td>+12 Nelson</td>
<td>NZ (Robert Rea)</td>
<td></td>
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<tr>
<td>+12 Patutahi</td>
<td>NZ (John Drummond)</td>
<td></td>
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<tr>
<td>+12 Blenheim</td>
<td>NZ (Bill Allen)</td>
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</tr>
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<td>+10 Canberra</td>
<td>AU (David Higgins)</td>
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<td>+08 Perth</td>
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<td>-04 CTIO</td>
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<td></td>
</tr>
<tr>
<td>-04 CAO</td>
<td>Chile (Franco Mallia)</td>
<td></td>
</tr>
<tr>
<td>-07 Mt Lemon</td>
<td>AZ US</td>
<td></td>
</tr>
<tr>
<td>-07 MDM</td>
<td>AZ US</td>
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<tr>
<td>-07 Hereford</td>
<td>AZ US (Bruce Gary)</td>
<td></td>
</tr>
<tr>
<td>-08 Palomar</td>
<td>CA US</td>
<td></td>
</tr>
<tr>
<td>-10 Southern StarsTahiti</td>
<td>(Roland Santallo)</td>
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</table>
OGLE-2005-BLG-169: Second Cold Neptune
<table>
<thead>
<tr>
<th>Event</th>
<th>Masses</th>
<th>Separation</th>
<th>Temperature</th>
<th>Detection Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OGLE-2005-BLG-390</strong></td>
<td>( q = 8 \times 10^{-5} )</td>
<td>( M_* = 0.2 , M_{\text{sun}} )</td>
<td>( M_p = 5.5 , M_{\text{earth}} )</td>
<td>( D = 7 , \text{kpc} )</td>
</tr>
<tr>
<td><strong>OGLE-2005-BLG-169</strong></td>
<td>( q = 8 \times 10^{-5} )</td>
<td>( M_* = 0.5 , M_{\text{sun}} )</td>
<td>( M_p = 13 , M_{\text{earth}} )</td>
<td>( D = 3 , \text{kpc} )</td>
</tr>
</tbody>
</table>
MICROLENS OGLE-2005-BLG-169 IMPLIES THAT COOL NEPTUNE-LIKE PLANETS ARE COMMON
A. Gould,1,2 A. Udalski,3,4 D. An,1,2 D. P. Bennett,5,6,7 A.-Y. Zhou,8 S. Dong,3,2 N. J. Rattenbury,3,9 B. S. Gaudi,1,10
P. C. M. Yock,3,11 I. A. Bond,3,12 G. W. Christie,1,13 K. Horne,9,14,15 J. Anderson,16 K. Z. Stanek,1,2
D. L. DePoy,1,2 C. Han,1,17 J. McCormick,1,18 B.-G. Park,1,19 R. W. Pogge,1,2 S. D. Poindexter,1,2 I. Soszyński,1,4,20
M. K. Szymański,3,4 M. Kubiak,3,4 G. Pietrzyński,3,4,20 O. Szewczyk,3,4 Ł. Wyrzykowski,3,4,21 K. Ulaczyk,3,4
B. Paczyński,3,22 D. M. Bramich,3,14,21 C. Snodgrass,14,23 I. A. Steele,14,24 M. J. Burgdorf,14,24
M. F. Bode,14,24 C. S. Botzler,5,11 S. Mao,9 and S. C. Swavining,5,11
Received 2006 March 10; accepted 2006 April 27; published 2006 May 24

ABSTRACT
We detect a Neptune mass ratio ($q \approx 8 \times 10^{-5}$) planetary companion to the lens star in the extremely high magnification ($A \sim 800$) microlensing event OGLE-2005-BLG-169. If the parent is a main-sequence star, it has mass $M \sim 0.5 \, M_\odot$, implying a planet mass of $\sim 13 \, M_\oplus$ and projected separation of $\sim 2.7 \, AU$. When intensely monitored over
OGLE-2007-BLG-368:
Cold Neptune #3

MOA-2009-BLG-266: Cold Neptune #4

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 = Saturn  4 = Jupiter
Planets 2010
Planets 2010

Exoplanet Discoveries vs. Snow-Line

Mass (Earth masses)

$(\text{semi-major axis})/(\text{snow-line})$
Planets 2011

Exoplanet Discoveries vs. Snow Line

Mass (Earth masses)

(semi-major axis)/(snow-line)
Selection Biases:

CMD (Apparent Mags)
Selection biases:
CMD (Absolute mags)
Relation of Mass and Distance to Lensing Observables

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

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

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

\[ \tilde{r}_E = \sqrt{\frac{4GM D_{rel}}{c^2}} \]

\[ \theta_E = \sqrt{\frac{4GM}{D_{rel} c^2}} \]
To measure angular Einstein Radius:

**Standard Sky-Plane Rulers**

![Graph showing measurements of angular Einstein Radius on the MOA-2008-BLG-310 system.](image)
To measure parallax:

Standard Observer-Plane Rulers
MOA-2007-BLG-400

“Buried” Jovian-Mass Planet
MOA-2008-BLG-310
Another Buried Planet

OGLE-2008-BLG-279:

\[ A = 1600 \]

OGLE-2007-BLG-050:

\[ A = 432 \]

Planet Sensitivity

OGLE-2008-BLG-279
Planet Sensitivity

OGLE-2007-BLG-050

\( r \) – projected planet/star separation (AU)

\( q \) – mass ratio

\( m_p \) – planet mass in Earth mass

\( d \) – separation (in \( R_E \))

\( \Delta \chi^2 \) threshold = 500
Well-covered events: fair sample

\[(A_{\text{max}} > 200)\]

Well-Covered

All Events
Planet Sensitivity Vs. Detections
RV & Microlensing

Inside vs Outside Snow Line

Mass–ratio $\sim 5 \times 10^{-4}$

Semimajor Axis (AU)
RV & Microlensing

Frequency vs. Mass Ratio

- Mayor et al. (2009)
  \( M_\sim M_\odot \)
  Periods < 50 days
- This Paper
  \( M_\sim 0.5M_\odot \), \( a \sim 3 \times a_{snow} \)
- Cumming et al. (2008)
  \( M_\sim M_\odot \)
  Periods < 2000 days
- Johnson et al. (2010)
  \( M_\sim 0.5M_\odot \)
  Periods < 2000 days

\( \propto q^{-0.68} \)

Sumi et al. (2010) (unnormalized)
Solar System is Richer than Average

... But Not Dramatically So

![Solar System Analogs Diagram]

- Jupiter (11.4)
- Saturn (6.4)
- Neptune (0.2)
- Uranus (0.3)

<table>
<thead>
<tr>
<th>Planets Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
</tr>
<tr>
<td>One Planet</td>
</tr>
<tr>
<td>Two Planets</td>
</tr>
<tr>
<td>Three Planets</td>
</tr>
<tr>
<td>Four Planets</td>
</tr>
<tr>
<td>(18.3)</td>
</tr>
<tr>
<td>(5.8)</td>
</tr>
<tr>
<td>(5.7)</td>
</tr>
<tr>
<td>(0.3)</td>
</tr>
<tr>
<td>(&lt;0.1)</td>
</tr>
</tbody>
</table>
MOA-2007-BLG-192: Cold Super-Earth

MOA-2007-BLG-192:
Step 2: V-I Source Color

MOA-2007-BLG-192:

Step 3: V-I --> I-K: $I_s \rightarrow K_s$

MOA-2007-BLG-192:

Step 4: VLT NACO: K baseline

\[ M_{\text{host}} = 0.08 \ M_{\text{sun}} ; \quad M_{\text{planet}} = 3.2 \ M_{\text{earth}} \]
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
log(M/M_\odot)=0.00, log(a/AU)=-0.35, N_{det}=1
M_* = 0.109, R_E = 0.50, \Gamma_s = 19.70, \Gamma_{lens} = 27.41, \Gamma_i = 0.3994
t_E = 13.13, u_0 = 0.1541, q = 2.76e-05, d = 0.82, \rho_* = 9.16e-03

Hawaii
South Africa
Chile
Australia

N_{dat} = 21327
\Delta \chi^2 = 2570.00
Bulge-bulge event
\[
\log(M/M_\odot) = 0.00, \log(a/AU) = 0.65, N_{\text{det}} = 31
\]
\[
M_* = 0.455, R_E = 2.36, I_s = 21.40, I_{\text{lens}} = 20.24, \Gamma_i = 0.2000
\]
\[
t_E = 49.21, u_0 = 0.1744, q = 6.60e-06, d = 0.83, \rho_* = 3.19e-04
\]

Magnification

Hawaii
South Africa
Chile
Australia

Fractional Deviation

Disk-bulge event

N_{\text{dat}} = 22016
\Delta \chi^2 = 2944.10
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>$\Gamma$ (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>$\Gamma$ (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/M$_\odot$)</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>$\Gamma$ (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
Approach: Threshold + Upgrades

- **THRESHOLD**: Major new telescope in Africa joined with existing/upgraded MOA and OGLE telescopes

- **POTENTIAL UPGRADES**:
  - Additional 2m/4sq.deg. telescope (Chile?)
  - Participation of other widefield telescopes e.g. PanStars (Hawaii), SkyMapper (Australia)
Heidelberg: November 2005

- Participants from France, Germany, Japan, Korea, New Zealand, Poland, UK, US
- Critically reviewed models to predict planet detection and their underlying assumptions
- Presentations about wide range of potential initiatives for implementation
- Generally enthusiastic response
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]
1136 Events (1\textsuperscript{st} half of 2011)
Conclusions

• High-mag μlens events: “controlled sample

• 1st Frequency measurement past snow line
  – 0.36 ± 0.15 /dex^2 at q = 5e-4 (saturn mass ratio)

• Solar system: 3 X more giants than average
  – 6 X more likely to have 2 giants

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