Extrasolar planets from
Gravitational microlensing

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I. Introduction & current status

II. Principle of extrasolar planet detection with microlensing

III. Examples & statistics

IV. Future directions
What is near-field microlensing?

Microlensing produces “symmetric”, non-repeating & achromatic light curves.

Small prob.: $10^{-6}$
Where are we looking?

- Mostly here
- Here
- And here
- Galactic bulge

Small Magellanic Cloud

Large Magellanic Cloud

NOAO/AURA/NSF Image/Eamonn Kerins
What do we see?

Challenges: probability $\sim 10^{-6}$, event rate $\sim 10$ events per year per $10^6$ stars.

Credit: OGLE
Two decades of microlensing

- OGLE, MOA, MACHO etc. assembled time series for hundreds of millions of stars toward GC, LMC, SMC, etc.

- To date ~ 15,000 events have been detected
  - The vast majority of events are detected towards the Galactic bulge
  - Current event rate by OGLE & MOA ~2000/yr, most in real-time
  - Durations: days to years, A=1 to thousands
A high mag. standard light curve

\( t_E \approx 42 \text{ days, typical} \)

\( \mu_{\text{max}} \approx 3000 \)

Obs. \( \mu_{\text{max}} \approx 36 \)

OGLE-2004-BLG-343

6 year data

\[ \text{JJD} - 2450000 \]
A star may be blended with other unrelated stars

✓ Reduces magnification
✓ Shortens the event duration ("iceberg" effect)
A short standard event

\[ t_E = 1.25 \text{ day} \]

Free-floating planets? \( t_E \sim M^{1/2} \)

8 years of data

\textbf{OGLE-2008-BLG-365}
Exotic microlensing events

- Standard light curve assumes single lens and point source with linear motions!

- Extra features in exotic light curves give additional constraints to break the microlens degeneracy

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parallax  finite source size  binary lens

- Smith, Mao et al. (2002)
- Alcock et al. (1997)
Applications of microlensing

- Dark matter: MACHOS?
- Galactic structure/dynamics
  - CMDs, microlensing optical depth maps, proper motions (kinematics)
- High magnification events/caustic crossing events
  - Stellar atmosphere (limb-darkening)
  - Metallicity, surface gravity, ages of stars
- Binary mass function
- Stellar mass black holes
- Extrasolar planets (Beaulieu’s talk)
Outline

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Microlensing: basic concepts

- Einstein radius \( r_E \sim M^{1/2} \), \( \sim \) few AU, coincident with size of the solar system!

- Einstein radius crossing time \( t_E \sim r_E/V \), lasting for days to years \( \rightarrow \) degeneracy!
The presence of the planet perturbs the image positions and magnifications.
Duration $\delta t \sim 1$ day $(M/M_j)^{1/2}$
In fact it can create one or three extra images! $\rightarrow$ caustics and critical curves

Mao & Paczynski 1991
Caustics in the real world

Parallel rays from the Sun are piled into bright optical caustics by waves

Wine glasses

In caustic crossing, a pair of images (dis)appears
critical curves and caustics for a point lens

On the plane of sky

Source: caustics

Images: critical curves

magnification=∞
Evolution of caustics & critical curves

Binary mass ratio $q=0.01$

Far
$\alpha=1.5$

Resonant
$\alpha=1.0$

Near
$\alpha=0.8$

Distance decreases
Light curves due to central & planetary caustics

- Central caustic crossing: peak, high S/N, easier to predict and observe; sensitive to multiple planets!
- Planetary caustic crossing can occur any time, more difficult to predict and time followup observations!
**Binary lens modelling**

- **Number of parameters:**
  - ✓ Lens \((q, a, t_E)\); source \(l_0, f_s\);
  - trajectory: \(u_0, \theta\)

- **Modelling gives** \(t_E\), mass ratio \(q\), and dimensionless separation \(a\)

- **Combined with other information** (finite source size, parallax, lens light)
  - ✓ Finite source size + parallax
    - → lens mass unique
  - ✓ Otherwise Bayesian analysis
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First Microlensing planet

• \( q = 0.004 \)

• If the lens is MS, \( M_{\text{planet}} \sim 1.5 \, M_J \), \( d \sim 5 \text{kpc} \)


• Discovered by OGLE/MOA surveys

• 7 day deviation!

Bond et al. 2004
A cold, low-mass planet: OGLE-2005-BLG-390

Deviation lasting a day

Population of cold, low-mass Neptunes and Super-Earths.

(Beaulieu et al. 2006; Gould et al. 2006; Bennett et al. 2009; Sumi et al. 2010; Muraki et al. 2011; Furusawa et al. 2013)
First multiple extrasolar planet: OGLE 2005-BLG-071

Gaudi et al. (2008); Bennett et al. (2010)

Rotation, parallax and finite source size effects are all seen.
Host:
Mass = 0.51 +/- 0.05 MSun
Luminosity ~ 5% LSun
Distance = 1510 +/- 120 pc

Planet b:
Mass = 0.73 +/- 0.06 MJup
Semimajor Axis = 2.3 +/- 0.5 AU

Planet c:
Mass = 0.27 +/- 0.02 MJup = 0.90
Semimajor Axis = 4.6 +/- 1.5 AU
Eccentricity = 0.15+0.17-0.10
Inclination = 64+4-7 degrees

AO Imaging from Keck
A Jupiter/Saturn Analog

Semi-major Axis Relative to Snow Line
Second multiple planets: OGLE-2012-BLG-0026

- $q_1 = 1.30 \times 10^{-4}$, $d_1 = 1.034$
- $q_2 = 7.84 \times 10^{-4}$, $d_2 = 1.304$
- $t_E = 93.92 \pm 0.58$ days

Han et al. (2013)

- 2 two-planets
- ~2 circumbinary planets
- Modelling still a challenge!
More than 50 microlensing planets discovered, but only 27 published, ~15/yr

Needs faster publications and better communications with other fields
Microlensing: pros & cons

**Pros:**
- Wide range of host stars
- Disk/bulge/extragalactic (M31)
- Free-floating planets
- Good for providing statistics of cold rocky planets; complement other methods

**Cons:**
- Too distant to observe
- No repeated observations possible
I don't understand. You are looking for planets you can't see around stars you can't see.

Debra Fisher

✓ Based on GR
✓ Caustic crossings always come in pairs
✓ Local light curves close to caustics follow simple asymptotic relations

☐ In some cases, the parameters can be determined using local expansions
Mostly beyond snow line

Low mass planets are more common

Between 0.5-10 AU - 17% have Jupiters, 50% Neptune and Super-Earths

Cassan et al. (2012); Gould (2006, 2010)
Comparison with radial velocity

*Microlensing gives ~ 0.36*

- Smaller host masses
- Larger separation

Free-floating planets

- Excess of short time scale events due to unbound or wide-separation planets.
- Implies roughly 2 Jupiter-mass free-floating planets per star. Hard to explain?
- Blending? Correlated data points? (Albrow 2014, Santa Barabara)

Sumi et al. (2011)

Mao & Paczynski (1996)
## Frequency of multiple planets

<table>
<thead>
<tr>
<th>Method</th>
<th>Total</th>
<th>Multiple</th>
<th>fraction (%)</th>
<th>Total Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV or astrometry</td>
<td>419</td>
<td>98</td>
<td>23.4</td>
<td>558</td>
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<tr>
<td>Transit</td>
<td>615</td>
<td>350</td>
<td>56.9</td>
<td>1133</td>
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<td>Microlensing</td>
<td>27</td>
<td>2</td>
<td>7.4</td>
<td>29</td>
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<tr>
<td>Imaging</td>
<td>43</td>
<td>2</td>
<td>4.7</td>
<td>47</td>
</tr>
<tr>
<td>Pulsar/timing</td>
<td>11</td>
<td>2</td>
<td>18.2</td>
<td>14</td>
</tr>
<tr>
<td>All</td>
<td>1105</td>
<td>460</td>
<td>41.6</td>
<td>1783</td>
</tr>
</tbody>
</table>

Are fractions in different methods consistent with each other? Selection effects and degeneracy (Song, Mao et al. 2014).
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Survey (MOA and OGLE collaborations) + follow-up (microFun/PLANET collaborations) around the globe

Current mode of discovery

MicroFun - 24 hour relay
Near-Future: Upgraded Microlensing Experiments

- OGLE IV is running in full power since 2011: 1.4 Deg$^2$ camera
- MOA-II: 1.8m telescope 2.2 Deg$^2$ camera
- Current survey + followup will likely continue

OGLE, 32 CCDs
Microlensing within ~5 years: KMTNet

- **KMTNet**
  - Three 1.6m telescope with ~4 deg² FoV, 10m cadence
  - ~2000 events per year
  - ~70 planets per year, depending on MF

SAAO, 10/14
CTIO, 03/14
SSO, 12/15
Monte Carlo simulations
(Zhu, Penny, Mao, Gould et al.)

- Planet population from Ida & Lin (2010)
- Choose primary star mass of 0.3 solar masses, and reasonable lens and source distances
- Orbital planes are randomly chosen
- All planets above 0.1 \( M_{\text{earth}} \) are retained
- Use rayshooting to generate light curves, with a cadence of 10min, as expected from KMTnet
A simulated light curve with an 1.6 Earth-mass planet

No.3927 event ($\Delta X^2 = 3.38 e+02$)

Single and double planets are selected by $\Delta X^2 (~ 300)$, and visual examination

- $q \sim 1.59 \times 10^{-6}$
- $\Delta X^2 = 358$
- Planetary caustics

Primary star •

Separation ($R_E=1.6$)

Graph showing light curve with markers and fitted curves.
A simulated light curve with two planets

No.3451 event ($\Delta \chi^2 = 5.67e+03$)

- double low-mass planets
  - $q_1 \sim 7.45 \times 10^{-3}$
  - $q_2 \sim 6.03 \times 10^{-4}$

- Central + resonant caustics

$\Delta X^2 = 5670$
• Probability of planetary events is \(\sim 2.9\%\), out of which \(5.5\%\) is doubles
  – Central caustic crossing are more common for multiple-planet systems
• super-Earths:Neptunes:Jupiters \(\sim 1:1:1\)
  – Sensitive to Mars-mass planets close to the Einstein radius
• **Planetary**: central: resonant = 107:128:78
Microlensing in ~10 years: space

- Space allows to observe in IR, and study fainter, smaller stars to discover very low-mass planets
- Direct lens-source separation partially/completely remove the degeneracies
A simulated event at baseline and peak

Euclid (2020) focus on weak lensing and BAO, but may have a microlensing component
• Default MF: $1/3$ per log $m$ per log $a$, flat log mass dependence
• total detections ($-1.5 < \log M/Me < 3$): $\sim 400$, 6 Earths (range: 6-100 in different models)
• Sensitivity to free floating planets
A complete census of planets

- Space microlensing, together with other can potentially provide a complete census of the planet population
summary

- Two decades of microlensing data have yielded large, still under-explored datasets
- Microlensing extrasolar planet detection complements other methods:
  - free-floating planets, planets in binaries, even extragalactic planets
  - Current planetary rate: \( \sim15/\text{yr} \)
  - KMTNet: a factor 5-10 increase in rate
  - space another factor of 5-10 down to lower masses with better determinations