Microlensing Searches for Extrasolar Planets

I. The Search for Planets.
II. Microlensing and Planets
III. Alerts and Follow-up.
IV. Detection and Efficiency.
V. 5 Years of PLANET Data.
VI. Future Prospects
VII. Conclusions.

Microlensing Searches for Extrasolar Planets, B. Scott Gaudi, IAS
The Search for Extrasolar Planets

Why Search for Extrasolar Planets?
- Frequency of Life
- Clues to Star Formation
- Low End of the Compact Object Mass Function

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The Search for Extrasolar Planets

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“Classical” Detection Methods:

- Radial Velocities
- Astrometry
- Transits
- Direct Detection

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“Classical” Detection Methods
Radial Velocities
Astrometry
Transits
Direct Imaging
The Search for Extrasolar Planets

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“Classical” Detection Methods:
- Radial Velocities
- Astrometry
- Transits
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Various Methods are Complimentary:
- Parameters Measured
- Separations Probed

Charbonneau et al. 2000

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The Search for Extrasolar Planets

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“Classical” Detection Methods:
   Radial Velocities
   Astrometry
   Transits
   Direct Detection

Various Methods are Complementary:
   ParametersMeasured
   Separations Probed

Drawbacks:
   Not sensitive to small mass planets.
   Limited to nearby systems.
   Period must be less than duration of observations.

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Microlensing and Planets

Time Delay

\[ \tau = \frac{1}{2} (\theta - \beta)^2 - \psi(\theta) \]

\[ \psi(\theta) = \frac{1}{\pi} \int \kappa(\theta') \ln |\theta - \theta'| \, d^2\theta' \]

\[ = \theta^2 E \ln \theta \]

Lens Equation

\[ \beta = \theta - \theta^2 E / \theta \]

Angular Einstein Ring Radius

\[ \theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_{OL}D_{OS}}} \approx 300 \mu as \left( \frac{M}{0.3M_\odot} \right)^{1/2} \]

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Single Lens Parameters:
- Impact parameter
- Time of Maximum Mag.
- Timescale

\[ t_E = \frac{\theta_E}{\mu} \approx 20\text{days} \left(\frac{M}{0.3M_\odot}\right)^{1/2} \]
Microlensing and Planets

Single Lens Parameters:
- Impact parameter
- Time of Maximum Mag.
- Timescale

$$t_E = \frac{\theta_E}{\mu} \simeq 20 \text{days} \left(\frac{M}{0.3M_\odot}\right)^{1/2}$$

Planet Parameters:
- Angle wrt Binary Axis
- Projected Separation
- Mass Ratio - $q$

$$t_p \simeq \sqrt{q} t_E \simeq 1 \text{day} \left(\frac{M_p}{M_J}\right)^{1/2}$$

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Detection Efficiency:

Naïve Estimate:
\[ \sim \frac{\theta_p}{\theta_E} \approx 3\% \left( \frac{q}{10^{-3}} \right)^{1/2} \]

Enhanced Probability:
\[ \sim A \frac{\theta_p}{\theta_E} \approx 15\% \left( \frac{q}{10^{-3}} \right)^{1/2} \]

High-Magnification Events

Higher Efficiencies

Maximized at \[ a \sim \theta_E \]

Mao & Paczynski 1991,
Gould & Loeb 1992,
Griest & Safizadeh 1998
Microlensing and Planets

Advantages:

Sensitive to Jupiters at 1-10 AU.
No Flux Needed.
Extend Sensitivity to Lower Masses.

Disadvantages:

Follow-up Difficult.
Non-repeatable.
Short Timescale Perturbations.

Basic Requirements:

Nearly Continuous Sampling.
Good Photometry for Detection.

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**Alerts and Follow-up**

- "Survey" Collaborations
  - Insufficient Sampling
  - Real-time Alerts

**Current and Past Alerts**

- EROS
  - (5 per year)
- MACHO*
  - (50 per year)
- MOA
  - (50 per year)
- OGLE II*
  - (75 per year)

**Future Alerts**

- OGLE III
  - (500 per year?)

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![Graph showing magnification and residuals over time](image)
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Follow-up Collaborations
- High Temporal Sampling
- Good Photometry

Current Collaborations
- EXPORT (12 events) (Tsapras et al. 2001)
- MOA (30 events) (Bond et al. 2002)
- MPS (50 events) (Rhie et al. 2000)
- PLANET (100+ events) (Albrow et al. 1998)
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**OGLE-1998-BUL-14**

**Total # of Points**
- 461 I-band
- 139 V-band

**Median Sampling:**
- 1 hour

**I-band Scatter**
- Entire event ~ 4%
- Over the peak ~ 1.5%

Albrow et al. 2000
Alerts and Follow-up

Extremely Crowded Fields

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Detection and Efficiency

Microlensing Searches for Extrasolar Planets

Gaudi & Sackett 2000

Fix Parameters: \((q, d, \theta)\)

\[ \Delta \chi^2 > \Delta \chi^2_{th} \]

Excluded

\[ \Delta \chi^2 < -\Delta \chi^2_{th} \]

Detection

OGLE-1998-BUL-14:
\[ \epsilon(q = 10^{-3}, d = 1.67) = 41\% \]

\[ \epsilon(d, q) = \frac{1}{2\pi} \int_0^{2\pi} d\theta \Theta(\Delta \chi^2 - \Delta \chi^2_{th}) \]

Gaudi & Sackett 2000

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Detection and Efficiency

Microlensing Searches for Extrasolar Planets

Albrow et al. 2000
Gaudi et al. 2002

Lensed out at 95% c.l.

Projected Separation (R_\text{E})

Mass Ratio

Lensing Zone Detection Efficiency (%)
Five Years of PLANET Data

95-99 PLANET Dataset
• 126 Events Monitored

Exclude
• Equal-Mass Binaries
• Poorly Sampled Events
• Poorly-Constrained Parameters

Final Sample
• 43 Events

Albrow et al. 2001
Gaudi et al. 2002

Microlensing Searches for Extrasolar Planets
Five Years of PLANET Data

43 Event Sample
- Most Events Sensitive to $q > 0.001$ Companions
- Thirteen $A > 10$ Events
- Not Sensitive to “Earths”

Microlensing Searches for Extrasolar Planets
Five Years of PLANET Data

Detection Threshold of $\Delta \chi^2_{th} = -60$

- Two Candidate “Detections”
- Better Explained by Other Models
- No Viable Detections out of 43 Events

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Microlensing Searches for Extrasolar Planets

Search for Planets
- $-4 < \log(q) < -2$
- $-1 < \log(d) < 1$

No Viable Detections

What does this mean?

- $>95$
- $75-95$
- $50-75$
- $25-50$
- $5-25$
Five Years of PLANET Data

Expected # of Events
\[ N_{\text{exp}}(d, q) = f(d, q) \sum \epsilon_i(d, q) \]

Probability of a Detection
\[ P(d, q) = 1 - \exp[-N_{\text{exp}}(d, q)] \]

95% c.l. Upper Limit
\[ f(d, q) \text{ for which } P(d, q) = 5\% \]

Microlensing Searches for Extrasolar Planets
<33% Have Jupiter-mass companions between 1.5-4 AU
<45% Have 3 x Jupiter-mass companions between 1-7 AU

Microlensing Searches for Extrasolar Planets
Microlensing Searches for Extrasolar Planets
Future Prospects - Ground

Pushing to Lower Fractions

- More Efficient Monitoring
- Image Subtraction Processing
Future Prospects - Ground

Pushing to Lower Fractions

• More Efficient Monitoring
• Image Subtraction Processing \[ \{ \text{Factor of 3 improvement} \]
Future Prospects - Ground

Pushing to Lower Fractions
- More Efficient Monitoring
- Image Subtraction Processing
- Increasing the Number of Alerts (OGLE III)

\[ R_{\text{exp}} \sim 0.1 f R_{\text{alert}} \]
\[ \sim 1 \text{yr}^{-1} \left( \frac{f}{5\%} \right) \left( \frac{R_{\text{alert}}}{200 \text{yr}^{-1}} \right) \]

OGLE-III Camera
- 8 2045x4096 CCDs
- 35’ x 35’ field-of-view
- > 300 alerts per year

Microlensing Searches for Extrasolar Planets
Future Prospects - Ground

Pushing to Lower Fractions
• More Efficient Monitoring
• Image Subtraction Processing
• Increasing the Number of Alerts (OGLE III)

Pushing to Lower Masses
• More Alerts
• Main Sequence Alerts
• Larger Apertures?
Future Prospects - Ground

Earth-mass Planets

\[ q \approx 10^{-5} \left( \frac{M_p}{M_{\oplus}} \right) \]

Bennett & Rhie 1996

Detection Probability \sim \text{few \%}

Microlensing Searches for Extrasolar Planets
Future Prospects - Ground

Pushing to Lower Fractions
- Increasing the Number of Alerts (OGLE III)
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Pushing to Lower Masses
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Require Main Sequence Sources

Microlensing Searches for Extrasolar Planets

Bennett & Rhie 1996
Future Prospects - Ground

Pushing to Lower Fractions
- Increasing the Number of Alerts (OGLE III)
- More Efficient Monitoring
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Pushing to Lower Masses
- More Alerts
- Main Sequence Alerts
- Larger Apertures?

Pushing to Larger Separations
- Longer Duration Monitoring
- Free Floating Planets?
Future Prospects - Space

Galactic Exoplanet Survey Telescope (GEST)

- 1.5m aperture
- 2.1 square degree field-of-view
- Monitor 0.1 billion main sequence stars
- 100f Earth-mass planets at 1 AU

Bennett & Rhie 2002

Microlensing Searches for Extrasolar Planets
Galactic Exoplanet Survey Telescope (GEST)
• 1.5m aperture
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• 100f Earth-mass planets at 1 AU

Space Interferometry Mission (SIM)
• Measure Masses of Planets to 5% accuracy
Conclusions

Microlensing offers a complementary way of searching for extrasolar planets.

Four collaborations obtaining useful data
- EXPORT, PLANET, MOA, MPS

Analysis of 95-99 PLANET database:
- No viable detections.
- <33% of M-dwafs in the Bulge have Jupiter-Mass Companions between 1.5-4 AU
- <45% have 3-Jupiter mass Companions between 1-7AU

Future Prospects
- Probe fractions of 1% in 5 Years with OGLE-III Alerts.
- Possible to push sensitivity to Earth-mass planets, but requires
  - Monitoring of many events.
  - Main-sequence sources.
- A space-based survey might be optimal for detecting Earths.