Exploring Planetary Systems with Transits and Microlensing

B. Scott Gaudi, Institute for Advanced Study

Available @ http://www.sns.ias.edu/~gaudi/presentations.html (soon)
Conclusions:
Transits and Microlensing offer complementary methods of exploring extrasolar planetary systems.

Transits & “Hot Jupiters”
• Need precise photometry, many (>20) consecutive nights.
• Optimal targets are homogeneous, compact, populous (#>3000) systems.
• Open clusters provide good (but not ideal) targets.
• NGC1245 (1 Gyr, [Fe/H]~ 0) f < 10% (95 c.l.) Preliminary!
• 1-2 clusters per year.

Microlensing & “Cool Neptunes”
• <33% of M-dwafs in the Bulge have Jupiter-Mass companions between 1.5-4 AU
• Probe fractions of 5% down to Neptune Mass in 5 Years with OGLE-III Alerts.
• Possible to push sensitivity to Earth-mass planets (but hard!)

Hot Jupiters and Cool Neptunes, B. Scott Gaudi, Institute for Advanced Study
Collaborators:

• Probing Lensing Anomalies NETwork (PLANET)
  Penny Sackett, PI
  http://mplanet.anu.edu.au/

• Microlensing Follow-Up Network (µFUN)
  http://www.astronomy.ohio-state.edu/~microfun

• Search for Transiting Extrasolar Planets in Stellar Systems (STEPSS)
  Chris Burke, S.G., Darren DePoy, Rick Pogge, Jennifer Marshall
  http://www-astronomy.mps.ohio-state.edu/~cjburch/STEPSS/

*Hot Jupiters* and *Cool Neptunes*, B. Scott Gaudi, Institute for Advanced Study
The Search for Planets

100 known planets via RV

Features:
• BD Desert
• “Hot Jupiters”
• Freq. vs. [Fe/H]
• Piling Up at P=3d
• Lack of Massive, Close-in Planets

Terrestrial Planets? Currently Undetectable via RV, Transits, Astrometry

http://exoplanets.org/
The Search for Planets

Piling up at $P=3d$
- Consequence of Migration?

Paucity of Giant, Close-In Planets
- Related to BD Desert?
How Many Transiting Planets?
The Search for Planets

Frequency Increases with Metallicity
Santos et al. (2001), Reid (2002)

Nature?
• Planet(esimal) Accretion?

Nurture?
• Low metallicity inhibits formation.

47 Tuc?
• Stellar density
Transits

Duration = 2t_T

Depth = \rho^2
Transits

Period = P

\[
\frac{(\Delta F/F_0^*)}{\rho^2}
\]

\[
(t-t_0)/t_T
\]
Transits

Signal from HD 209458b
(Brown et al. 2001 parameters)
Transits – What can we measure?

Measure

\[ \rho, t_T, P \]
(also inclination, limb darkening)

\[ \rho = \frac{R_p}{R_*} \]
• Depth

\[ t_T \equiv \frac{\theta_*}{\mu_*} = \frac{R_*}{a} \frac{P}{2\pi} \]
• Duration

\[ P = \frac{2\pi}{\sqrt{GM_*}} a^{3/2} \]
• Period

Infer

\[ R_p, a \]

(if \( R_*, M_* \) are known, or very precise lightcurve)

Need to know the properties of the primary

→ **Need absolute magnitude & color**

Late M dwarfs, BD, giant planets have similar radii

→ **Need RV follow-up of candidates.**
Transits - Detection

\[ P = P_T P_Q P_W \]

- \( P_T \): Probability of Transit
- \( P_Q \): Probability of Exceeding S/N Requirement
- \( P_W \): Probability of Transit(s) Occurring in Window
Transits - Detection

\[ P = P_T P_Q P_W \]

\[ P_T = \frac{\int_{0}^{1} d(\cos i) \cos i_{\text{min}}}{\int_{0}^{1} d(\cos i)} = \frac{R_* + R_p}{a} \approx \frac{R_*}{a} \]
### Transits - Detection

\[ P = P_T P_Q P_W \]

\[ P_Q = \Theta(Q - Q_{\text{min}}) \]

Where Q is the signal-to-noise ratio.

\[ Q = \sqrt{N} \frac{\rho^2}{\sigma} = \sqrt{\frac{2t_T}{t_{\text{exp}}}} \frac{\rho^2}{\sigma} \]

\[ \frac{R_p}{R_*}, a^{1/4} \]
Transits - Detection

\[ P = P_T P_Q P_W \]

“Window” Probability- probability that \( n \) transits occur during the observation windows.
Transits - Detection

\[ P = P_T P_Q P_W \]

\[ P_T \approx 8\% \quad \text{(uniform for } 3\text{d}<P<11\text{d}) \]
\[ P_Q \approx 1 \]
\[ P_W \approx 20\% \quad \text{(uniform for } 3\text{d}<P<11\text{d}) \]

\[ P = 1.6\% \]

\[ N_{\text{det}} = fN_\star P = 3 \left( \frac{P}{1.6\%} \right) \left( \frac{N_\star}{3750} \right) \left( \frac{f_{a<0.1AU}}{5\%} \right) \]
Transit Searches - Flavors

Bright Targets
• RV Follow-up
• All-Sky

Intermediate Targets
• Large FOV
  STARE, Vulcan, WASP

Faint Targets
• Field Stars (Galactic Disk, Bulge)
  EXPLORE, OGLE
• Clusters*
  PISCES, EXPORT, STEPSS

Amenable to Follow-up
- RV, Oblateness, Atmospheres,
  Rings, Moons, etc.

Not Amenable to Follow-up
Primaries too faint for precise mass measurement.
  Confirmation (limits) only.

Why? Statistics!
Survey for Transiting Extrasolar Planets in Stellar Systems (STEPSS) (Open Clusters)

Advantages:
• *Primaries have common properties*
  Explore the effects of:
  Stellar Density
  Age
  Metallicity $[\text{Fe/H}] > 0$
• *Primaries have known properties*
  Statistics easy.
• *Compact systems*
  Point-and-shoot

Disadvantages:
• *Relatively Faint Stars*
  Follow-up difficult
• *Small Number of Stars*
  Difficult to probe $f < 5\%$

Requirements:
• Many (20) Consecutive Nights
• Relatively Large FOV
• Modest Aperture

Members: **Chris Burke**, S.G., Darren DePoy, Rick Pogge, Jennifer Marshall
• MDM 2.4m

• 8192x8192 4x2 Mosaic CCD

• 25x25 arcmin\(^2\)

• 0.18”/pixel

Fall 2001

• 19 nights

• NGC 1245

1 Gyr

[Fe/H]~0.0
NGC 1245

- 4-5 minute sampling
- 15 nights with data
- 9 full nights
- 0 photometric nights
NGC 1245

- Saturate at I=16
- Sensitive to Jupiter-size for G0-M0 primaries

- 6881 objects
  - 259 variable
  - 519 saturated
  - 652 blended
  - 43 too faint
- 5408 pass all cuts
- ~2500 cluster members
NGC 1245

**Ideal Sampling:**
19 Nights
8 Hours per Night
$< P_W >_{3-11} = 19\%$ (uniform)
$< P_W >_{3-11} = 24\%$ (log)

**Actual Sampling:**
19 Nights
8 Hours per Night
$< P_T >_{3-11} = 12\%$ (uniform)
$< P_T >_{3-11} = 15\%$ (log)

Expect ~2 transits for f=10% (uniform)
Expect ~3 transits for f=10% (log)
NGC 1245

Period = 3.2 days, Depth ~ 4% Grazing Binary
NGC 1245
• $f_{3-10} \leq 10\%$
• [Fe/H]=??

NGC 2099
• [Fe/H]=0.05
• 35 nights (now!)

Future:
• 1-2 Clusters/Year
• Metallicity determinations
Microlensing and Planets

Lens Equation:

\[ \beta = \theta - \frac{\theta_E^2}{\theta} \]

Angular Einstein Ring Radius

\[ \theta_E = \sqrt{\frac{4GM}{c^2}} \frac{D_{LS}}{D_{OL} D_{OS}} \]

\[ \approx 300\mu as \sqrt{\frac{M}{0.3M_\odot}} \]

Physical Radius

\[ r_E = \theta_E D_{OL} \approx 2\text{AU} \]
Microlensing and Planets

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

\[ t_E = \frac{\theta_E}{\mu} \approx 20\text{days} \sqrt{\frac{M}{0.3M_\odot}} \]

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

\[ t_p = \sqrt{q} t_E \approx 1\text{day} \sqrt{\frac{M_p}{M_J}} \]

Microlensing Searches for Extrasolar Planets
Detection Efficiency:

Naïve Estimate:
$$\frac{\theta_p}{\theta_E} \approx 3\% \sqrt{\frac{q}{10^{-3}}}$$

Enhanced Probability:
$$\approx A\frac{\theta_p}{\theta_E} \approx 15\% \sqrt{\frac{q}{10^{-3}}}$$

High-Magnification Events

Higher Efficiencies

Maximized at \( a \approx r_E \)

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

Advantages:

Sensitive to Jupiters at 1-10 AU.
Extend Sensitivity to Lower (>Mars!) Masses.

Disadvantages:

Follow-up Difficult (almost purely statistical information).
Non-repeatable.
Short Timescale Perturbations.

Basic Requirements:

Nearly Continuous Sampling.
Good Photometry for Detection.
Alerts and Follow-up

“Survey” Collaborations
- Insufficient Sampling
- Real-time Alerts

Current and Past Alerts
- EROS
- MACHO*
- MOA
- OGLE III
  (500 per year?)
Alerts and Follow-up

Follow-up Collaborations
- High Temporal Sampling
- Good Photometry

Current Collaborations
- EXPORT (Tsapras et al. 2001)
- µFUN (new collaboration)
- MOA (Bond et al. 2002)
- MPS (Rhie et al. 2000)
- PLANET (Albrow et al. 1998)
Detection and Efficiency

Microlensing sensitive to Jupiters from 1-10 AU

Albrow et al. 2000
Five Years of PLANET Data

95-99 PLANET Sample
• 43 Events

Albrow et al. 2001
Gaudi et al. 2002

Search for Planets
• \(-4 < \log(q) < -2\)
• \(-1 < \log(d) < 1\)
No Viable Detections
<33% Have Jupiter-mass companions between 1.5-4 AU
<45% Have 3 x Jupiter-mass companions between 1-7 AU
Future Prospects - Ground

Pushing to Lower Fractions

- More Efficient Monitoring
- Image Subtraction Processing

\[ \text{Factor of 3 improvement} \]  

(Gaudi & DePoy in prep)

- Increasing the Number of Alerts (OGLE III)

OGLE-III Camera

- 8 2045x4096 CCDs
- 35’ x 35’ field-of-view
- ~500 alerts per year

\[ R_{\text{exp}} \approx 1 \text{ yr}^{-1} \left( \frac{q}{10^{-3}} \right)^{1/2} \left( \frac{f}{5\%} \right) \left( \frac{R_{\text{alert}}}{500\text{yr}^{-1}} \right)^{1/2} \]
Future Prospects - Ground

- BD from 0.5-30 AU
- Mass ratio to "Cool Neptunes"

Expect $N \approx 10^f$ per year

$P = 25\%$ for $A > 10$

"Cool Neptunes"

$M_p = 0.05 M_J$, $a = 2$ AU
Future Prospects - Ground

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

Pushing to Earth Masses
- Main Sequence Alerts

Need Main Sequence Sources
Future Prospects - Ground

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

Pushing to Earth Masses
- Main Sequence Alerts
- Larger Apertures?
- Difficult with 2-tier approach

Next Generation/Space Based?
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