Serendipitous Detection of Transiting Planets in Future Synoptic Surveys

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Special Thanks To...

• Thomas Beatty (CfA, MIT)

• Cullen Blake (CfA)
Detecting Transiting Planets
Properties of current transit surveys

- Reach a required S/N on enough main-sequence stars to detect a transiting planet

- For a given type of star (i.e. FGK dwarfs):
  - At what depth (i.e. limiting magnitude) do you have enough stars in your survey area?
  - S/N should be larger than some required minimum value at that depth

\[
\frac{S}{N} \approx N^{1/2} \frac{\delta}{\sigma}
\]
Properties of current transit surveys

• Reach a required S/N on enough main-sequence stars to detect a transiting planet

• For current dedicated surveys for transiting planets:
  – At the depth where there enough stars to detect a planet:
  – S/N per point is low
  – Detection achieved using many points
For brighter stars, detection could be achieved with fewer points, but...

- Correlated noise
- Not enough stars

\[ N \propto 10^{-0.6 \Delta m} \]
A Different Regime:
Sparse Sampling, Large Area, Few Observations

Avoid correlated noise:
• Sample on timescales $\gg$ correlation timescale

Sufficient number of stars:
• Very wide area

This is the precisely the regime of future large synoptic surveys!!
Synoptic Surveys
Future Synoptic Surveys

Synoptic, adj,
1. pertaining to or constituting a synopsis; affording or taking a general view of the principal parts of a subject.

2. Meteorology Of or relating to data obtained nearly simultaneously over a large area of the atmosphere.

Astronomer’s definition: Repeated observations of a large area of the sky.
Current/Future Synoptic Surveys

SDSS-II
  • now

Pan-STARRSS
  • Early 2008

LSST
  • 2012

MPF
  • ?
Estimating the Yields of Synoptic Surveys
(with Thomas Beatty)
Estimating the Yields

• Accurate estimates difficult.

• Depend on:
  – survey strategy
  – equipment specifications
  – data analysis methods

• Approximate yields
  – Estimate total number of main-sequence stars in survey area
  – Estimate the number of transiting planets
  – Estimate limiting magnitude
Estimating the Sky Densities

Present-Day Mass Function

$M_L$, $M_R$ relations

Double Exponential Thin Disk

$M_V$-dependent scale height

Extinction

Transit Probability


Beatty & Gaudi (in prep)
## Sky Densities, Sun-like Stars

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## Sky Densities, M Dwarfs

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Limiting Magnitudes

\[ \frac{S}{N} \approx N^{1/2} \frac{\delta}{\sigma} \]

(white noise)

\[ N \approx \frac{R}{\pi a} N_{total} \]

\[ N_{total} = \frac{\epsilon T}{t_{exp} N_{fields}} \]

\[ N_{fields} = \frac{\Omega_{survey}}{\Omega_{FOV}} \]

\[ \frac{S}{N} = \left( \frac{\epsilon T}{t_{exp}} \frac{\Omega_{FOV}}{\Omega_{survey}} \frac{R}{\pi a} \right)^{1/2} \]

\[ \frac{\delta}{\sigma} \]

(white noise)
Limiting Magnitudes

\[
\frac{S}{N} = \left( \frac{\varepsilon T}{t_{\text{exp}}} \frac{\Omega_{\text{survey}}}{\Omega_{\text{FOV}}} \frac{R}{\pi a} \right)^{1/2} \frac{\delta}{\sigma}
\]

\[
\sigma = \sigma_0 \left( \frac{t_{\text{exp}}}{t_{\text{exp},0}} \right)^{1/2} \left( \frac{D}{D_0} \right) 10^{0.2(V - V_0)}
\]

\[
V_{\text{lim}} = 5 \log \left[ \left( \frac{\varepsilon T}{t_{\text{exp},0}} \frac{\Omega_{\text{FOV}}}{\Omega_{\text{survey}}} \frac{R}{\pi a} \right)^{1/2} \frac{D}{D_0} \frac{\delta}{\sigma} \left( \frac{S}{N} \right)^{-1} \right] + V_0
\]
Magnitude Limits and Yields
SDSS Magnitude Limits and Yields

• **SDSS-II**
  - Observation time = 37.5 days
  - Telescope Diameter = 2.5m
  - Efficiency = 0.5
  - Field of View = 6.25 deg²
  - Area Surveyed = 300 deg²

• **Magnitude limits**
  - Sun-like stars = 15.6
  - M dwarfs = 20.2

• **Total Yields for S/N=20**
  - Sun-like stars = 6
  - M-dwarfs = 12
Pan-STARRS Magnitude Limits and Yields

- **Pan-STARRS (Medium-Deep)**
  - Observation time = 5 months
  - Telescope Diameter = 1.8m
  - Efficiency = 0.5
  - Field of View = 7 deg²
  - Area Surveyed=1200 deg²

- **Magnitude limits**
  - Sun-like stars = 14.99
  - M dwarfs = 19.61

- **Total Yields for S/N=20**
  - Sun-like stars = 19
  - M-dwarfs = 37
Pan-STARRS Magnitude Limits and Yields

- **Pan-STARRS (Wide??)**
  - Observation time = 5 months
  - Telescope Diameter = 1.8m
  - Efficiency = 0.5
  - Field of View = 7 deg$^2$
  - Area Surveyed=12,000 deg$^2$

- **Magnitude limits**
  - Sun-like stars = 12.5
  - M dwarfs = 17.1

- **Total Yields for S/N=20**
  - Sun-like stars = 48
  - M-dwarfs = 82
LSST Magnitude Limits and Yields

- **LSST**
  - Observation time = 10 years
  - Telescope Diameter = 6.5m
  - Efficiency = 0.5
  - Field of View = 9.6 deg²
  - Area Surveyed = 20,000 deg²
- **Magnitude limits**
  - Sun-like stars = 18.5
  - M dwarfs = 23.1
- **Total Yields for S/N=20**
  - Sun-like stars = 7700
  - M-dwarfs = 15500 (4000 to V~20)
A Worked Example
(with Cullen Blake, Guillermo Torres, Josh Bloom)
SDSS-II Transit Search

- **SDSS-II M dwarfs**
  - 300 deg$^2$
  - Point sources
  - $i-z > 0.84$
  - $r < 21.2$ (5% precision)
  - M4 and later
  - $r,i,z$ light curves for 19,000 M dwarfs
  - 10-30 observations in each band
  - *At most a few points in transit*

- **Transit Search**
  - Flux decreases of $> 0.2$ mag
  - All three bands
  - Jupiter radii companions for $R<0.2 R_\odot$
SDSS031824-010018

$g=20.818$

$r=19.290$

$i=17.681$

$z=16.792$

Depth $> 0.3$ mag

(Blake et al. 2007)
PAIRITEL Follow-Up

937 JHK measurements

(Blake et al. 2007)
LRIS Keck Spectra

(Blake et al. 2007)
Mass-Radius Constraints

(Blake et al. 2007)
Other DEB in SDSS-II

Estimate:
- Color-magnitude relations
- Mass-magnitude relation
- 30% binary fraction
- Duquennoy & Mayor $q$ and $P$ distributions.
- $i<19$
- Double lined, $K>30$ km/s
- Luminosity ratio $>0.1$
- 10% duty cycle
- Eclipse depth $>10$

(Blake et al. 2007)
Planets?

Targets:
• $i-z > 0.37$, $i < 19$
• 40,000 targets with $R < 0.3R_\odot$
• Depths > 10% for Jupiters

Planet Yield:
• 21 HJ+VHJ

Follow-up:
• $K > 30$ km/s
• $M\sin i > 95 M_J$ for $P < 3$ days
• IR spectroscopy?

Smaller Planets?
• Depths > 1% for Neptunes
• Calibrate SDDS to better than 1%?
The Coming Storm
An Embarrassment of Riches?

- LSST
  - Sun-like stars = 7700
  - M-dwarfs = 15500 (4000 to V~20)
- Calibrate photometry to ~0.1%?
- All fainter than V=16
- $10^5$-$10^6$ false positives?
- Is there anything we can do with these planets?
Microlensing Planet Finder

- Monitor \( \approx 10^8 \) MS stars
- 9 months/year, 4 years
- 15 minute sampling
- \( S/N \approx 90 \) for 3 days
- \( \approx 30,000 \) Hot Jupiters
- \( S/N \approx P^{-1/3} \) \( \rightarrow \) Thousands of planets out to \( P \approx 2 \) years
- Single Transits to tens of AU
- All will have \( I > 20! \)
Statistical Analysis of Transit Candidates?

SWEEPS experience (Sahu et al. 2006)
• Statistical determination of the frequency of false positives
• Also model of Brown (2003)

More needs to be done:
• What are the uncertainties in these models?
• Variations in the binary fraction with environment?
• Do Kozai-created hierarchical triples (Fabrycky & Tremaine, Wu et al) change the results?
• Can we determine $f(M_*, r, P)$ robustly from a statistical analysis?

Can we rule out false positives without RV (for shallow transits)?
• How useful are planet detections without planet mass?