OBSERVATIONAL STUDIES OF TRANSITING EXTRASOLAR PLANETS

John Southworth
Keele University, UK
Extrasolar planets – a history

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51 Peg velocity curve
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- Current census:
  - \(\approx 1800\) planets in total
  - \(\approx 1150\) are transiting

Velocities from Torres et al. (2004)
Sky positions of the known transiting extrasolar planets

The symbol size is larger for the brighter systems (roughly proportional to the apparent V magnitude)
Finding transits

- Dedicated robotic telescopes
  - e.g. SuperWASP
  - 8 cameras with 200 mm lenses
  - $483 \text{ deg}^2$ per observation
  - 14″ per pixel
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  - search for shallow transits
  - get many types of variable stars

WASP-South installation (South Africa)
Finding transits

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- Or go to space:
  - Past: *Kepler* and CoRoT
  - Future: TESS and PLATO
Are they planets?

- False positives: not all transits are due to planets
  - Eclipsing binaries can mimic planet transits
  - Low-mass stars and brown dwarfs can have similar radius as a planet
  - WASP-South claim success rate 1 in 14; *Kepler* much higher

Mass–radius plot from planets to low-mass stars
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- Solution: spectroscopy
  - Precise radial velocities give mass
  - Observables:
    - $K_A$: orbital velocity amplitude
    - $e$: orbital eccentricity
    - $\omega$: argument of periastron

[HARPS spectrograph (credit: ESO)]
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  - Observables:
    - $K_A$: orbital velocity amplitude
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    - $\omega$: argument of periastron
  - Also get nature of parent star:
    - $T_{\text{eff}}$: effective temperature
    - $\log g$: surface gravity
    - $[\text{Fe/H}]$: metallicity

HARPS spectrograph (credit: ESO)
Follow-up light curves

- Transit shape vital for analysis
  - directly yields stellar density
- Ground-based survey photometry usually very scattered
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  - collect more photons per image
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- Example: WASP-103
  - orbital period 0.926 days
  - defocussed photometry: light curve scatter of 0.6 mmag

SuperWASP data for WASP-103 (Gillon et al., 2014)
PSFs in focus (left) and defocussed (right)
Follow-up light curve of WASP-103 (submitted)
Example: WASP-2

Discovery light curve
(Collier Cameron et al. 2007)
\( \sigma = 10 \text{ mmag} \)
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**Charbonneau et al. (2007)**

\[ \sigma = 1.9 \text{ mmag} \]

**Defocussed-photometry light curve**
(Southworth et al. 2009)

\[ \sigma = 0.46 \text{ mmag} \]
Anatomy of a transit light curve

Light curve gives: $P_{\text{orb}}$ orbital period
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- $i$: inclination of the orbit
Getting the physical properties

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- Radial velocities:
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  ⇒ density ⇒ composition and core size
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• Do we believe eclipsing binaries?
Alternatives

- Transit timing variations (TTVs):
  - gravitational perturbations shift transit times
  - transit times give planet masses
  - problems: difficult minimisation, low precision
  - only worked for *Kepler* planets so far: e.g. Kepler-11, Kepler-51
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  - calculate probabilities of each type of false positive
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- Doppler beaming:
  - stars are brighter when moving towards us
  - detecting this gives planet mass
  - e.g. Kepler-76 (Faigler et al., 2013, ApJ, 771, 26)
Total number of transiting planets: 1142
Homogeneous studies of transiting planets

- Light curve fit: JKTEBOP
- Limb darkening:
  - five different laws
- Contaminating light
- Numerical integration

Light curve of WASP-2 (Southworth et al. 2009)
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- Now done 114 transiting systems
TEPCat is a catalogue of the physical properties of the known transiting extrasolar planet and brown dwarf systems. All parts of the catalogue are available as HTML tables, with and without errorbars, and machine-readable ASCII and CSV files for detailed analysis. Most of numbers are a careful compilation of literature results, and the remainder come from my Homogeneous Studies of Transiting Extrasolar Planets papers.

- All transiting planets (html/ascii/csv)
- Homogeneous Studies (html/ascii/csv)
- For planning observations (html/ascii/csv)
- Rossiter-McLaughlin catalogue (html/ascii/csv)

http://www.astro.keele.ac.uk/jkt/tepcat/
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<th>System</th>
<th>Orbital period</th>
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<th>Teff (K)</th>
<th>[Fe/H] (dex)</th>
<th>Mass (Msun)</th>
<th>Radius (Rsun)</th>
<th>log(g) (cgs)</th>
<th>Density (psun)</th>
<th>Mass (Mjup)</th>
<th>Radius (Rjup)</th>
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<td>1.09</td>
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<td>1.251</td>
<td>51.8</td>
<td>1.56</td>
<td>1490</td>
<td>2011A&amp;A...533</td>
</tr>
<tr>
<td>CoRoT-19</td>
<td>3.897</td>
<td>0.0</td>
<td>0.0512</td>
<td>6090</td>
<td>-0.02</td>
<td>1.181</td>
<td>1.578</td>
<td>4.115</td>
<td>0.302</td>
<td>1.090</td>
<td>1.190</td>
<td>19.1</td>
<td>0.60</td>
<td>1630</td>
<td>2012A&amp;A...537</td>
</tr>
</tbody>
</table>

http://www.astro.keele.ac.uk/jkt/tepcat/
## TEPCat

[Image of the TEPCat table]

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## TEPCat

![TEPCat](http://www.astro.keele.ac.uk/jkt/tepcat/)

### Table of Rossiter-McLaughlin Effect Observations of Transiting Planets

<table>
<thead>
<tr>
<th>System</th>
<th>Teff (K)</th>
<th>$\lambda$ (degrees)</th>
<th>$\psi$ (degrees)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 Cnc e</td>
<td>5196 ± 24</td>
<td>72.4 ± 23.7, -11.5</td>
<td>indeterminate</td>
<td>Bourrier &amp; Hébrard (2014), López-Morales et al. (2014)</td>
</tr>
<tr>
<td>CoRoT-1</td>
<td>5650 ± 150</td>
<td>77 ± 11</td>
<td></td>
<td>Pont et al. (2010)</td>
</tr>
<tr>
<td>CoRoT-2</td>
<td>5598 ± 50</td>
<td>7.2 ± 4.5, 4.0 ± 5.9</td>
<td>6.1</td>
<td>Bouchy et al. (2008), Gillon et al. (2010)</td>
</tr>
<tr>
<td>CoRoT-3</td>
<td>6740 ± 140</td>
<td>37.6 ± 10.0, -22.3</td>
<td></td>
<td>Triaud et al. (2009)</td>
</tr>
<tr>
<td>CoRoT-11</td>
<td>6440 ± 120</td>
<td>prograde</td>
<td>0.1 ± 2.6</td>
<td>Gandolfi et al. (2010), Gandolfi et al. (2012)</td>
</tr>
<tr>
<td>CoRoT-18</td>
<td>5440 ± 100</td>
<td>-10 ± 20</td>
<td>20 ± 20</td>
<td>Hébrard et al. (2011)</td>
</tr>
<tr>
<td>CoRoT-19</td>
<td>6090 ± 70</td>
<td>-52 ± 27, -22</td>
<td></td>
<td>Guenther et al. (2011)</td>
</tr>
<tr>
<td>HAT-P-1</td>
<td>5975 ± 50</td>
<td>3.7 ± 2.1</td>
<td></td>
<td>Johnson et al. (2008)</td>
</tr>
<tr>
<td>HAT-P-2</td>
<td>6290 ± 60</td>
<td>1.2 ± 13.4, 0.2 ± 12.2</td>
<td>9 ± 10</td>
<td>Winn et al. (2007), Loeillet et al. (2008), Albrecht et al. (2012)</td>
</tr>
<tr>
<td>HAT-P-4</td>
<td>5860 ± 80</td>
<td>-4.9 ± 11.9</td>
<td></td>
<td>Winn et al. (2011)</td>
</tr>
<tr>
<td>HAT-P-6</td>
<td>6570 ± 80</td>
<td>166 ± 10, 160 ± 6</td>
<td></td>
<td>Hébrard et al. (2011), Albrecht et al. (2012)</td>
</tr>
<tr>
<td>HAT-P-7</td>
<td>6310 ± 15</td>
<td>182.5 ± 9.4, -132.6 ± 10.5, -16.3</td>
<td>155 ± 37, 220.3 ± 8.2, 9.3</td>
<td>Winn et al. (2009), Narita et al. (2009), Albrecht et al. (2012), Benomar et al. (2014), Lund et al. (2014)</td>
</tr>
<tr>
<td>HAT-P-9</td>
<td>6350 ± 150</td>
<td>-16 ± 8</td>
<td></td>
<td>Moutou et al. (2011), Winn et al. (2010)</td>
</tr>
</tbody>
</table>

[Source](http://www.astro.keele.ac.uk/jkt/tepcat/)
Rossiter-McLaughlin effect

- Spectroscopic anomaly during transit
  - transiting planet blocks out part of the rotating stellar surface
  - spectral line broadening no longer symmetric
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- Anomaly shape depends on orbital obliquity, $\psi$
  - $\psi$ is angle between orbital axis and stellar spin axis
  - we actually measure $\lambda$, the sky-projected obliquity
  - RM is a window on the dynamical history
Rossiter-McLaughlin measurements for transiting extrasolar planets

Sky-projected orbital obliquity $\lambda$ (degrees)

Host star effective temperature (K)
Orbital obliquity from starspots

- Starspots cause mini-brightenings during transit
  - measure spot position, size and brightness
  - multiple observations give spot motion
  - can yield orbital obliquity

Starspot anomalies in transits of WASP-19
Orbital obliquity from starspots

- Starspots cause mini-brightenings during transit
  - measure spot position, size and brightness
  - multiple observations give spot motion
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- Example: WASP-19
  - $\lambda = 1.0 \pm 1.2$ degrees
  - three anomalies could give $\psi$

Occultations

- Planet passes behind star
  - drop in brightness gives flux from dayside of planet
  - infrared: thermal emission
  - optical: reflected starlight

*Spitzer* light curves of occultations in the HD 189733 system (Charbonneau et al., 2008, ApJ, 686, 1341)
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- Results
  - some planets have large radii in the blue \( \Rightarrow \) Rayleigh or Mie scattering
  - some planets have a featureless spectrum \( \Rightarrow \) clouds
  - some planets show VO, TiO and Na in the optical
  - some planets show H\(_2\)O, CO\(_2\), CH\(_4\) in the infrared

Transmission spectrum of HD 189733 b
Future – from the ground

- Current surveys
  - WASP, HAT, HAT-South, KELT
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- Current surveys
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- Forthcoming: NGTS
  - Next Generation Transit Survey
  - near-infrared survey
  - aim: Neptune-size planets
Future – from space

- Continue to exploit *Kepler* and CoRoT data
  - *Kepler* has thousands more candidates
  - CoRoT has another $\sim 20$ objects
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- PLATO (2022-2024)
Future follow-up

- High-stability spectrographs
  - RV precision to 10 cm s$^{-1}$: VLT/Espresso (Pepe et al., 2014AN....335....8P)
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- JWST: infrared telescope
  - MIRI: 5–28 $\mu$m
  - NIRSpec: 0.6–5 $\mu$m
  - occultation and transmission spectroscopy
  - atmospheres of *habitable* transiting planets
Summary

- Transiting planets are good
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  - still need to understand host stars
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