The Transit Method: Results from the Ground

- Results from individual transit search programs
- The Mass-Radius relationships (internal structure)
- Global Properties
- The Rossiter-McCloughlin Effect
There are now 124 transiting extrasolar planets

First ones were detected by doing follow-up photometry of radial velocity planets. Now transit searches are discovering exoplanets
Radial Velocity Curve for HD 209458

Period = 3.5 days

$M_s \sin i = 0.63 \ M_{Jup}$

The probability is 1 in 10 that a short period Jupiter will transit. HD 209458 was the 10th short period exoplanet searched for transits.
Charbonneau et al. (2000): The observations that started it all:

- Mass = 0.63 $M_{\text{Jupiter}}$
- Radius = 1.35 $R_{\text{Jupiter}}$
- Density = 0.38 g cm$^{-3}$
Exoplanet transit over HD209458
September 16, 2000 - Nyrölä Observatory, Finland

An amateur’s light curve.

Hubble Space Telescope.
HD 209458b has a radius larger than expected.

Evolution of the radius of HD 209458b and τ Boob

Models I, C, and D are for isolated planets
Models A and B are for irradiated planets.

One hypothesis for the large radius is that the stellar radiation hinders the contraction of the planet (it is hotter than it should be) so that it takes longer to contract. Another is tidal heating of the core of the planet if you have nonzero eccentricity.
The OGLE Planets

- OGLE: Optical Gravitational Lens Experiment (http://www.astrouw.edu.pl/~ogle/)
  - 1.3m telescope looking into the galactic bulge
  - Mosaic of 8 CCDs: 35′ x 35′ field
  - Typical magnitude: $V = 15-19$
  - Designed for Gravitational Microlensing
  - First planet discovered with the transit method
The first planet found with the transit method
TABLE 2
PARAMETERS FOR OGLE-TR-56b

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital period (days)</td>
<td>$1.2119189 \pm 0.0000059$</td>
</tr>
<tr>
<td>Transit epoch (HJD – 2,400,000)</td>
<td>52,075.1046 \pm 0.0017</td>
</tr>
<tr>
<td>Center-of-mass velocity (km s$^{-1}$)</td>
<td>$-48.317 \pm 0.045$</td>
</tr>
<tr>
<td>Eccentricity (fixed)</td>
<td>0</td>
</tr>
<tr>
<td>Velocity semi-amplitude (m s$^{-1}$)</td>
<td>265 \pm 38</td>
</tr>
<tr>
<td>Inclination angle (deg)</td>
<td>81.0 \pm 2.2</td>
</tr>
<tr>
<td>Stellar mass ($M_\odot$) (adopted)</td>
<td>1.04 \pm 0.05</td>
</tr>
<tr>
<td>Stellar radius ($R_\odot$) (adopted)</td>
<td>1.10 \pm 0.10</td>
</tr>
<tr>
<td>Limb-darkening coefficient ($I$ band)</td>
<td>0.56 \pm 0.06</td>
</tr>
<tr>
<td>Planet mass ($M_{\text{Jup}}$)</td>
<td>1.45 \pm 0.23</td>
</tr>
<tr>
<td>Planet radius ($R_{\text{Jup}}$)</td>
<td>1.23 \pm 0.16</td>
</tr>
<tr>
<td>Planet density (g cm$^{-3}$)</td>
<td>1.0 \pm 0.3</td>
</tr>
<tr>
<td>Semimajor axis (AU)</td>
<td>0.0225 \pm 0.0004</td>
</tr>
</tbody>
</table>
OGLE transiting planets: These produce low quality transits, they are faint, and they take up a large amount of 8m telescope time.

- $K = 510 \pm 170 \text{ m/s}$
- $i = 79.8 \pm 0.3$
- $a = 0.0308$
- Mass = 4.5 $M_J$
- Radius = 1.6 $R_J$
- Spectral Type = F3 V
Prior to OGLE all the RV planet detections had periods greater than about 3 days.

The last OGLE planet was discovered in 2007. Most likely these will be the last because the target stars are too faint.
The TrES Planets

• TrES: Trans-atlantic Exoplanet Survey (STARE is a member of the network http://www.hao.ucar.edu/public/research/stare/)

  • Three 10cm telescopes located at Lowell Observatory, Mount Palomar and the Canary Islands

  • 6.9 square degrees

  • 4 Planets discovered
TrEs 2b

P = 2.47 d
M = 1.28 M_{Jupiter}
R = 1.24 R_{Jupiter}
i = 83.9 deg
The HAT Planets

- HATNet: Hungarian-made Automated Telescope (http://www.cfa.harvard.edu/~gbakos/HAT/)
  - Six 11cm telescopes located at two sites: Arizona and Hawaii
  - 8 x 8 square degrees
  - > 20 Planets discovered
HAT-P-12b

Star = K4 V
Planet Period = 3.2 days
Planet Radius = 0.96 R_{Jup}
Planet Mass = 0.21 M_{Jup} (~M_{Sat})
\rho = 0.3 \text{ g cm}^{-3}

The best fitting model for HAT-P-12b has a core mass \leq 10 M_{\text{earth}} and is still dominated by H/He (i.e. like Saturn and Jupiter and not like Uranus and Neptune). It is the lowest mass H/He dominated gas giant planet.
WASP: Wide Angle Search for Planets (http://www.superwasp.org). Also known as SuperWASP

- Array of 8 Wide Field Cameras
- Field of View: $7.8^\circ \times 7.8^\circ$
- 13.7 arcseconds/pixel
- Typical magnitude: $V = 9-13$
- >50 transiting planets discovered so far
The First WASP Planet
Coordinates
RA 00:20:40.07 Dec +31:59:23.7

Constellation
Pegasus

Apparent Visual Magnitude
11.79

Distance from Earth
1234 Light Years

WASP-1 Spectral Type
F7V

WASP-1 Photospheric Temperature
6200 K

WASP-1b Radius
1.39 Jupiter Radii

WASP-1b Mass
0.85 Jupiter Masses

Orbital Distance
0.0378 AU

Orbital Period
2.52 Days

Atmospheric Temperature
1800 K

Mid-point of Transit
2453151.4860 HJD
WASP 12: Hottest Transiting Giant Planet

Orbital Period: 1.09 d
Transit duration: 2.6 hrs
Planet Mass: $1.41 \, M_{\text{Jupiter}}$
Planet Radius: $1.79 \, R_{\text{Jupiter}}$
Planet Temperature: 2516 K
Spectral Type of Host Star: F7 V
Comparison of WASP 12 to an M8 Main Sequence Star

| Planet Mass: 1.41 M\textsubscript{Jupiter} | Mass: 60 M\textsubscript{Jupiter} |
| Planet Radius: 1.79 R\textsubscript{Jupiter} | Radius: \sim 1 R\textsubscript{Jupiter} |
| Planet Temperature: 2516 K | Teff: \sim 2800 K |

WASP 12 has a smaller mass, larger radius, and comparable effective temperature than an M8 dwarf. Its atmosphere should look like an M9 dwarf or L0 brown dwarf. One difference: above temperature for the planet is only on the day side because the planet does not generate its own energy.
GJ 436: The First Transiting Neptune

Host Star:
Mass = 0.4 M_☉ (M2.5 V)

Butler et al. 2004
Photometric transits of the planet across the star are ruled out for gas giant compositions and are also unlikely for solid compositions

Butler et al. 2004
The First Transiting Hot Neptune!

Gillon et al. 2007

**Fig. 1.** OFXB (black) and Wise (red: 1m, green: 46cm) photometry phase-folded using the ephemerids and period presented in Maness et al. (2007).

**Fig. 2.** Euler V-band transit photometry. The best-fit transit curve is superimposed in red.
**GJ 436**

**Star**
Stellar mass \( M_\odot \) \( 0.44 \pm 0.04 \)

**Planet**
Period [days] \( 2.64385 \pm 0.00009 \)
Eccentricity \( 0.16 \pm 0.02 \)
Orbital inclination \( 86.5 \pm 0.2 \)
Planet mass \( M_E \) \( 22.6 \pm 1.9 \)
Planet radius \( R_E \) \( 3.95^{+0.41}_{-0.28} \)

Mean density = 1.95 gm cm\(^{-3}\), slightly higher than Neptune (1.64)
HD 17156: An eccentric orbit planet

\[ P = 21.22 \text{ day} \]
\[ K = 275. \text{ m s}^{-1} \]
\[ e = 0.67 \]

\[ \text{RMS} = 3.98 \text{ m s}^{-1} \]

\[ M = 3.11 \, M_{\text{Jup}} \]

Probability of a transit \( \sim 3\% \)
Barbieri et al. 2007

\[ R = 0.96 \ R_{\text{Jup}} \]

Mean density = 4.88 g/cm\(^3\)

Mean for M2 star \( \approx 4.3 \) g/cm\(^3\)
HD 80606: Long period and eccentric

\[ a = 0.45 \text{ AU} \]

\[ d_{\text{min}} = 0.03 \text{ AU} \quad d_{\text{max}} = 0.87 \text{ AU} \]

\[ R = 1.03 \, R_{\text{Jup}} \quad \rho = 4.44 \, (\text{cgs}) \]
MEarth-1b: A transiting Superearth

Change in radial velocity of GJ1214.

\[ \rho = 1.87 \ (\text{g/cm}^3) \]

### Table 1 | System parameters for GJ 1214

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital period, ( P ) (days)</td>
<td>1.5803925 \pm 0.0000117</td>
</tr>
<tr>
<td>Times of centre of transit, ( T_c ) (HJD)</td>
<td>2454864.944208 \pm 0.000403 \n 2454960.7479702 \pm 0.0000903 \n 2454983.9087558 \pm 0.0000901 \n 2454999.0712703 \pm 0.000126</td>
</tr>
<tr>
<td>Planet/star radius ratio, ( R_p/R_s )</td>
<td>0.1162 \pm 0.00067</td>
</tr>
<tr>
<td>Scaled semimajor axis, ( a/R_s )</td>
<td>14.66 \pm 0.41</td>
</tr>
<tr>
<td>Impact parameter, ( b )</td>
<td>0.354 \pm 0.001</td>
</tr>
<tr>
<td>Orbital inclination, ( i ) (deg)</td>
<td>88.62 \pm 0.28</td>
</tr>
<tr>
<td>Radial velocity semi-amplitude, ( K ) (m/s)</td>
<td>12.2 \pm 1.6</td>
</tr>
<tr>
<td>Systemic velocity, ( \gamma ) (m/s)</td>
<td>(-21.100 \pm 1.000)</td>
</tr>
<tr>
<td>Orbital eccentricity, ( e )</td>
<td>&lt;0.27 (95% confidence)</td>
</tr>
<tr>
<td>Stellar mass, ( M_s )</td>
<td>0.157 \pm 0.019( M_{\odot} )</td>
</tr>
<tr>
<td>Stellar radius, ( R_s )</td>
<td>0.2110 \pm 0.0097( R_{\odot} )</td>
</tr>
<tr>
<td>Stellar density, ( \rho_s ) (kg/m(^3))</td>
<td>23,900 \pm 2,100</td>
</tr>
<tr>
<td>Log of stellar surface gravity (CGS units), ( log g_s )</td>
<td>4.991 \pm 0.029</td>
</tr>
<tr>
<td>Stellar projected rotational velocity, ( v \ sin \ i ) (km/s)</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>Stellar parallax (mas)</td>
<td>77.2 \pm 5.4</td>
</tr>
</tbody>
</table>
| Stellar photometry                              | \(|V| = 15.1 \pm 0.6 \)
\(|I| = 11.52 \pm 0.1 \)
\(|J| = 9.750 \pm 0.024 \)
\(|H| = 9.094 \pm 0.024 \)
\(|K| = 8.782 \pm 0.020 \)                                         |
| Stellar luminosity, \( L_s \)                  | 0.00328 \pm 0.000045\( L_{\odot} \)                                |
| Stellar effective temperature, \( T_{\text{eff}} \) (K) | 3.026 \pm 130                                                      |
| Planetary radius, \( R_p \)                    | 2.678 \pm 0.13\( R_{\oplus} \)                                     |
| Planetary mass, \( M_p \)                      | 6.55 \pm 0.98\( M_{\oplus} \)                                      |
| Planetary density, \( \rho_p \) (kg/m\(^3\))    | 1870 \pm 400                                                        |
| Planetary surface acceleration under gravity, \( \varrho_p \) (m/s\(^2\)) | 8.93 \pm 1.3                                                       |
| Planetary equilibrium temperature, \( T_{\text{eq}} \) (K) | \begin{align*}
                  \text{Assuming a Bond albedo of 0} & 555 \\
                  \text{Assuming a Bond albedo of 0.75} & 393
                \end{align*} |

To convert the photometric and radial velocity parameters into physical parameters for the system, we require a constraint on the stellar mass. Using the observed parallax distance\(^a\) of 12.95 \pm 0.9 pc and apparent \( K \)-band brightness, we employ an empirical relation\(^b\) between stellar mass and absolute \( K \)-band magnitude to estimate the stellar mass. With this value we find the planetary radius and mass. The uncertainty on the planet mass is the quadrature sum of the propagated uncertainty on the radial-velocity amplitude and those from the uncertainty in the stellar mass, which contribute 0.85\( M_{\oplus} \) and 0.50\( M_{\oplus} \) to the error budget, respectively. We use the observed \( I - K \) colour and an empirical relation\(^c\) to estimate the bolometric correction and subsequently the stellar luminosity and stellar effective temperature (assuming the stellar radius quoted in the table). Using the luminosity, we estimate a planetary equilibrium temperature, assuming a value for the Bond albedo, HJD, heliocentric Julian date.
So what do all of these transiting planets tell us?

JUPITER

\[ \rho = 1.24 \text{ g/cm}^3 \]

Molecular hydrogen

Metallic hydrogen

SATURN

\[ \rho = 1.25 \text{ g/cm}^3 \]

Hydrogen, helium, methane gas

URANUS

\[ \rho = 0.62 \text{ g/cm}^3 \]

Mantle (water, ammonia, methane ices)

NEPTUNE

\[ \rho = 5.5 \text{ g/cm}^3 \]

Core (rock, ice)

\[ \rho = 1.6 \text{ g/cm}^3 \]
The density is the first indication of the internal structure of the exoplanet.

<table>
<thead>
<tr>
<th>Solar System Object</th>
<th>$\rho$ (g cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>5.43</td>
</tr>
<tr>
<td>Venus</td>
<td>5.24</td>
</tr>
<tr>
<td>Earth</td>
<td>5.52</td>
</tr>
<tr>
<td>Mars</td>
<td>3.94</td>
</tr>
<tr>
<td>Jupiter</td>
<td>1.24</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.62</td>
</tr>
<tr>
<td>Uranus</td>
<td>1.25</td>
</tr>
<tr>
<td>Neptune</td>
<td>1.64</td>
</tr>
<tr>
<td>Pluto</td>
<td>2</td>
</tr>
<tr>
<td>Moon</td>
<td>3.34</td>
</tr>
<tr>
<td>Carbonaceous Meteorites</td>
<td>2–3.5</td>
</tr>
<tr>
<td>Iron Meteorites</td>
<td>7–8</td>
</tr>
<tr>
<td>Comets</td>
<td>0.06-0.6</td>
</tr>
</tbody>
</table>
Take your favorite composition and calculate the mass-radius relationship.
Masses and radii of transiting planets.

- **H/He dominated**
- **Pure H₂O**
- **75% H₂O, 22% Si**
- **67.5% Si mantle, 32.5% Fe (earth-like)**
The mass-radius relationship of planets depends on their mass, composition and inner structure.

**Cold & Hot Jupiters**

**Hot Neptunes**

**Super Earths**
HD 149026: A planet with a large core

Sato et al. 2005

Period = 2.87 d

\[ R_p = 0.7 \, R_{\text{Jup}} \]

\[ M_p = 0.36 \, M_{\text{Jup}} \]

Mean density = 2.8 gm/cm³
HD 149026 b provides strong support for the core accretion theory.

~70 $M_{\text{earth}}$ core mass is difficult to form with gravitational instability.

HD 149026 b provides strong support for the core accretion theory.

$R_p = 0.7 \, R_{\text{Jup}}$

$M_p = 0.36 \, M_{\text{Jup}}$

Mean density = 2.8 gm/cm$^3$
Most transiting planets tend to be inflated. Approximately 68% of all transiting planets have radii larger than $1.1 \, R_{\text{Jup}}$. 
Possible Explanations for the Large Radii

1. Irradiation from the star heats the planet and slows its contraction it thus will appear „younger“ than it is and have a larger radius
Possible Explanations for the Large Radii

2. Slight orbital eccentricity (difficult to measure) causes tidal heating of core → larger radius

Slight Problem:

HD 17156b: e=0.68 \quad R = 1.02 \, R_{\text{Jup}}
HD 80606b: e=0.93 \quad R = 0.92 \, R_{\text{Jup}}
CoRoT 10b: e=0.53 \quad R = 0.97R_{\text{Jup}}

Caveat: These planets all have masses 3-4 \, M_{\text{Jup}}, so it may be the smaller radius is just due to the larger mass.

3. We do not know what is going on.
Comparison of Mean Densities

Giant Planets with $M < 2 \, M_{\text{Jup}} : 0.78$ cgs

- HD 17156, $P = 21$ d, $e = 0.68$, $M = 3.2 \, M_{\text{Jup}}$, density = 3.8
- HD 80606, $P = 111$ d, $e = 0.93$, $M = 3.9 \, M_{\text{Jup}}$, density = 6.4
- CoRoT 10b, $P = 13.2$, $e = 0.53$, $M = 2.7 \, M_{\text{Jup}}$, density = 3.7
- CoRoT 9b, $P = 95$ d, $e = 0.12$, $M = 1 \, M_{\text{Jup}}$, density = 0.93

The three eccentric transiting planets have high mass and high densities. Formed by mergers?
Period Distribution for short period Exoplanets

Number

Period (Days)

0.25 1.75 3.25 4.75 6.25 7.75 9.25

Transits
RV

Transits
RV
Both RV and Transit Searches show a peak in the Period at 3 days.

The ≈ 3 day period may mark the inner edge of the proto-planetary disk, => where migration stops?
Mass-Radius Relationship

Radius is roughly independent of mass, until you get to small planets (rocks)
Close in planets tend to have lower mass, as we have seen before.

RV Planets

Transiting Planets
Stellar Magnitude distribution of Exoplanet Discoveries

Percent

V- magnitude

0.5 4.5 8.5 12.5 16.5

Transits
RV
Summary of Global Properties of Transiting Planets

1. Mass – Radius Diagram !!!! => internal composition
2. Transiting giant planets (close-in) tend to have inflated radii (much larger than Jupiter)
3. A significant fraction of transiting giant planets are found around early-type stars with masses $\approx 1.3 \, M_{\text{sun}}$.
4. The period distribution of close-in planets peaks around $P \approx 3$ days.
5. Most transiting giant planets have densities near that of Saturn. It is not known if this is due to their close proximity to the star (i.e. inflated radius)
6. Transiting planets have been discovered around stars fainter than those from radial velocity surveys
• Early indications are that the host stars of transiting planets have different properties than non-transiting planets (more details later).

• Most likely explanation: Transit searches are not as biased as radial velocity searches. One looks for transits around all stars in a field, these are not pre-selected. The only bias comes with which ones are followed up with Doppler measurements

• Caveat: Transit searches are biased against smaller stars. i.e. the larger the star the higher probability that it transits
The Rossiter-McClaurhlin Effect

The R-M effect occurs in eclipsing systems when the companion crosses in front of the star. This creates a distortion in the normal radial velocity of the star. This occurs at point 2 in the orbit.
The effect was discovered in 1924 independently by Rossiter and McClaughlin.

ON THE DETECTION OF AN EFFECT OF ROTATION DURING ECLIPSE IN THE VELOCITY OF THE BRIGHTER COMPONENT OF BETA LYRAE, AND ON THE CONSTANCY OF VELOCITY OF THIS SYSTEM

By R. A. Rossiter

ABSTRACT

The spectroscopic velocity of the Beta Lyrae system.—Elements from a series of spectrograms taken at the Allegheny Observatory in 1907 and from seven series, comprising a total of 442 spectrograms, taken at Ann Arbor in the years 1911 to 1921, show that the velocity of the center mass of the system is constant and that elliptical motion is very well satisfied. Probably no third body exists, since no disturbance of the two-body system can be detected. The accompanying elliptic velocity curve, with radial velocities indicated by the large dots, shows how well elliptical motion is satisfied.

The rotational effect.—A secondary oscillation confined to the region of the velocity curve extending 1.6 days on each side of the principal minimum (or center of the eclipse of the small bright body by the large faint body) has been isolated from the orbital velocity and measured. It has been shown to be due to the velocity of rotation of the partially eclipsed smaller component, and is here termed the rotational effect. In Beta Lyrae it has a total range of 26 kilometers. A graphical determination of this curve of rotational velocity from Shapley's light-elements of Beta Lyrae gives a duration of eclipse 40 per cent longer than the spectroscopic has shown and an amplitude correspondingly too great. Further investigation of this subject is under way.

Curves show Radial Velocity after removing the binary orbital motion.
The Rossiter-McLaughlin Effect or "Rotation Effect"

For rapidly rotating stars you can "see" the planet in the spectral line
The Rossiter-McClauothing Effect

As the companion crosses the star the observed radial velocity goes from + to – (as the planet moves towards you the star is moving away). The companion covers part of the star that is rotating towards you. You see more positive velocities from the receding portion of the star) you thus see a displacement to + RV.

When the companion covers the receding portion of the star, you see more negative velocities of the star rotating towards you. You thus see a displacement to negative RV.

As the companion crosses the star the observed radial velocity goes from + to – (as the planet moves towards you the star is moving away). The companion covers part of the star that is rotating towards you. You see more positive velocities from the receding portion of the star) you thus see a displacement to + RV.
The Rossiter-McCloughlin Effect

What can the RM effect tell you?

1) The orbital inclination
The Rossiter-McCloughlin Effect

2) The direction of the orbit
The Rossiter-McCloughlin Effect

2) The alignment of the orbit
What can the RM effect tell you?

3. Are the spin axes aligned?
HD 209458

$\lambda = -0.1 \pm 2.4 \text{ deg}$
What about HD 17156?

Fig. 2. Radial velocities of HD 17156 as a function of orbital phase, and the best-fitting model with the a priori constraint on $V \sin I_\ast$. Three symbols represent the different data sets (circle, OAO; triangle, Subaru; square, Keck). Left panel: The entire orbit. Right panel: A zoom of transit phase. Bottom panels: Residuals from the best-fit curve.

Narita et al. (2007) reported a large ($62 \pm 25$ degree) misalignment between planet orbit and star spin axes!
Cochran et al. 2008: $\lambda = 9.3 \pm 9.3$ degrees → No misalignment!

**Fig. 1.**—The fit of our Rossiter-McLaughlin effect model (solid black line) to the observational data sets. The HJST cs23 data are shown as the (red) Xs, the HET HRS data are (blue) solid squares, and the OAO/HIDES data are (green) open triangles. The dashed black line is the orbital velocity of the star in the absence of any Rossiter-McLaughlin velocity perturbation.
Hebrard et al. 2008

\[ \lambda = 70 \text{ degrees} \]
Winn et al. (2009) recent R-M measurements for X0-3

\[ \lambda = 37 \text{ degrees} \]
Table 1

Summary of RM Measurements

<table>
<thead>
<tr>
<th>Exoplanet</th>
<th>Projected Spin–Orbit Angle $\lambda$ (deg)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 189733b</td>
<td>$-1.4 \pm 1.1$</td>
<td>1</td>
</tr>
<tr>
<td>HD 209458b</td>
<td>$0.1 \pm 2.4$</td>
<td>2, 3, 4, 5, 6*</td>
</tr>
<tr>
<td>HAT-P-1b</td>
<td>$3.7 \pm 2.1$</td>
<td>7</td>
</tr>
<tr>
<td>CoRoT-Exo-2b</td>
<td>$7.2 \pm 4.5$</td>
<td>8</td>
</tr>
<tr>
<td>HD 149026b</td>
<td>$1.9 \pm 6.1$</td>
<td>9, 6*</td>
</tr>
<tr>
<td>HD 17156b</td>
<td>$9.4 \pm 9.3$</td>
<td>10, 11*</td>
</tr>
<tr>
<td>TrES-2b</td>
<td>$-9.0 \pm 12.0$</td>
<td>12</td>
</tr>
<tr>
<td>HAT-P-2b</td>
<td>$1.2 \pm 13.4$</td>
<td>13*, 14</td>
</tr>
<tr>
<td>XO-3b</td>
<td>$70.0 \pm 15.0$</td>
<td>15</td>
</tr>
<tr>
<td>WASP-14b</td>
<td>$-14.0 \pm 17.0$</td>
<td>16</td>
</tr>
<tr>
<td>TrES-1b</td>
<td>$30.0 \pm 21.0$</td>
<td>17</td>
</tr>
</tbody>
</table>

References: (1) Winn et al. (2006); (2) Queloz et al. (2000); (3) Bundy & Marcy (2000); (4) Wittenmyer et al. (2005); (5) Winn et al. (2005); (6) J. N. Winn & J. A. Johnson (2009, in preparation); (7) Johnson et al. (2008); (8) Bouchy et al. (2008); (9) Wolf et al. (2007); (10) Narita et al. (2008); (11) Cochran et al. (2008); (12) Winn et al. (2008); (13) Winn et al. (2007b); (14) Loeillet et al. (2008); (15) Hebrard et al. (2008); (16) Joshi et al. (2009); (17) Narita et al. (2007). Where multiple references are given, the quoted result is taken from the starred reference.
\( \lambda = 182 \text{ deg!} \)
HIRES data: M. Endl  HARPS data: F. Bouchy  Model fit: F. Pont

$\lambda \sim 80$ deg!
40% of Short Period Exoplanets show significant misalignments
20% of Short Period Exoplanets are even in retrograde orbits

What are the implications? Very violent past, probably due to gravitational scattering of 2 (or more) gas giant planets!