Transit Timings of HD 209458b

Karen I. Hutchins
San Diego State University
Master of Science in Astronomy
Thesis Defense
2006 July 24
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  – 51 Peg b (Mayor & Queloz 1995)
  – Discovered by radial velocity method
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• Future missions will find Earth-like planets
Jupiter versus Earth

- Jupiter $\rightarrow$ Gas Giant
- Earth $\rightarrow$ Terrestrial Planet
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- $M_{\text{Jupiter}} \sim 318 \text{ times } M_{\text{Earth}}$
- $R_{\text{Jupiter}} \sim 11 \text{ times } R_{\text{Earth}}$
- $\rho_{\text{Jupiter}} \sim 0.24 \text{ times } \rho_{\text{Earth}}$
Jupiter versus Earth

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- Earth $\rightarrow$ Terrestrial Planet
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- $R_{Jupiter} \sim 11$ times $R_{Earth}$

\[ \forall \rho_{Jupiter} ~ 0.24 \text{ times } \rho_{Earth} \]

\[ \forall \rho_{Earth} \sim 5.5 \text{ g/cm}^3, \rho_{Mars} \sim 3.9 \text{ g/cm}^3, \rho_{Asteroid} \sim 3 \text{ g/cm}^3 \]

\[ \forall \rho_{Jup} \sim 1.3 \text{ g/cm}^3, \rho_{Water} \sim 1.0 \text{ g/cm}^3, \rho_{Saturn} \sim 0.7 \text{ g/cm}^3 \]
Planet Detection Methods: Astrometry

- Measures changes in the position of a star over time
- Oldest method
- No success yet
- SIM PlanetQuest:
  - 9-meter baseline
  - Micro-arcsec accuracy
  - Earth-like planets
  - Scheduled launch 2015

Astrometric displacement of the Sun as it would be seen from 10 parsecs away (~33 light-years).
http://planetquest.jpl.nasa.gov/science
Planet Detection Methods: Radial Velocity

- Measures variations in the speed of a star as it orbits center of mass
- Uses spectroscopy
  - Shift of spectral lines
- Very successful!
- Drawbacks:
  - Calculate $M \sin i$, not $M$
  - Can’t calculate $R_{\text{planet}}$

http://planetquest.jpl.nasa.gov/science
Planet Detection Methods: Gravitational Microlensing

- Gravitational field of the star & planet bend and focus light rays
- Disadvantage:
  - Chance alignment
- Advantage:
  - Potential to detect Earth-like planets
- OGLE: 4 planets (one is only ~5.5 $M_{\text{Earth}}$)

http://planetquest.jpl.nasa.gov/science
Planet Detection Methods: Transits

- The star’s light dims as the planet transits.
- Advantages:
  - Calculate $M$, $R$, and $\rho$!
  - Planet’s atm., $T_{\text{planet}}$
- Kepler mission:
  - 0.95-m space telescope
  - Monitor ~100,000 stars
  - Earth-like planets
  - Launch: ~Oct 2008

http://planetquest.jpl.nasa.gov/science
Planet Detection Methods: Direct Imaging

- Planets are $\sim 10^9 - 10^{11}$ times fainter in V-band, $\sim 10^5 - 10^6$ in IR
- 3 “potential” planets
- TPF mission:
  - V-band coronagraph
  - mid-IR interferometer
  - 150 stars, up to $\sim 14$ pc
  - Target habitable zones

Image taken at Cerro Paranal in Chile.

**VLT-NaCo K-band**
- Distance to star $\sim 140$ pc.
- Separation is $\sim 1.4$ pc $\rightarrow \sim 300,000$ AU!
- Companion is 6 mag fainter and 1–42 $M_{\text{Jup}}$.

20 multiple-planet systems

1 extrasolar planet with orbit larger than Jupiter

10 known transiting planets

(http://exoplanets.org/massradiiframe.html)
HD 209458

- In the constellation Pegasus
- Distance ~50 parsecs away
- B = 8.18, V = 7.645, R = 7.287, I = 6.985
- G0 V (main sequence star)
- Surface temperature ~6000 K
- Solar metallicity
- $M \sim 1.1 \, M_{\odot}$, $R \sim 1.2 \, R_{\odot}$
• 1st transiting planet discovered
  - (Charbonneau et al. 2000, Henry et al. 2000)
• M ~0.66 M\textsubscript{Jup}, R ~1.35 R\textsubscript{Jup}, ρ ~0.33 g/cm\textsuperscript{3} (Witt./05)
• Radius ~10 to 20% larger than predicted:
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  3. Obliquity tides $\rightarrow$ precession of spin axis resonates with precession of orbital normal (Winn & Holman 2005)
Solid line: best-fit model, 
$R_p = 1.27 \, R_{\text{Jup}}$, $i = 87.1^\circ$
Dashed lines: planet 10% smaller (top) and 10% larger (bottom)
Partial transit observed on 1999 November 7 with the APT. Error bar represents the predicted time of inferior conjunction from the radial velocities. Transit depth is $1.58\% \pm 0.18\%$. Figure 3 in Henry et al. 2000, ApJ, 529, L41.
Planetary Ephemeris

- Ephemeris equation: $T_C = T_0 + PE$
- $T_C$ = time of mid-transit
- $T_0$ = fiducial time of mid-transit ($E = 0$)
- $P$ = orbital period
- $E$ = cycle number, an integer
Importance of a Precise Ephemeris \( (T_C = T_0 + PE) \)

1. Inference of additional bodies through deviations in the times of mid-transit
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   - An Earth-mass moon around HD 209458b would alter the time of mid-transit by up to 13 sec
   - A Jupiter-mass planet orbiting at 10 AU would alter the time of mid-transit by up to 5 sec
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   - If period of HD 209458b (~3.5 days) was accurate to 1 sec, after 1 year from $T_0$ (~100 cycles), ~2 min of error have accumulated
Discrepancy Between Ephemerides of HD 209458b

• Wittenmyer et al. 2005
  - 27 light curves → ground and space-based observations

• Knutson et al. 2006
  - 8 light curves → space-based observations (STIS)
Discrepancy Between Ephemerides of HD 209458b

- Wittenmyer et al. 2005
  - 27 light curves → ground and space-based observations
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  - 8 light curves → space-based observations (STIS)
- Periods differ by 0.26 seconds (17 sigma)
- $T_0$ differs by 91.6 seconds (12 sigma)
- Discrepancy needs to be resolved
- I calculate a revised ephemeris
Previous Observations from Wittenmyer et al. 2005

- **MLO 1-m (Wittenmyer):** 12 I-band transits
  - 2001 June through 2003 August
- **APT (Henry):** 6 B-band transits
  - 2001 October through 2004 September
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- MLO 1-m (Wittenmyer): 12 I-band transits
  - 2001 June through 2003 August
- APT (Henry): 6 B-band transits
  - 2001 October through 2004 September
- STIS (Brown): 4 R-band transits
  - 2000 April & May
- FGS (Schultz): 5 V-band transits
  - 2001 June through 2002 September
APT & MLO data were binned by a factor of 5 for clarity. Solid line is the ELC model.
New Observations

• MLO 0.6-m (Hutchins): 6 I-band transits
  – 2005 September & November
• APT (Henry): 1 B-band transit
  – 2005 November
New Observations

- **MLO 0.6-m (Hutchins):** 6 I-band transits
  - 2005 September & November
- **APT (Henry):** 1 B-band transit
  - 2005 November
- **Additional values of $T_C$:**
  - **STIS:** 4 values of $T_C$ (Knutson et al. 2006)
    - 2003 May through July
  - **Spitzer:** 2 values of $T_C$ (Richardson et al. 2006)
    - 2004 December & 2005 June
Transits Observed with the MLO 0.6-m Telescope

Reduced Chi-square values are 3.0, 2.7, and 1.9.
Transit Observed with the 0.8-m APT
Reduced Chi-square is 0.94
Tilt-correction of MLO Light Curves

- Tilt-correction process:
  1. Compute residuals (data minus model)
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     - I modified a subroutine from Numerical Recipes called “svdfit” that uses $\chi^2$ minimization to find the best-fit polynomial (a line in this case).
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3. Subtract best-fit line from the light curve
   - Light curve has now been tilt-corrected
Tilt-correction Applied

- MLO 1-m data tilt-correction:
  - 0.002 to 0.05% in rms % change (avg=0.02%)
  - Change in $T_c$ of 5.3 to 369.0 sec (avg=111.5 s)
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- Conclusion: Tilts can greatly affect $T_C$!
Transit Observed with the MLO 1-m Telescope

Before Tilt-correction Reduced Chi-square is 3.7
Transit Observed with the MLO 1-m Telescope

After Tilt-correction Reduced Chi-square is 1.4
Transit Observed with the MLO 0.6-m Telescope

Before Tilt-corrrection Reduced Chi-square is 4.9

I-band Magnitude

Residuals (mag)

Orbital Phase

HJD 2453640
Transit Observed with the MLO 0.6-m Telescope

After Tilt-correction Reduced Chi-square is 2.7
Calculating Observed Times of Mid-transit

1. Start with an initial value of $T_c$
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5. Repeat process for a range in $T_C$ of 0.02 days (~30 min) above and below initial $T_C$
6. $T_C$ that yields the best fit to the model is selected as the observed time of mid-transit
Calculation of the Best-fit $T_c$

$\chi^2_\nu + \left(\frac{\chi^2_\nu}{\text{NDOF}}\right)$
Calculating Predicted Times of Mid-Transit

• Use Wittenmyer et al.’s ephemeris to calculate the predicted times of mid-transit

• \( T_{\text{predicted}} = T_0 + (P \times E) \)

\[ \forall \sigma_{T_{\text{predicted}}} = (\sigma_{T0}^2 + (\sigma_P^2 \times E^2))^{\frac{1}{2}} \]
O-C Diagrams

- Observed $T_C$ minus Calculated $T_C$
- Trends in the O-C values:
  1. Linear trend indicates an incorrect period
     - Positive slope $\rightarrow$ Period is too small
     - Negative slope $\rightarrow$ Period is too big
O-C Diagrams

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- Trends in the O-C values:
  1. Linear trend indicates an incorrect period
     - Positive slope $\rightarrow$ Period is too small
     - Negative slope $\rightarrow$ Period is too big
  2. Parabola/Sinusoid pattern indicates a changing period
     - Changing period could be due to a 3rd body
O-C Diagram Using Ephemeris of Wittenmyer et al. (2005)
Dashed lines indicate the uncertainty in the ephemeris.
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Reduced Chi-square is 9.5

[Graph showing O-C (seconds) against Time (HJD - 24500000) with various data points and error bars.]
Includes all of the data that Wittenmyer had.
1=Charbonneau et al. 2000
2=Mazeh et al. 2000
3=Jha et al. 2000
4=STIS (Brown et al. 2001)
5=STIS (Schultz et al. 2003)
6=Deeg et al. 2001
7=FGS & STIS (Schultz et al. 2004)
8=FGS (Schultz et al. 2003)

Cycle 0=Wittenmyer et al. 2005

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Calculation of New Ephemeris

Time of Mid-transit (HJD - 2450000)

Cycle Number

y-intercept = T0
slope = Orbital Period
Comparison of Ephemerides

- **Wittenmyer et al. 2005:**
  - \( T_0 = 2452854.82545 \pm 1.35 \times 10^{-4} \) HJD (11.7 seconds)
  - \( P = 3.52474554 \pm 1.8 \times 10^{-7} \) days (0.016 seconds)

- **Knutson et al. 2006:**
  - \( T_0 = 2452826.628521 \pm 8.7 \times 10^{-5} \) HJD (7.5 seconds)
  - \( P = 3.52474859 \pm 3.8 \times 10^{-7} \) days (0.033 seconds)

- **My ephemeris:**
  - \( T_0 = 2452854.825942 \pm 4.5 \times 10^{-5} \) HJD (3.9 seconds)
  - \( P = 3.52474714 \pm 1.6 \times 10^{-7} \) days (0.014 seconds)
O-C Diagram Using Revised Ephemeris

Reduced Chi-square is 8.8
O-C Diagram Using Ephemeris of Wittenmyer et al. (2005)

Reduced Chi-square is 9.5

Time (HJD - 2450000)

O-C (seconds)
Conclusions

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3. Need to revise Wittenmyer et al.’s period
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4. Inconsistency between the FGS & STIS data
   - Future projects could look into this
Thank you!