TRANSIT TIMING

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Outline

• Transit method and its observables
• Using transit timing to detect other planets
• The Transit Light Curve (TLC) Project
• Summary
Transit Observables

- Times of transit center
- Duration of transits
- Depth of transits
- Shape of transits

HD 209458b
HST/STIS photometry
Brown et al (2001)
Transit Observables

- Times of transit center
- Duration of transits
- Depth of transits
- Shape of transits

HD 209458b
HST/STIS photometry
Brown et al (2001)
Orbit variations affect transit timings

• The intervals between successive transits of a planet on a fixed Keplerian orbit are constant.
• But the intervals will gradually change for orbits that precess due to the oblateness of the central star, general relativity, or the presence of other mass in the system (Miralda-Escude 2002).
• Tidal dissipation will alter the semimajor axis and eccentricity of a close-in planet, thereby changing the transit timings (Sasselov 2003).
• HOWEVER, the short-term interactions with other planets can have an even more important influence on the intervals between successive transits. This has been suggested for HD209458b (Bodenheimer et al 2004).
Orbit variations affect transit timings

• Many of the theoretical aspects of the Transit Timing Variations (TTV) method have been worked out in a series of theory papers.

Holman & Murray 2005 Science 307, 1288
Agol, Steffen, Sari, and Clarkson 2005 MNRAS 359, 567

Heyl & Gladman 2007 MNRAS 377, 1511 (long-term variations)
Simon et al. 2007 A&A 470, 727 (“Exomoons”)

• The method has already been applied to specific systems
TrES-1: Steffen & Agol 2005 MNRAS 364, 96
HD 209458b: Agol & Steffen 2007 MNRAS 374, 941
HD 209458b: Miller-Ricci 2007 (submitted)
The CoRoT Mission

Suzanne Aigrain’s talk today

CoRoT-Exo-1b
The Kepler Mission

Bill Borucki’s talk today

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Michelson Summer Workshop

26 July 2007
Our Solar System

Variation in the time between successive transits, recorded by a distant observer in the plane of each planet.
HD209458b with a hypothetical additional planet

Method

• Three-body problem (star and two planets, co-planar)
• $M_2 = M_j$
• Numerical integration of the heliocentric equations of motion
  • Bulirsch-Stoer numerical integrator
  • Relative energy error $dE/E \sim 10^{-12}$
• Iteratively search for times of transit center
• Calculate interval between successive transits

Not a traditional O-C plot.
Timing variations vs Period and Eccentricity

1 $M_J$ transiting planet
1 $M_J$ perturber
Co-planar

Analytic approximation:

$$\Delta t \sim \frac{45}{16\pi} \left( \frac{M_2}{M_\star} \right) P_1 \alpha^2 \left( 1 - \sqrt{2} \alpha^{3/2} \right)^{-2}$$

$$\alpha = \frac{a_1}{a_2 (1 - e_2)}$$

- Linear in $M_2$
- Inversely proportional to $M_\star$
- Factor of $P_1$
- Factor of $(P_1/P_2)^2$
Timing variations vs Period and Eccentricity

1 $M_J$ transiting planet
1 $M_E$ perturber
Resonant planets are not uncommon

- GJ 876b & c 1:2
- HD 82943b & c 1:2
- 55 Cnc b & c 1:3

Thommes 2005

Zhou et al 2005
Extreme case of GJ876: planets in resonance

Transit interval variation

Eccentricity

Semimajor axis
Transit timing of Trojan planets

Figure from Ford & Gaudi 2007
Transit timing of Trojan planets

Ford & Holman 2007

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Comparison of TTV signals

1 $M_E$ Trojan

28 $M_E$ in exterior 2:1

5 $M_E$ in interior 3:2

Ford & Holman 2007
Transit timing of “Exomoons”

Simon et al. 2007
Double Transiting Systems

• If one sees transits of one planet in a multiple planet system, what is the probability of seeing transits of a second planet?
• Can obtain estimates of masses and radii of both planets
• This allows estimates of the densities of the planets, without radial velocity measurements.

(Also David Koch’s 1995 DPS abstract and poster)
Detection limits

\[
\frac{\sigma_{t_c}}{t_T} \sim (\Gamma t_T)^{-1/2} \rho^{-3/2}(1 - \beta^2)^{-1/4}
\]

\(\sigma_{t_c}\) = error in measurement of transit center
\(t_T\) = transit duration
\(\Gamma\) = stellar photon count rate
\(\rho = R_p/R_\star\)
\(\beta\) = impact parameter (in stellar radii)

Assumes photon noise limited observations

For Kepler (\(D = 0.95\ m\), broad filter):

\(\Gamma = 7.8 \times 10^8 10^{-0.4(V-12)}\ \text{hr}^{-1}\)

- For a hot Jupiter orbiting a \(V = 12\) solar-type star, \((\rho \sim 0.1, t_T \sim 3\text{hr})\):
  \(\sigma_{t_c} \sim 10\ \text{s}\)

- For an Earth-sized planet in a 1-year orbit about a \(V = 12\) solar-type star, \((\rho \sim 0.01, t_T \sim 13\text{hr})\):
  \(\sigma_{t_c} \sim 500\ \text{s}\)

For Magellan (\(D = 6.5\ m\), broad filter):

\(\Gamma = 3.7 \times 10^{10} 10^{-0.4(V-12)}\ \text{hr}^{-1}\)

- For a hot Jupiter orbiting a \(V = 12\) solar-type star, \((\rho \sim 0.1, t_T \sim 3\text{hr})\):
  \(\sigma_{t_c} \sim 1\ \text{s}\)

Requires control of systematic effects
What can we do while we wait for results from CoRoT and Kepler?
We can use existing ground-based observations: TrES-1

Steffen & Agol 2005

Winn, Holman, Roussanova 2007
We can use existing space-based observations: HD 209458b

Agol & Steffen 2007
HD 209458b perturber mass limits

Interior perturber

Exterior perturber

Agol & Steffen 2007

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HD 209458b

Agol & Steffen 2007
TrES-1 vs HD 209458b

Agol & Steffen 2007
HD 209458b

Agol & Steffen 2007
Transit timing with Spitzer

HD 189733b

~6 sec timing precision for primary transit.

~24 sec timing precision for secondary eclipse.

Best achieved to date.

Eric Agol has a Spitzer program to observe 6 primaries and 6 secondaries of HD 189733b.

Knutson et al 2007
We can collect more ground-based data: The Transit Light Curve Project
The Transit Light Curve (TLC) Project

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Guillermo Torres (CfA)
Gil Esquerdo (CfA, PSI)
Mark Everett (PSI)
Anna Roussanova (MIT)
Andras Pal (Eotvos)
Wesley Fraser (U. Vic)
Lynne Jones (NRC Canada)
Carl Hergenrother (LPL)
The TLC Project:

We have initiated a long-term campaign to build a library of high-precision transit photometry.

The goals of the project are:

1. To refine the physical and orbital parameters of all suitable known transiting extrasolar planets.

2. To search for transit time variations that may result from the perturbation of other planets, precession, tidal dissipation, etc.

3. To search for stellar flux reflected from extrasolar planets near times of secondary eclipses to constrain the atmospheric properties of such planets.
FLWO 1.2m, KeplerCam z-band observations: 30 sec exposures, auto-guiding, 11.5 sec read/reset time
Aperture photometry with 4 nearby comparison stars of similar magnitude and color,
differential extinction correction.

\[ M_S = 1.00 \pm 0.03 \, M_{\text{sun}} \, \text{assumed.} \]

\[ R_p = 1.184 \pm 0.025/-0.018 \, R_{\text{jup}} \]

\[ R_s = 0.928 \pm 0.018/-0.013 \, R_{\text{jup}} \]

Uncertainties dominated by stellar mass.

Uncertainties in \( T_C \) unc. \( \sim 15-20 \) sec, comparable or better than with HST.

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Kepler cam z-band observations: 30 sec exposures, auto-guiding, 10 sec read/reset time
Aperture photometry with nearby comparison stars of similar magnitude and color, differential extinction correction.

Mild a priori constraint on limb darkening coefficients.

$$T_C \text{ uncertainties} \sim 15 \text{ sec.}$$

$$R_P = 1.085 +/- 0.029 \ R_{jup}$$
$$R_S = 0.812 +/- 0.020 \ R_{jup}$$
$$M_S = 0.89 +/- 0.05 \ M_{sun} \text{ assumed.}$$

Uncertainties dominated by stellar mass.
TrES-1

$T_C$ uncertainties $\sim 10$-15 sec
TrES-1

The KeplerCam data are remarkably free of systematic errors!
The TLC Project
What is the TLC Project doing right?

KeplerCam has rapid readout and excellent cosmetic properties.

For moderately bright (V~10-12) northern hemisphere targets we have

- Plenty of signal and little scintillation in 30 sec exposures with 1.2-m.
- Numerous nearby comparison stars of similar magnitude and color.
- Good sampling of the PSF.
- Good resolution of the 4 points of contact in $z$ band.
- Apparent lack of significant systematic errors (for many targets).

We are able to obtain and schedule, through the formal TAC process and informal trading and collaboration, multiple nights of observation near the time of announcement.

High-precision, high cadence photometry allows us to fit for the radius of the star and planet, assuming only the stellar mass.
We can re-use spacecraft to observe transiting planets

EPOXI selected!

A’Hearn (DIXI PI)  
Deming (EPOCH PI)

Charbonneau (CfA)  
Holman (CfA)
Kuchner (GSFC)  
Lisse (JHU)
Livengood (GSFC)  
Pedelty (NASA)
Richardson (GSFC)  
Schutz (NASA)
Seager (DTM)  
Veverka (Cornell)
Wellnitz (U. MD)

Drake Deming’s talk today
We propose new space missions: There is an Announcement of Opportunity for NASA Small Explorer Missions.
Summary of Transit Timing

• The presence of one or more additional planets in transiting systems can lead to variations in the times, durations, and light curve shapes of transits.

• Many of these variations will be detectable with Kepler, CoRoT, EPOXI/EPOCh, or ground-based telescopes, allowing one to detect the presence of additional planets in transiting systems.

• More theoretical work is needed:
  - The non-co-planar case, including transit durations and depths.
  - The inverse problem of determining the perturbing planet’s orbit and mass.
  - More detailed work on the observational limits.

• There is an opportunity to propose new Small Explorer Missions.