Title: Transit Timing and Duration Variations for Discovery and Characterization of Exoplanets

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Abstract Transiting exoplanets in multi-planet systems have non-Keplerian orbits which can cause the times and durations of transits to vary. We review the theory and observations of transit timing variations (TTV) and transit duration variations (TDV).

Introduction

- Non-Keplerian perturbations [DF] - Uranus/Neptune (Leverrier/Adams) [DF] - Discovery of transits - refer to other chapters [DF] - Definition of TTVs/TDVs [DF] (Figure? O-C method) (Holman and Murray 2005; Holman et al 2010) - History: theory, observation (Schneider TTV, Miralda-Escude' TTV) [EA] (Miralda-Escudé 2002; Holman et al 2010)

Preliminaries

Since the gravitational interactions between planets occurs on the orbital timescale, the amplitude of transit timing variations is proportional to the orbital period of each planet, as well as a function of other dimensionless quantities. Thanks to Newton's second law and Newton's law of gravity, the acceleration of a body does not depend on its own mass. Thus, the transit timing variations of each planet scale with the

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masses of the *other* bodies in the system. In a two-planet system, then, to lowest order in mass ratio,

$$\delta t_1 \propto P_1 \frac{m_2}{m_0} f_1(),$$
$$\delta t_2 \propto P_2 \frac{m_1}{m_0} f_2(), \quad (1)$$

where the masses of the star and planets are m_0, m_1, and m_2, and f_1 and f_2 are a function of the period ratio and the angular orbital elements of the planets.

- Basic scalings: ∝P, $\propto m/M_{star}$ for the perturber, stronger near resonance [EA] - Energy/angular momentum conservation [DF] - Linear TTV (independently adds from different planets, off resonance) - - Applications: [EA] - Detection - Confirmation - Characterization - Sensitive to density since time-dependent: transits are sensitive to density of star; TTV are sensitive to mass ratio; transit depth radius ratio - so we get density of planet from transits + TTV. Dimensions of G are density and time. - TTV + RV gives Mass + radius ; CBPs as example

Theory

- TTVs: - Inner Keplerian variation; CBPs as example (Kepler-16) [DF] - Near-resonant TTVs - Lithwick et al. [DF] (Figure - mechanism + data) - Degeneracy - multiple resonances can give same solution (Kepler-19); Breaking degeneracy with TDV as well [DF] - Chopping/other harmonics - KOI 1353 / KOI-872 [EA] (Figure) - Resonance - Kepler-30? Ne'svorny (1603.07306); Boue'+2012 - Kepler-223 (resonant chain - to fit data & stability); room for more work on this. [DF] - Exomoons [EA] - Light time? Borkovits deconvolution [DF] - Borkovits(?) - KOI 1474 cleaner example? Or leave out? Future – circumstellar planets in binaries; Schwartz et al. w/ Haghighipour. [DF] - TDVs - Precession - Kepler-108 1606.04485 / KOI-142 Nesvorny / KOI-13 (Mazeh) - and CBPs turning on or off. [DF] Ragozzine/Wolf/Pal/Koscis/Jordan - GR precession - Heyl & Gladman; J2 (Figure - CBP? - Kepler-47? Kostov? Kepler-35? Try them out.) - Exomoons [EA]

Observations/Practical considerations

Confirmation of multi-planet systems in Kepler anti-correlated sinusoids, Ford GPs [DF] [Some firsts to history section; some best-cases as examples in theory section] - Timing precision: [EA] - Comes from steepest part of lightcurve ingress/egress - Signal-to-noise of TTV/TDV measurements (Carter/Winn; Rogers/Page) - Finite-exposure time effects - Effects of stellar variability: flux variability, star spots.

Science Results

- Best characterization, specifically mass: Kepler-36 - conjunctions/impulse/Hill approximation (N-body) [EA] - Other favorite systems? Kepler-11 puffy/packed planets [DF] - Best eccentricity constraint for a super-Earth? Kepler-36? Include? - Ensemble TTV analysis: Xie - differing architecture for the single-transiters due to less frequent TTV, Hadden-Lithwick - eccentricity distribution; Hot Jupiters lonely (Steffen); Latham - gas giants less frequent in multi-transiting (no TTVs) [DF] - Measuring masses - Steffen bias? [DF] - N-body modeling of Kepler-systems: Jontof-Hutter [DF] (Mass-radius Figure? - ask Daniel Jontof-Hutter) Transparency to avoid big error bars visually dominating. EA will make the figure. Referenced Wayne Hu figure on cosmo constraints. - CBPs [DF]

Future

- More thorough TTV analysis: GPs - for measuring transit times - Follow-up of Kepler targets - Comparison of TTV masses with RV masses: better constraints and confidence in both methods? - MCMC with high-multiplicity systems - TESS, JWST, CHEOPS, PLATO, ? - TTV/TDV of exomoons - HZ exoplanets - Smaller CBPs - Stellar/planet characterization: TTV + RV

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Neptune: Bouvard/Adams/Le Verrier/Galle

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