High-Accuracy Measurements of Variations in Transit Timing: A New Method for Detecting Terrestrial-Class Extrasolar Planets

A science white paper submitted to Astro2010 Decadal Survey
(Planetary Systems and Star Formation)

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Introduction

One of the most important goals of exoplanetary science is to detect and characterize low-mass planets similar to our Earth. The detections of these objects, in particular in the habitable zones of their host stars, will not only increase our knowledge of the possibility of the existence of life elsewhere in the universe, it will also help us to refine theories of planet formation. This white paper aims to describe a new planet detection technique, namely the Transit Timing Variation (TTV) method, that is capable of making large advances towards both of these objectives.

The transit photometry technique has been successful in detecting close to 50 extrasolar planets. Beyond the existing ground-based transit surveys, the ESA's CoRoT satellite (Baglin et al. 2002) has detected several transiting planets, and the planned launch of NASA's Kepler mission (Borucki et al. 2003) is expected to discover many additional transiting systems. Given that the simulations of planet formation indicate that planets tend to form in multiples, it is quite likely that many of these transiting systems are hosts to smaller planetary bodies. The gravitational forces of the latter objects can perturb the motions of their giant counterparts causing variations in the times of their transits. The focus of this white paper is on presenting high-accuracy measurements of such transit timing variations as an efficient method to search for additional and smaller planets in transiting systems.

During the past few year, a great deal of theoretical research has been done on the extension of the applicability of the TTV method (e.g., Heyl & Gladman 2007 and Miralda-Escude 2002 on searching for long-term effects, Pal & Kocsis 2008, Jordan & Bakos 2008, Ragozzine & Wolf 2008, and Kipping 2008 on variations in transit duration or TDVs, Scharf 2007, and Rafikov 2008 on the effects of parallax, Ford & Holman 2007, Madhusudhan & Winn 2008 on the detection of Trojans by comparing transit times to RV phase, and Ford & Holman 2007, and Simon et al. 2007 on the timing influence of Trojan planets and exomoons).

The sensitivity of the TTV method is strongly enhanced when the perturbing planet is in a mean-motion resonance (MMR) with the transiting object (Fig. 1). In such orbits, the transit timing variation depends on the planet-planet mass-ratio rather than planet-star mass-ratio. For example, for a transiting Jupiter-mass planet in a 3-day orbit, an Earth-mass planet in the 2:1 resonance will cause periodic variations in the transit timing that have an amplitude greater than one minute (Fig. 1). Simulations of the long-term stability of transiting systems indicate that Earth-like or Super-Earth objects in low-order resonances and with orbital eccentricities and inclinations smaller than 0.2 and 25 deg., respectively, produce much stronger TTV signals (Fig.3 and 4, Haghighipour, Steffen & Agol 2008, Haghighipour 2009). Analyzing the variations of transit times in planetary systems can address many important questions regarding planetary populations, characteristics, planet formation, and evolution theories. We address several of these questions here.

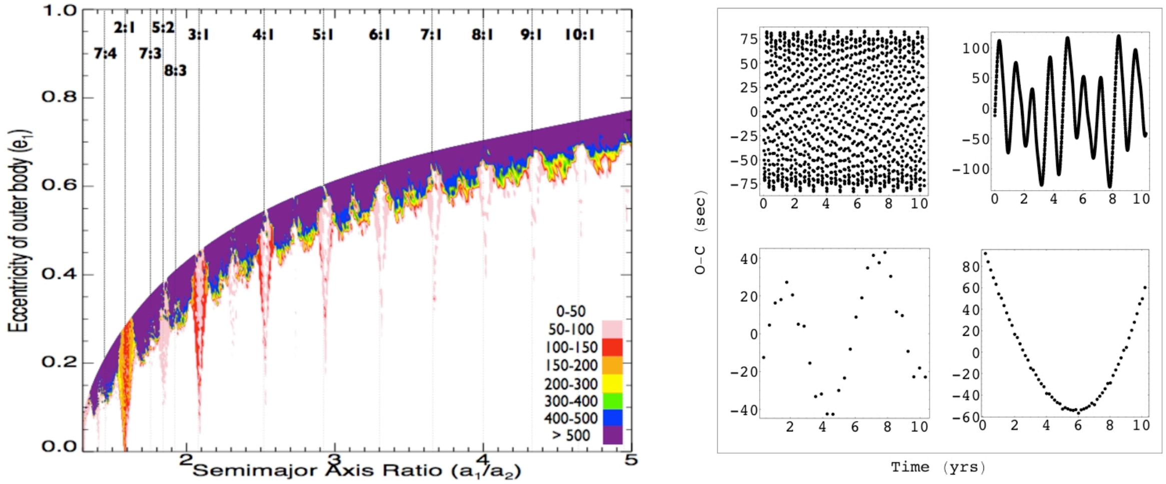

Fig. 1 *Left*: The TTV signal induced by an outer planet of one Earth-mass in the *(a-e)* space. The color indicates the median RMS TTV amplitude (in seconds) of 10 systems with the specific orbital parameters. Simulations assume data are known for 50 consecutive transits. The upper envelope defines the Hill stability limit. As shown here, TTV signals are enhanced near several mean-motion resonances. *Right*: The TTV signal of a Jupiter-mass transiting planet that orbits a solar-mass star and is perturbed by an Earth-mass planet. The orbits of both planets were initially circular. The Jupiter-mass planet was on a 3-day orbit and the orbit of the perturber was in an interior 1:2 MMR (upper left), or exterior 1:2 MMR (upper right). For the graph in the lower left, the gas-giant has a period of 130 days, both planets have an eccentricity of 0.05, and the perturber orbits at 1 AU. For the graph on the lower right, the perturber is at 1 AU, its eccentricity is 0.25 and it is in an exterior 6:1 MMR. The orbit of the gas-giant planet in this case has an eccentricity of 0.15.

Planet Detection

- The TTV method can increase the scientific value of other transit search programs such as NASA's Kepler mission. It provides the capability to discover additional planets around stars with a transiting planet, even if the second planet does not transit the star. This could be particularly useful for detecting terrestrial-mass planets in the habitable zone where such a planet has a reduced geometric probability of transiting.
- Transit timing can be quite sensitive to low-mass planets. As such, it can test theoretical models of planet formation and migration, which predict that terrestrial mass planets should be common around stars with a short-period giant planet (Fig. 5, Narayan et al. 2005).

Planet Formation Theory

- The core-accretion model of giant planet formation predicts that many stars in transiting systems may have lower-mass planets in or near interior and/or exterior mean-motion resonances. The details of the trapping in different resonances depend on the migration timescale, the disk lifetime, and the eccentricities and inclinations of both bodies at the time they approach a resonance. The study of the frequency of planets in or near various resonances can therefore provide constraints on the migration process. (This is similar to the constraints on the timescale and extent of migration for Neptune based on the resonant Kuiper belt objects).
- Provided that sufficient TTV observations are made, a null result would also be significant. While the core-accretion model predicts that trapped terrestrial-class planets should

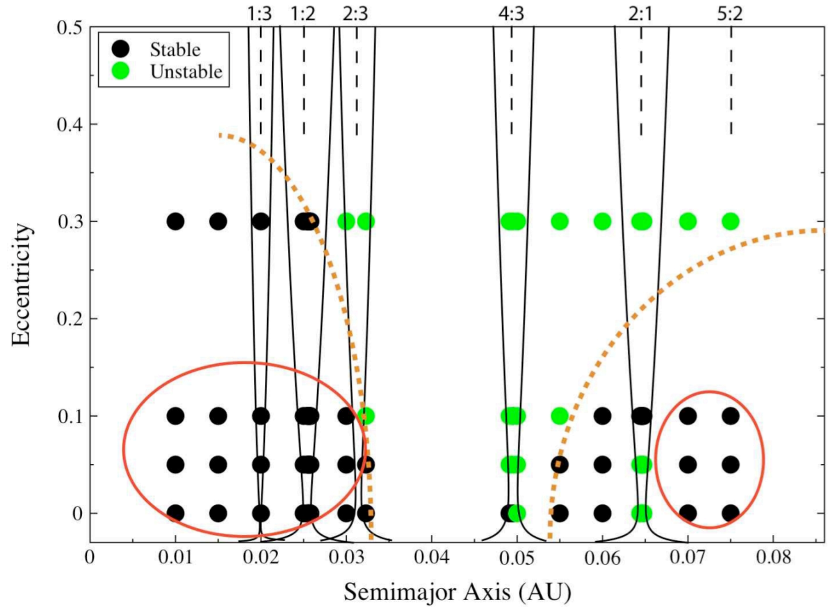

Fig. 3 Graph of stability for an Earth-size planets in a transiting system. The central star is Sun-like. The transiting planet (not shown here) is Jupiter-like in a 3-day circular orbit at 0.0407 AU. The circles correspond to the values of the semimajor axis and eccentricity of the Earth-like planet at the beginning of each simulation. Black circles show stable planets and green shows instability. The orange dotted lines show the boundaries of the unstable region for the Earth-size planet. An Earth-size planet with initial semimajor axis and eccentricity in this region will be certainly unstable. The red circles present conservative regions of the stability of a terrestrial-class object. The locations and widths of MMRs between the Earth-size and transiting planets are also shown (Haghighipour 2009).

be common, the gravitational instability model of planet formation does not anticipate the presence of such planets in any quantity. Thus, the discovery of small objects in or near MMR with transiting planets (precisely the regime where the TTV technique is most sensitive) would support the former theory (Zhou et al. 2005) while the lack of such planets would support the latter or place strong constraints on parameters of migration theory, particularly if the period of the transiting planet were a few tens of days, and the effects of stellar-induced tides are reduced.

- The TTV method can also measure the ubiquity of closely packed planetary systems (e.g. Juric & Tremaine 2007) and/or study the dynamical properties of systems with strongly interacting planets (see the white paper by Ford et al submitted to PSF for details on these theoretical challenges). Small planets on interior resonant orbits with a hot Jupiter (or the lack thereof) would constrain models of tidal interactions that may cause the orbit of the inner planet to decay (D. Fabrycky, private communication).
- The origin of the eccentricities of extrasolar planets remains unclear. One possible evolution scenario, which occurs post-migration and post-disk dissipation, is gravitational scattering among multiple massive planets. Several recent studies (Chatterjee et al. 2008; Ford & Rasio 2008; Juric & Tremaine 2008) have explored the feasibility of this model as a function of separation from the star. TTV discoveries will help confirm or refute this scenario by the new eccentricity and semimajor axes distributions inferred by the method.

Characterization of Planetary Systems

- Extrasolar planetary orbits range from circular to nearly parabolic, as indicated by known planets (HD 20782 b, HD 80606 b, HD 4113 b) with eccentricities > 0.9. As indicated by Fig. 1, highly eccentric perturbers most often produce the largest (> 500 s), most clearly detectable

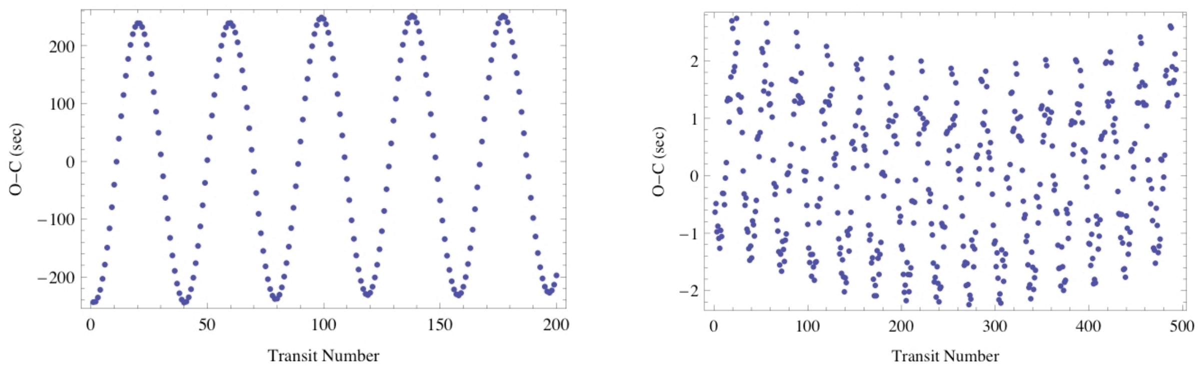

Fig. 4 Graphs of TTV signals for an Earth-size planet in an interior 1:2 (Left) and exterior 5:2 (right) MMR with a transiting giant planet (Haghighipour et al 2008).

TTV signals. Therefore, the detection or lack thereof of such signals may help constrain the typical locations at which highly eccentric exoplanetary orbits are found.

- From TTV analyses, one may be able to identify the mutual inclination of planets in a transiting system (Miralda-Escude 2002). That quantity has implications for mechanisms that allow the growth of eccentricities among planets (e.g., Chatterjee et al. 2007). It can also provide a determination of the mass of a non-transiting perturbing planet, something that is very difficult to identify with other planet detection techniques.
- As with double-lined eclipsing binaries, in systems where multiple planets transit, there can be sufficient information which allow the determination of the absolute masses and radii of the two interacting and transiting planets as well as those of the host star, independent of stellar models. This is crucial when detecting planets with terrestrial masses (which would otherwise be challenging or impossible with the radial-velocity technique) and allows for a measurement of the densities of these objects (Holman 2009).
- The knowledge of the mass and orbit of additional planets can help to interpret observations of the transiting planet. For example, it has been proposed that planets with unexpectedly large radii might have been heated by a combination of tidal dissipation in the planet and orbital perturbations from other bodies (Bodenheimer et al. 2001). For low-mass planets, measuring masses and radii with ~5% precision could enable theorists to place significant constraints on the composition of Super-Earth planets (Valencia et al. 2007). For an Earth-mass planet in the habitable zone of a solar like star, such precise masses could come from hundreds of high-precision radial velocity measurements. Transit timing variations would provide a complimentary data set that could significantly reduce the number of radial velocity observations needed.

Requirements for a Successful Transit Timing Program

- **Transit Observations** Searching for planets with the TTV method requires precise photometric observations during many transits. For a photometric precision σ_{ph} the central time T_c of a given transit can be measured with an accuracy of $\sigma_{T_c} \sim [t_e/(2\Gamma)]^{1/2}\sigma_{ph}\,\rho^{-2}$ (Ford & Gaudi 2006, Holman & Murray 2005) where t_e is the duration of ingress/egress, Γ is the rate at which observations are taken, and ρ is the ratio of the planet radius to stellar radius (this equation ignores limb-darkening). For typical parameters and millimagnitude photometry $\sigma_{ph} \sim 10^{-3}$, and T_c can be measured to the tens of seconds (e.g., Brown et al. 2001; Holman et al. 2006). Such precision enables the detection of Earth-mass companions to transiting 3-day period gas-giants for optimal (i.e. resonant) configurations (Steffen & Agol 2005). For longer period transiting planets, the sensitivity is correspondingly better, scaling as $m_2 \propto P_1^{-1}$, where P is period and 1,2 label the transiting and perturbing planets.

Achieving millimagnitude photometry on stars of V~11-13 magnitude is generally not a problem of a sufficient photon rate, even for telescopes as small as ~ 20". Rather the difficulties are due to the limited dynamic range, the scarcity of comparison stars of similar magnitude, and systematic errors in the photometry, such as correlated noise (Pont et al. 2006). In this sense, large-format, high quality, monolithic cameras on relatively small aperture telescopes are ideal.

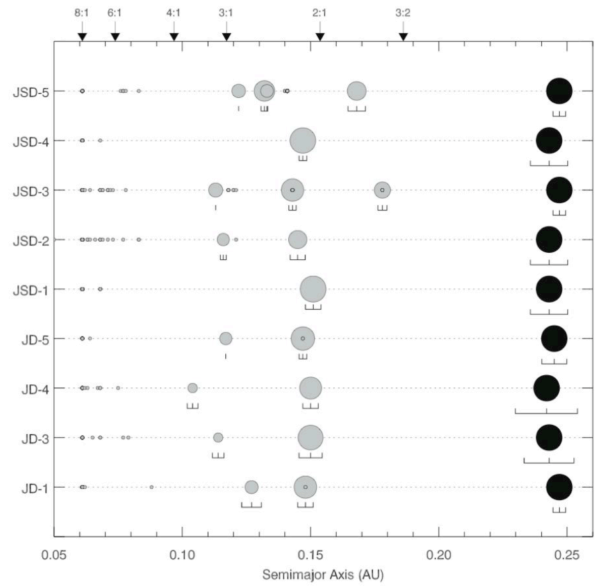

Fig. 5 Terrestrial planet formation interior to the orbit of a hot-Jupiter (Mandell et al 2007). As shown here, terrestrial planets can form near MMR resonances with the giant planet.

A proper TTV study of a significant fraction of the known transiting planets over the next decade will require additional observatories. While transit timing can be performed with a relatively modest aperture, it does require a high-quality, large-format camera. Relatively few small observatories are outfitted with such a detector. The observations must occur at a specific time, so scheduling can be difficult, particularly for observatories that are scheduled by the night and/or are shared by multiple institutions. Also, the transit of a typical hot Jupiter lasts less than two hours, which makes it difficult to effectively use an observatory with a per-night scheduling system. Additionally, weather and day-night aliasing make it difficult to observe many consecutive transits from a single site. These difficulties will be exacerbated when ongoing transit search programs produce more transiting planets in the near future.

A typical planet on a 3-day orbit is in transit for roughly 3% of its orbit. Therefore with approximately 50 known transiting planets, we are now fast approaching the time that at least one planet will be in transit at all times[1]. Figure 6 shows the fraction of nights with at least one observable transit, made for Winer observatory in Sonoita, AZ. As shown here, the efficiency of observing a transit is up to 75% at some times during the year. See the caption for details. If the Kepler and CoRoT missions identify even a moderate fraction of their anticipated yield, then additional telescopes (perhaps located in pairs to mitigate against coincidence losses or separated by a few hundred miles to mitigate against weather) would be required to search most of the expected discoveries of stars hosting transiting planets. A network of small telescopes could easily and rapidly be expanded and optimized to meet the increasing demands of new discoveries. This capability represents a significant advantage for the choice of small, low-cost telescopes.

- **Funding** The Las Cumbres Observatory Global Telescope (LCOGT), with approximately 50 telescopes, offers an ideal network that satisfies the above-mentioned conditions. As stated by Hidas et al. (2008), assuming that each telescope site may have 200 clear nights per year, and

[1] Of course from any particular observatory, this probability will be less than unity due to declination & seasonal constraints.

given that at present 9 astronomers work for the LCOGT, this organization will have ~1100 telescope nights per year per astronomer at its disposal. LCOGT time allocation committee has shown interest in allocating these times to projects requiring a large amount of telescope time, targeting relatively bright objects, and taking advantage of the global distribution of their facilities (Hidas et al. 2008). Observations of stars of transiting systems can certainly benefit from the large network of telescopes of LCOGT, however, the limiting factor in this case will be the funding that is necessary for the collection and archiving data, and their dynamical analysis. An initial investment to provide for robotic observatories and automated observing procedures could significantly reduce the long-term cost of transit timing campaign.

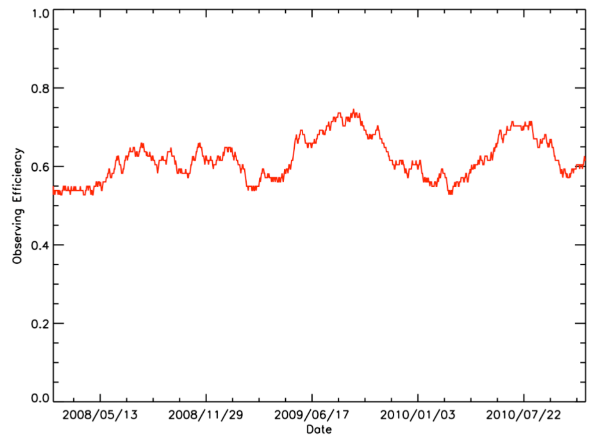

Fig 6. Graph of the efficiency of observing at least one observable transit from Winer observatory in Sonoita, AZ. The plot is a running average over 90 days. An observable transit is when the entire transit happens when the airmass is less than or equal to 2 during the night, and the Sun's altitude is less than or equal to -12.

- **Transit Timing Analysis** Inferring the orbital elements and mass of a perturbing planet via TTV is generally more complex than other planet detection schemes. In transit timing data, the signal is a combination of several effects including the reflex motion of the star, the mutual gravitational interaction between the planets, the changing light travel time, or changing tidal field of a distant companion (Borkovits et al. 2003; Heyl & Gladman 2006). Unlike other dynamical detection techniques, the salient characteristic of the TTV approach is the deviations from Keplerian orbits. This requires high accuracy N-body simulations of each model in order to calculate its TTV signature (Holman & Murray 2005; Agol et al. 2005). Given the computational requirements of N-body integrations, practical algorithms must explore a high-dimensional parameter-space efficiently. While challenging, preliminary tests involving simulated data show that a large fraction of systems can be correctly identified with appropriate analysis techniques (Steffen & Agol 2006).

Conclusions

High precision measurements of the transit timing of known transiting planets provide an efficient method to search for additional low-mass objects in these systems. A serious transit timing campaign would provide constraints for planet formation theory, including migration history, tidal interactions, and the frequency of low-mass planets in or near mean-motion resonances. We expect that the telescopes currently making transit timing observations will soon be overwhelmed by detections from both ground and space-based transit searches. A network of small, inexpensive telescopes could rapidly be deployed to search for Earth-mass planets around solar-type stars and to address many outstanding scientific questions about planet formation.

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