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Uniform and Precise Mass Determination for TTV-Bearing *Kepler* planets

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Abstract

In multi-planet systems, planet-planet interactions result in non-Keplerian orbits which deviate from strict periodicity [5], also known as transit timing variations (TTVs). The TTV signal depends on planetary masses and eccentricities, and therefore can be used to constrain them [2]. In the case of small exoplanets with shallow transits, individual transit times may be difficult or impossible to determine. To circumvent this difficulty, a global photodynamic model is required, fitting the entire *lightcurve*. For this purpose, we develop a novel non-linear photodynamical optimization algorithm which couples a global dynamical model with a TTVs-capable lightcurve generator of a multi-planet system. With this tool, we analyze the entire sample of TTV-bearing planets from the *Kepler* data set presented in [3], amassing to ~360 planets from a total of ~160 systems. We report ~100 significant mass detections, of which about half are of planets with previously unknown or poorly constrained masses. By comparing our mass estimates with literature values of all objects in our sample for which they exist, we find that previously published values may overestimate the planetary masses due to neglecting non-zero eccentricities, accounted for in our study as eccentricity *differences* [6]. Amongst our preliminary results, we report a new mass constraint on a previously known object, limiting its mass to be Mars-like with high significance (>3σ).

1. Introduction

The *Kepler* mission found thousands of transiting exoplanets. From this data set, TTVs of hundreds of planets in multi-planet systems were identified by several studies (*e.g.* [3]). As the shape of TTVs depends on masses and orbital parameters of the planets and their host star, they may serve as means of determining exoplanet masses and their orbital parameters, quantities which are photometrically inaccessible without TTVs [1, 2]. This is especially useful in the case of small exoplanets, as the reflex motion they induce on their host star is often too small to be accurately measured. Moreover, since TTVs exist in already-available photometric data, analyzing them requires no additional observations.

A persisting challenge in TTV analysis, however, lies in the well-known degeneracy between mass and eccentricity [6], which often prevents inversion for a unique solution. However, when a high-frequency (and mass-dependent) "chopping" component in the TTV signal is found, the degeneracy can be broken and unique solution can be identified. Moreover, in the regime of small eccentricities (*i.e.* TTVs model depend only linearly on e), TTVs depend mostly on the difference of the eccentricity vectors, rather than on individual eccentricities of the planets [6,7]. In this case, an attempt to fit for both individual eccentricities yields highly degenerate results. The reduction of two dimensions of the search space enables significant reduction in the degeneracies in our study.

2. Method

We analyse the entire sample of all systems presented in [9]. For every multi-planet system, we define $3n_{pl} - 2$ parameters, consisting of the dynamical masses of every planet and the difference in eccentricity vector component of every pair of neighbouring planets (Δe_x and Δe_y). We compute a photodynamical model in three steps: First, we simulate a TTV signal using *TTVFaster* [1], a semi-analytic model accurate to first order in eccentricity which approximates TTVs using a series expansion. We then couple the TTV signal with a circular multi-planet lightcurve generated using the Mandel-Agol model [8], effectively shifting each individual transit time by its corresponding TTV value. Finally, we optimize relevant parameters and estimate their uncertainties using *MultiNest* MCMC algorithm [3], a Bayesian inference tool.

3. Results and Conclusions

We present Kepler-23 (KOI-168), a three-planet system, as an example of a single system analysis and its corresponding mass and eccentricity constraints compared with previously published values. In Fig. 1 we plot the convergence of the MCMC optimization routine for planet masses and both components of the eccentricity difference vector of each pair of neighbouring planets. We show that significant constraints can be placed on all planet masses (*i.e.* $m/\Delta m > 3$), that are considerably more physically plausible than previously published values, given the planets' radii of $1.72^{+0.11}_{-0.07}$, $3.06^{+0.19}_{-0.12}$, $2.17^{+0.13}_{-0.09}$ $[r_{\oplus}]$, respectively. The best-fit masses are: $3.92^{+0.49}_{-0.31}$, $12.66^{+1.55}_{-0.97}$, $3.49^{+0.92}_{-0.55}$, $[m_{\oplus}]$, respectively (compared to $15.2^{+3.2}_{-2.9}$, $60.2^{+11.4}_{-10.4}$, $17.6^{+13.7}_{-11.9}$ $[m_{\oplus}]$, respectively from [4]). For example, in Fig. 2 we plot posterior distributions of the two inner planets' mass and eccentricity difference components to examine their degeneracy. Indeed, despite notable degeneracy, our algorithm was able to identify a unique solution and constrain the individual parameters, strongly ruling out the too-high mass estimated reported thus far.

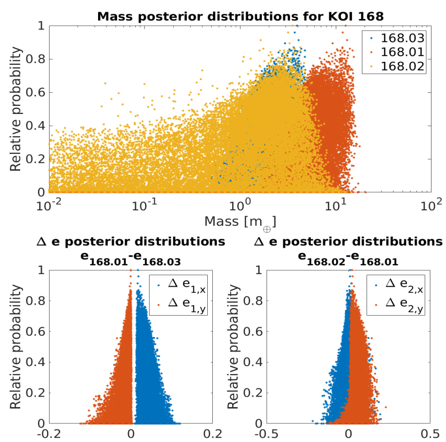

Figure 1: MultiNest optimization convergence for KOI-168 (planet b: blue dots, planet c: orange dots, planet d: yellow dots): **Top panel**: Goodness of fit for planetary masses. **Bottom panel**: goodness of fit for $\Delta e_x, \Delta e_y$ of both neighboring planet pairs.

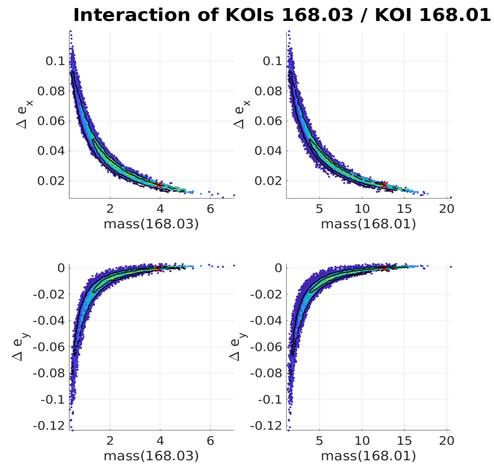

Figure 2: Posterior distribution of mass *vs.* $\Delta e_x, \Delta e_y$.

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