On the resonant multi-planet system TOI-1408

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Abstract. We perform a self-consistent analysis of Doppler and photometric transit observations of TOI-1408, known to host a two-planet system in 2:1 mean-motion resonance. In general we confirm its orbital configuration, however we found that the likelihood function contains multiple local maxima spread over a wider parametric domain, thus making some uncertainties significally larger than deemed before. In particular, the planet b radius still appears poorly constrained (from $\sim 1.2\ R_{\rm Jup}$ to $\sim 3.5\ R_{\rm Jup}$) because of the near-tangential transit geometry. Simultaneously, the task allows for a purely dynamical estimation of the star mass which becomes $1.321\left(^{+0.049}_{-0.042}\right)\ M_\odot$.

Introduction

TOI-1408 b is a TESS planet candidate confirmed in [5] based on Doppler measurements acquired in 2021-2023 by the FFOREST spectrograph mounted at the SAO RAS BTA-6 telescope [10, 11]. The planet mass was estimated as $1.69\pm0.20\ M_{\rm Jup}$, but the planet radius was ill-fitted because of the tangential transit, with a low limit of about $1\ R_{\rm Jup}$. The Doppler curve implied a significant non-sinusoidal shape consistent with the orbital eccentricity of $e_b \simeq 0.25$, possibly indicating the presence of other unseen companions in the system. Later on, in [7] a massive set of new Doppler observations for TOI-1408 obtained at multiple sites was presented and analysed together with TESS and ground-based photometry. They revealed the second small planet c with $r_c = 2.22\pm0.06\ R_\oplus$, moving on an internal orbit in the 2:1 mean motion resonance with planet b. The second planet is transiting as well, although its transits cannot be detected individually. The planets are gravitationally perturbing each other, causing observationally detectable transit timing variations (TTVs). Contrary to [5], in [7] a robust estimate for $r_b = 2.2\pm0.4\ R_{\rm Jup}$ was obtained. They also noticed a nonlinear Doppler trend indicating a yet another, long-period, body, The goal of the present work is to perform a more detailed analysis treating several unresolved issues, and also taking into account new TESS observations of TOI-1408 that appeared since [7].

1. Data

We used the same 12 TESS Sectors as in [7], but also added newer observations for six more Sectors 77, 78, 79, 84, 85, and 86, downloadable from the Mikulski Archive for Space Telescopes. Each sector is about a month long. In [7] a set of 18 ground-based lightcurves of planet b transits was also released. We removed four of these lightcurves from our final analysis because they revealed small but statistically significant long-term or quasiperiodic variations.

First high-precision Doppler data for TOI-1408 were published in [5] and contained 19 RV measurements. Further on, [7] released a large set of additional Doppler measurements obtained at multiple other sites. In total we had 12 independent Doppler datasets corresponding to either different telescopes or, in some cases, to different detectors on the same telescope, or to different spectrum calibration methods.

2. Models

TESS data were treated using individual per-transit model that involved a cubic polynomial and a classic transit model [8, 1] with quadratic limb-darkeing. The limb-darkening law was tuned to better fit the near-limb ring of the stellar disc, because of the grazing geometry of planet b transits. We omit these details here.

In [7] it was noticed that Doppler data may be affected by stellar rotation which they modelled by "a sinusoidal stellar rotational signal". However, such variations do not usually manifest themself as a literal sinusoid. A standard way to treat such variations is the Gaussian Process (GP) method relying on some parametric model for the correlation function [2, 3, 9], which we adopt here. The Doppler noise was fitted with an individual model per each dataset.

Regarding the planetary system itself, we assumed a three-planet model, in which the two inner planets (b and c) were gravitationally interacting, while the third body (d) was gravitationally detached, moving along a distant unperturbed circular orbit. The system was assumed to be coplanar. We also considered newer estimations for the star mass and radius from [6].

3. Results

All the fitting was performed using the PlanetPack software [4], which implements the maximum-likelihood approach involving GP noise models. In general we can confirm the orbital model given in [7], in particular, the planetary TTVs coming from the primary secular period of the mean motion resonance, see Fig 1.

However we found that the likelihood function has numerous local maxima, demonstrating a "rippled" shape. In Fig 2 we show 1D slices of the likelihood along the axis of the planet radius r_b (the most affected parameter). The log of the likelihood ratio statistic, $\Delta \log L$, is shown as a function of the given parameter, relative to the global optimum (the maxima are inverted into minima here).

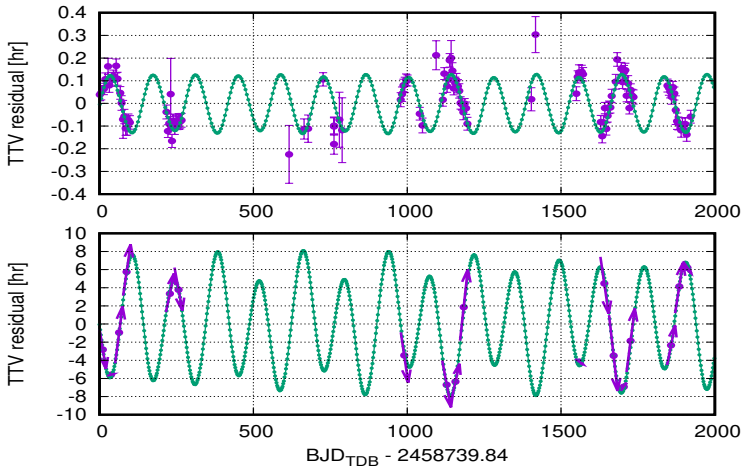


FIGURE 1. TTVs of TOI-1408 b (top) and c (bottom) against their dynamical models. In the second case we show per-sector TTV trends as vectors, because individual transits are not detectable; vector uncertainties are omitted for clarity.

As one can also see, the effect of the astrophysical constraints on the star mass amd radius is important, for example it can shift different local maxima vertically, and may affect their total number. Unfortunately crucial information, like the correlation between $M_\star$ and $R_\star$, is not available to assess this effect reliably.

Conclusion

In this work we performed a detailed reassessment of the TOI-1408 planetary system, including additional new TESS data as well as involving a more detailed analysis of the limb darkening, photometric and Doppler noises, and the structure of the likelihood function. We generally confirm the three-body system interpretation from [7]. However we derived considerably larger parametric uncertainties, in particular the planet b radius still remains ill-determined.

We found that the astrophysical estimates for the star mass and radius has to be characterized very detailedly to be useful with TOI-1408. For example, the model depends significantly on the correlation between $M_\star$ and $R_\star$. Otherwise we can only place conservative ranges on fit parameters, for example $[1.2-3.5]\ R_{\rm Jup}$ for r_b. Our purely dynamical estimation for $M_\star$ is $1.321\ \binom{+0.049}{-0.042}\ M_\odot$. The parameters of the long-period body TOI-1408 d are poorly constrained, but our conservative lower limit is $m_d \gtrsim 50\ M_{\rm Jup}$. Probably its planetary nature can be already ruled out under an assumption that there is just a single body contributing to the trend.

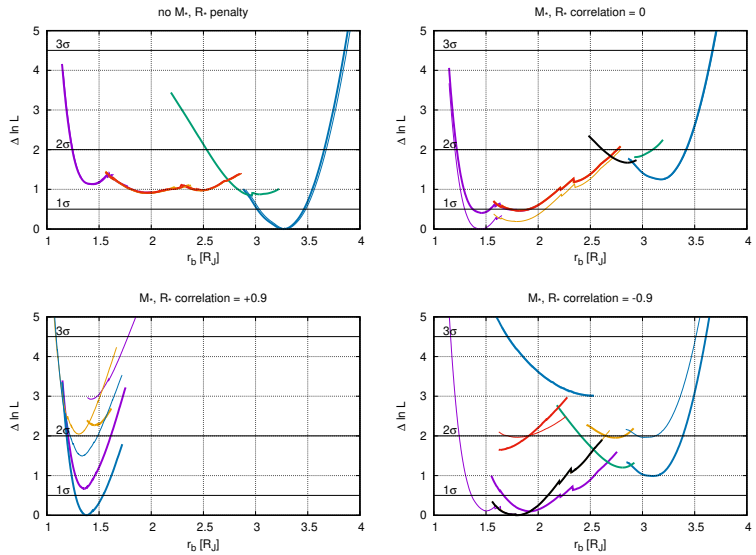


FIGURE 2. The log-likelihood for TOI-1408 b radius, assuming different correlation between the star mass and radius.

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