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Doppler confirmation of TESS planet candidate TOI-1408.01: updated analysis and fitting

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Abstract. Based on the Doppler observations from the FFOREST spectrograph of the 6-meter telescope (BTA) and on the photometric observations from the TESS spacecraft, we provide an updated analysis for TOI-1408, an F-type main sequence star, located 140 pc away, that hosts exoplanet TOI-1408.01. We confirm the qualitative conclusions from our initial paper: (1) a grazing transit geometry such that the planet obscures its host star by only a portion of the visible disc,(2) unreliably fitted planet radius, (3) which nonetheless has a lower bound constraint of $\sim 1\ R_{\rm Jup}$, (4) unexpectedly large planet mass of $\simeq 1.7\ M_{\rm Jup}$, and (5) significant evidence in favor of a moderately eccentric orbit with $e \simeq 0.27$. This solution may suggest that the planet is likely to experience a high tidal eccentricity migration at the stage of intense orbital rounding or may indicate the possible presence of other unseen companions in the system, yet to be detected.

Keywords: techniques: radial velocities, spectroscopic; planets and satellites: detection; stars: individual: TOI-1408

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1 Introduction

The first planet orbiting a solar type star was 51 Pegasi b, discovered in 1995 by Mayor & Queloz (1995) using the radial velocity (Doppler) technique, while the first exoplanetary transit was observed for the exoplanet HD 209458 b (Henry et al. 2000; Charbonneau et al. 2000). Since then, hundreds of hot Jupiters have been discovered. The details of their formation are still unclear (Dawson et al. 2018), but the most common view assumes that giant planets form outside the system's icy boundary and then migrate close to the star (Armitage 2007).

This paper considers Doppler observations carried out using the fiber-optic high resolution echelle spectrograph FFOREST[1] mounted on the 6-m telescope (BTA) of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). The instrument is a fiber-fed high spectral resolution echelle spectrograph with a resolving power R in the range from $\sim$30 000–35 000 to $\sim$60 000–70 000. The portable fiber-optic input module is mounted in the prime focus of the BTA. Presently, the instrument has two working fiber channels with equivalent widths of fiber cores of $0''.7$ and $1''.4$. With these cores and a binning of 2×2 pixels that we have applied, the instrument provides the resolving power of $R \sim 60\,000$ and $R \sim 30\,000$, respectively. An additional calibration channel provides simultaneous observation of spectra from a ThAr calibration source. Currently, the spectrograph with a CCD system constructed by the Advanced Design Laboratory of SAO RAS (Ardilanov et al. 2020) is efficient for planetary observations of stars as faint as 12^{m}. The electronics of the CCD system based an E2V CCD 4k × 4k sensor with a pixel size of 15×15 µm provides a readout noise of 2–3 electrons. For more details about FFOREST, see Valyavin et al. (2014, 2020).

Galazutdinov et al. (2023) (Paper I) reported a confirmation of the TESS candidate TOI-1408.01 based on the FFOREST Doppler observations. The planet mass was measured to be about 1.7 M_{Jup}, apparently characterizing it as a typical hot Jupiter. But given that a large mass, the transit depth of $\sim$2 ppt provided by the TESS team appeared surprisingly small. This was explained by the "grazing transit" effect, when the planet obscures the star by only a portion of its projected disc. Additionally, the planet seemed to move along an elongated orbit with a moderate eccentricity $e \approx 0.26$. This is unusual among hot Jupiters, which typically have almost circular orbits.

However, after the publication of Paper I we noticed a mistake in our script extracting photometric TESS light curves from the downloaded archive. It had been unnoticed that the TESS data archive contains results from multiple DVT pipeline

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[1] Fiber-Fed Optical Russian Echelle SpecTrograph

runs, including the same observations reprocessed with a slightly different output. Therefore, there had been multiple duplicated transit light curves among the 96 ones used in our analysis (see Section 2.1 of Paper I). Here we perform a reanalysis with the correct TESS dataset, including just the latest processing available for a given light curve. This included just 57 unique transit light curves.

2 Observations and data reduction

The Doppler observations are the same 20 measurements given in Paper I. They were carried out with the BTA from 2021 to 2023 under the EXPLANATION[2] program (Valyavin et al. 2022a,b). One in-transit point was removed because it could be affected by the Rossiter–McLaughlin effect. The spectra were processed using our software DECH (Galazutdinov 2022). At the time of the observations, the FFOREST had a Doppler accuracy limit of ~ 10–20 m/s for stellar spectra and ~ 1 m/s for ThAr spectra.

In the Mikulski Archive for Space Telescopes[3], we identified 57 unique TESS transit light curves of TOI-1408 (this also includes some new light curves appeared after the publication of Paper I). After extracting the range of ±100 min around each mid-transit point, we had 13 557 photometric data points in total.

3 Stellar parameters

We used that same star parameters as in Paper I. They were initially obtained spectroscopically using the ionization balance method optimized for solar-type stars (Takeda et al. 2002) and then refined using the MIST isochrones (Dotter 2016). For the goal of our analysis, we need the estimates of the star mass $M_\star = 1.332 \pm 0.014$ and star radius $R_\star = 1.276 \pm 0.015$, with a correlation coefficient between them of 0.87. Also, the limb-darkening coefficients were fixed at the values obtained by the trilinear interoplation of the Claret (2017) tables: $A = 0.2615$ and $B = 0.2771$ (quadratic law). Unfortunately, it is difficult to estimate their uncertainties, while our joint Doppler + transit model does not allow us to fit A and B reliably because of the degeneracies inferred by the grazing transit geometry.

4 New analysis and its results

We redid our analysis from Paper I using the same models and the same general scheme but with the correct set of TESS transit light curves. All the analysis was

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[2] EXoPLANet And Transient events InvestigatiON

[3] https://archive.stsci.edu/

performed using the PlanetPack software (Baluev 2013, 2018), which is based, in general, on optimizing the likelihood function of the task.

All the same issues appeared regarding the grazing transit geometry, which results in some model degeneracies. In particular, the planet radius r upper bound appears unconstrained and possibly limited only by *a priori* physical reasons. We can arbitrarily increase r, simultaneously increasing the transit impact parameter so that the light curve model remains nearly unchanged. This is illustrated in the left panel of Fig. 1, where we show the contour plot of the likelihood function as viewed in the $(r, R_\star)$ plane (and maximized against all the other fitted parameters). Nevertheless, based on the domains of the 2–3σ level, there is a rough *lower* limit $r \gtrsim 0.8$–$1\ R_{\rm Jup}$. It appears slightly lower than in Paper I, but still larger than that provided by the TESS team ($0.7\ R_{\rm Jup}$). As in Paper I, the TESS solution for $(r, R_\star)$ lies well outside of reasonable significance domains, while our increased planet radius estimate physically agrees with the Doppler-derived Jovian mass.

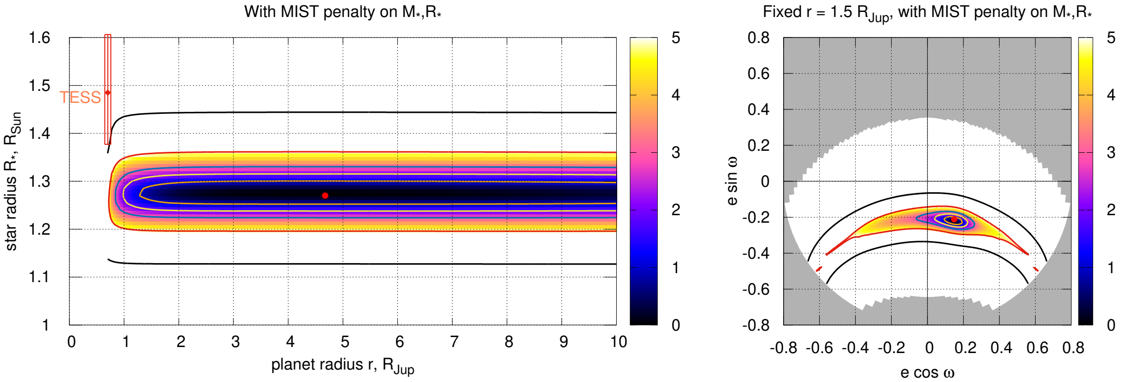

Fig. 1. Left: confidence regions for $(r, R_\star)$ constructed as level curves of the likelihood function. The five colored curves outline significance levels of 1σ, 2σ, 3σ, 5σ, and 10σ. The colormap shows the same significance (from 0 to 5σ). Right: similar confidence regions for $(e\cos\omega, e\sin\omega)$.

The updated best-fit parameters are given in Table 1, and in Fig. 2 we show the corresponding reference models together with the TESS transit light curves and our Doppler data.

In Paper I it was claimed that Doppler data reveal important hints of orbital eccentricity. In our updated analysis this conclusion looks unchanged, as can be seen from Table 1. For a more detailed presentation of the issue, we also computed 2D confidence plots for the eccentric parameters $(e\cos\omega, e\sin\omega)$, shown in the right

Table 1. Best-fit parameters for TOI-1408.

Planet				Star			
K	179 ± 22 m/s	ω	$304\overset{\circ}{.}4 \pm 5\overset{\circ}{.}4$	$M_\star$	$1.331 \pm 0.014\ M_\odot$	Radial acceleration:*	
P	$4.4247173 \pm 1.2 \cdot 10^{-6}$ d	l^*	$273\overset{\circ}{.}6 \pm 4\overset{\circ}{.}5$	$R_\star$	$1.275 \pm 0.015\ R_\odot$	c_0	−5740 ± 79 m/s
M	$1.69 \pm 0.20\ M_{\mathrm{Jup}}$	i	$84\overset{\circ}{.}819 \pm 0\overset{\circ}{.}095$	$\rho_\star$	$0.642 \pm 0.017\ \rho_\odot$	c_1	−24 ± 37 m/s/yr
a	0.05805 ± 0.00020 AU	$r/R_\star$	0.1182 ± 0.0014			RV jitter:	
e	0.265 ± 0.025	r	$1.5\ R_{\mathrm{Jup}}$ (fixed)			σ_{RV}	53 ± 11 m/s

*Epoch JD2459000

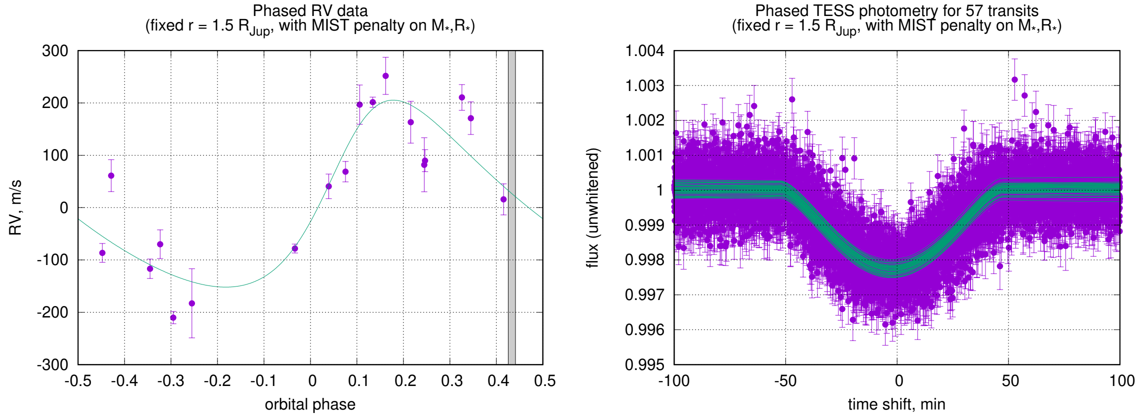

Fig. 2. Doppler and photometric data for TOI-1408 and their best-fit models. In the radial velocity panel (left), the position of the transit is marked as a vertical narrow band. In the photometry panel (right), each of 57 transits has an individual polynomial trend, so we show a bunch of close curves that differ due to these trends.

panel of Fig. 1. The zero eccentricity (the origin of coordinates) lies clearly outside of any reasonable significance level.

5 Summary

Based on the updated analysis of the TOI-1408 data with a correct set of transit light curves, we confirm all qualitative conclusions from Paper I. The light curve of the transits has a pronounced V-shape, indicating the “grazing” geometry of the planetary transit, therefore we cannot estimate the planet radius reliably. Only its lower limit can be estimated, and it appears to be $r \sim 0.8 R_{\mathrm{Jup}}$, which is higher than the TESS estimate (at least when it is considered together with the star radius estimate). The planet mass can be measured quite reliably using the FFOREST Doppler data and is about $\sim 1.7 M_{\mathrm{Jup}}$. This is unexpectedly large but physically consistent with the increased estimate for the planet radius. We also confirm the significant evidence in favor of non-zero eccentricity. A non-zero orbital eccentricity is not typical for hot Jupiters because of the tidal orbit rounding effect. Possible explanations include the presence of an additional unseen companion that excites this eccentricity dynamically, or it is possible that we have “catched” this planet–star system before the evolutionary stage when the intense orbital rounding is finished.

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