Revisiting the Transit Timing Variation of Extra-solar Planets TrES-3b and Qatar-1b with TESS data

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Abstract: We have investigated the possibility of transit timing variation (TTV) and its plausible cause in the hot-Jupiter systems TrES-3 and Qatar-1. In this study, total 160 transit light curves of TrES-3b and 197 transit light curves of Qatar-1b are considered. Using the mid-transit times determined from these light curves, we have improved the transit ephemeris for both these hot-Jupiters. Our timing analysis show the presence of TTVs in these planetary systems that are unlikely to be periodic. To explore the possibility of a long-term TTVs, the orbital decay model was fitted to transit timing data which reveals the period change of 2.71 ± 1.49 ms/yr and 12.39 ± 2.74 ms/yr for TrES-3b and Qatar-1b, respectively. It is worth to mention here that we have observed increasing period for both hot-Jupiters in contrast to the previous results available in literature. Because of the statistically less significant estimate of period change of TrES-3b, we prefer a linear ephemeris model over the decay model. However, the linear model does not appear to represent the transit data of Qatar-1b considered here as the observed change in period is highly significant. This change may not be attributed to orbital decay and there may be some other possible reasons such as presence of a third body in wider orbit and the apsidal precession.

Motivation

- According to tidal theory, the orbit of hot-Jupiters: TrES-3b and Qatar-1b should be decaying due to transferring orbital angular momentum to stellar spin through tidal dissipation (Levrard et al. 2009, Matsumura et al. 2010).
- The recent timing analysis (TrES-3b: Mannaday et al. 2020 and Qatar-1b: Su et al. 2021) reports the orbital decay for these two hot-Jupiters. The statistically less significant estimate of decay rates motivated us to further perform the TTV analysis to probe the possibilities of the additional planet and the orbital decay in these planetary systems by considering new transit data.
- To do this, 160 transit light curves of TrES-3b and 197 transit light curves of Qatar-1b with the time spans of decade are considered in this work.

Observational Data

Object Name	No. of Transit Light Curves	Data Reference
TrES-3b	36	TESS[1] (sectors 25, 26)
	41	Exoplanet Transit Database[2] (ETD)
	83	Literature
Qatar-1b	02	Our New observations
	67	TESS (Sectors 17, 21, 24 ,25)
	61	Exoplanet Transit Database (ETD)
	67	Literature

Light Curve Analysis

- To determine mid-transit times all the above said light curves were analyzed using the Transit Analysis Package (TAP: Gazak et al. 2012).
- For each light curve analysis, 5 MCMC chains each with a length of 10^5 links were used.
- For the TrES-3b light curve analysis, the procedure described in Mannaday et al. (2020) was adopted. For Analyzing light curves of Qatar-1b, procedure described in Su et al. (2021) was used.
- For TESS light curves, the values of quadratic limb-darkening coefficients were taken from the Tables of Claret et al. (2017), whereas the values of quadratic limb-darkening coefficients for V, R, I and Sloan filters were calculated using EXOFAST[3] online-tool.
- The mid-transit times determined from transit light curves of TrES-3b and Qatar-1b are then used for the timing analysis.

[1]https://www.nasa.gov/tess-transiting-exoplanet-survey-satellite
[2] http://var2.astro.cz/ETD/
3https://astroutils.astronomy.osu.edu/exofast/limbdark.shtml

Timing Analysis Results

New Linear Ephemeris

- By fitting a linear function: $T_m(E) = PE + T_0$ of epoch E to mid-transit data through 'emcee' MCMC sampler implementation (Foreman-Mackey et al. 2013), we have refined the ephemeris for the orbital period P and mid-transit time T_0 at reference epochs. The resulting values of P and T_0, as well as the values of χ^2_{red} and Bayesian Information Criteria (BIC) corresponding to this linear model fits are given below:

TrES-3b:	$P = 1.30618629 \pm 0.00000003$ days $T_0 = 2454185.9111371 \pm 0.0000529$ (BJD_{TDB})	$\chi^2_{red} = 1.58$ BIC = 260.23
Qatar-1b:	$P = 1.42002437 \pm 0.00000004$ days $T_0 = 2455647.6331487 \pm 0.0000503$ (BJD_{TDB})	$\chi^2_{red} = 1.60$ BIC = 322.49

- As the above $\chi^2_{red} > 1$ indicates a poor fitting of a linear function to mid-transit time data, we suspect the possibility of TTV in the TrES-3 and Qatar-1 systems.

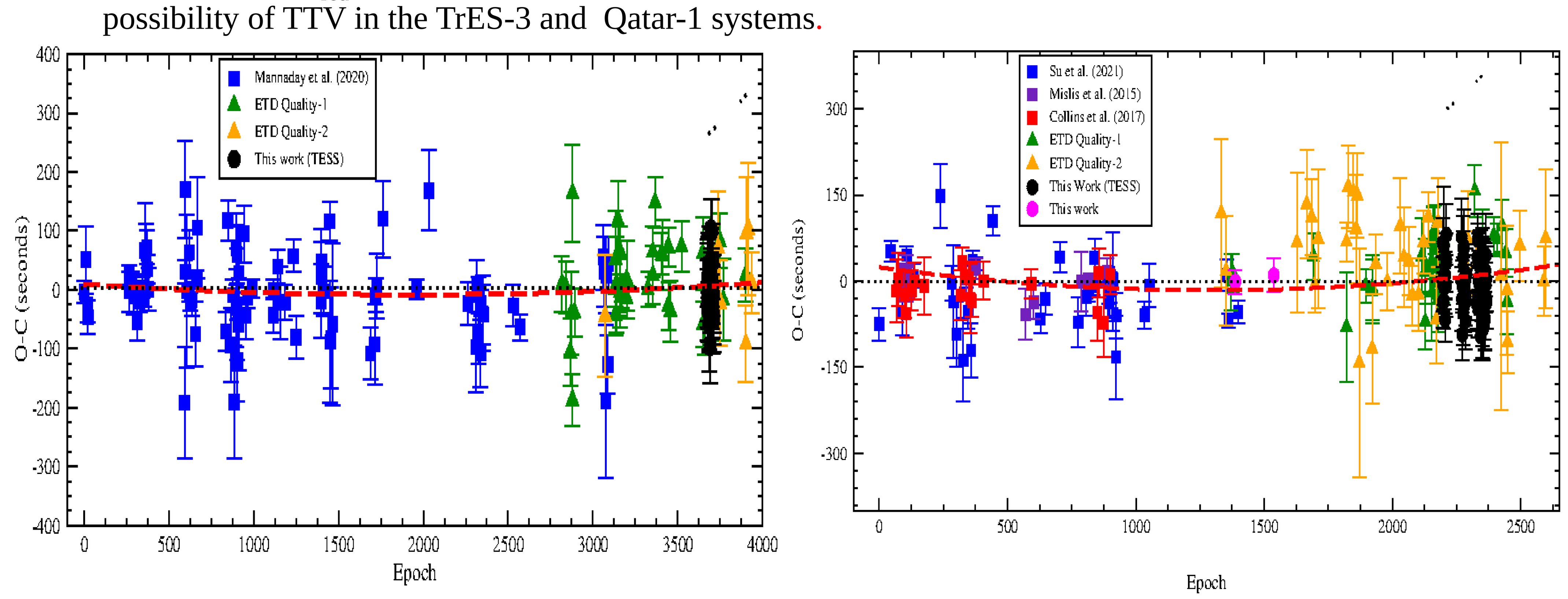

Figure 1. Left panel: O−C diagram for the 160 mid-transit times of TrES-3b considered in this work. Right panel: O−C diagram for the 197 mid-transit times of Qatar-1b considered in this work. The doted black line in each panel indicates the linear ephemeris (constant period) model, while the dashed red curve indicates the orbital decay model.

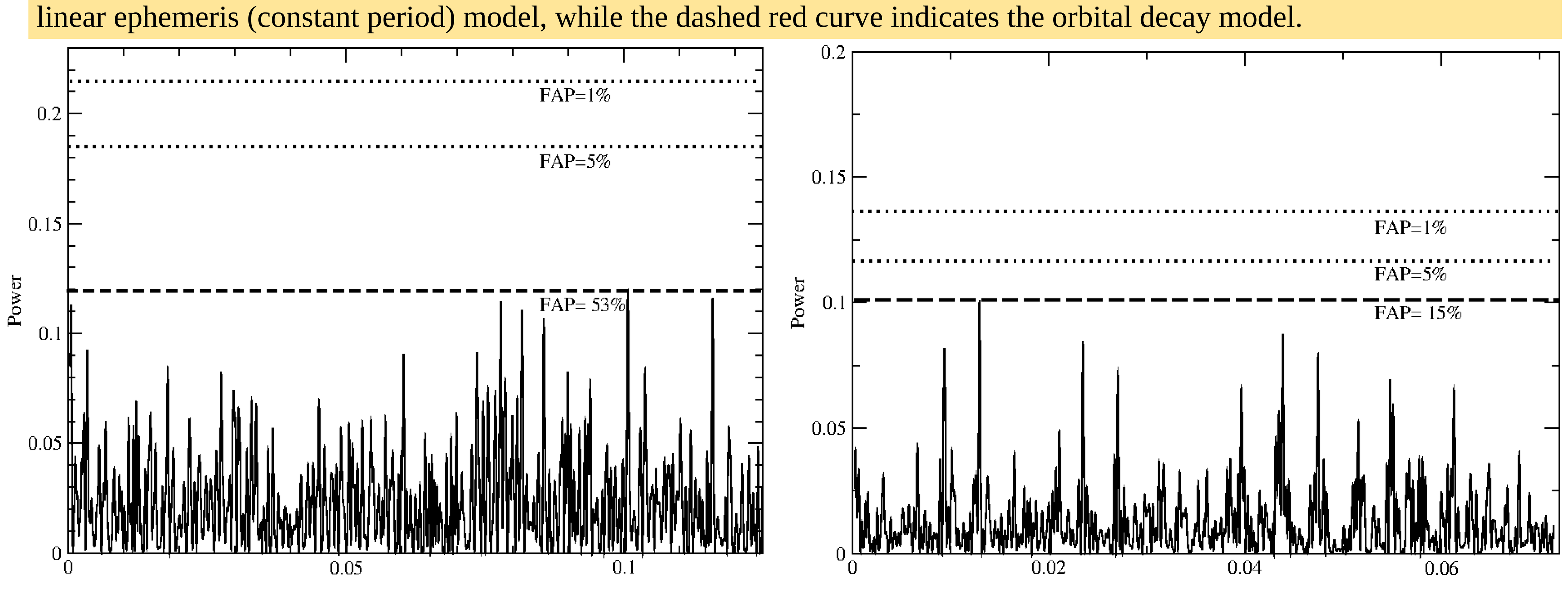

Figure 2. Left Panel: Generalized Lomb–Scargle periodogram for 160 O-C data of TrES-3b. Right panel: Generalized Lomb–Scargle periodogram for 197 O-C data of Qatar-1b. The dashed lines indicate the FAP level of the highest power peak at the frequency of 0.10077 cycle/epoch and 0.012966 cycle/epoch for the TrES-3b and Qatar-1b, respectively. The dotted lines from top to bottom in each panel indicate the threshold levels of FAP=1% and FAP=5%, respectively.

Orbital Decay Study

The finding of lack of significant periodicity in the timing residuals, encouraged us to look for orbital decay of hot-Jupiters as an other cause of TTVs. To do this, we fitted the orbital decay ephemeris model: $T_{qm}(E) = P_q E + T_{q0} + \frac{1}{2}\delta P E(E-1)$ to the timing data of TrES-3b and Qatar-1b. The best-fit values representing the orbital decay ephemeris for TrES-3b and Qatar-1b along with their corresponding values of χ^2_{red} and BIC are given below:

Orbital Decay Ephemeris

TrES-3b:	$P_q = 1.30618607 \pm 0.00000012$ days $T_{q0} = 2454185.9112490 \pm 0.00008006$ (BJD_{TDB}) $\delta P = 1.12 \times 10^{-10} \pm 6.15 \times 10^{-11}$ days/epoch	$\chi^2_{red} = 1.57$ BIC = 261.71
Qatar-1b:	$P_q = 1.42023663 \pm 0.00000016$ days $T_{q0} = 2455647.6334072 \pm 0.0000764$ (BJD_{TDB}) $\delta P = 5.57 \times 10^{-10} \pm 1.23 \times 10^{-10}$ days/epoch	$\chi^2_{red} = 1.50$ BIC = 307.08

Current Conclusion

The homogeneously determined mid-transit times from our considered transit light curves of TrES-3b and Qatar-1b enabled us to refine the transit ephemeris. The derived ephemeris are consistent and are more precise than the previous studies. The timing analysis indicates the possible presence of TTVs in both planetary systems that are unlikely to be periodic. The orbital decay study reveals increasing rates of 2.71 ± 1.49 ms/yr and 12.39 ± 2.74 ms/yr for orbital periods of TrES-3b and Qatar-1b, respectively. As the estimated period change for TrES-3b is statistically less significant, we prefer linear model over the orbital decay. However, the same conclusion can not be made for Qatar-1b because of the highly significant estimate of period change, as well as the smaller value of BIC obtained in decay model fit as compared to linear model. Since the observed increasing period of Qatar-1b may not be the cause of orbital decay, there may be some other cause such as presence of a third body in wider orbit and the apsidal precession for the TTVs. Further follow-up observations would be important to provide more strong conclusion.

References:

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