Investigating Transit Timing Variations in the Exoplanet TrES-2b in TESS Era

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Abstract:- Transit timing variations (TTVs) are proving to be a very valuable tool in the field of exoplanetary detection. Up to now, WASP-4 and WASP-12 are the most promising candidates for presenting TTVs. For our work, we have analyzed total 214 transit light curves of TrES-2b, which include 47 transits recently observed by the Transiting Exoplanet Survey Satellite (TESS) in multiple sectors, 59 light curves with data quality < 3 from the Exoplanet Transit Database (ETD) and 108 from the literature to investigate the possibility of transit timing variation (TTV).

We found that the sequence of transits occurred 31.48s later than had been predicted, based on transit-timing measurements spanning 15 yr. To explore the possible origins of TTV, the orbital decay and apsidal precession ephemeris models are fitted to the transit time data and to identify the theoretically correct model, we calculated the Bayesian information criterion (BIC). The ΔBIC metric favors the orbital decay model over a constant period, but it does not favor the apsidal precession model over a constant period. Our timing analysis shows decreasing orbital period of Qatar-1b. We further probed whether the observed TTV originated from line-of-sight acceleration or Applegate mechanism, but the TTV does not seem to be originated either due to line-of-sight acceleration or Applegate mechanism. In order to confirm these findings, further high-precision transit, occultation and radial velocity observations of the system would be worthwhile. To distinguish unequivocally between decay and precession will probably require a few more years of monitoring.

Introduction:-

- The hot Jupiter **TrES-2b** ($M_p = 1.28M_J$, $R_p = 1.24R_J$), the first planet detected in the Kepler field, was discovered by **O'Donovan et al. (2006)** and it has a large inclination angle of about 84°, implying a nearly grazing transit.
- Early publications suggest evidence of short-term TTVs (Rabus et al. 2009; Mislis & Schmitt 2009). Later studies, however, were not able to support these claims, thus citing no evidence of short or long-term transit timing variations for TrES-2b (Kipping & Bakos 2011; Schroter et al. 2012; Raetz et al. 2014). Motivated from these contradictory findings regarding the presence of short-term or long-term TTVs, we have taken **total 214 transit light curves** and examined the TTV.

Observational Data:-

Object Name	No. of Transit Light Curves	Data Reference
TrES-2b	47	TESS[1] (sectors 26, 40, 41, 54, 55)
	59	Exoplanet Transit Database[2] (ETD)
	108	Literature

Light Curve Analysis:-

- To determine the best fit values of transit parameters, all the 214 transit light curves were analyzed using the ***Transit Analysis Package (TAP:Gazaketal.2012).***
- For each light curve analysis, 5 MCMC chains each with a length of 10^5 links were used.
- To set up the initial values of parameters, as well as to analyze the transit light curves, we followed the same procedure as adopted by Jiang et al. (2013).
- 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 clear filters were calculated using **EXOFAST[3]** onlinetool.
- The mid-transit times determined from transit light curves of TrES-2b are then used for the timing

The Initial Parameter Setting:-

Parameter	Initial Value	During MCMC Chains
P (days)	2.47063	Fixed
i (degree)	83.71	A Gaussian prior with σ = 0.42
a/R_*	7.969	A Gaussian prior with σ = 0.055
R_p/R_*	0.1278	Free
T_m	Set by eye	Free

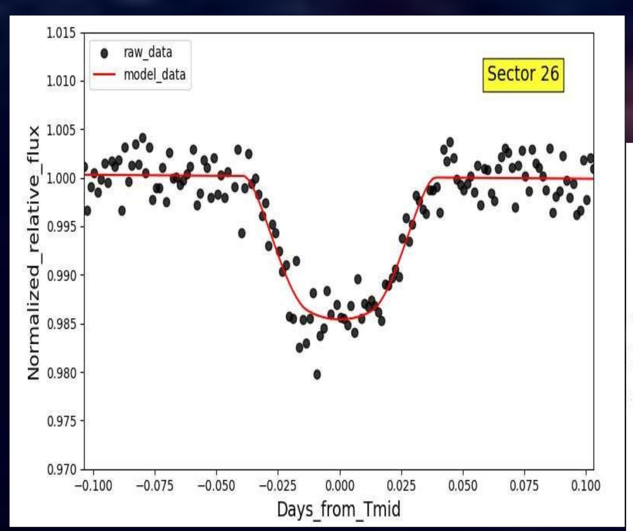


Figure 1. :- the normalized relative flux of TrES-2b as a function of the time

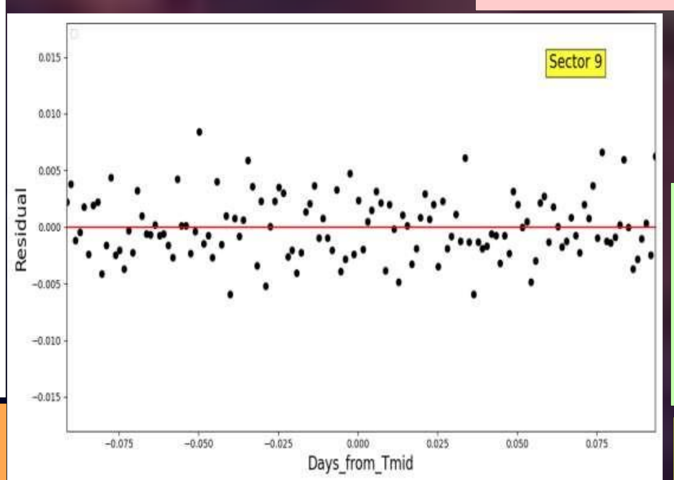


Figure 2. :- the corresponding residuals.

Transit Timing Analysis:-

✓ Following Patra et al. (2017), Ivshina & Winn (2022), we have tried to fit three different models to our timing data assuming –

1) The first model assumes ***a circular orbit*** and ***a constant orbital period***.
2) The second model also assumes ***a circular orbit*** and ***a constant period derivative.***
3) The third model assumes the planet has ***a nonzero eccentricity e and its argument of pericenter ω is precessing uniformly.***

A Periodicity Search for Additional Planets:-

✓ To probe the periodicity in the timing residuals of the hot Jupiter that may be induced due to presence of a short-term TTV caused by an additional body, we computed ***generalized Lomb–Scargle periodogram (Figure 3) (GLS; Zechmeister&Kürster2009)*** for their timing residuals in the frequency domain.

In this periodogram, we found the highest power peak (power = 0.07197) at the frequency of 0.00625 rad/period. The ***False Alarm Probability (FAP) of 49%*** for the highest power peak was determined empirically by randomly permuting the O-C data to the observing epochs using Py-astronomy Routines.

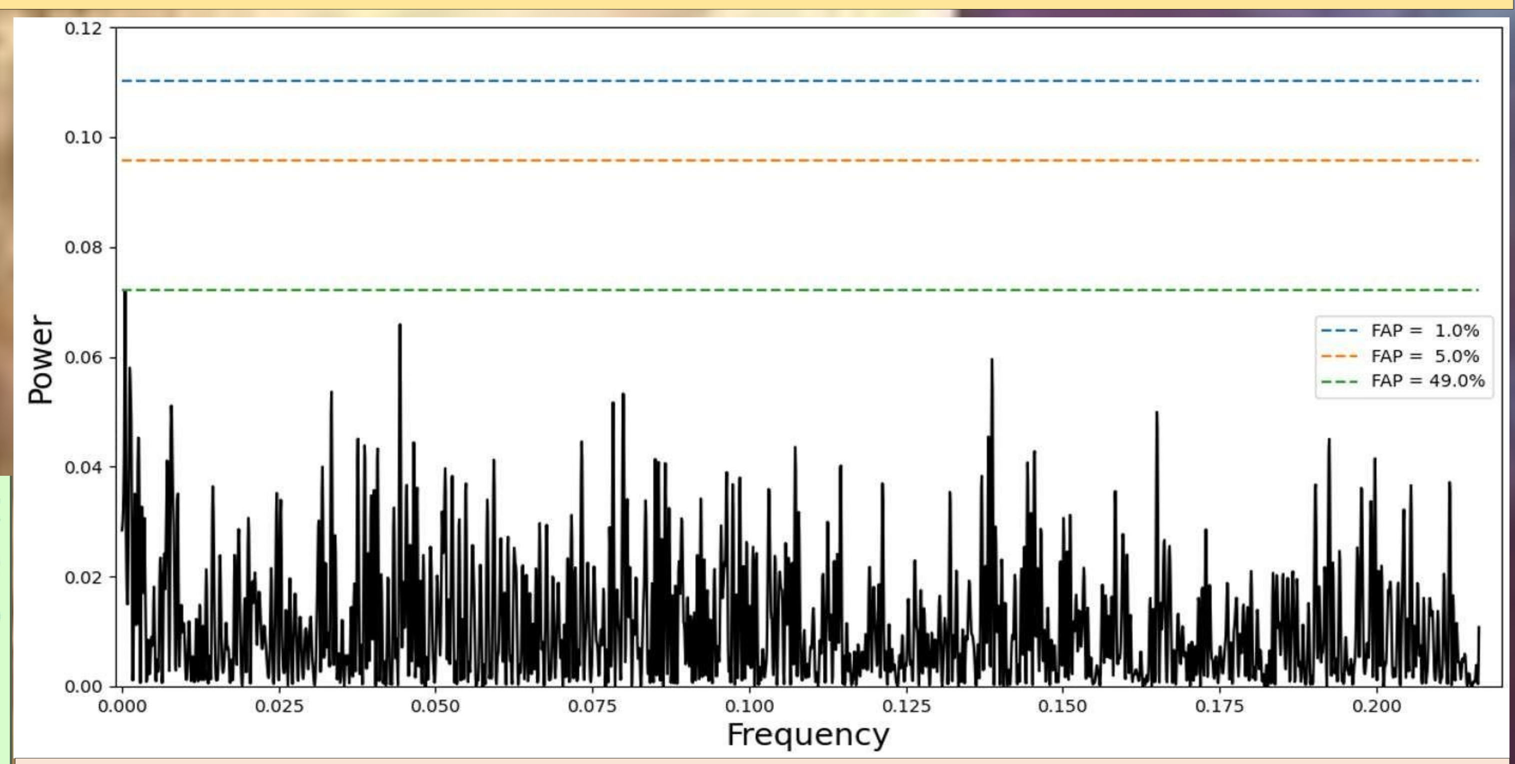
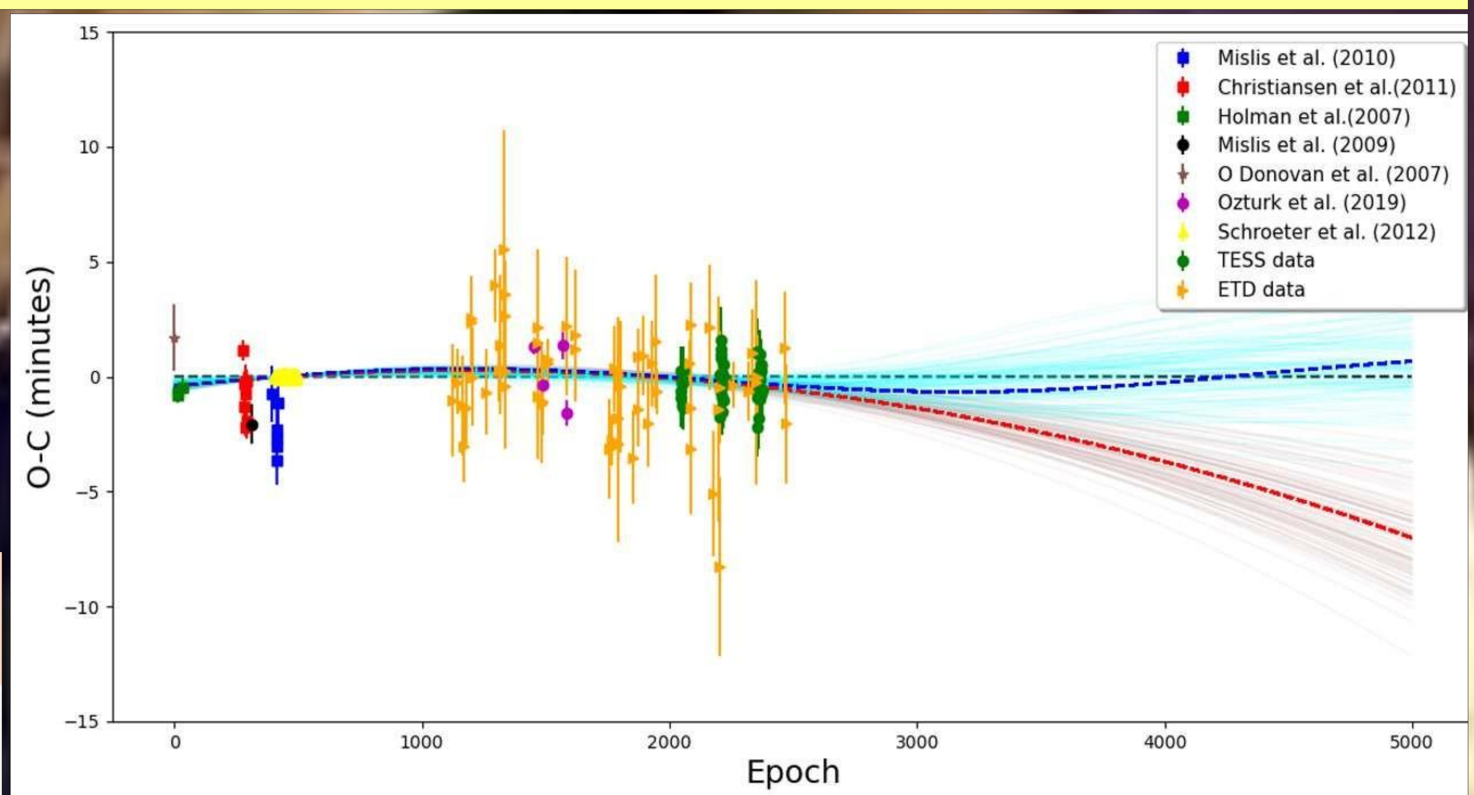


Figure 3 :- Generalized Lomb–Scargle periodogram for 214 O-C data of TrES-2b.

In order to Investigate the plausible causes of the observed TTV, we obtained the ***O-C diagram*** as a ***function of epoch E,*** shown below.



Line-of-sight Acceleration:-

From transit data, we observed a decreased orbital period, **$\dot{P}$ = - 0.0088575 s yr^{-1}**. To check, whether this period change is due to line-of-sight acceleration, we collected the RV data of the system from the literature and modelled using the ***radvel*** package. We find the rate of acceleration = 0.0636 m s^{-1} day^{-1}. By substituting this value in the following equation of Maciejewski et al. (2021):

$$\dot{v}_{RV} = \frac{\dot{P}_q}{P_q} c$$

We find **$\dot{P}$ = 16.52 ms yr^{-1}**, which indicates an increased orbital period. This clearly contradicts the value obtained from transit data. So, it appears that the observed TTV in the TrES-2 system may not be due to line-of-sight acceleration.

1 https://www.nasa.gov/tess-transiting-exoplanet-survey-satellite

2 http://var2.astro.cz/ETD/

3 https://astroutils.astronomy.osu.edu/exofast/limbdark.shtml

Parameter	Best-fit Values with 1σ Uncertainties
Linear Ephemeris	
P (days) T_0 (BJD_{TDB})	$2.47061357^{+0.0000000481297}_{-0.0000000477182}$ $2453957.6353721^{+0.0000224801}_{-0.0000225813}$
af, τ, N_{eff}	~0.44, ~19, ~1052
χ^2, χ^2_{red} (Ndo_f)	575.66, 2.69(214)
BIC	580.40
AIC	573.67
Orbital Decay Ephemeris	
P_q (days) T_q0 (BJD_{TDB})	$2.47061438^{+0.000000201683}_{-0.000000201267}$ $2453957.635075^{+0.0000744318}_{-0.0000745850}$
$\frac{dP_q}{dE}$ (days)	$-6.93539736 \times 10-10^{+1.656715 \times 10-10}_{-1.654948 \times 10-10}$
a_f, τ, N_{eff}	~0.35, ~30, ~1066.67
χ^2, χ^2_{red} (Ndo_f)	560.68, 2.62(214)
BIC	568.35
AIC	558.25
Apsidal Precession Ephemeris	
P_s (days) $T_{ap}0$(BJD_{TDB})	$2.47061365^{+0.000000236900}_{-0.000000183595}$ $2453957.635082^{+0.000294482}_{-0.000359515}$
e	$0.00143787^{+0.0005631}_{-0.0003407}$
ω_0 [rad]	$1.585641^{+0.670161}_{-0.859289}$
$\frac{d\omega}{dE}$ [rad/Epoch]	$0.000547629^{+0.000239232}_{-0.000222015}$
a_f, τ, N_{eff}	~0.248, ~690, ~290
χ^2, χ^2_{red} (N_{dof})	569.24, 2.66(214)
BIC	583.53
AIC	566.70

Applegate Mechanism:-

Applegate & Patterson (1987) realized that period changes in binary systems without either mass or angular momentum loss could be driven by variations in the quadrupole moment of one or both stars. And Watson & Marsh (2010) proposed that changes in the quadruple moment of the host star (Applegate 1992) may also induce long-term TTVs in exoplanetary systems.

The largest TTV amplitude expected by them for TrES-2b due to an Applegate mechanism was **δt ~ 3.7 s**, which is an order of magnitude smaller than the TTV amplitude of **~31.48 s** found by us.

Conclusions:-

- Motivated from the previous results of Rabus et al. 2009; Mislis & Schmitt 2009, Kipping & Bakos 2011, Raetz et al. 2014, we have combined in total 214 transit light curves for the precise TTV analysis. The frequency analysis shows that the ***short-term periodic TTVs in the timing residuals of the hot Jupiter is not detected.*** Therefore, the possibility of an additional body in the orbits close to the hot Jupiter is ruled out and these findings are fully consistent with the previous results that are available in the literature.
- As the ΔBIC metric favors the orbital decay model over a constant period and it does not favor the apsidal precession, ***orbital decay is statistically favoured over apsidal precession*** as the best explanation for the timing data.
- Looking at only the values, ***the constant period model is a worse fit than both the apsidal precession and orbital decay models.***
- ✓ The observed TTV in the TrES-2 system may not be due to ***line-of-sight acceleration*** or ***Applegate mechanism***.
- ✓ In order to confirm our findings, further high-precision photometric follow-up observations of the primary and secondary eclipses, as well as RV measurements of this hot-Jupiter system are required.

References:-

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