Exploring the Existence of an Additional Planet in the hot-Jupiter Extra-solar Planetary System TrES-5

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Abstract- We present seven new transit light curves of the hot-Jupiter TrES-5b observed with the 2-m Himalayan Chandra Telescope, Hanle, India during 2016-2020 to look for the transit timing variation (TTV). For this study, total 59 transit light curves have been considered which include seven light curves from our new observations, 37 from the literature, and 15 from the Exoplanet Transit Database (ETD). In order to have homogeneously derived mid-transit times for precise TTV study, all the light curves were analyzed with a uniform procedure using the Transit Analysis Package (TAP). By fitting a linear ephemeris model to the mid-transit time data, we derive new transit ephemeris with χ^2_{red} = 2.43 for TrES-5b, which is consistent and even more precise than the previous results. The best-fit ephemeris with χ^2_{red}>1 indicates that the linear ephemeris model does not represent the transit time data well. To look for the periodicity in the timing residuals of linear ephemeris model, a generalized Lomb-Scargle periodogram is computed. However, we have not found any significant periodicity in the timing residuals. The highest peak power obtained in the periodogram at the frequency of 0.005232 rad/period has the false alarm probability (FAP) of 12%, which is found below from the threshold values (i.e. FAP =5% and 1%). This result enable us to conclude that the additional planet might not be present in the TrES-5 system. To confirm this, the further high-precision follow-up observation of the TrES-5 system would be required.

1. Motivation

The TrES-5b is a short period (P=1.48 days) Jupiter sized massive (R_p =1.29 R_J, M_p = 1.778 M_J) transiting extra-solar planet discovered by Mandushev et al. (2011) around a cool G dwarf GSC 0 3949–00967. Due to short period and close proximity to its host star, this planetary system has been followed by several researchers (e.g. Mislis et al. 2015; Maciejewski et al. 2016; Sokov et al. 2018) to improve the estimation of physical and orbital parameters, as well as to examine the transit timing variation (TTV) of TrES-5b. The presence of additional planet can be confirmed in the planetary system when the TTV is signal periodic. Based on the TTV analysis, Mislis et al. (2015) and Maciejewski et al. (2016) have discarded the presence of an additional planet in this system. On the other hand, the study of Sokov et al. (2018) indicates the presence of an additional planet in this system. Motivated from these contradictory findings regarding the presence of additional planet, we have observed seven new transits of TrES-5b and examined the TTV by combining our newly observed transits data with the transit light curves available in the literature and the Exoplanet Transit Database[1] (ETD).

2. Observational Results

2.1 New Observations:

In this study, we have observed seven new transits of TrES-5b during 2016-2020 with the 2m Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory (IAO), Hanle, India. All the transit observations were carried out in R-filter. For each transit observation, the telescope was slightly defocused to achieve the high-precision as well as to have longer exposure time of 60 seconds (see Soutworth et al. 2009a, b).

2.2 Data Reduction:

All the science images taken from HCT telescope were calibrated using the standard tasks such as trimming, bias subtraction and flat-field division available within the Image Reduction and Analysis Facility (IRAF) software[2].

- After the pre-processing, the aperture photometry was performed on the target star (TrES-5) and its nearby comparison stars, whose brightness and colors were found to be similar to that of TrES-5.
- To get the transit light curve (relative flux as function of time) for each transit observation, the flux of TrES-5 was divided by the sum of flux obtained from the best possible combinations of comparison stars with minimum out-of-transit (OOT) root mean sqaure.
- In order to remove time varying atmospheric effects, the light curves were normalized by fitting a linear function of time to OOT data.
- The resulting transit light curves from our new observations are shown in Figure 1, where black points are the data and the red lines are the best-fitted model light curves (see transit light curve analysis section for details).

2.3 Other Observational Data from the Literature and Exoplanet Transit Database (ETD)

In addition to our seven new transit light curves, total 52 transit light curves, which include 37 light curves from the literature and 15 light curves with quality 1 from the ETD, were considered for this work.

[1] http://var2.astro.cz/ETD/

[2] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. For more details, http://iraf.noao.edu/.

2.4 Transit Light Curve Analysis

To determine the best fit values of transit parameters: orbital period (P), ratio of planet to star radius (R_p/R_*) and scaled semi-major axis (a/R_*), orbital inclination (i), mid-transit transit time (T_m), linear and quadratic limb-darkening coefficients (u_1 and u_2) from our 59 considered transit light curves, we have analyzed all these light curves by the Transit Analysis Package (TAP: Gazak et al. 2012). The TAP employs wavelet based MCMC technique and the model of Mandel & Agol (2002) to fit transit light curves. For each light curve analysis, we have used 5 MCMC chains each with a length of 10^5 links. Before to run the TAP, the initial values of the parameters P, R_p/R_*, a/R_* i were taken from Maciejewski et al. (2016) and the value of e=0.017 was adopted from Sokov et al. (2018). The values of linear and quadratic limb-darkening coefficients for different filters were linearly interpolated from the table of Claret (2000, 2004) using the JKTLD code (Southworth 2015). During each light curve analysis, the parameters P, e, and w were fixed, u_1 and u_2 were fitted under Gaussian penalties, and the remaining parameters R_p/R_*, a/R_*, i, *and* T_m were fitted freely. The best-fitted transit parameters derived from our new light curves are listed in Table 1, whereas the best-fit model model light curves derived from the TAP run are plotted with solid red lines in Figure 1.

Table-1

The best-fitted values of parameters T_m, R_p/R_*, a/R_*, i, u_1, and u_2 *for our seven transit light curves*

Date of Obs.	T_m (in BJD_{TDB})	i (in deg)	a/R_*	R_p/R_*	u_1	u_2
30.09.2016	$2457662.17721^{+0.00023}_{-0.00023}$	$84.62^{+0.64}_{-0.53}$	$6.13^{+0.22}_{-0.19}$	$0.1456^{+0.0020}_{-0.0023}$	$0.046^{+0.046}_{-0.046}$	$0.235^{+0.049}_{-0.049}$
26.06.2019	$2458661.20989^{+0.00056}_{-0.00052}$	$87.40^{+1.8}_{-2.0}$	$7.190^{+0.38}_{-0.68}$	$0.1248^{+0.0054}_{-0.0039}$	$0.721^{+0.043}_{-0.045}$	$0.193^{+0.044}_{-0.046}$
27.07.2019	$2458784.23629^{+0.00067}_{-0.00074}$	$86.0^{+2.4}_{-2.0}$	$6.380^{+0.56}_{-0.64}$	$0.1409^{+0.0076}_{-0.0058}$	$0.724^{+0.043}_{-0.046}$	$0.193^{+0.043}_{-0.046}$
30.07.2019	$2458787.20085^{+0.00049}_{-0.00049}$	$88.30^{+1.2}_{-1.6}$	$7.270^{+0.21}_{-0.40}$	$0.1316^{+0.0038}_{-0.0028}$	$0.712^{+0.044}_{-0.046}$	$0.192^{+0.044}_{-0.047}$
05.11.2019	$2458793.13087^{+0.00083}_{-0.00085}$	$84.90^{+3.2}_{-2.2}$	$6.200^{+1.1}_{-0.84}$	$0.1311^{+0.0092}_{-0.0084}$	$0.720^{+0.043}_{-0.046}$	$0.193^{+0.044}_{-0.046}$
11.05.2020	$2458981.37503^{+0.00039}_{-0.00037}$	$87.5^{+1.6}_{-1.5}$	$6.980^{+0.29}_{-0.45}$	$0.1357^{+0.0043}_{-0.0031}$	$0.708^{+0.043}_{-0.046}$	$0.194^{+0.045}_{-0.047}$
20.05.2020	$2458990.26899^{+0.00060}_{-0.00063}$	$86.70^{+2.0}_{-1.7}$	$6.930^{+0.50}_{-0.61}$	$0.1379^{+0.0063}_{-0.0051}$	$0.709^{+0.044}_{-0.046}$	$0.192^{+0.045}_{-0.047}$

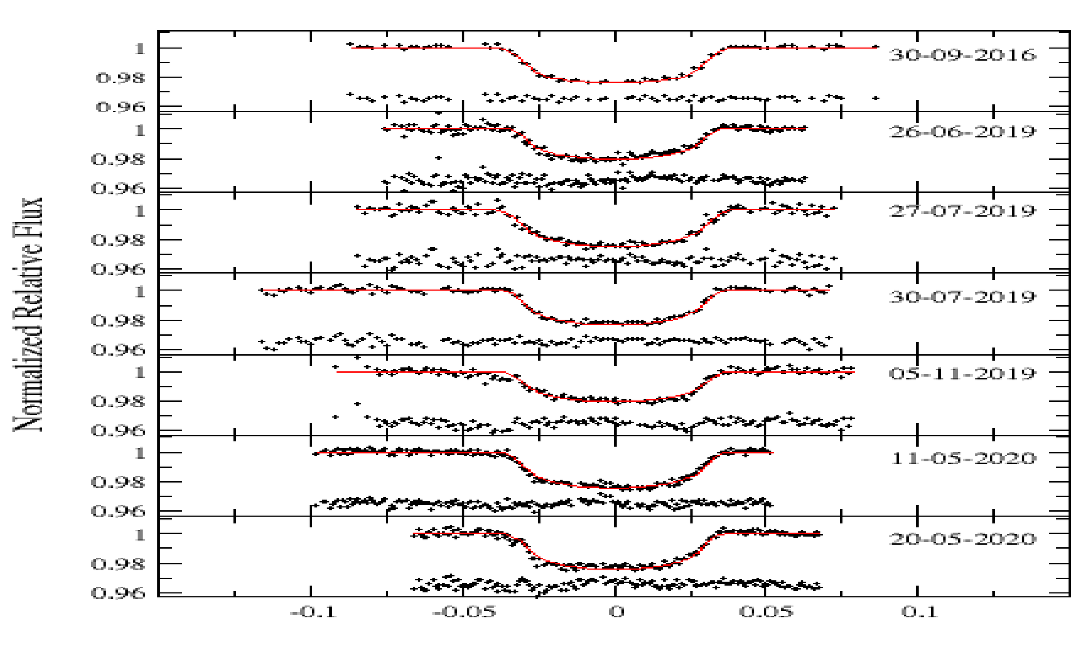

Figure 1. Normalized relative flux as a function of the time (the offset from mid-transit time and in TDB-based BJD) of seven transit light curves of this work. The points are the data and solid red lines are best-fit models. The corresponding residuals is shown in the bottom of each light curve.

2.5 New Ephemeris

We have refined the transit ephemeris for the orbital period P and mid-transit time T_0 by fitting a linear function: $T_m(E)$ = PE + T_0 to 59 mid-transit times data with the emcee MCMC sampler implementation (Foreman-Mackey et al. 2013) . The best-fit values of P and T_0 obtained with χ^2_{red} = 2.43 are given below:

P = 1.482247105 ± 0.000000096694 days
T_0= 2455152.7323218 ± 0.0001396 (BJD_{TDB})

The χ^2_{red} >1 indicates that the fitting of a linear function to mid-transit time data is poor and also suggest the possibility of TTV in the TrES-5 system.

2.6 O-C Diagram and Generalized Lomb-Scargle Periodogram:

In order to Investigate whether the possible TTV is produced by the presence of additional planet or not, we obtained the O-C diagram. The O-C diagram shows the difference between the observed mid-transit time, O, and the calculated mid-transit time derived from the transit ephemeris, C,. The resulting O-C diagram as function of epoch E is shown in Figure 2.

If any additional planet exist in the TrES-5 system, then periodic TTV should be present in the O-C data. To search for periodicity in the O-C data, a generalized Lomb-Scargle periodogram (Zechmeister & Kurster 2009) was computed in the frequency domain. The periodogram defined by the resulting spectral power as a function of frequency is shown in Figure 3. In this periodogram, we found the highest power peak (power = 0.4333) at the frequency of 0.005232 rad/period. The False Alarm Probability (FAP) of 12% for the highest power peak was determined empirically by randomly permuting the O-C data to the observing epochs using a *"bootstrap"* resampling method with 10^5 trials. As shown in Figure 3, this FAP of highest power peak is found below the threshold levels (i.e. FAP=5% and FAP=1%). This indicates that the presence of possible TTV in the TrES-5 system does not show any signature of periodicity.

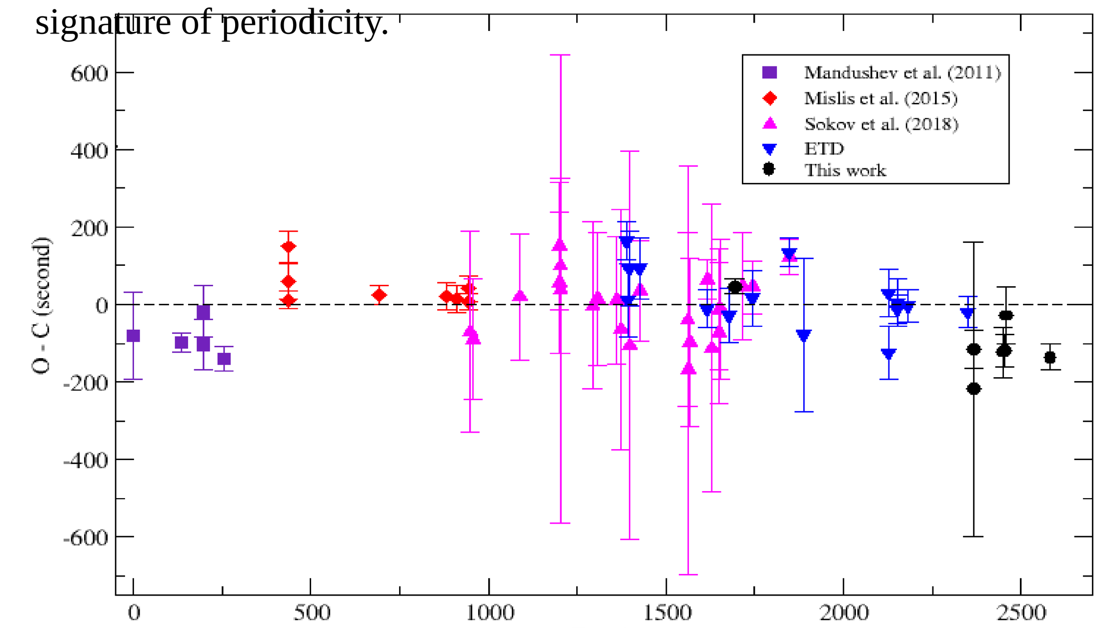

Figure 2. O−C diagram for the 59 mid-transit times considered in this work. Indigo filled squares are for the data from Mandushev et al. (2011), red filled diamonds are for Mislis et al. (2015), magneta filled up-triangles are for Sokov et al. (2018), blue filled down triangles are for ETD, and the black filled circles are the data from this work.

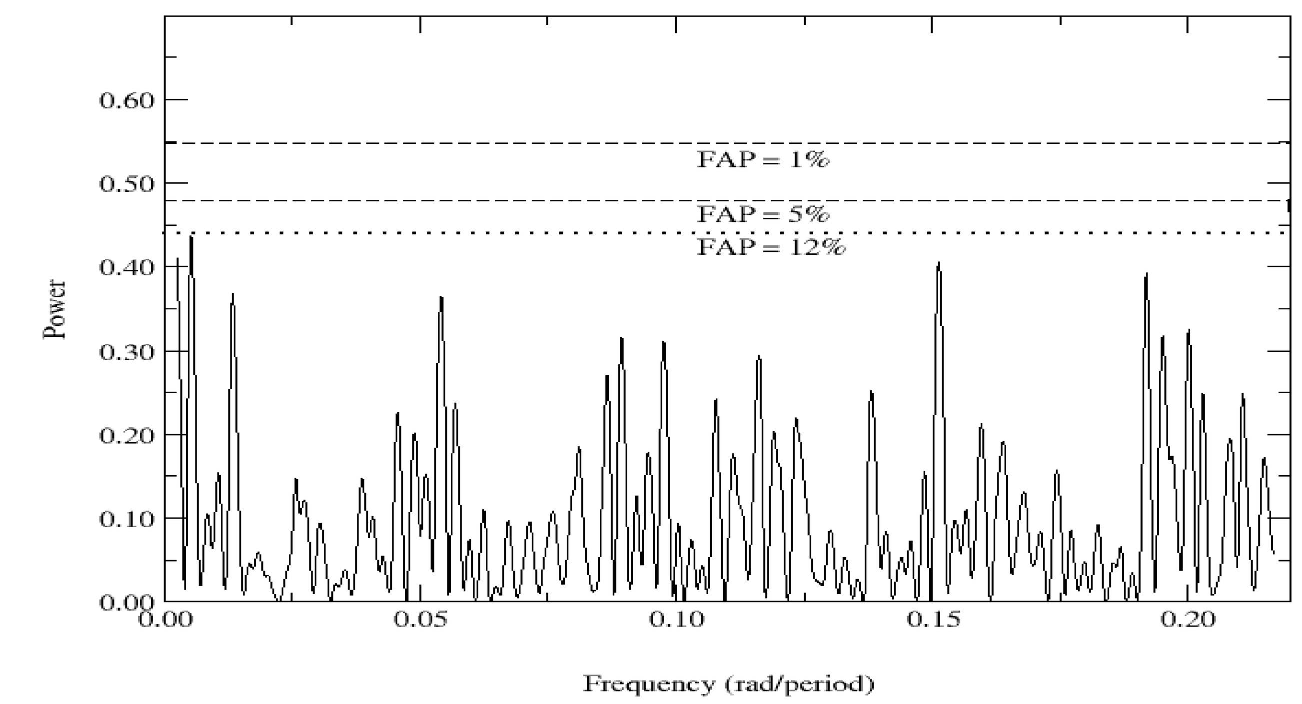

Figure 3. Generalized Lomb–Scargle periodogram for 59 O-C data of TrES-5b. The dotted line indicates the FAP level of the highest power peak at the frequency of 0.005232 rad/period. The dashed lines from top to bottom indicate the threshold levels of FAP=1% and FAP=5%, respectively.

3. Conclusion:

Motivated from the previous results of Mislis et al. (2015), Maciejewski et al. (2016), and Sokov et al. (2018), we have observed seven new transits of TrES-5b during 2016-2020. For the precise TTV analysis, we have combined our new transits data with the 15 light curves taken from the ETD with quality 1 and 37 from the literature. In total 59 transit light curves are considered for this work. The homogeneously determined mid-transit times from these light curves enabled us to refine the transit ephemeris. The derived ephemeris are consistent and even more precise than the previous results. From our timing analysis, we have found the possible presence of TTV in the TrES-5 system. However, the frequency analysis indicates that additional planet may not be present due to lack of periodic TTV signal. In order to confirm the presence or absence of additional planet in the TrES-5 system, further follow-up observation of transits would be required.

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