Exploring Transit Timing Variation of Extra-solar Planet TrES-5b through follow-up observations using the 2-m HCT

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Abstract- We present seven new transit curves of the extra-solar planet TrES-5b observed with the 2-m Himalayan Chandra Telescope (HCT), Hanle, India during 2016-2020 to look for the transit timing variation (TTV). For the precise TTV analysis, total 52 transit light curves are considered which include seven light curves from our new observations, 37 from the literature, and 15 light curves with quality one from the Exoplanet Transit Database (ETD). Fitting a linear ephemeris model to homogeneously determined mid-transit times from these light curves, we have refined the linear ephemeris and found presence of TTV in the TrES-5 system. To search periodic TTV, a generalized Lomb-Scargle periodogram is computed for the timing residuals of linear ephemeris model. The highest peak power obtained in the periodogram has the false alarm probability (FAP) of 12%, which is below from the threshold levels of FAP =1% and 5%, suggesting that the observed TTV is unlikely to be periodic. Based on this finding, we conclude that additional planet might not be present in the TrES-5 system, otherwise a significant periodicity would definitely be appeared in the periodogram. Since our results show the agreement with the previous findings of Mislis et al. (2015) and Maciejewski et al. (2016), as well as disagreement with the result of Sokov et al. (2018), the further high-precision follow-up observations of the transits of TrES-5b are being carried out to confirm our finding using 2-m HCT.

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 03949–00967. Due to its short period and close proximity to its host star, the transit of this extra-solar planet 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 (Mannaday et al. 2020). Based on the TTV analysis, Mislis et al. (2015) and Maciejewski et al. (2016) have discarded the presence of an additional planet in the TrES-5 system, whereas the recent study of Sokov et al. (2018) indicates the possibility of an additional planet TrES-5c 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 those available in the literature and the Exoplanet Transit Database[1] (ETD).

New Photometric Observations

In this study, we have observed seven new transits of TrES-5b between 2016, Sept. 30 and 2020, May 20 with the 2-m 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 60-120 seconds (see Soutworth et al. 2009a, b).

Data Reduction

- All the science images taken from HCT were pre-processed calibrated using the Image Reduction and Analysis Facility (IRAF) software[2].
- 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 event, 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 square.
- 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 red lines are the best-fit model.

Other Observational Data

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/.

Results

- To determine the best fit values of transit parameters, all the 59 transit 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 was used.
- 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 ω 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-fit parameters derived from our new light curves are shown in in Table 1, whereas the best-fit model light curves derived from TAP run are plotted with red lines in Figure 1.

Table-1
The Best-fit Values of Parameters T_m, R_p/R_*, a/R_*, *i*, u_1, and u_2 Derived from Seven Transit Light Curves Observed with 2-m HCT

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	$2458990.26899^{+0.00060}_{-0.00063}$	$86.70^{+2.0}_{-1.7}$	$6.930^{+0.50}_{-0.61}$	$0.1379^{+0.0063}_{-0.0051}$	$0.709^{+0.044}_{-0.046}$	$0.192^{+0.045}_{-0.047}$

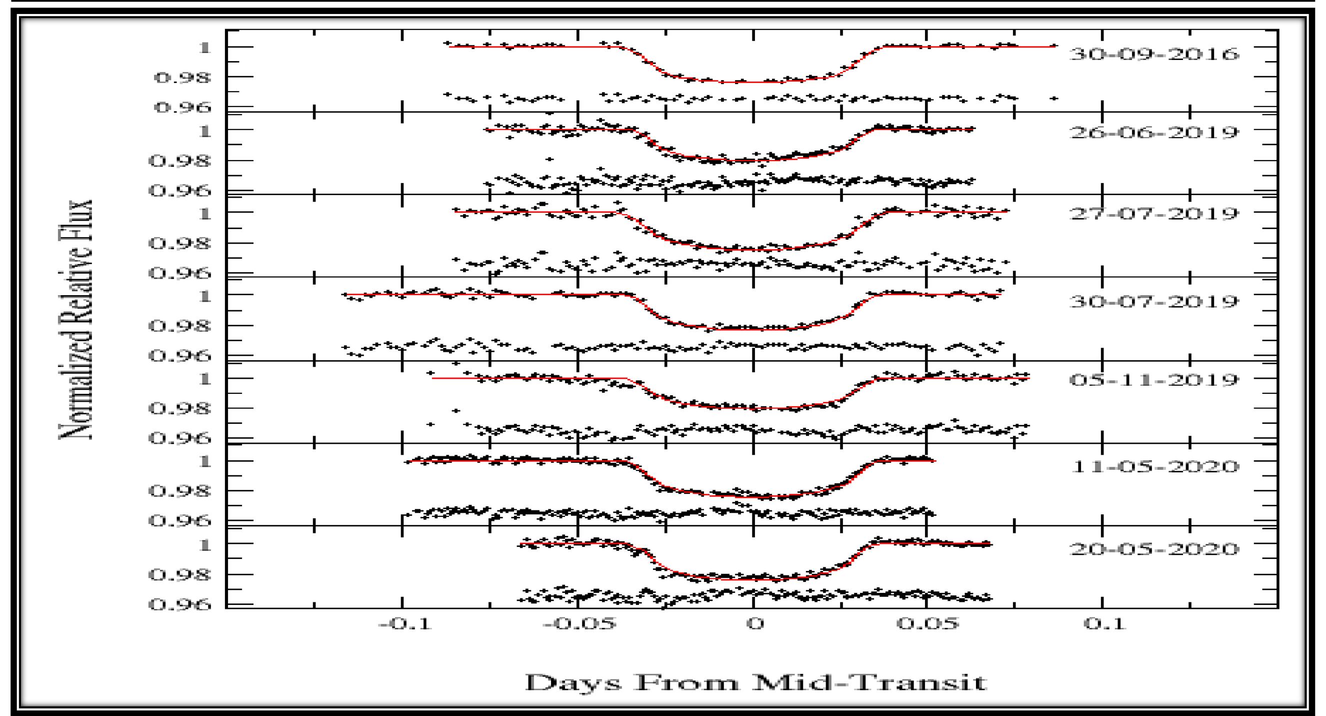

Figure 1. Normalized relative flux as a function of the time (the offset from mid-transit time and in TDB-based BJD) of seven transit light curves observed with 2-m HCT. The points are the data and solid red lines are best-fit models. The corresponding residuals is shown in the bottom of each light curve. All the above light curves show the milli-magnitude levels of accuracies in the OOT regions.

Transit Timing Analysis

New Ephemeris

- By fitting a linear function: $T_m(E)$ = PE + T_0 of epoch E to 59 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. 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.

O-C Diagram and Generalized Lomb-Scargle Periodogram

- To Investigate whether the possible TTV is produced by the presence of additional planet or not, the timing residual (O-C data) was obtained for each epoch E using the above given refined ephemeris.
- The O-C diagram, a plot between the timing residuals and considered epochs E, is shown in Figure 2.
- If additional planet exist in the TrES-5 system, then periodicity should always be present in the timing residuals.
- To search for periodicity in the timing residuals, a generalized Lomb-Scargle periodogram (Zechmeister & Kurster 2009) was computed in the frequency domain
- The resulting periodogram defined by the spectral power as a function of frequency is shown in Figure 3.
- The False Alarm Probability (FAP) of 12% determined for the highest power peak by randomly permuting the timing residuals to the observing epochs using a "*bootstrap*" resampling method with 10^5 trials, is found below the threshold levels (i.e. FAP=5% and FAP=1%).
- This indicates the lack of periodicity in the timing residuals and hence absence of additional planet in the TrES-5 system.

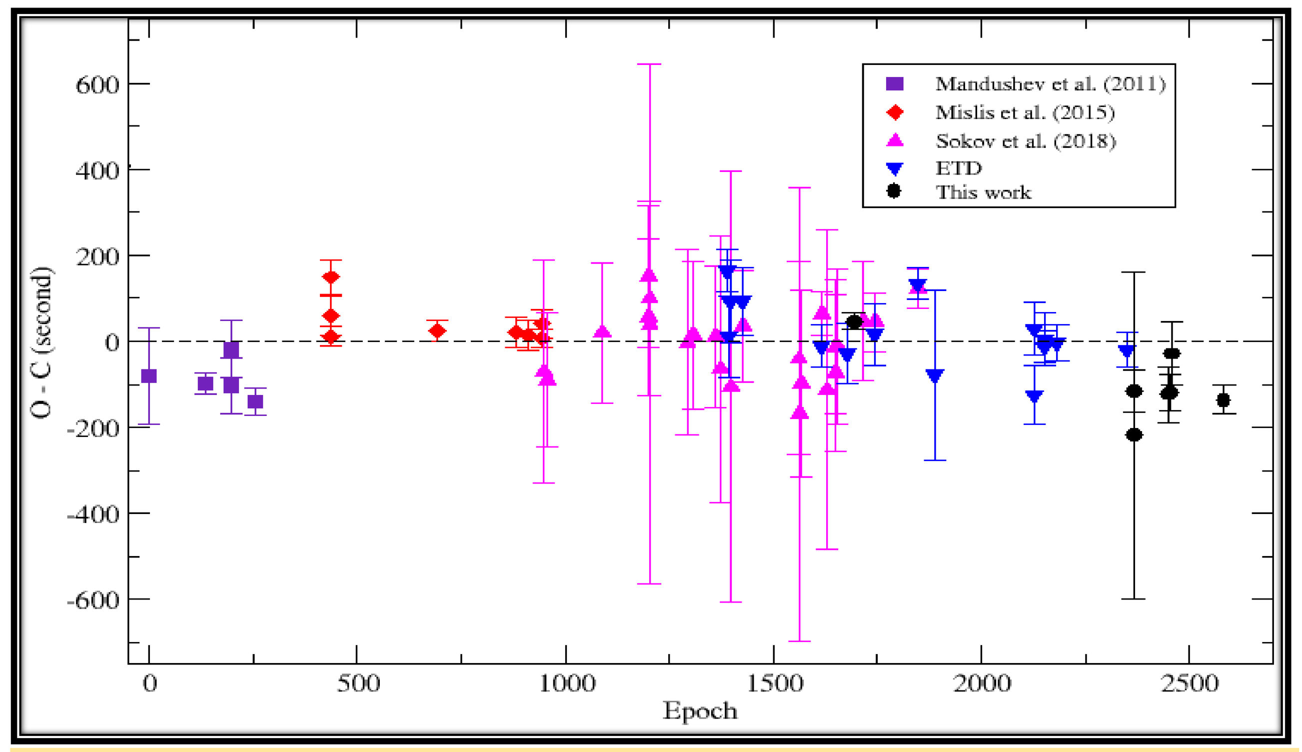

Figure 2. O−C diagram for the 59 mid-transit times considered in this work. Indigo filled squares are for the data from Mandushev et al. (2011), red filled diamonds are for Mislis et al. (2015), magneta filled up-triangles are for Sokov et al. (2018), blue filled down triangles are for ETD, and the black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

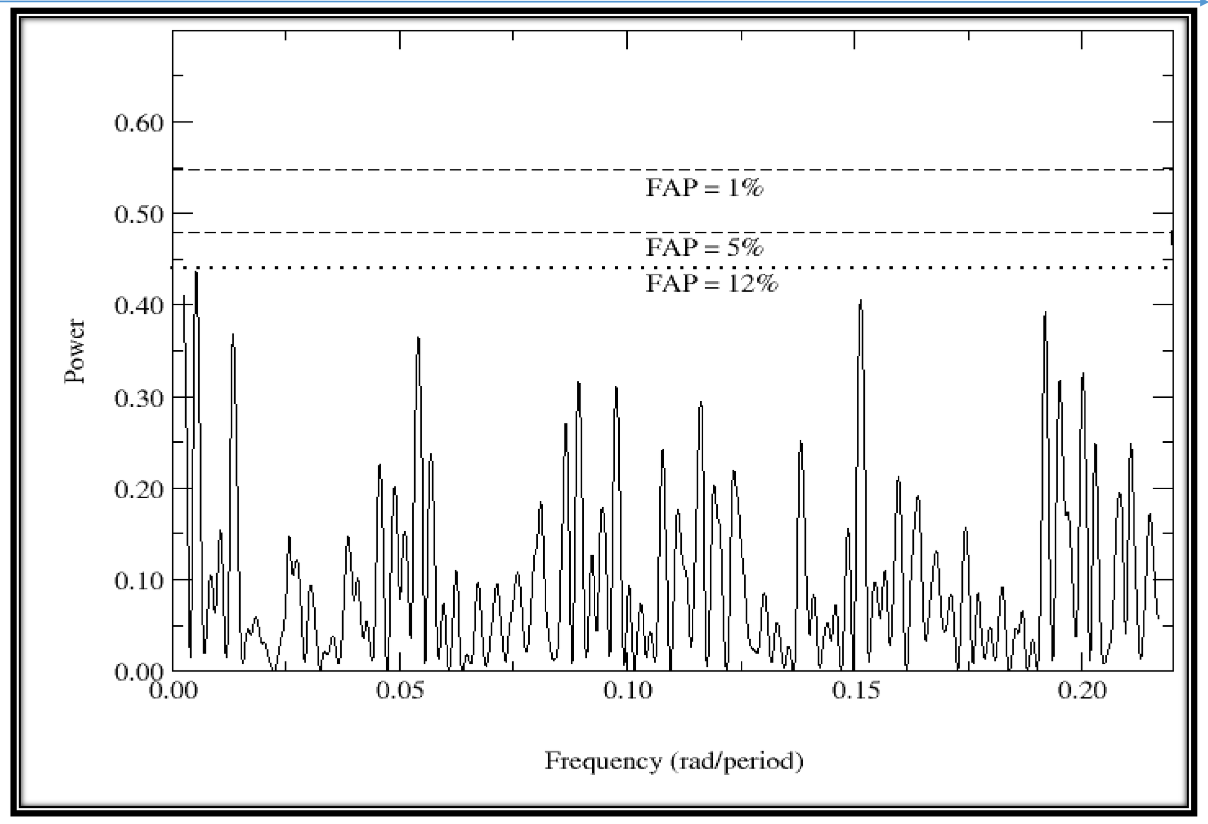

Figure 3. Generalized Lomb–Scargle periodogram for the O-C data of TrES-5b. The dotted line indicates the FAP (=12%) level of the highest power peak at the frequency of 0.005232 rad/period. The dashed lines from top to bottom indicate the threshold levels of FAP=1% and FAP=5%, respectively.

Conclusion

The homogeneously determined mid-transit times from the 59 light curves (7 from 2-m HCT, 37 from literature and 15 from ETD) enabled us to refine the transit ephemeris. The derived ephemeris are consistent and even more precise than the previous studies. From the timing analysis, we have found the possible presence of TTV in the TrES-5 system. However, the frequency analysis indicates that the TTV is unlikely seem to be periodic. This lack of periodic TTV allow us to conclude that the additional planet may not present in the TrES-5 system. To fully confirm the presence or absence of additional planet in the TrES-5 system, further follow-up observation of transits are being carried out with 2-m HCT.

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