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Transit Timing Variations Analysis of Extra-Solar Planet Qatar-1b

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Abstract— *We report the results of the transit timing variation analysis of the extra-solar planet Qatar-1b using thirty eight light curves. Our analysis combines thirty five previously available transit light curves with three new transits observed by us on June 30, 2016, July 10, 2016 and September 2, 2016 using the 2-m Himalayan Chandra Telescope at the Indian Astronomical Observatory, Hanle, India. From these transit data, the physical and orbital parameters of the Qatar-1 system are determined. In addition to this, the ephemeris for the orbital period and mid- transit time are refined to investigate the possible transit timing variation (TTV). To investigate transit timing variations (TTVs), we fitted the straight line of zero variation to the O-C data of this system. We obtained* χ^2_{red} *=1.12, which indicates that the null-TTV model provides the better fit to the (O-C) data. This suggests that there is no evidence of TTVs in the extra-solar planetary system Qatar-1. Our result confirms the finding of Maciejewski et al. (2015)[9] and Collins et al. (2017)[1] that there is no existence of the additional planet in this system.*

Keywords— *planetary systems – stars – individual (Qatar-1) – technique – photometry*

1. INTRODUCTION

The development of the research in extra-solar planets has been successful for nearly two decades. The Doppler-shift method allows us to know many extra-solar planets. In addition to this, the method of transit also produces fruitful results. Particularly, more than *2691* extra-solar planetary systems have been found to transit their parent stars. In order to study the perturbation from small unknown planets and to constrain the overall orbital configuration in planetary systems, the transit timing variations *(TTVs)* have been seriously investigated in recent years (Agol et al. 2005; Holman et al. 2005, 2010; Miller- Ricci et al. 2008; Winn et al. 2009; Maciejewski et al. 2010, 2011, 2013, 2015, 2016)[2-11]. Among the detected planetary systems, Qatar-1 attracts many attentions due to its strong transit signal and short orbital period. For the Qatar-1 system, Von Essen et al. (2013)[15] have found the indication for possible transit timing variations (TTVs), whereas some workers in this field (e.g. Maciejewski et al. 2015; Collins et al. 2017)[8,1] have not claimed the detection of transit time variations (TTVs). These results imply that further photometric follow-up of transits for the extra-solar planetary system Qatar-1 is necessary to confirm the presence or absence of TTVs. Here, in addition to our three transit observations of this system from *2-m Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory, Hanle, India,* we try to cover much more epochs by including many transit data from literature as well as from Exoplanet Transit Database (ETD) to improve the estimates of the physical and orbital parameters of this system, as well as to refine the ephemeris for the orbital period and mid-transit time required for the future transit observations.

The reminder of this paper is organized as follows. In the section 2, we describe about observations and data reduction. Section 3 presents the methods for analysis of transit light curves. Section 4 and 5 are devoted to the transit timing variations analysis and finally the concluding remarks are provided in Section 6.

2. OBSERVATION AND DATA REDUCTION

In this study, we have monitored Qatar-1 system by the 2-m HCT Telescope. During June-September 2016, three runs of transit observations were done by us in R-band with 60 second of exposure time. In addition to our three transit data, eight from ETD, five from Covino et al. (2013)[12], seven from Von Essen et at. (2013)[15], fifteen from Maciejewski et al. (2015)[8] are considered. Thus, the thirty eight light curves have been analyzed in the present study. The HCT CCD images of Qatar-1 system were calibrated using the standard *IRAF* procedures such as trimming, dark and bias subtractions, and flat field division. After pre-processing, the aperture photometry was performed on the Qatar-1 and the nearby comparison stars using *'phot'* task within *IRAF*. Using the flux of Qatar-1 and the comparison stars, we carried out the differential photometry to plot the light curves for each transit data.

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3. ANALYSIS OF LIGHT CURVES

The Transit Analysis Package (TAP) as described in Gazak et al. (2012)[13] has been used for our light curves analysis. The TAP employs MCMC technique and the model of Mandel & Agol (2002)[14] to fit the light curves. This model derived for a simple two-body star-planet system. Hence, for each *TAP* run, we obtain most likely orbital parameters separately for each epoch.We analysed each light curve through TAP separately using five chains with lengths of 1000000 links each. To start *TAP*, we follow the procedure as given in Jiang et al. (2013)[16]. All the initial parameters required in each TAP run are taken from Maciejewski et al. et al. (2015)[8]. The results of our three new light curves derived through TAP are shown in

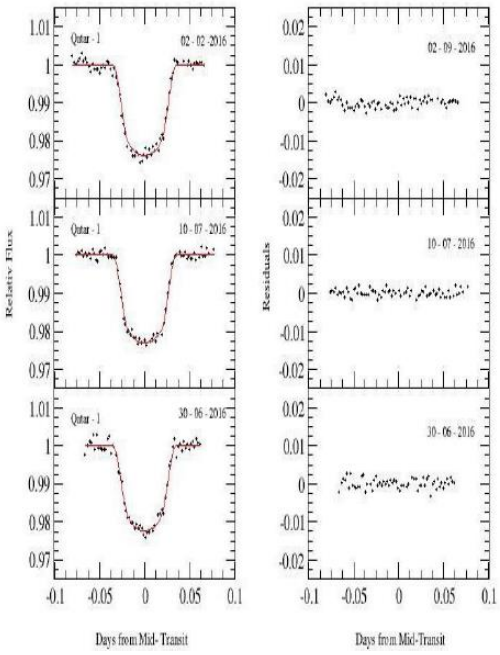

Fig. 1: Left panel : the normalized relative flux as a function of the time (the offset from the mid-transit time in TDB based BJD) of three light curves in this work; points are the data and curves are the models. Right panels: the corresponding residuals.

Table 1: The first transit observation of Qatar-1 by Covino et al. (2013)[12] is considered here as epoch $E = 0$, and other transits epochs are calculated accordingly. The observed light curves with the best-fitting modelled light curves are presented in Figure-1, where the points are observational data and solid curves are the best-fitting models.

4. NEW TRANSIT TIMING

We determine refined ephemeris for orbital and mid-transit time using the linear function, $Tm^c = EP + T0$. We have done the $\chi 2$ fitting on all the 38 data sets of $(E,T0)$ and calculated the best fit values of P and T_O *with* $\chi 2_{red}$ = 1.12 as

P=1.42002368 ± 0.000000145d and
T_0=2455711.53470424 ± 0.000109675167.

5. O-C DIAGRAM

To investigate possible TTVs, it necessary to make the O-C diagram. This shows the difference between the observational mid-transit time, O, and the calculated mid-transit time of a simple two body star-planet system, C. For this, we first calculated the T_m for each epoch (E) employing the best fitted values of P and T_O. We have plotted O-C diagram as shown in Fig. 2. If we use a straight line of zero variation to fit the data in O-C diagram, we obtained a $\chi 2_{red}$ = 1.12. Thus, the assumption with no TTV provides better fit to the O-C data. This suggests that there is no evidence of TTVs in the extra-solar planetary system Qatar-1, which allows us to conclude that there is no existence of additional planet in this system. Our result agrees with those reported in Maciejewski et al. (2015)[8] and Collins et al. (2017)[1].

6. CONCLUSION

The three new transit light curves of extra-solar planetary system Qatar-1 are analysed. Together with these three light curves, those available in literature are all further analysed through the same procedure for uniform

Table 1: Results of best fitted parameters using TAP

Parameters	30.06.2016	10.07.2016	02.09.2016
T_m	$570.34628^{+0.00050}_{-0.00050}$	$580.28552^{+0.00022}_{-0.00021}$	$634.24666^{+0.00035}_{-0.00034}$
i(deg)	$84.23^{+0.14}_{-0.13}$	$84.30^{+0.12}_{-0.12}$	$84.28^{+0.13}_{-0.13}$
R_p/R_*	$0.1431^{+0.0028}_{-0.0029}$	$0.1461^{+0.0013}_{-0.0013}$	$0.1477^{+0.0021}_{-0.0022}$
a/R_*	$6.335^{+0.059}_{-0.059}$	$6.348^{+0.053}_{-0.053}$	$6.323^{+0.055}_{-0.055}$
u_1	$0.567^{+0.047}_{-0.047}$	$0.512^{+0.045}_{-0.045}$	$0.520^{+0.046}_{-0.047}$
u_2	$0.1660^{+0.049}_{-0.048}$	$0.130^{+0.048}_{-0.048}$	$0.520^{+0.046}_{-0.047}$
Sigma red	$0.0029^{+0.0031}_{-0.0020}$	$0.001^{+0.00130}_{-0.00071}$	$0.0044^{+0.0016}_{-0.0014}$
Sigma white	$0.00121^{+0.00023}_{-0.00028}$	$0.00068^{+0.000076}_{-0.000074}$	$0.00057^{+0.00014}_{-0.00020}$

estimation of physical and orbital parameters. All the determined parameters values are consistent with the previous works. Our result suggests that there is no evidence of TTVs in the extra-solar planetary system Qatar-1. Therefore, it is concluded here that the additional planet may not exist in this system. However, one needs further high-cadence and high-precision follow-up observations of this system to confirm the presence or absence of the additional planet.

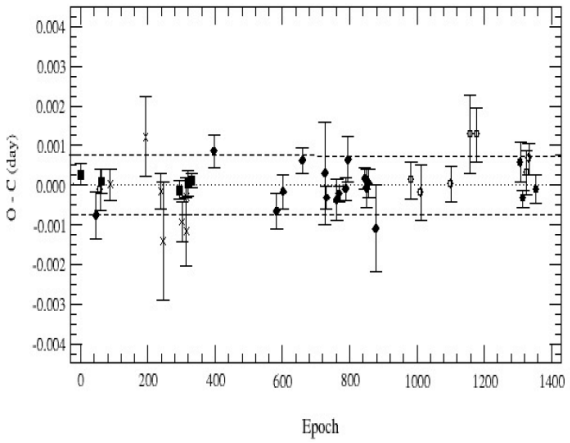

Fig.2: Residuals of transit times from the refined linear ephemeris; square symbols indicates the data from Covino et al. (2013)[12], diamonds from Maciejewski et al. (2015)[8] crosses from Von Essen et al. (2013)[15], open circles from ETD and filled circles denote the new transits data of this work. The dotted lines denote null TTV model. Dashed lines denote the uncertainties at the confidence level of 95.5% (i.e. 2σ), where σ is the weighted standard deviation.

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