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TTV analysis of the exoplanet Qatar-1b

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Here, we present the transit times and transit timing variation (TTV) analysis of the hot Jupiter Qatar-1b, based on our archival observations. A total of 19 transit events were observed using the 0.6-m Zeiss-600 telescope at Maidanak Observatory in Uzbekistan. Transit light-curve fitting was performed using the Transit Analysis Package (TAP) software. Our results did not indicate the presence of any additional bodies in the observed exoplanetary system.

Keywords: Exoplanets, timing variation methods, transit timing variation method

1 Introduction

The discovery of the first confirmed extrasolar planet, 51 Pegasi b, marked a pivotal moment in the initiation of systematic searches and investigations of exoplanets. The scientific interest in the study of these celestial bodies, in all their diversity, is largely driven by their potential to enhance our understanding of the formation and evolution of the Solar System. Moreover, the rapid advancement of astronomical instrumentation, coupled with increasingly sophisticated mathematical methodologies for processing and analyzing observational data, has substantially elevated the scope and precision of exoplanetary research. The transit method of exoplanet detection, which involves observing the periodic dimming of a star as an exoplanet passes across its disk, has fundamentally transformed the search for, and characterization of extrasolar planets. According to the NASA Exoplanet Archive[1], as of today 4,408 out of 5,876 confirmed exoplanets have been identified using this technique. Furthermore, systematic monitoring of multiple transit events and the analysis of transit timing variations (TTVs) (Agol et al., 2005) enables the detection of additional, non-transiting exoplanets within a given planetary system. Currently, the TTV method has led to the confirmation of 35 exoplanets, as reported by the same archive. The increasing

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[1] https://exoplanetarchive.ipac.caltech.edu/

accessibility of small telescopes capable of high-precision photometric measurements has further facilitated the expansion of such observational studies.

In this study, we present the results of archival transit observations of the exoplanet Qatar-1b, a gas giant comparable in size and mass to Jupiter. Qatar-1b orbits a brown dwarf and was originally discovered in 2010 through transit observations conducted by the Qatar Exoplanet Survey team (Alsubai et al., 2011).

2 Observations and data reduction

All transit observations of the exoplanet were conducted between 2017 and 2019 using the 0.6 meter Zeiss-600 telescope at the Maidanak Astronomical Observatory in Uzbekistan. A consistent instrumental configuration and an observational procedure were maintained throughout all sessions. Data were acquired using an FLI 1024 $\times$ 1024 CCD camera in combination with a Bessell R filter. The integration time for each exposure was 120 seconds. The detector provided a pixel scale of $0''.678$ pix^{-1}, and the field of view of $11'.7 \times 11'.7$. Preliminary data reduction and aperture photometry of the acquired observations were performed using the standard IMRED/CCDRED and DIGIPHOT/APPHOT packages within the Image Reduction and Analysis Facility (IRAF) software suite. Differential photometry was performed relative to the averaged light curve of the comparison stars. Details of the observational sessions are summarized in Table 1, while Figure 1 illustrates the telescope's field of view, indicating the target object and the comparison stars used in the analysis.

Table 1 Summary of transit observations of Qatar-1b.

Date	Number of data points	Duration (hours)	Start time (HJD system)
09.10.2017	68	2.3	2458036.07893
26.10.2017	87	2.9	2458053.10011
09.12.2017	90	3.0	2458097.11377
19.12.2017	73	2.4	2458107.07748
21.03.2018	102	3.4	2458199.35076
07.05.2018	71	2.4	2458246.24472
07.07.2018	89	3.0	2458307.26660
24.07.2018	87	2.9	2458324.35302
03.08.2018	84	2.8	2458334.25343
10.08.2018	79	2.6	2458341.37319
23.08.2018	106	3.5	2458354.14114
09.09.2018	135	3.4	2458371.16461
16.09.2018	50	1.7	2458378.29035
19.09.2018	70	2.3	2458381.12564
23.09.2018	40	1.3	2458385.38432
04.05.2019	83	2.8	2458608.33399
07.05.2019	67	2.2	2458611.18439
06.10.2019	69	2.3	2458763.12803
23.10.2019	132	4.4	2458780.09193

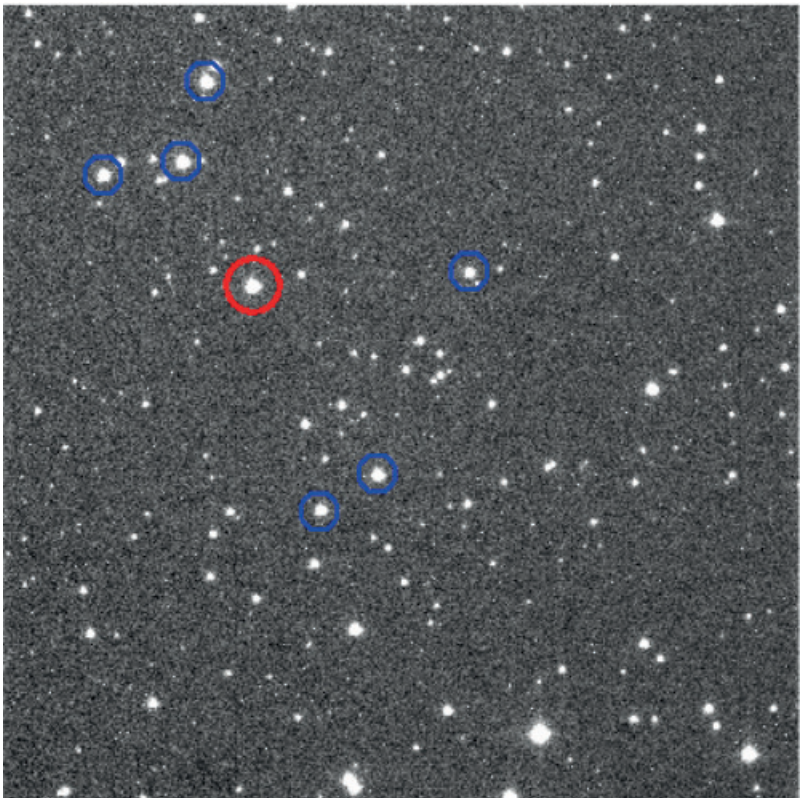


Figure 1 Field of view of the telescope used for the observations. The target object is indicated in red, while the comparison stars are marked in blue.

3 Light curves analysis and results

The analysis of the light curve and transit timing for the exoplanet was performed using the Transit Analysis Package (TAP) software (Gazak et al., 2012). The light curve fitting within this program is based on Markov Chain Monte Carlo (MCMC) techniques and utilizes the analytical model of Mandel and Agol (Mandel and Agol, 2002), which assumes a spherically symmetric star and planet. We separately analyzed each of the obtained transit light curves using the Transit Analysis Package to determine the transit times. The system parameters were fixed to the values provided by Alsubai (Alsubai et al., 2011) and the transit times were solved for each observation night. A quadratic limb darkening effect was assumed, with the linear and quadratic limb darkening coefficients taken from the tables of Claret and Bloemen (Claret and Bloemen, 2011). The resulting light curves are presented in Figure 2. The derived transit times extend the data coverage to more than 500 cycles. We therefore used a weighted linear fit (with weights based on timing uncertainties) to refine ephemeris:

$$\mathrm{HJD} = (245518.4096 \pm 0.0063) + (1.4200247 \pm 0.0000032) \times E.$$

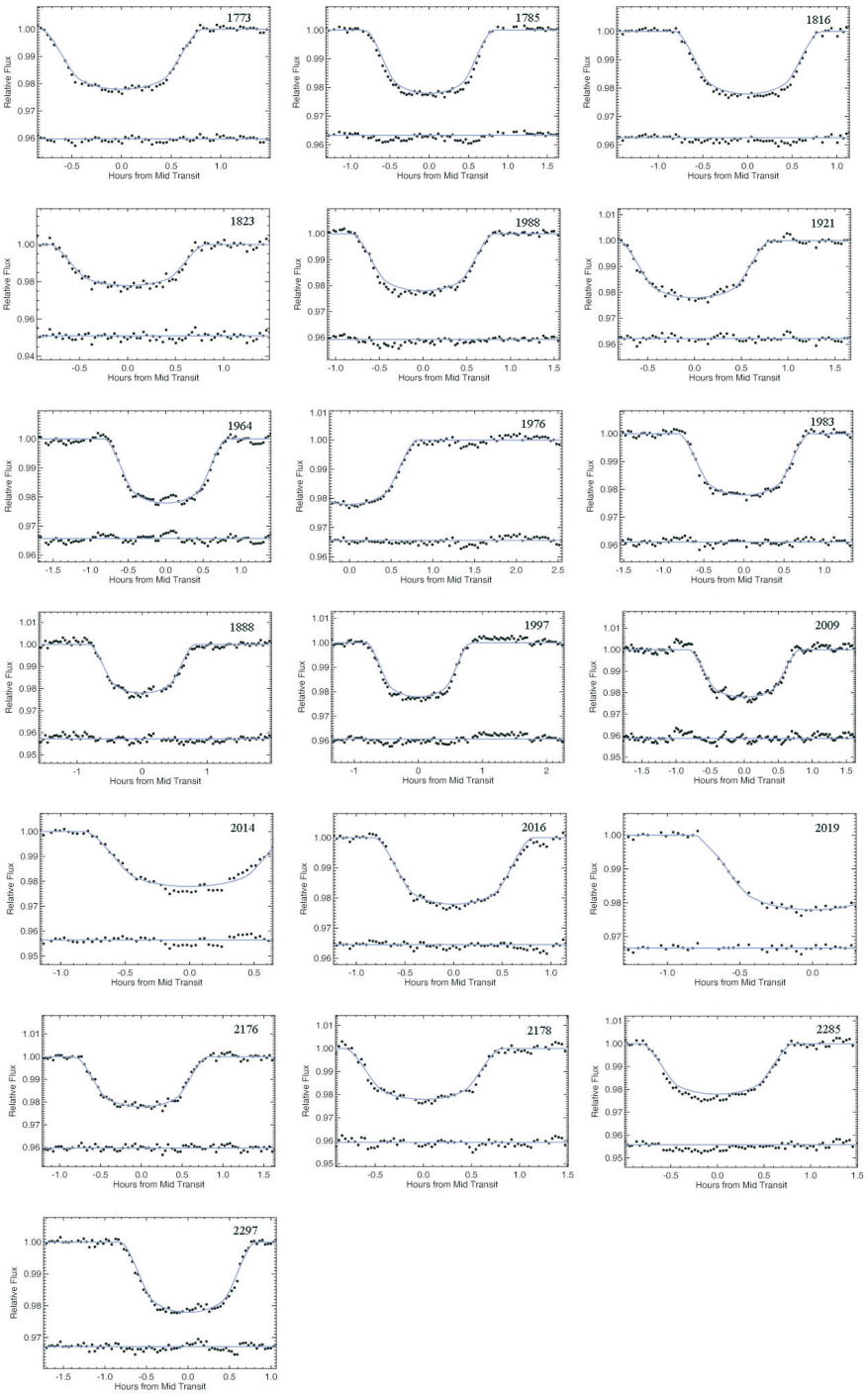


Figure 2 Light curves of the transit events. The numbers on the figures represent the epochs of the transits.

The calculated transit times, along with the differences between the observed and calculated values, are shown in Table 2 and Figure 3.

Table 2 Transit midpoints (HJD time system) and calculated O–C.

Epoch	Observed transit midpoint	O–C (days)
1773	2458036.11419	0.00036
1785	2458053.15469	0.00056
1816	2458097.17491	0.00002
1823	2458107.11683	0.00177
1888	2458199.41696	0.00029
1921	2458246.27871	0.00122
1964	2458307.33804	–0.00051
1976	2458324.37927	0.00042
1983	2458334.31841	–0.00061
1988	2458341.41957	0.00043
1997	2458354.19825	–0.00112
2009	2458371.23937	–0.00029
2014	2458378.33580	–0.00399
2016	2458381.17775	–0.00209
2019	2458385.43925	–0.00066
2176	2458608.38518	0.00139
2178	2458611.22307	–0.00077
2285	2458763.16479	–0.00169
2297	2458780.20957	0.00279

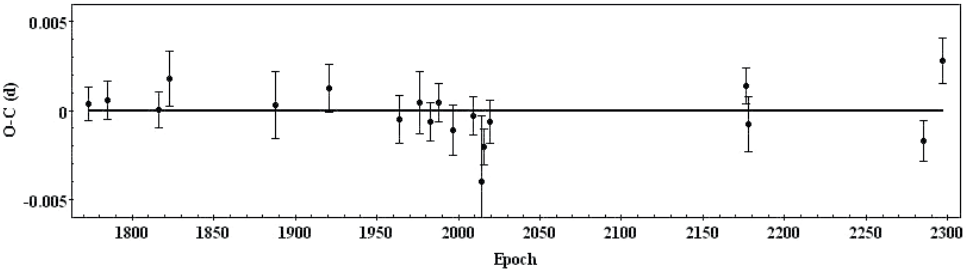


Figure 3 Residuals of the transit times relative to the refined ephemeris.

4 Conclusions

Here, we present the observed transit times and the residuals from the refined linear ephemeris. A TTV analysis of observations of the Qatar-1b system obtained between 2011 and 2012 suggested the presence of statistically significant long-term time variations, which could be attributed to a weak perturbation from a third body in the system (von Essen et al., 2013). However, subsequent studies have not been able to

confirm these findings. Our results are consistent with those of (Maciejewski et al., 2015; Collins et al., 2017b; and Yang et al., 2022), who concluded that Qatar-1b has no detectable planetary companions in nearby orbits.

In our analysis, we did not use the TTV data presented in previously published studies on this object due to the significant heterogeneity among the available datasets. Instead, we used only data obtained from a single telescope and processed using the same method.

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