Analyzing Transit Timing Variations of Qatar-1b

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Received June 5, 2021; revised January 7, 2022; accepted January 17, 2022

Abstract This study investigates 13 transits of Qatar-1b from archival data collected using 6-inch telescopes in the MicroObservatory network. The purpose of this transit analysis was to update transit midpoints of Qatar-1b to maintain the ephemeris. Additionally, the study sought to uncover trends in the transit data, which could provide more information about the exoplanet. In order to achieve this goal, the EXOplanet Transit Interpretation Code (EXOTIC) pipeline was used to process these transits and generate light curves, which were contributed to the American Association of Variable Star Observers (AAVSO) Exoplanet Database. The analysis of the data did not indicate the presence of other planets in the system. This study contributes observations of the star system Qatar-1b and supports the current ephemeris of this planet.

1. Introduction

Exoplanet transit photometry takes advantage of the fact that if an exoplanet passes in front of a star relative to Earth's line of sight, there will be a dip in the brightness that will result in a characteristic curve (Deeg and Alonso 2018). This is described by the equation

$$\Delta F \approx (R_p / R_s)^2 = k^2 \qquad (1)$$

where ΔF is the change in flux, R_p is the radius of the planet, R_s is the radius of the host star, and k is the ratio of the two radii. Thus, by measuring the percentage of light that is blocked by a transiting planet, the radius of an exoplanet relative to its host star can be determined. In addition, the shape of the curve and the period with which it repeats allows determination of many more characteristics of the planet, the orbit, and the host star.

Observations of confirmed transiting exoplanets can help refine the ephemerides of targets used for detailed spectroscopic characterization (Zellem *et al.* 2020). When its transits are not observed for an extended period of time, a planet's mid-transit time uncertainty increases, and recovering its ephemeris becomes more difficult. A network of smaller telescopes can be used to observe bright, high-priority targets, which allows larger telescopes to allocate their observing time to the dimmer, smaller targets for which they are optimized. The NASA Exoplanet Watch program facilitates citizen scientists conducting research on bright exoplanet targets (brighter than 12 magnitude) using small telescopes, and collates their results in the AAVSO Exoplanet Database (Zellem *et al.* 2020). Such observations not only help to maintain the ephemerides of these exoplanets, but also facilitate analysis that require a large pool of measurements.

One example of a type of analysis that can be done with a pool of transit mid-point measurements is to search for transit timing variations (TTVs) (Zellem *et al.* 2020). TTVs can be used to detect additional exoplanets in the system, because their gravitational influence causes the planet under study to transit slightly earlier or later than expected. Thus, if the difference between the expected and observed midpoints of a planet exhibits a patterned variation, this can be analyzed to identify and characterize the perturber. However, such variations occur only within systems that contain massive, tightly packed planets, and they can only be detected with a sufficiently large collection of data (Cortés-Zuleta *et al.* 2020). Such a collection is currently accumulating in the AAVSO Exoplanet Database. Exoplanet Watch will reduce these data via a common pipeline to update their ephemerides and identify TTV's.

This study analyzes 13 transits from the planet Qatar-1b, which is characterized as a "hot Jupiter" (Alsubai *et al.* 2011). Hot Jupiters are a class of exoplanets characterized by large radius, high temperature, and short orbital period as a result of their being located close to their primary star (e.g. within 0.1 AU), with a mass similar to that of Jupiter. The short orbital period (~1.43 d) and deep transit depth (~2.1%) of Qatar-1b allows for frequent opportunities to observe the planet's transit using small telescopes (Collins *et al.* 2017a).

Previous studies have indicated no evidence of additional planets in the Qatar-1 system (Collins *et al.* 2017a). In Collins *et al.* (2017a), it was found that Qatar-1b transit times were well modeled by the ephemeris with transit midpoint T_0 = 2456234.10321800 ± 0.00006071 and period P = 1.4200242 ± 0.0000002173.

2. Instruments used

The MicroObservatory Robotic Telescope Network is a network of 6-inch telescopes operated by the Harvard-Smithsonian Center for Astrophysics (Sadler *et al.* 2001). This network allows teachers across the U.S. to provide their students access to use the telescopes over the World Wide Web. With this access, students can easily take and analyze images. Students can also adjust many of the settings, such as field of view and exposure times.

Data for this study were collected using the MicroObservatory telescope Cecilia, located at the Fred Lawrence Whipple Observatory on Mount Hopkins, Arizona. The unfiltered images were taken using a KAF-1400 ME camera that has a CCD image sensor, at a focal length of 560mm, and an exposure time of 60 seconds. Exoplanet transit data have been collected by Cecilia since 2011 and are ongoing. Observations made on 13 dates between 17 May 2011 and 09 June 2014 were analyzed. The observations have been uploaded to the AAVSO Exoplanet Database under observer code YELA.

3. Data reduction and light curves

The EXOplanet Transit Interpretation Code (EXOTIC) pipeline is a Python-based tool for reducing transit data. It takes raw fits files or a pre-reduced photometric time series as input. To use it, the user first identifies a comparison star or stars. A comparison star should be close to the target star so that its light is affected by Earth's atmosphere in the same way, well-separated from other stars, not saturated or too dim, not variable, and similar in color to the target star. AstroImageJ (Collins *et al.* 2017a) was used to identify suitable comparison stars. Figure 1 indicates comparison stars found through this method.

EXOTIC performed dark field subtraction using darks taken the same night as the science images. Additionally, instrument specifications along with parameters from the NASA Exoplanet Archive (NEA), shown in Table 1, were used to compute priors for EXOTIC's Markov Chain Monte Carlo (MCMC) fitting algorithm. Note that the latest versions of EXOTIC use dynamic nested sampling, which is similar to MCMC but more efficient. The NEA parameters input as priors were a mid-transit time of 2456234.10321800 days, a mid-transit time uncertainty of ±0.00006071 day, and a period of 1.42002420 ± 0.00000022 days (Collins *et al.* 2017a).

EXOTIC analyzes the image files by first performing multi-object optimal aperture photometry (Zellem *et al.* 2020). It takes the pixel coordinates of a target star and a comparison star as input, and tracks the location of the target star relative to the comparison star through the series of images. The MCMC fits the raw photometric data with a model light curve and a function accounting for airmass to calculate the transit midpoint and its uncertainty.

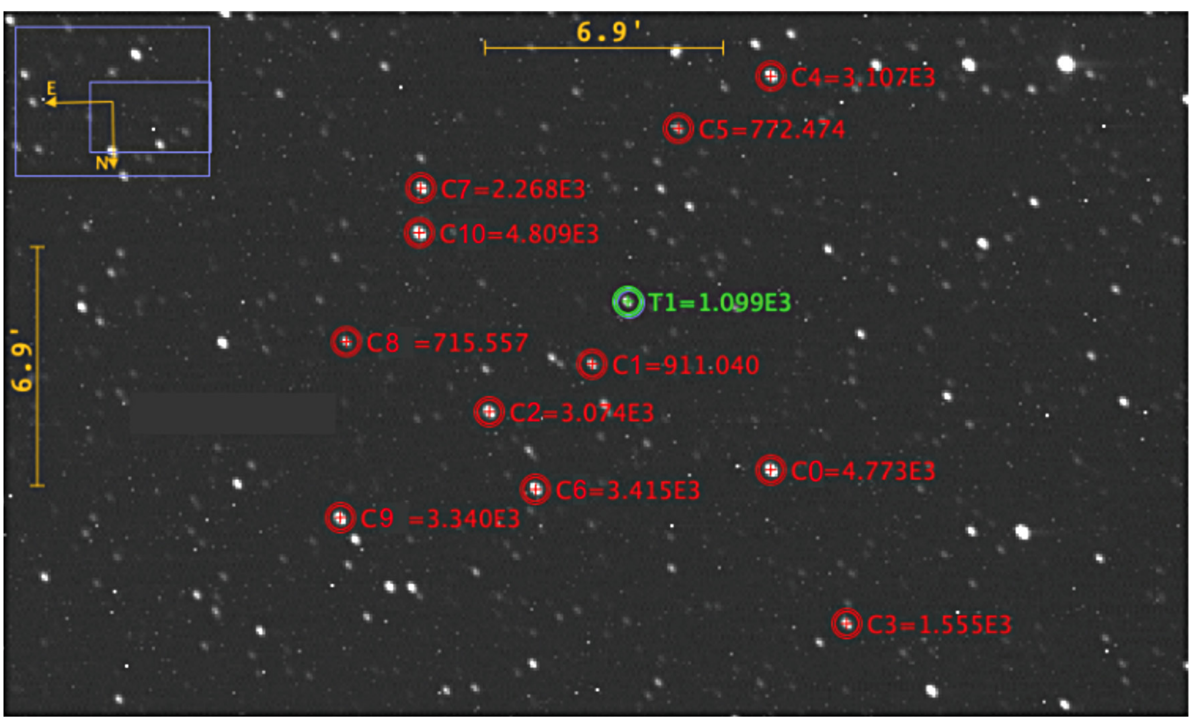

Figure 1. Qatar-1b starfield with labeled comparison stars.

Table 1. Input parameters queried from the NASA Exoplanet Archive used for the fits files by EXOTIC.

Parameter	*Value*
Target Star R.A.	$20^h\ 13^m\ 31.6^{5s}$
Target Star Dec.	+65° 09' 44.39"
Planet Name	Qatar-1b
Host Start Name	Qatar-1
Orbital Period (days)	1.42002420
Orbital Period Uncertainty	± 0.00000022
Published Mid-Transit Time (BJD-UTC)	2456234.10321800
Mid-Transit Time Uncertainty	0.00006071
Planet to Stellar Radius (R_p/R_s)	0.14629
R_p/R_s (+) Uncertainty	+0.00063
R_p/R_s (–) Uncertainty	–0.00064
Ratio of Distance to Stellar Radius (a/R_S)	6.247
a/R_S (+) Uncertainty	+0.067
a/R_S (–) Uncertainty	–0.065
Orbital Inclination i (deg)	84.08
i (deg) (+) Uncertainty	+0.16
i (deg) (–) Uncertainty	–0.15
Orbital Eccentricity (0 if null)	0
Star Effective Temperature (K)	4910.0000
K (+) Uncertainty	+135.9410
K (–) Uncertainty	–80.7669
Star Metallicity ([M/H])	0.2
Star Metallicity Uncertainty	0.1
Star Surface Gravity (log(g))	4.5724800
Star Surface Gravity (+) Uncertainty	+0.0674466
Star Surface Gravity (–) Uncertainty	–0.0982458

The fits files of Qatar-1b were run through EXOTIC to produce light curves for each of the thirty-seven observation dates on which images were acquired by Cecilia. The light curves were classified into four categories: good light curve, poor light curve, partial light curve, and technical issue. "Good light curves" were the light curves where there was a clear dip, and the transit depth looked close to its expected value of approximately 2.1%. The good light curves, shown in Figure 3, were used for analysis; in total, thirteen of the thirty-seven dates yielded good light curves. "Poor light curves" describes light curves in which no dip or no notable dip was observed. Two of the thirty-seven dates analyzed yielded poor light curves. "Partial light curves" showed a clear dip, but did not capture the entire transit of the exoplanet; two of the thirty-seven dates analyzed yielded partial light curves. "Technical issues" describes cases in which fitting errors or poor weather led to a light curve not being output or being unclear, so that data could not be collected. These issues can be caused by cloudy weather (shown in Figure 2), an external light source, a star getting too close to the edge of the field of view, an inadequate comparison star, and rain. Twenty of the thirty-seven dates analyzed yielded technical issues. Examples of each of these types of light curves can be seen in Figure 4.

4. Results

For each successful light curve fit, EXOTIC estimated values for the residual scatter, observed transit midpoint, and transit midpoint uncertainty using the BJD time system. With the observed transit midpoint, the expected transit midpoint can be calculated using the formula:

$$T = T_0 + E \cdot P \tag{2}$$

where E is the epoch, P is the orbital period, T_0 is the optimal transit time in a zero epoch (picked as the first transit date from the reduced data so that all the following transit dates have positive E values), and T is the transit time at the given epoch.

Table 2 shows these values, where each row is a successful transit using the comparison star that yielded the lowest residual scatter percentage. Observed minus Calculated (O–C) values are found by subtracting the midpoint found by Equation 2 using the period derived by Collins *et al.* (2017a) from the midpoint fit by EXOTIC (T_{obs}). The O–C uncertainty values were determined using the equation:

$$\Delta(O–C) = \sqrt{\Delta T_{obs}^2 + E^2 \cdot \Delta P^2 + 2 \cdot E \cdot \Delta P \cdot \Delta T_0 + \Delta T_0^2} \tag{3}$$

which is Equation 3 from Zellem *et al.* (2020).

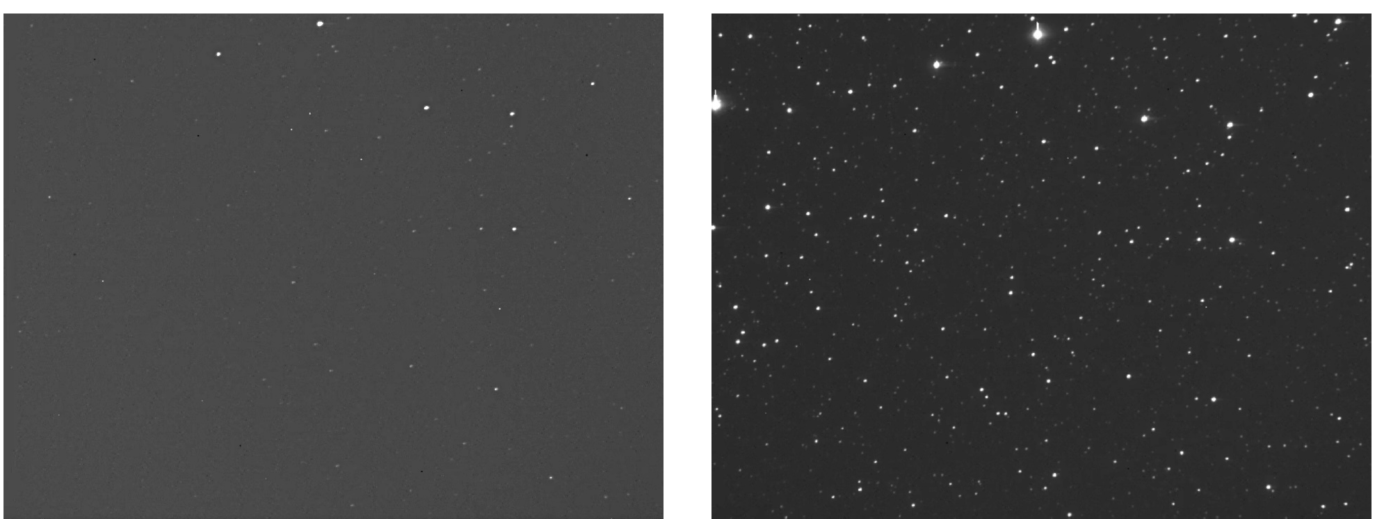

Figure 2. Image showing poor weather (left) versus image showing clear weather (right).

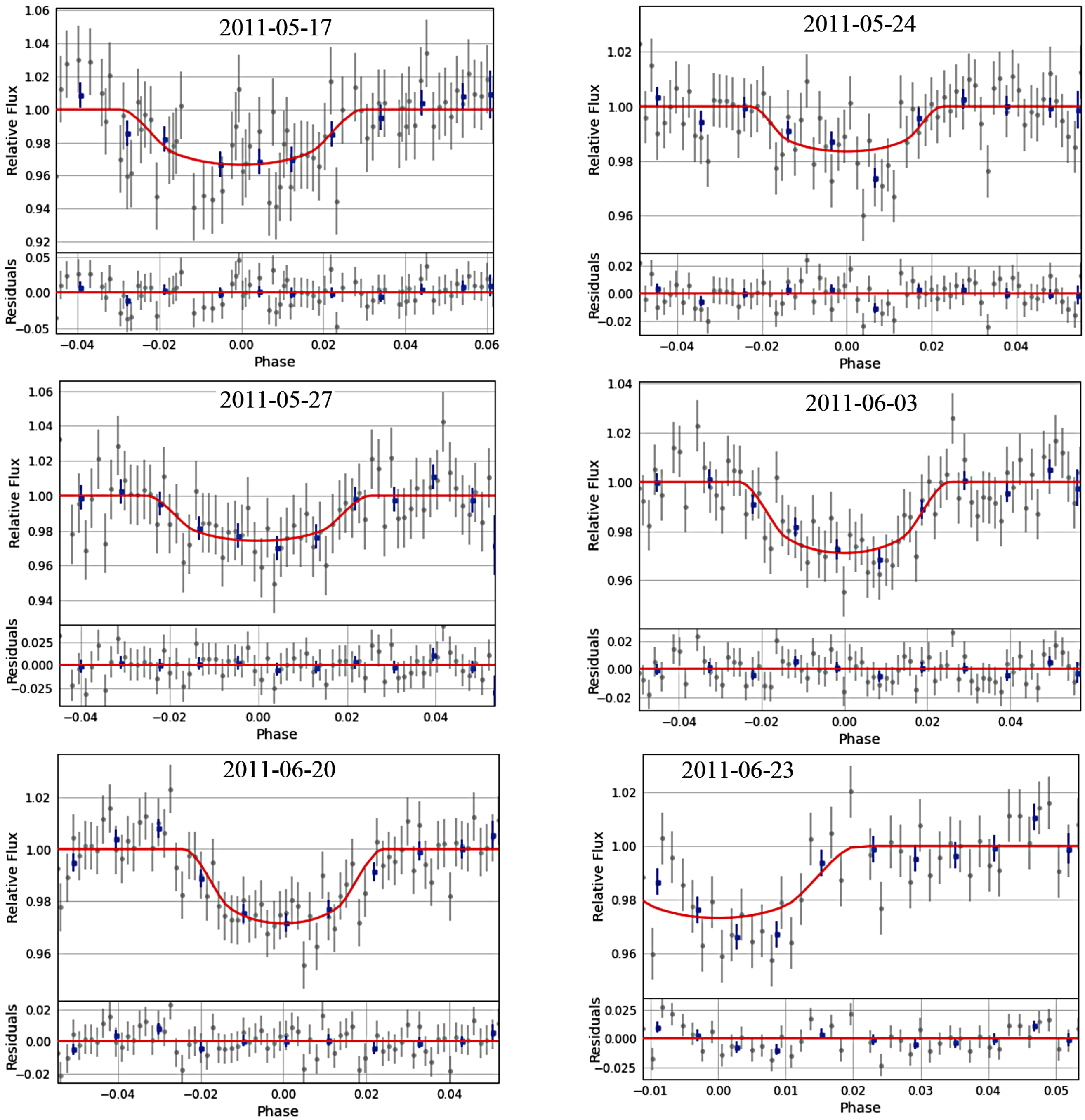

Figure 3. Successful light curve fits by EXOTIC for the transits of Qatar-1b on 17 May, 24 May, May 27, 03 June, 20 June, 23 June of 2011; 18 September, 02 October, 05 October of 2012; 05 October, 12 October, 22 October of 2013; and 09 June of 2014. After an EXOTIC update on 09 July 2020, the color of the outputted light curves changed from black to gray (observe the difference between 2011-06-03 and 2011-06-24). (Figure continued on next page).

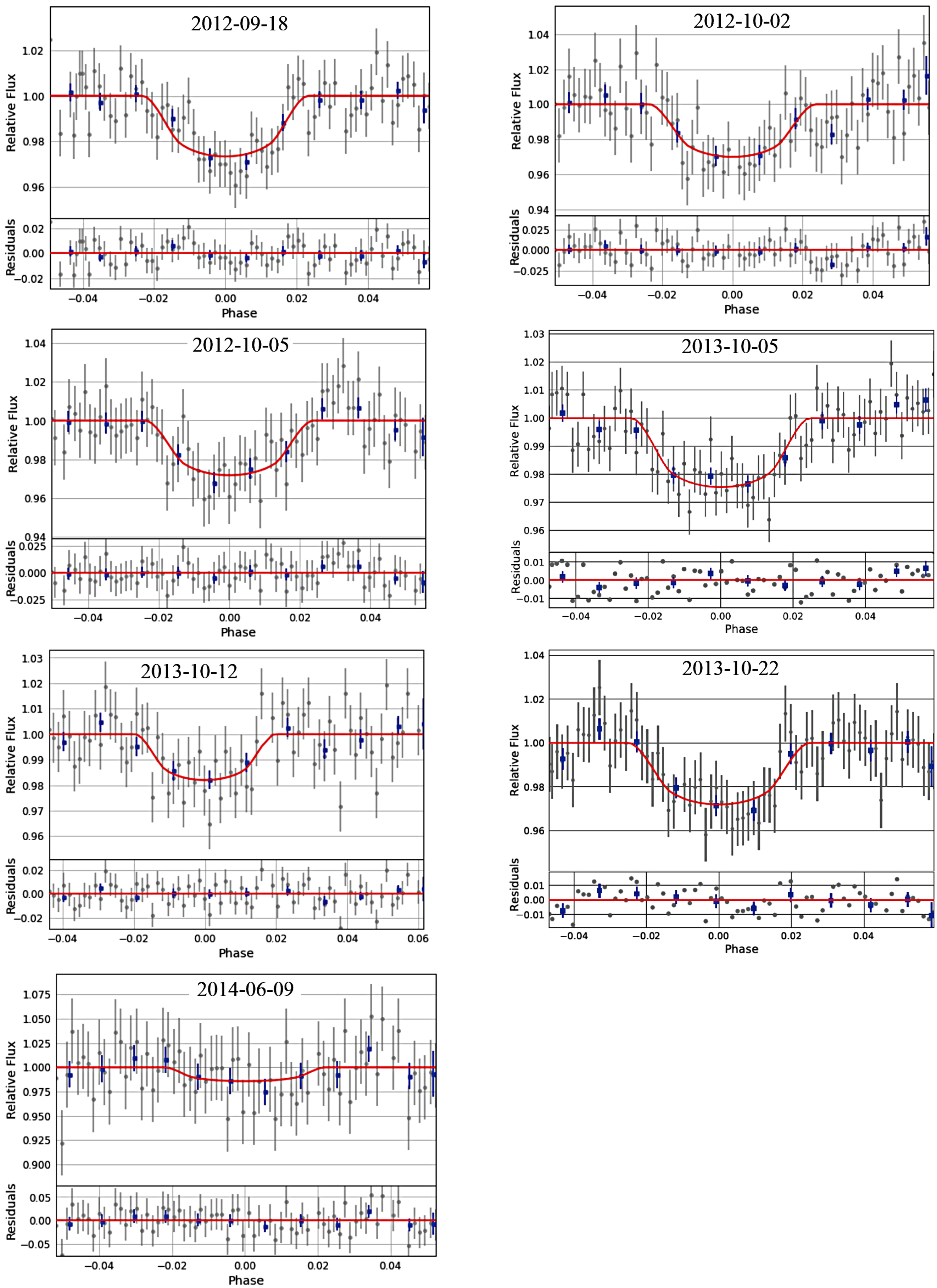

Figure 3. Successful light curve fits by EXOTIC for the transits of Qatar-1b (cont.)

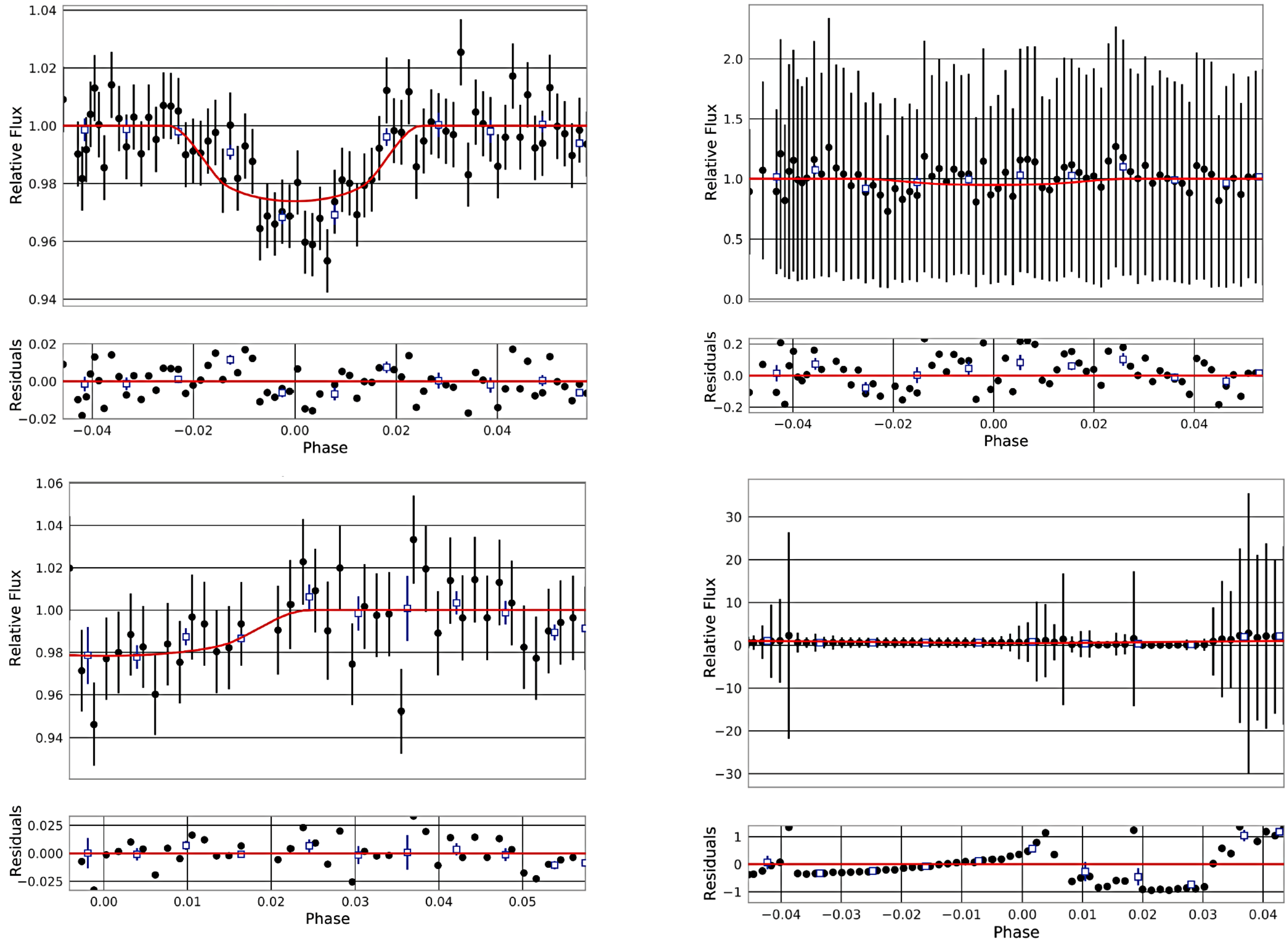

Figure 4. Top left: Good light curve from images taken on 09 June 2014. Top right: Poor light curve from images taken on 26 July 2012. Bottom left: Partial light curve from images taken on 08 September 2019. Bottom right: Technical issue from images taken on 21 September 2016.

Table 2. Transit midpoints (BJD time system) from EXOTIC and calculated O–C and O–C error values.

Date (yyyy-mm-dd)	*Residual Scatter (%)*	*Observed Transit Midpoint*	*Transit Midpoint Uncertainty*	*Expected Transit Midpoint*	*O–C (min)*	*O–C Uncertainty (min)*
2011-05-17	1.69	2455698.7537	0.0031	2455698.7541	–0.57	4.46
2011-05-24	0.99	2455705.8512	0.0029	2455705.8542	–4.34	14.26
2011-05-27	1.47	2455708.6955	0.0036	2455708.6943	1.78	5.18
2011-06-03	0.97	2455715.7906	0.002	2455715.7944	–5.45	2.88
2011-06-20	0.86	2455732.8377	0.0018	2455732.8347	4.36	2.59
2011-06-23	1.24	2455735.6722	0.003	2455735.6747	–3.63	4.32
2012-09-18	0.94	2456188.6631	0.0018	2456188.6624	0.95	2.60
2012-10-02	1.42	2456202.8646	0.0027	2456202.8627	2.76	3.89
2012-10-05	1.08	2456205.7046	0.0028	2456205.7027	2.69	4.04
2013-10-05	2.65	2456205.7090	0.0034	2456205.7027	9.02	4.90
2013-10-12	0.97	2456577.7466	0.0015	2456577.7491	–3.56	2.18
2013-10-22	0.95	2456587.6890	0.00196	2456587.6892	–0.39	2.84
2014-06-09	2.50	2456817.7326	0.00035	2456817.7332	–0.83	0.61

An O–C diagram plots each O–C value as a function of epoch. If the observed transit midpoint always matches the calculated transit midpoint, the diagram will show a horizontal line, signifying that there is no difference between the observations and the model. If the line is slanted, then the predicted period may have significant error, indicating that the ephemeris needs to be updated. If there is a sinusoidal curve in the diagram, this may be a TTV indicating other bodies in the system.

In order to determine whether the ephemeris is up-to-date, a chi-squared test of the observed transit midpoint and the expected transit midpoint (see Table 2) was performed. A chi-squared test demonstrates whether the observed data fits the model created by the previous data well. If the chi-squared test value is not close to zero, the model of expected values as computed using previous transit data needs to be updated (Kane *et al.* 2009). The chi-squared test value computed using the

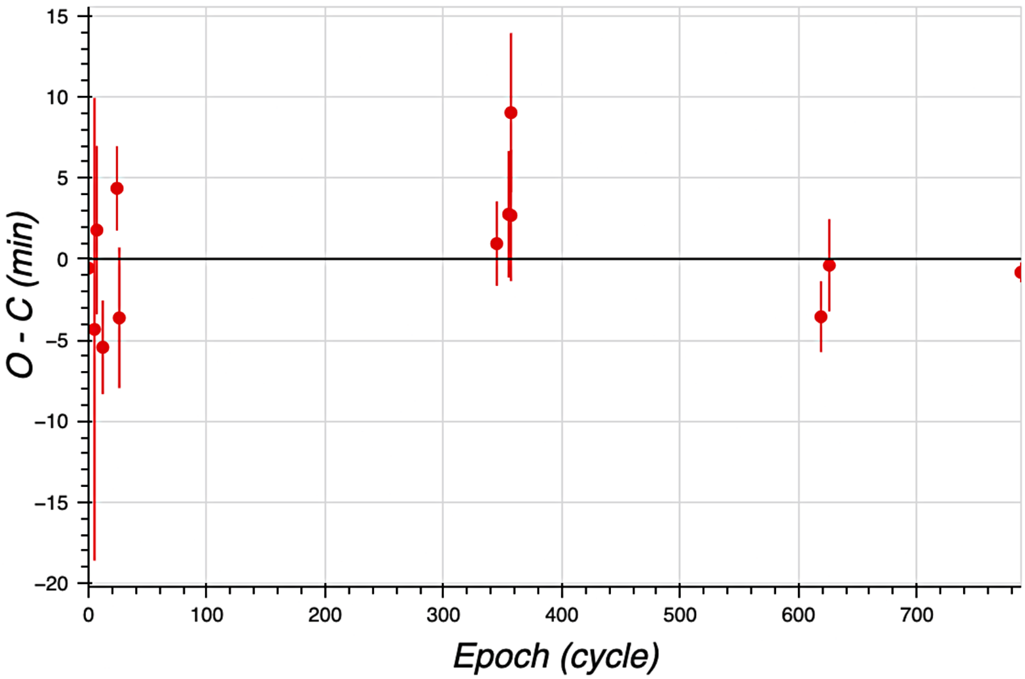

Figure 5. O–C plot from the reduction of Qatar-1b transit data in EXOTIC.

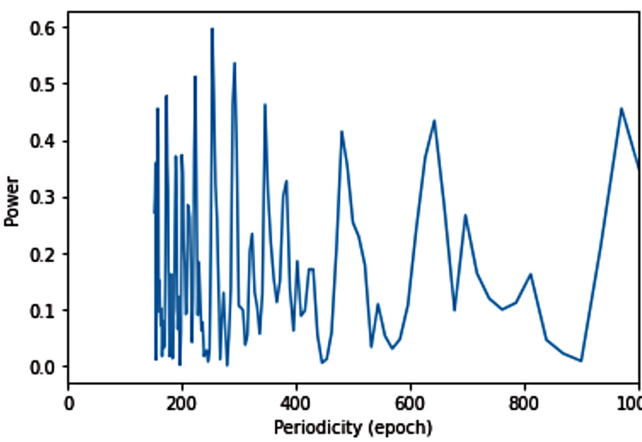

Figure 6. Lomb-Scargle periodogram for the O-C values.

observed transit midpoints was 0.114. This value is compared to the critical value for a 0.05 significance level with n – 1, or 11, degrees of freedom, which is 19.675. The test value is much smaller than the critical value, so these data support the validity of the current ephemeris.

A Lomb-Scargle graph in Figure 5 was created to check if there is any periodicity of the variations from the predicted transit midpoints. The graph is unlikely to show visible results with fewer than 50 data points, unless there was a very strong signal. The graph demonstrates a visualization of the temporally unevenly sampled data. It represents an estimate of the Fourier power at a given epoch value, which aids in the determining of periodicity in the data which would be impossible to discern with the naked eye. Ideally, in the event of another body existing within the Qatar-1b system, the Lomb-Scargle periodogram would be expected to display a singular clear spike, indicating that there is a clear period in the data, supporting periodicity and suggesting the existence of another body in the system. However, the periodogram in Figure 6 does not suggest that another body exists in the Qatar-1b system. This is due to the expression of many uneven spikes in the periodogram, which indicate a lack of periodicity (VanderPlas 2018).

5. Conclusion

This study contributes observations and reductions of observations of the planet Qatar-1b using small telescopes in the MicroObservatory network to help maintain the ephemeris and check for other planets in the system. Analysis of the O-C values shows that the period does not show evidence of periodicity or a slope in the O-C results, so our data support the current ephemeris (Collins *et al.* 2017b). From this analysis of TTVs in Qatar-1b, evidence of more planets in the system was not found. This lack of significant TTVs is consistent with the findings presented in Collins *et al.* (2017b).

6. Acknowledgements

This research has made use of the astropy.io.fits Python module.

Data from the Harvard-Smithsonian Institute for Astrophysics MicroObservatory telescope network was incorporated. Special thanks to Frank Sienkiewicz for making the data available.

This publication makes use of the EXOTIC data reduction package from Exoplanet Watch, a citizen science project managed by NASA's Jet Propulsion Laboratory on behalf of NASA's Universe of Learning. This work is supported by NASA under award number NNX16AC65A to the Space Telescope Science Institute.

Additionally, this research used the imaging software AstroImageJ. We would like to formally thank the creators of AstroImageJ along with the NASA Exoplanet Watch team and the American Association of Variable Star Observers for making this research possible. We would also like to thank Henry Heiberger, Harry Heiberger, Quennie Nguyen, Katie Kolodner, Damian Musk, and David Crair for contributing transit data to our research.

We would like to thank Kalée Tock, Ryan Caputo, Quinn Perian, Elliott Chalcraft, and Peyton Robertson for hosting the Exoplanet Research Workshop, which greatly assisted us in the research process. We would especially like to thank Kalée Tock, Martin Fowler, and Michael Fitzgerald for reviewing this paper and guiding the writing process.

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