Observation and Analysis of Qatar-1b Transit Timing Variations: No Evidence for Additional Bodies in Qatar-1

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Abstract Existing literature confirms that the Qatar-1 stellar system has a transiting exoplanet, Qatar-1b, which past research suggests is the sole planetary member of this system. Using archival images from the Harvard-Smithsonian MicroObservatory and NASA's EXOplanet Transit Interpretation Code (EXOTIC), 28 transits of Qatar-1b were reduced to further analyze the nature of the Qatar-1 system. Corrupted image series were edited to ensure the reliability of the light curves outputted by EXOTIC; the resulting Observed – Calculated plot, which was produced after these reduced transits were compiled, indicates that no transit timing variations were found for Qatar-1b, meaning that there are likely no other proximal bodies impacting the exoplanet's orbit. χ^2 and Lomb-Scargle analysis were also conducted, revealing no significant periodicity in Qatar-1b's orbit and further confirming the absence of additional bodies impacting the exoplanet's orbit.

1. Introduction

Small telescopes have become of increasing significance to the exoplanet community, serving as effective vehicles for follow-up observation of transiting exoplanets. Minimizing observing overheads is necessary for large telescopes such as NASA's James Webb Space Telescope and ESA'S ARIEL; as mid-transit times can become uncertain over time, these observatories run the risk of requiring greater overheads to fully detect a transit (Zellem *et al.* 2020). Amassing data collected worldwide by smaller observatories can assist in pinpointing exoplanets' expected mid-transit times. This optimizes future large telescope time allocation and space telescope missions. Among these efforts, NASA's Universe of Learning Exoplanet Watch relies on citizen scientist-powered research to observe transiting exoplanets and reduce and analyze their own data. Professional astronomers can access the data collected by citizen scientists when uploaded to the American Association of Variable Star Observers (AAVSO) Exoplanet Database.

Among star systems of interest is the Qatar-1 system. Using previously identified planetary parameters of Qatar-1b, this study involves the reduction of photometric data collected by MicroObservatory network telescopes on exoplanet Qatar-1b. Discovered in 2010 (Alsubai *et al.* 2011), Qatar-1b is part of a group of exoplanets known as Hot Jupiters, which are gas giants with an orbital period of less than 10 days and a mass greater than or equal to 0.25 of Jupiter's (Dawson and Johnson 2018). The relative proximity of Hot Jupiters to their host stars (generally far less than 1 AU) means that they can readily be discovered and observed via the transit method of exoplanet detection (Dawson and Johnson 2018). Qatar-1b orbits a K-type star with an orbital radius of 0.023 AU and orbital period of 1.42002 ± 7.1^{-07} days, as identified by NASA's Exoplanet-Catalog (NASA 2021). The Qatar-1 system (Figure 1) is located in the Draco constellation (R.A. $20^h 13^m 31^s$, Dec. $+65° 09' 44''$). Qatar-1b's mid-transit time was defined as $2456234.103218 \pm 6 \cdot 10^{-5}$ in BJD-UTC (Collins *et al.* 2017). The ratio of the Qatar-1b radius to its host star's radius is 0.146 ± 0.00065 (R_p / R_s). EXOTIC also gave parameters for the ratio of distance to stellar radius as 6.6 ± 0.04 (a / R_s), orbital inclination of 84.5 ± 0.1 (deg), and orbital eccentricity as 0.012.

Recent research has investigated the possible presence of additional planets in the Qatar-1b system (von Essen *et al.* 2013), yet no evidence of sinusoidal transit timing variations (TTVs) indicative of additional bodies has been found (Collins *et al.* 2017), even when dynamical simulations modeled fictitious planets (Maciejewski *et al.* 2015). This information strengthens certainty in the precision and accuracy of the light curves generated in this investigation. It also reinforces previously observed trends noting how Hot Jupiters are singular orbiting bodies in planetary systems (Maciejewski *et al.* 2015).

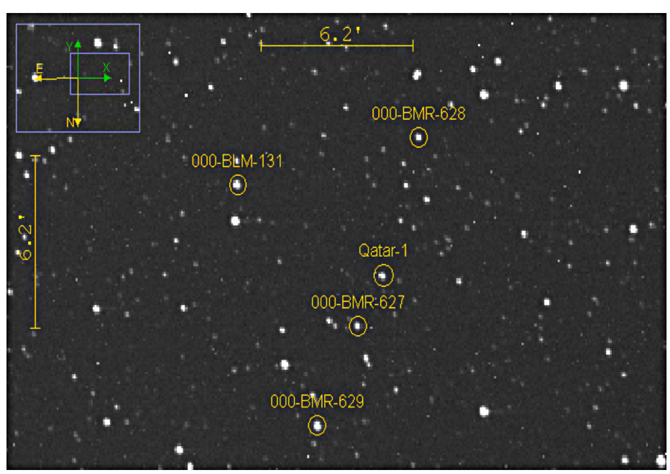

Figure 1. Labeled Qatar-1b starfield. As recommended by the AAVSO Variable Star Plotter, comparison star 000-BMR-627 was most frequently consulted. Comparison stars are labeled according to the AAVSO Variable Star Plotter.

This study aims to determine if there is periodic variation in the residuals of Qatar-1b's observed transits. Data collected as part of this investigation are contributions to a larger group research project under the Exoplanet Research Workshop. Project teams were each assigned Qatar-1b transit observations spanning from 2011 to 2019 for interpretation by EXOTIC. Teams individually uploaded light curves outputted by the program to the AAVSO Exoplanet Database.

The software utilized for this project, along with the preparation of image series for input into EXOTIC and the light curves and planetary parameters outputted by the program, is discussed in greater detail below.

2. Instruments used

The images were taken by 6-inch robotic telescopes in the MicroObservatory network, a group of automated imaging telescopes designed for remote student and public use and operated by the Harvard-Smithsonian Center for Astrophysics (Sadler *et al.* 2001). The network comprises five compact telescopes situated in Amado, Arizona; Cambridge, Massachusetts; Mauna Kea, Hawaii; and Canberra, Australia (Sadler *et al.* 2001). The telescopes have been in service since 1995 (Sadler *et al.* 2001), and the images obtained for this study were taken from 2014 to 2018.

Specifically, the images for Qatar-1b were taken by a MicroObservatory telescope located in Fred Lawrence Whipple Observatory's visitor center on Mount Hopkins, Arizona (Lat. +31.675°, *Long.* –110.952°); the visitor center has an altitude of 1,268 meters. The telescope has an aperture of 138 mm and a focal length of 560 mm, and utilizes a CCD detector and a Kodak KAF-1403-ME camera with 1400 × 1000 (w × h) resolution where pixels are 6.9 micrometers on each side (Sadler *et al.* 2001). It also has a pixel scale of 5.2" per pixel. The CCD detector utilizes 2 × 2 binning to help reduce image noise, and images are taken with a clear (CV) filter (Sadler *et al.* 2001).

3. Light curves

Following the reduction of images, EXOTIC outputs a light curve, a graph representing the decrease in stellar flux from Qatar-1 during the transits of Qatar-1b. These transits have continuously shown Qatar-1b blocking ~2.5% of the relative flux, as seen on the y-axis of the plot, during the peak of the transits. In Figure 2, a clear dip in light levels can be seen due to the exoplanet blocking its host star. Observed dips in stellar flux align with transit parameters outputted by EXOTIC, as a dip of ~2% is expected from the exoplanet's stellar radius ($0.146 \pm 0.00065\ R_p / R_s$).

To generate accurate light curves, optimal comparison stars were consistently of similar magnitude to the target, Qatar-1. To provide accurate reference points, all comparison stars used were also relatively close to the target in the night sky and isolated from other stars in the MicroObservatory images. Additionally, oversaturated comparison stars were not entered for EXOTIC to analyze.

4. Data reduction

Data collected during specific transit observation dates were reduced using the EXOplanet Transit Interpretation Code (EXOTIC), a Python program that analyzes astronomical images to produce light curves. The program reduces a series of FITS file images, plate-solves most images, and determines the best comparison star and alignment to fit a light curve to the transit data. EXOTIC also outputs several planetary parameters after the target's and comparison stars' x and y pixel locations are manually inputted. EXOTIC also performs other calculations, including determining the transit depth and mid-transit time. As a basis for selecting comparison stars to produce the clearest light curves, nearby stars with a similar luminosity to Qatar-1b and preferably in an isolated region of the night sky were used. EXOTIC would then locate and align those stars on a plate-solved version of the images to create a light curve reflective of variations in the images' stellar flux, thus allowing the visualization of the planet's movement across its host star.

5. Results

Out of 28 transits, EXOTIC fitted light curves to 25, and of those, 16 were clean (Table 1). Clean light curves were distinguished by their transit's residual scatter and midpoint uncertainty: transits with a residual scatter of 0.01 ± 0.04 and a midpoint uncertainty value of 0.001 ± 0.004 displayed prominent dips in light, and were therefore considered clean.

Of the nine poor results, five contained images that were saturated or contained passing clouds, yielding low signal-to-noise ratios; two failed to plate solve; and two others encountered technical errors where the estimated mid-transit time was not within an observable range. Consequently, EXOTIC fit poor light curves to them (Table 2).

Zellem's equation (Equation 1) was used to calculate O–C uncertainty, as seen in Figure 3, where T_{obs} is defined as uncertainty in the observed transit time based on EXOTIC's output. To determine a planet's expected transit midpoint time in Keplerian motion, the product of the period P is added to an integer number of epochs and to a published midpoint time T_0 (Zellem *et al.* 2020).

$$\sqrt{(\Delta T_{obs} + E^2 \cdot \Delta P^2 + 2 \cdot E \cdot \Delta P \cdot \Delta T_0 + \Delta T_0^{\ 2})} \quad (1)$$

A transit's epoch is calculated in days and is determined by the subtraction of the published midpoint transit time (2456234.1 days) from a transit's expected transit midpoint, divided by the orbital period (1.42 days).

Performing a χ^2 test assuming 22 degrees of freedom resulted in the deviation being statistically insignificant using a p-value of 0.025, with a reduced χ^2 test indicating that the observed and expected transit midpoints are very close (χ^2 value $< 10^{-5}$) Lomb-Scargle analysis, produced by Astropy, a common core Python astronomy package, is useful for unevenly-sampled time-series data as it can check for a periodic trend among residuals of the O–C plot (Astropy Collaboration *et al.* 2013). Since there are multiple varied peaks present rather than a single clear peak, the

Table 1. EXOTIC's outputted parameters; transits which yielded good light curves.

Date (yyyy-mm-dd)	*Residual Scatter*	*Observed Transit Midpoint (BJD)*	*Transit Midpoint Uncertainty*	*Expected Transit Midpoint (BJD)*	*Epoch*	*O–C (min)*	*O–C Uncertainty (min)*
2014-06-16	0.0214	2456824.833	0.0027	2456824.833	416	–1.13	3.90
2014-07-20	0.0128	2456858.914	0.00073	2456858.914	440	–0.25	1.06
2014-08-19	0.0352	2456888.735	0.0011	2456888.734	461	1.19	1.60
2014-09-12	0.0138	2456912.874	0.0013	2456912.875	478	–0.70	1.88
2017-09-21	0.0064	2458017.654	0.0012	2458017.654	1256	–0.16	1.77
2017-10-08	0.0096	2458034.696	0.0019	2458034.694	1268	2.73	2.77
2017-10-15	0.0117	2458041.79	0.0023	2458041.794	1273	–5.22	3.34
2017-10-18	0.0299	2458044.616	0.0051	2458044.634	1275	–26.31	7.36
2017-10-25	0.0083	2458051.735	0.0013	2458051.734	1280	0.73	1.92
2018-03-13	0.0146	2458190.895	0.0027	2458190.897	1378	–1.68	3.91
2018-04-09	0.0127	2458217.875	0.0045	2458217.877	1397	–2.77	6.50
2018-05-06	0.0117	2458244.854	0.0021	2458244.857	1416	–4.44	3.06
2018-05-16	0.0092	2458254.802	0.002	2458254.798	1423	6.55	2.92
2018-05-23	0.0087	2458261.899	0.0019	2458261.898	1428	1.33	2.77
2018-06-02	0.0097	2458271.84	0.0019	2458271.838	1435	3.10	2.77
2018-06-05	0.0168	2458274.675	0.0027	2458274.678	1437	–4.31	3.91

Note: 16 out of 28 transits yielded clean light curves. All clean light curves (above table) were used to determine the existence of transit timing variations for Qatar-1b.

Table 2. EXOTIC's outputted parameters; transits which yielded poor light curves (not used in analysis).

Date (yyyy–mm–dd)	*Residual Scatter*	*Observed Transit Midpoint (BJD)*	*Transit Midpoint Uncertainty*	*Expected Transit Midpoint (BJD)*	*Epoch*	*O–C (min)*	*O–C Uncertainty (min)*
2014-07-06	0.5431	2456844.713	0.00061	2456844.714	430	–0.80	0.89
2014-07-23	0.4412	2456861.753	0.00078	2456861.754	442	–0.78	1.13
2014-08-02	0.0699	2456871.694	0.00085	2456871.694	449	–0.77	1.23
2014-08-09	0.0202	2456878.794	0.00092	2456878.794	454	–0.78	1.33
2017-09-23	1.0577	2458019.074	0.012	2458019.074	1257	0.52	17.28
2017-10-06	0.0119	2458031.855	0.012	2458031.854	1266	1.65	17.28
2017-11-04	0.2727	2458061.674	0.0013	2458061.674	1287	–0.52	1.92
2017-11-11	0.2554	2458068.797	0.0095	2458068.774	1292	32.71	13.69
2017-11-14	0.0165	2458071.615	0.012	2458071.615	1294	0.67	17.28

Note: 12 out of 28 transits yielded poor light curves. These were not used in analysis, but are displayed above for completeness.

data do not follow a periodic trend (VanderPlas 2018). Lack of a periodic trend in Figure 4 indicates that there are few variations in the timing of Qatar-1b's orbit, further suggesting that there are no additional bodies impacting the exoplanet's orbit.

6. Conclusion

While the results do not reveal any significant transit timing variations, the data collected in this study can still update Qatar-1b's ephemeris. Figure 5 displays all light curves that were used for this study. These light curves were contributed to the American Association for Variable Star Observers (AAVSO) Exoplanet Database for use by the larger exoplanet research community and can be found under observer codes LIVA, KLIC, LPIC, and TVIC. This will further assist with time allocation for future large-scale space telescope missions.

Future replication of this study with different MicroObservatory archival data will further confirm that no additional bodies surround Qatar-1b. This study analyzed light curves from 2014, 2017, and 2018, but comparing results with other dates, including more recent measurements, will continue to help update the accuracy of Qatar-1b's ephemeris. Additionally, as EXOTIC is updated, further research can be conducted on Qatar-1b and other exoplanets. This study is a testament to the promising nature of small telescopes and the accessibility of transit data reduction programs for the larger exoplanet community.

7. Acknowledgements

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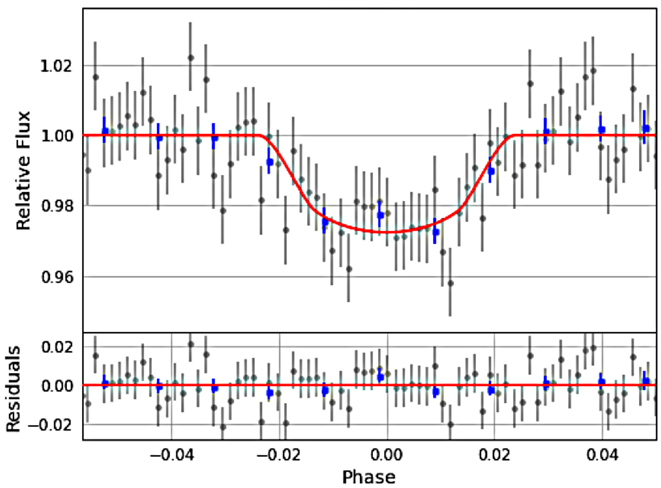

Figure 2. Final light curve produced by EXOTIC from a transit observed 2018-05-16 using 74 MicroObservatory images.

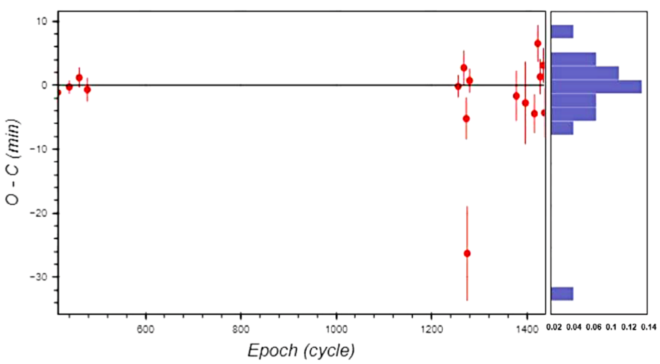

Figure 3. Observed – Calculated plot for Qatar-1b.

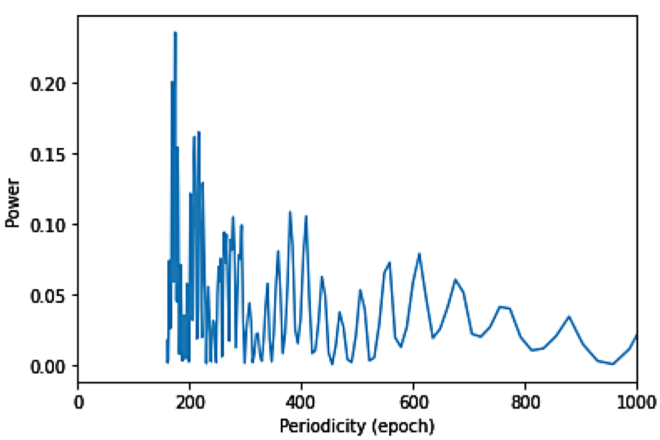

Figure 4. Lomb-Scargle periodogram for Qatar-1b TTVs.

Poor FITS image files were edited using SAOImageDS9, an astronomical image display and visualization tool currently funded by the NASA High Energy Astrophysics Science Archive Center and the Chandra X-ray Science Center. This study benefits from the American Association of Variable Star Observers for its support of the exoplanet community with free access to its Exoplanet and Variable Star Databases.

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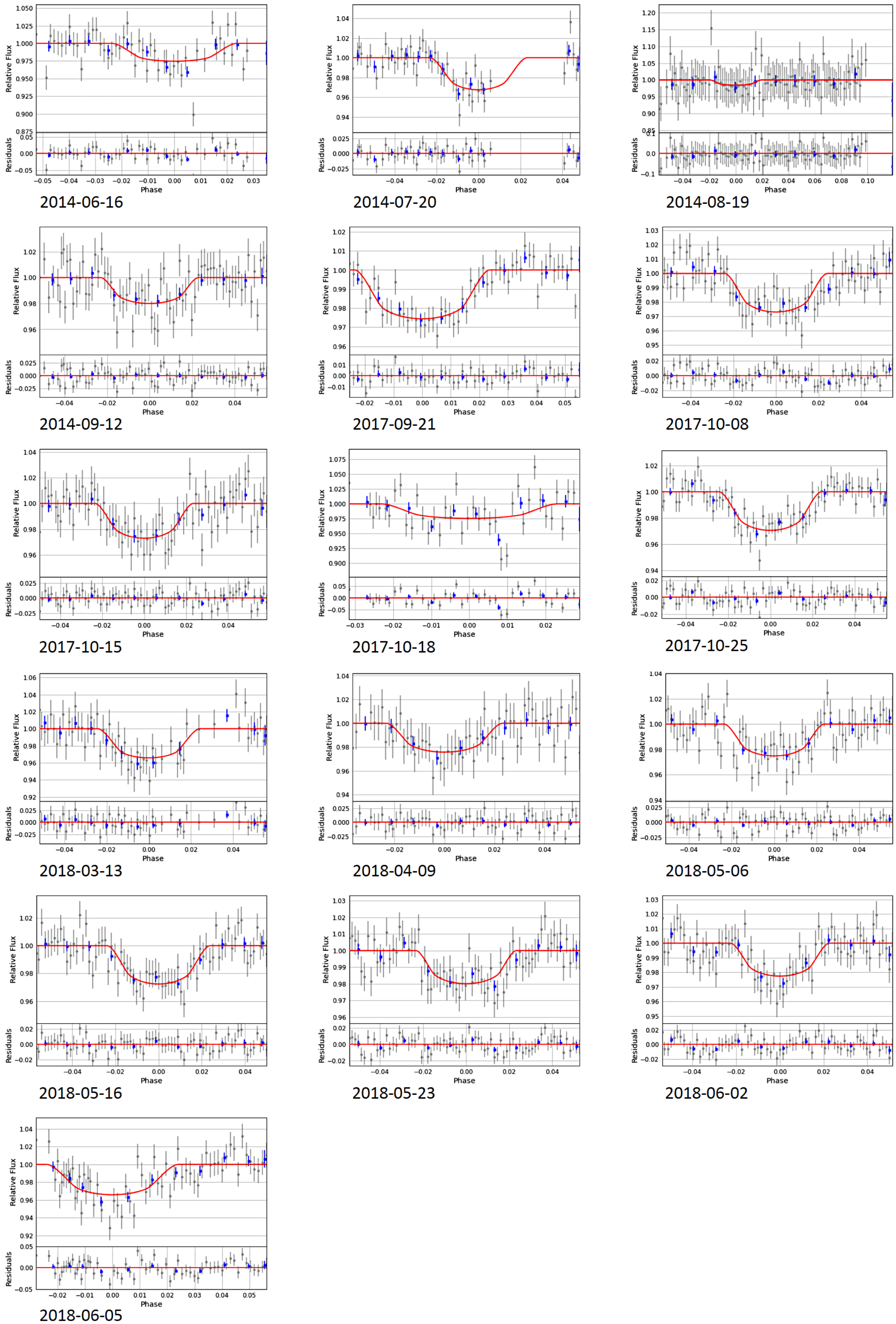

Figure 5. All clean light curves used in this study.