Transit Timing Variations of Five Transiting Planets

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Abstract. Transiting planets provide a unique opportunity to search for unseen additional bodies gravitationally bound to a system. It is possible to detect the motion of the center-of-mass of the observed transiting planet-host star duo due to the gravitational tugs of the unseen bodies from the Roemer delay. In order to achieve the goal, determination of the mid-times of the transits of the planets in high precision and accuracy and correct them for the orbital motion of the Earth is a primary condition. We present transit timing variations and update the ephemeris information of 5 transiting planets; HAT-P-23b, WASP1-103b, GJ-1214b, WASP-69b, and KELT-3b within this contribution, based on all the quality transit light curves from amateur and professional observers, converted to Dynamic Barycentric Julian Days (BJD-TDB).

Introduction

We have started a project following transiting hot-Jupiters [8] to search for variations in their transit timings. We have carried out transit observations of several exoplanet systems selected according to the radial velocity residuals that they display and eccentricities of their orbits. We have made use of 1 m Turkish telescope T100, located in the Bakırlıtepe campus of TÜBİTAK National Observatory of Turkey (TUG) and 35 cm telescope T35 in Ankara University Kreiken Observatory (AUKR) for the observations. Within this contribution, we present the preliminary analyses of mid-transit timings that we determined from our own observations of 5 selected, together with the mid-transit times that we collected from the literature as well as that from the observations of amateur astronomers presented in the Exoplanet Transit Database (ETD, http://var2.astro.cz/ETD/) [16]. We have updated the ephemeris information (reference epoch T_0, and orbital period P) based on our analyses of these heterogeneous data sets of mid-transit times as a result.

Observations and Data Acquisition

We observed 6 transits of our five targets with T100 and 2 transits of WASP-103b and WASP-69b with T35 in good atmospheric conditions. T100 has a cryogenically cooled, SI-1100 CCD camera with 4098 x 4098 pixels attached on it and it is located 2500 m above sea level, in close proximity of the city of Antalya in the south coast of Turkey. T35 is a 35 cm telescope located in the campus of Ankara University Kreiken Observatory in Ankara. It has a 1-megapixel Apogee ALTA U47+ CCD camera attached on it. We used a Bessel R filter except for the observation of WASP-69b transit on 2017-08-26 in Bessel I passband. We aggressively defocused the telescope in the observations with T100 in order to extend the exposure time to achieve better photometric precision, which had been shown to improve the timing precision [6, 17]. Although we have attempted multiple times with T100, we were not able to observe a transit of GJ-1214b [7], which is too faint (m_V = 13.4) to observe with T35. We present a log of our observations in Table-1.

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TABLE 1. Log of our observations with T100 and T35.

Planet	Date of Obs.	Telescope	Band	σ_{ph} [mmag]	Exp. Time [s]
HAT-P-23b	2014-09-25	T100	Bessel R	0.13	135
WASP-103b	2017-06-11	T100	Bessel R	0.76	90
WASP-103b	2014-05-30	T100	Bessel R	0.31	90
WASP-103b	2018-07-01	T35	Bessel R	2.51	60
WASP-69b	2019-07-27	T35	Bessel R	3.38	90
WASP-69b	2017-08-26	T100	Bessel I	0.34	100
WASP-69b	2016-10-09	T100	Bessel R	2.34	90
KELT-3b	2014-02-18	T100	Bessel R	0.49	150

We made use of AstroImageJ (from hereafter AIJ) software package [10] for the reductions of our own CCD images (bias, dark, and flat corrections) as well as ensemble aperture photometry and airmass detrending. We selected best comparison stars for differential photometry in terms of spatial proximity on the detector, brightness, and spectral type, and averaged their fluxes in units of Analog-to-Digital Units (ADUs) to create high Signal-to-Noise Ratio (from hereafter SNR) artificial comparison stars with AIJ. We have employed various aperture sizes fixed for each of the nights of our observations, which heavily depend on the average atmospheric seeing throughout the night, to obtain the light curves that we detrended from the changing airmass effect at the end

We then modeled our light curves with the web-interface version of the software package EXOFAST [11] for speed. This version of EXOFAST (http://astroutils.astronomy.ohio-state.edu/exofast/exofast.shtml) makes use of Levenberg-Marquardt algorithm to fit a physical model by Mandel & Agol [13] to the observed transit data with the non-linear least-squares method. We fixed the atmospheric (T_{eff}, log g, [Fe / H]) and orbital parameters (e, ω, P, K, Vγ) to their values determined from high resolution spectroscopic observation of the host stars published in the studies announcing the discovery of each the planets [1, 4, 7, 12, 15), while adjusting the radius ratio (R_p / R_*), orbital inclination (i) and the scaled orbital size (a / R_*). We have acquired and fixed the coefficients of the quadratic limb darkening law (u_1 and u_2) by a linear interpolation from the tables given by Claret & Bloemen [9] with help of the online tool provided by EXOFAST for the Johnson-Cousins R_c and I_c filters, which have similar transmission curves with that of the Bessel filters that we used during the observations, and by making use of the stellar properties (T_{eff}, log g, [Fe / H]) from the discovery studies. We present a sample EXOFAST model of WASP-69b in Figure-1. The transit mid-time (in BJD-TDB) and its uncertainty are amongst the output parameters of a transit model.

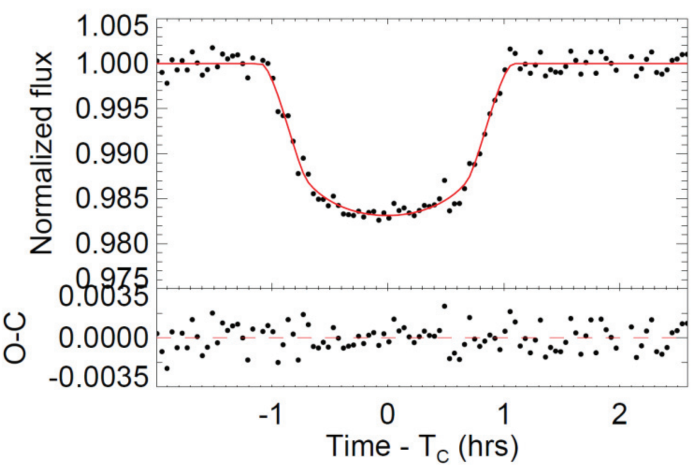

FIGURE 1. EXOFAST model (continuous curve on top panel) of the T100 transit light curve of WASP-69b on 2017-08-26 in Bessel I band.

We have also collected all the mid-transit times published in the literature as well as that in the Exoplanet Transit Database (ETD), which publishes transit observations of amateur and professional observers online. We have only made use of the quality light curves from ETD, flagged as Q1 and Q2, and for which we made sure about the accuracy and precision of the timings by contacting the observers. We then converted the mid-transit times that are not reported in BJD-TDB to this timing reference frame by using a code that we developed based on astropy functionality [2, 3].

Analyses and Results

We then constructed the O-C (or TTV) diagrams by subtracting the calculated mid-transit times (C) from the observed (O). Since the reference epoch and orbital period, with respect to which we have derived the calculated mid-transit timings have their own uncertainties, they expected to be accumulated over time causing a linear trend in the TTV diagrams. In order to fit the linear trends on TTV diagrams, we took random samples from a set of epoch (dT) and orbital period (dP) values that we generated within Markov Chain Monte Carlo (MCMC) runs. 500 walkers have been employed with 5000 iterations for each of the TTV diagrams in each of these runs, and the first 500 steps have been thrown away for the burn-in period. We used X^2 statistics as an indicator of the goodness of the fit, and integrated it into our log likelihood functions; and finally computed the posterior probability of each (dT,dP) pair based on these likelihood functions and uniform priors. We took the median values of each parameter, after leaving the values outside of $\pm 1\sigma$ from the distributions and accepted these as the best fitting parameters, that we list in Table-2 together with their uncertainties. We provide posterior probability distributions of ephemeris parameters together with the best fitting lines (red continuous lines) on TTV diagrams for only WASP-103b in Figure-2 as an example. Although the distributions are almost symmetric around the mean, there is a small asymmetry reflected in the errors in both directions. Despite being small, we have used more than necessary number of digits in the uncertainties of both parameters in Table-2 to indicate their asymmetric nature.

TABLE 2. Refined Ephemeris Information For 5 Transiting Exoplanets.

Planet	T_0 [BJD-TDB]	σ_T [s]	Period [days]	σ_P [s]
HAT-P-23b	2456539.390435	$^{+5.00}_{-4.98}$	1.21288651	$^{+0.00471}_{-0.00473}$
WASP-103b	2456459.599350	$^{+8.08}_{-8.13}$	0.92554537	$^{+0.00739}_{-0.00741}$
WASP-69b	2455748.834082	$^{+14.41}_{-14.38}$	3.86814098	$^{+0.03641}_{-0.03640}$
KELT-3b	2456023.480384	$^{+21.17}_{-21.19}$	2.70339216	$^{+0.07490}_{-0.07544}$
GJ-1214b	2454980.748826	$^{+2.72}_{-2.72}$	1.58040428	$^{+0.06765}_{-0.06750}$

Conclusions

Our results show that the reference epoch can be determined very precisely within a level of less than 20 seconds (21.2 seconds for WASP-69b is the largest uncertainty value). For all the planets, the observational errors are always less than a few minutes, allowing us to perform such a precise work. Linear model to TTVs is only successful to a level of a few minutes, and when they are detrended; the residuals display a variation from a few seconds (WASP-103b) to almost 15 minutes (KELT-3b). That is why, we attempted at performing Fourier analysis on the residuals. However, we failed in finding significant periodicities in any of the exoplanet systems that we studied. This should not mean that the potential of these systems in terms of harboring additional bodies can be neglected. But, in fact, it is crucial to continue the observations of these systems, since a potential third body might have an orbital period much longer compared to the time baseline of the available data (~ 13 years for HAT-P-23b). Precision and accuracy of these quantities should also encourage amateur observers and small university observatories provided that their timings are synchronized with a GPS device or a time-server and that more attention is paid to photometric precision. Finally, this work has made use of a heterogeneous set of data points collected from the literature and an open database. ETD users [14] and researchers make use of different models in order to determine the mid-transit times from their transit light curves, which are not detrended from the airmass effects in most cases Therefore, we have started an effort to homogenize the data sets (as in [5]) that we use, starting with the detrending of the light curves and ending with the measurements of the mid-transit times and their uncertainty by ourselves with the same tools consistently.

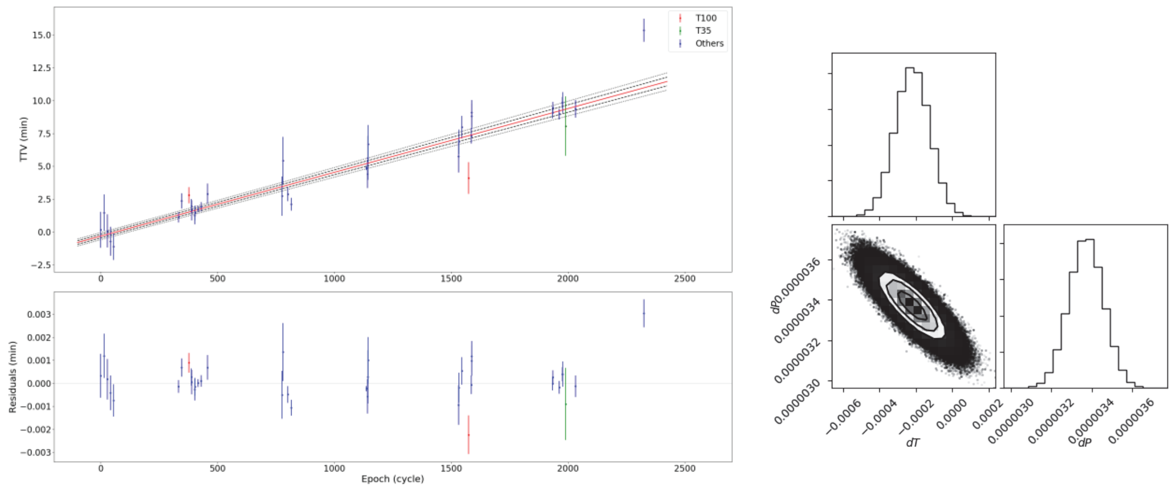

FIGURE 2. TTV diagram (upper panel on left) for WASP-103b and the residuals from the best fit (lower panel left). Red data points are T100 observations, green is for T35, blue are from the literature and ETD. Normalized posterior distributions for the light elements (T0, P) and the correlation between those two parameters (on right).

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REFERENCES

1. Anderson, D. R., et al., *Monthly Notices of the Royal Astronomical Society,* Volume **445**, Issue 2, p.1114-1129 (2014).
2. Astropy Collaboration, Price-Whelan, A. M., *The Astronomical Journal,* Volume **156**, Issue 3, article id. 123, pp. 19 (2018).
3. Astropy Collaboration, Robitaille, T., et al., *Astronomy & Astrophysics*, Volume **558**, id.A33, pp. 9 (2013).
4. Bakos, G., et al., *The Astrophysical Journal,* Volume 742, Issue 2, article id. **116**, 19 pp. (2011).
5. Baluev, R. V., et al., *Monthly Notices of the Royal Astronomical Society,* DOI: **10.1093/mnras/stz2620** (2019).
6. Baştürk, Ö., et al., *Contributions of the Astronomical Observatory Skalnaté Pleso*, vol. **43**, no. 3, p. 402-407 (2014).
7. Charbonneau, D, et al., *Nature*, Volume **462**, Issue 7275, pp. 891-894 (2009).
8. Charbonneau, D, et al., *The Astrophysical Journal,* Volume **529**, Issue 1, pp. L45-L48 (2000).
9. Claret, A., Bloemen, S., *Astronomy & Astrophysics,* Volume **529**, id.A75, pp. 5 (2011).
10. Collins, K., et al., *The Astronomical Journal,* Volume **153**, Issue 2, article id. 77, 13 pp. (2017).
11. Eastman, J., et al., *Publications of the Astronomical Society of the Pacific*, Volume **125**, Issue 923, pp. 83 (2013).
12. Gillon, M., et al., *Astronomy & Astrophysics*, Volume **562**, id.L3, pp. 4 (2014).
13. Mandel, K., Agol, E., *The Astrophysical Journal*, Volume **580**, Issue 2, pp. L171-L175 (2002).
14. Pejcha, O., *http://var2.astro.cz/ETD/FitProcedureDescription-Pejcha2008.pdf* (2008).
15. Pepper, J., et al., *The Astrophysical Journal,* Volume **773**, Issue 1, article id. 64, 11 pp. (2013).
16. Poddany S., Brat L., Pejcha O., *New Astronomy,* **15**, pp. 297-301 (2010).
17. Southworth, J., et al., *Monthly Notices of the Royal Astronomical Society,* Volume **396**, Issue 2, pp. 1023-1031 (2009).