Significant TESS Timing Offsets of 31 Hot Jupiters

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ABSTRACT

A precise transit ephemeris serves as the premise for follow-up exoplanet observations. The transit timing variation (TTV) as an important scientific output potentially reveals planetary orbital evolution. We compare transit timings of 262 hot Jupiters from TESS with the archival ephemeris and find 31 of them having significant TESS timing offsets, among which WASP-161b shows the most significant offset of $-203.7 \pm 4.1$ minutes. The median value of these offsets is 17.8 minutes, equivalent to 3.4 $\sigma$. We evaluate the timing precision of TESS Objects of Interest (TOI) which provides the TESS timings in this work. The evaluation is applied by deriving TESS transit timing from a self-generated pipeline. We refine and update the previous ephemeris, based on precise timing (uncertainty within 1 minute) and a long timing baseline ($\sim 10$ years). Our refined ephemeris gives the transit timing at a median precision of 1.11 minutes until 2025 and 1.86 minutes until 2030. All the targets with timing offset larger than 10 $\sigma$ present earlier timings than the prediction, which cannot be due to underestimated ephemeris uncertainty, apsidal precision, or Roemer effect as those effects should be unsigned. We regard the timing offsets mainly originating from the underestimated ephemeris uncertainty. For some particular targets, timing offsets are due to tidal dissipation. We find a tentative TTV of XO-3b (timing offset $> 10 \sigma$) yielding a period derivative of $5.8 \pm 0.9 \times 10^{-9}$. The TTV may be explained by tidal dissipation. Our result provides direct observational support for the tidal dissipation of XO-3b, reported in previous work.

Keywords: Exoplanet systems (484), Exoplanet astronomy (486), Transit photometry (1709), transit timing variation method (1710)

1. INTRODUCTION

Transit ephemeris is crucial for exoplanet follow-up investigations, e.g., atmosphere analysis (Berta et al. 2012; Deming et al. 2013; Yang et al. 2021) and orbital evolution (Lendl et al. 2014; Dawson & Johnson 2018; Millholland & Laughlin 2018; Yee et al. 2020). The newly commissioned Transiting Exoplanet Survey Satellite (Ricker et al. 2015, TESS) provides precise timings in a long baseline when combined with previous works, which enables us to obtain a better transit ephemeris.

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The observed transit timing could deviate from the ephemeris prediction due to either underestimation of ephemeris uncertainties (Mallonn et al. 2019), or physical processes (Agol & Fabrycky 2018). The TTV could originate from tidal dissipation, orbital precession, Roemer effect, mass loss and multi-planets (Patra et al. 2017; Yee et al. 2020; Turner et al. 2021; Bouma et al. 2020; Ragozzine & Wolf 2009; Lai et al. 2010; Mazeh et al. 2013; Agol & Fabrycky 2018). For hot Jupiters, the interactions of planet companions are usually not massive and close enough to generate significant TTVs (Huang et al. 2016; Dawson & Johnson 2018).

TTV provides direct evidence of tidal dissipation that likely drives hot Jupiter migration (Dawson & Johnson 2018). WASP-12b has been reported to undergo tidal dissipation by observational TTVs (Patra et al. 2017; Yee et al. 2020; Turner et al. 2021). The TTVs are at the level of $\sim 5$ minutes.
in a 10-year baseline compared to the ephemeris obtained from a constant period (Yee et al. 2020). Apsidal precession is reported to be the major arguing explanation and seems to be ruled out with more than 10-year observations, including most recent TESS timings (Patra et al. 2017; Yee et al. 2020; Turner et al. 2021). The referred works also discuss and exclude the other possible effects, including Romer effect and mass loss (Ragozzine & Wolf 2009; Lai et al. 2010).

The Romer effect, i.e. the acceleration towards the line-of-sight probably due to stellar companions, has been reported to dominate the TTV of WASP-4b (Bouma et al. 2020). Using TESS light curves, Bouma et al. (2019) present a period decreasing at -12.6 ± 1.2 ms yr\(^{-1}\). Further radial velocity (RV) monitoring indicates the Doppler effect contributes most of the period decreases (Bouma et al. 2020). For another example, WASP-53b and WASP-81b should harbor brown dwarf companions which could cause TTVs \(\sim 30s\), according to the calculation of Triaud et al. (2017).

We compare TESS timings and archival ephemeris predictions\(^1\), and report significant transit timing offsets of 31 hot Jupiters in this work. The paper is organized as follows. We present the sample selection and data reduction in Section 2. In Section 3, transit timings and offsets compared to the previous ephemeris are shown. The ephemeris refinement is also shown in this section. In Section 4, we discuss the possible physical origin of the timing offsets. We briefly summarize the work in Section 5.

2. SAMPLE SELECTION AND TESS TIMING

The exoplanet sample in this work are hot Jupiters identified from previous work and have access to transit timings from the TESS Objects of Interest (TOI) Catalog (Guerrero et al. 2021). The sample selection requires an orbital period of less than 10 days, a planet mass larger than 0.5 \(M_J\) and a planet radius larger than 0.5 \(R_J\). These criteria leave 421 hot Jupiters among which 262 are listed in the TOI catalog with transit timings.

2.1. TESS Photometry and TOI Catalog

TESS is launched in 2018, possessing four cameras with a total field of view (FOV) of 24×96 square degrees, equivalent to a pixel resolution of 21 arcseconds (Ricker et al. 2015). The full frame image covering FOV is released in a cadence of 30 minutes while \(\sim 200,000\) targets are recorded with 11 \(\times\) 11 pixel cut-off images in a cadence of 2 minutes (as shown in Figure 1).

The TOI catalog is built based on the light curves obtained from TESS image products, including both 2 minute and 30 minute frames (Guerrero et al. 2021). The 2-minute cadence

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\(^1\) Exoplanet Archive: https://exoplanetarchive.ipac.caltech.edu/index.html
light curve is generated by the Science Processing Operations Center (SPOC) pipeline and the 30 minute light curves by the Quick Look Pipeline (QLP) (Twicken et al. 2016; Huang et al. 2020). Guerrero et al. (2021) generate an automated pipeline to derive transit parameters and thereby identify planet candidates with the method referred to the Kepler Robovetter (Thompson et al. 2018). More than 2000 planet candidates (continuously updating) are identified in the TOI catalog including both newly discovered and previously known planets.

The timing from the TOI catalog provides a long time baseline when compared with the previous ephemeris. The median timing baseline of the 262 exoplanets is 2368 days, while the median uncertainties of timings from archival data and from the TOI catalog are 0.59 and 0.84 minutes. The median uncertainty of archival periods is $4 \times 10^{-6}$ days. 159 of 262 hot Jupiters show consistent TESS timings within 1 $\sigma$ when compared to the previous ephemeris predictions. This circumstantially demonstrates the accuracy of TOI timings. We neglect the difference between the Barycentric Julian Date (BJD) and Heliocentric Julian Date (HJD) in this work. The difference is within ±4s, beyond the timing precision discussed.

The TOI catalog has been well utilized for exoplanet research, including TTV analysis which uses the data in a similar condition to this work (Pearson 2019; Martins et al. 2020; Howard et al. 2021).

### 2.2. TESS Transit Timing Validation

A precision validation of TOI timing is necessary, in the purpose of the study on timing offsets to the previous ephemeris. A majority of the hot Jupiters (159 of 262) present consistent TOI timings which could be circumstantial evidence. Direct evaluation is performed by independently reducing the data and obtaining the TESS timings.

We have generated a photometric pipeline for the TESS image products (as shown in Figure 1) and applied it to the analysis of transit exoplanets (Yang et al. 2020a, 2021). The pipeline includes modules of e.g., astrometry checking, aperture photometry, deblending of the nearby contamination flux, light curve detrending. The details and evaluations of the pipeline are referred to in previous work (Yang et al. 2020a, 2021). From the tests and applications so far, the derived transit parameters are within 1 $\sigma$ when we apply the same fitting to the TESS SPOC light curves.

We check if the timing obtained from our pipeline is consistent with TOI timing and find the difference is within 2 minutes. The comparison is performed on the planets WASP-161b with the largest time difference earlier than TESS timing, WASP-17b with the largest time difference later than TESS timing, WASP-58b that is consistent TESS timing compared to the previous ephemeris (Anderson et al. 2010; Barkaoui et al. 2019; Mallonn et al. 2019). The comparison also includes WASP-121b, KELT-19Ab which have been applied for analysis of the transit depth in previous work (Yang et al. 2020a, 2021).

Applying Monte-Carlo Markov Chain (MCMC) (Patil et al. 2010; Czesla et al. 2019), the light curve is fitted with a planet transit model (Mandel & Agol 2002). The detrended light curve is performed with a stellar activity check from archival data and TESS photometry to avoid possible timing bias. The choice of ‘circular orbit’ or ‘Keplerian orbit’ is consistent with the archival reference work. The details of the free parameters and priors are as described in (Yang et al. 2020a, 2021).
Figure 3. The timing difference of HAT-P-31b. The timing difference is the observed mid-transit times minus the ephemeris predictions. The red point refers to TESS timing difference; black points refer to timing differences of other observations from literature paper (Kipping et al. 2011; Mallonn et al. 2019); the black dashed line is reference ephemeris; blue line alternative reference ephemeris; the red line is the refined ephemeris derived by combining TESS observation; green region 1σ significant region of reference ephemeris; brown region 1σ significant region of alternative reference ephemeris. We note that our refined ephemeris overlaps the alternative reference ephemeris, indicating the consistency of the two ephemerides.

et al. 2020a, 2021). For ‘circular orbit’, the free parameters are transit mid-point (T0), the radius ratio of planet to star (Rp/R∗), the semi-major axis (a/R∗), the inclination (i), and the limb darkening parameters. For ‘Keplerian orbit’, the model has extra free parameters of the longitude of the ascending node, the orbital eccentricity (e), the ascending node, the periapsis passage time, and the periapsis argument. The MCMC fitting runs 50,000 steps after the first 50,000 steps as initialization. All the priors are uniform, except for the limb darkening which applies Gaussian prior interpreted in limb darkening table (Claret 2018).

We apply the transit model to both the light curve of a single epoch and the light curve folded from multiple epochs (examples as shown in Figure 2). The folding is based on the archival ephemeris and we evaluate the fitting parameter bias if folding an inappropriate period (using the same method as in Yang et al. 2021). For TESS one sector, the timing bias is \( \sim 4 \) minutes if the period is biased at 0.0004 days. Such large period bias would cause significant TESS timing offsets when compared to ephemeris prediction and thereby are flagged. The fold-and-check method has been well utilized in period searching researches (Schwarzenberg-Czerny 1989; Yang et al. 2020b; Yang et al. 2021).

The fitted timings from our pipeline are consistent within 4 minutes when compared to TOI timings in the contrast sample. The median timing offset between our results and TOI timings are 1.43 minutes. The median TOI timing uncertainty is 0.83 minutes. We conclude that it is reasonable to use TOI timings. And the TOI timing offset to the previous ephemeris is regarded as significant if the offset is larger than 4 minutes which is 3 times the median difference. We also require the timing offset to be larger than 1 combined \( \sigma \) which is the square root of the quadratic sum of archival ephemeris uncertainty and TESS timing uncertainty. These criteria lead to a final sample of 31 hot Jupiters.

3. HOT JUPITERS WITH TESS TIMING OFFSETS

We obtain a sample of 31 targets with significant timing offsets compared to the previous ephemeris prediction. An example is as shown in Figure 3 with the whole sample as shown in Figure A1. The parameters are present in Table
1, including planet ID, TESS time minus the predicted time from the previous ephemeris ($\Delta T_C$), transit midpoint $T_C$, orbital period $P$, category flag, parameter reference.

In our sample, the median $\Delta T_C$ is 17.8 minutes while the median combined uncertainty is 5.2 minutes. Therefore the signal-to-noise ratio (SNR) is 3.4. Among 31 Jupiters, WASP-161b presents the earliest offset timing of -203.7±4.1 minutes. WASP-17b gives the latest offset timing of 70.8±11.7 minutes. The timing uncertainty is derived as the quadratic sum of uncertainties of previous ephemeris and TESS timing.

We classify the sources into four categories, according to the potential properties implied by the timing offsets. Type I target refers to a source of which timings are modeled with a linear function. The time offset could be either due to systematic error underestimation or some physical process. The linear indicates a model with a constant derivative, referring to a constant period. Most type I targets only have two timings that we can hardly distinguish the origin of the period difference referring to different linear functions. We regard the period obtained by the linear function fitted to TESS timing as a refined period. Type II refers to the targets of which the timing differences can not be modeled by a linear function but a quadratic function. The quadratic function can be due to abnormal points or physical processes which lead to a constant period derivative. We identify the targets as type III if the TESS timing offset is probably due to the systematic effect in the previous ephemeris and timing differences (at least three data sets) can be well fitted by a linear function. The fitted linear function refines the ephemeris. The sources are classified as type IV if the timings can not be fitted with any linear or quadratic functions. The possible physical origin of the timing offsets is discussed in Section. 4.

Table 1. Exoplanet parameters. ‘1’ in column ‘Planet ID’ indicates to the reference ephemeris in Figure 3 and A1, while ‘2’ presents the alternative ephemeris.

| Planet ID | $\Delta T_C$ minutes | $T_C$ HJD | $P$ days | Category flags | Reference |
|-----------|----------------------|-----------|----------|----------------|-----------|
| WASP-161b 1 | -203.7±4.1 | 2459249.03567±0.000594 | 5.405625±0.000003 | I | This work |
| WASP-161b 2 | 2457416.5289±0.0011 | 5.006425±0.0000048 | I | Barkaoui et al. (2019) |
| HAT-P-31b 1 | -206.0±131.6 | 2459010.82673±0.001149 | 5.005272±0.000005 | II | This work |
| HAT-P-31b 2 | 2454320.8866±0.0052 | 5.005425±0.0000092 | II | Bonomo et al. (2017) |
| KELT-1b 1 | -67.4±53.9 | 2458765.53381±0.000299 | 5.005272±0.0000063 | III | This work |
| KELT-1b 2 | 2455914.1628±0.0023 | 1.217494±0.0000002 | III | Mallonn et al. (2019) |
| TOI-163 b 1 | -57.2±22.0 | 2459310.502978±0.00617 | 1.217514±0.0000015 | I | This work |
| TOI-163 b 2 | 2458328.87970±0.0063 | 1.217444±0.00000080 | I | Siverd et al. (2012) |
| WASP-54b 1 | -55.9±8.6 | 2458931.236409±0.000435 | 4.231135±0.000003 | I | This work |
| WASP-54b 2 | 2455518.35087±0.00053 | 4.231306±0.0000063 | I | Kossakowski et al. (2019) |
| WASP-173Ab 1 | 1.2±0.9 | 2458355.195662±0.00047 | 3.693599±0.000001 | I | This work |
| WASP-173Ab 2 | -30.4±1.1 | 2458355.173660±0.000620 | 3.693461±0.000009 | I | Bonomo et al. (2017) |
| KELT-18b 1 | -26.8±2.3 | 2458714.181140±0.000380 | 1.386632±0.000001 | III | This work |
| KELT-18b 2 | 2457542.52054±0.00039 | 1.3866529±0.0000027 | III | TOI timing |
| XO-3b 1 | -17.8±1.2 | 2458819.064098±0.000279 | – | IV | This work |
| XO-3b 2 | 2455292.43266±0.00015 | 3.19153285±0.00000058 | IV | Wong et al. (2014) |
| WASP-101b 1 | -17.3±5.2 | 2459223.302264±0.000132 | 3.1915239±0.00000068 | IV | Winn et al. (2008) |
| WASP-101b 2 | 2456164.6934±0.0002 | 3.1913247±0.00000055 | IV | Wong et al. (2014) |
| K2-237b 1 | -15.5±3.9 | 2458626.800781±0.000869 | 3.585708±0.0000002 | I | This work |
| K2-237b 2 | 2457656.4633789±0.0000048 | 3.585722±0.0000004 | I | Hellier et al. (2014) |

Continued on next page
| Planet ID | $\Delta T_{\text{C}}$ | $T_{\text{C}}$ | $P$ | Category flags | Reference |
|-----------|----------------|-------------|-----|----------------|-----------|
|           | minutes       | HJD         | days|                |           |
| KELT-7b   | -12.4±5.4     | 2458819.2534 | 2.734765±0.000002 | I | This work    |
|           |               | 245635.229809 | 2.734775±0.0000039 |           |
| WASP-76b  | 11.9±2.9      | 2459117.6872 | 1.809881±0.000001 | I | This work    |
|           |               | 2456107.85507 | 1.809886±0.000003  |           |
| WASP-95b  | 10.7±2.9      | 2459084.585010 | 2.184667±0.0000001 | I | This work    |
|           |               | 2456338.458510 | 2.184673±0.0000014 |           |
| WASP-14b  | -10.7±5.2     | 2459252.535529 | 7.315485±0.0000002 | I | This work    |
|           |               | 2457091.0286832 | 7.315497±0.0000002 |           |
|           |               | 2456665.224010 | 7.315498±0.0000002 |           |
| WASP-21b  | -9.8±2.4      | 2458686.841940 | 3.612747±0.0000003 | I | This work    |
|           |               | 2457295.934340 | 3.612765±0.0000003 |           |
| WASP-35b  | -9.5±3.5      | 2459176.768453 | 3.161569±0.0000002 | I | This work    |
|           |               | 2455531.479070 | 3.161575±0.0000002 |           |
| TOI-133b  | 2.67±1.44     | 2458715.1230 | 4.720712±0.0000025 | I | This work    |
|           |               | 2458715.11740 | 4.720714±0.00000116 |           |
|           |               | 2458913.370330 | 4.720719±0.00000110 |           |
| WASP-17b  | 70.8±11.7     | 2458627.126221 | 3.735485±0.0000003 | II | This work    |
|           |               | 2454559.181020 | 3.735492±0.00000072 |           |
|           |               | 2454577.858060 | 3.735498±0.00000068 |           |
|           |               | 2454592.801540 | 3.735494±0.00000019 |           |
|           |               | 2457192.697980 | 3.735438±0.00000000 |           |
| WASP-99b  | 61.6±31.2     | 2459135.796019 | 5.752595±0.00000020 | I | This work    |
|           |               | 2456224.983200 | 5.752510±0.00000040 |           |
| WASP-58b  | 37.4±13.5     | 2458986.981902 | 5.017215±0.0000013 | III | This work    |
|           |               | 2455183.933500 | 5.017180±0.00000110 |           |
|           |               | 2457261.059700 | 5.017213±0.00000026 |           |
| WASP-187b | 34.5±8.7      | 2458764.856300 | 5.147913±0.00000033 | I | This work    |
|           |               | 2455197.352900 | 5.147878±0.00000050 |           |
| HAT-P-6b  | 26.3±9.2      | 2458740.188710 | 3.853000±0.00000003 | I | This work    |
|           |               | 2454035.675750 | 3.852985±0.00000050 |           |
|           |               | 2454347.767630 | 3.852985±0.00000050 |           |
| KELT-23Ab | 23.8±7.7      | 2458683.911214 | 1.219871±0.00000001 | IV | This work    |
|           |               | 2458140.379200 | 1.219867±0.00000012 |           |
|           |               | 2458140.386980 | 1.219868±0.00000011 |           |
| WASP-33b  | 22.4±6.9      | 2458791.414307 | 1.219871±0.00000001 | III | This work   |
|           |               | 2454163.223730 | 1.219867±0.00000012 |           |
|           |               | 2455507.522200 | 1.219868±0.00000011 |           |
| WASP-78b  | 18.8±11.1     | 2459175.589610 | 2.175185±0.00000006 | III | This work    |
|           |               | 245882.359640 | 2.175176±0.00000047 |           |
|           |               | 2456139.030300 | 2.175173±0.00000030 |           |
| KELT-19Ab | 15.2±5.9      | 2459222.789720 | 4.611734±0.00000007 | I | This work    |
|           |               | 2457281.249537 | 4.611709±0.00000088 |           |
| WASP-178b | 12.9±3.1      | 2458602.836430 | 3.344842±0.00000014 | III | This work    |
|           |               | 2456927.068390 | 3.344829±0.00000012 |           |
|           |               | 2458321.867240 | 3.344841±0.00000033 |           |

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We verify the TOI timings of 31 hot Jupiters among which WASP-173Ab, TOI-1333b, and TOI-628b need timing recalibration. We check the TESS raw data (2-minute cadence) of WASP-173Ab and find an abnormal data point around a transit at 2468356.564637 (HJD). The abnormal data biases the modeling if not clipped when performing an automatic pipeline. We refit the TESS light curve with abnormal data clipped. The timing is 2458355.195662 ± 0.000020 (HJD) when we fit one transit visit and 2458355.195907 ± 0.0001 (HJD) when fitting visits folded through the whole sector. These two results are consistent within 0.35 minutes and are different from TOI timing at 29 minutes. The refitted TESS timing is consistent with the previous ephemeris (as shown in Figure 4).

TOI-1333b timing derived by refitting TESS light curve is 2458715.1230 ± 0.0022 (HJD) which is 8.4 minutes later than TOI derived timing (as shown in Figure 4). The TESS 30 minute data (available for the TOI-1333b) has some abnormal points around transits which would bias the timings if not applying the sigma clipping process. Removing the abnormal data points, we refit the light curve for the timing. The timings derived from single transit and conjunct transits have a difference of 1.8 minutes (within 0.3 combined σ). The timing is close (∼ 1 σ) to the prediction of previous ephemeris (Figure 4).

We derive a conjunct timing of 1469.23270 ± 0.00222 (HJD) for TOI-628b while a single transit visit obtains a midpoint at 1469.2332 ± 0.0074 (HJD). The value is ∼ 1 σ earlier than TOI timing and is consistent with the previous ephemeris. We note that TOI timings are highly reliable that only two sources among 262 TOI hot Jupiters are found with significant inappropriate values.

3.1. Ephemeris Refinement

We refine the ephemeris of type I and III targets in our sample. We do not apply any ephemeris refinements to type II and IV sources. The new ephemeris consists of TESS timing and a refined period (as shown in Table 1). The refinement has a median precision of 1.11 minutes until 2025 and 1.86 minutes until 2030. The largest uncertainty is 7.22 minutes at 2030 referring to WASP-187.

The ephemeris precision depends on the length of the time baseline and transit timing precision. The timing uncertainties could be underestimated due to the techniques in light curve generation and high dimension model fitting (Yang et al. 2020a, 2021). Empirically, the timings obtained from a single transit visit are usually within two times of the reported uncertainty (Yang et al. submitted). Conjunction timing derived from multi-visits based on a constant period assumption might be biased if the folding period is not precise, especially when the light curves partially cover the transits. Correcting the timing biases in archival papers (if present) is beyond the scope of this work.

The period could be updated when more observations are available (Mallonn et al. 2019; Edwards et al. 2021; Wang et al. 2021). For type I Jupiters, the periods from the previous works are significantly different from the periods derived in our refinement. We note that these period differences might origin from physical processes which make the refinement inappropriate (as discussed in Section 4). The type III exoplanets are likely to present significant uncertainty underestimation in the previous ephemeris. Type II and IV targets might be due to abnormal timings included or due to more complicated physical processes.

4. DISCUSSION: POSSIBLE PHYSICAL ORIGIN

Some targets in our sample present very significant period differences when compared to former results. It might not be a good hypothesis to regard all the differences originating from the underestimation of archival period uncertainties. Period bias caused by a timing shift of 2 minutes would be only ∼ 10⁻⁵ days when the time baseline is 1 year.

We argue that a very significant period difference might be attributed to physical period-changing processes. We find in our sample that the targets with offset SNR larger than 10 all present earlier observation timings. These sources are
WASP-161b, XO-3b, and KELT-18b. The period difference caused by systematic underestimation should be unsigned which is not the case. The tidal dissipation could explain the observational phenomenon, to the best of our knowledge.

The tidal torque transfers the energy between the star-planet orbit and the rotation of star and planet (Goldreich & Soter 1966; Lin et al. 1996; Naoz et al. 2011; Wu & Lithwick 2011; Dawson & Johnson 2018; Rodet et al. 2021). The process could cause the period decay and the apsidal procession (Hut 1981; Ragozzine & Wolf 2009). The induced TTV has been discovered in WASP-12b at \( \sim \) a few minutes (Campo et al. 2011; Patra et al. 2017). And TESS provides the most recent evidence for WASP-12b TTV (Turner et al. 2021).

We report WASP-161b, which shows the most significant TESS timing offsets in this sample, presenting a period derivative of \(-1.16 \times 10^{-7} \pm 2.25 \times 10^{-8}\) (as details described in Yang et al. 2021, submitted). WASP-161b possibly is undergoing tidal dissipation. We have approved CHEOPS for two visit observations in early 2022 for further investigation. WASP-161b is regarded as a type I target in this work.

The period of XO-3b has been reported differently in previous works (Winn et al. 2008, 2009; Johns-Krull et al. 2008; Wong et al. 2014; Bonomo et al. 2017, and references therein). TESS timing presents an offset of \(-17.8 \pm 1.2\) minutes (14.8 \(\sigma\)) to the newest archival ephemeris from Bonomo et al. (2017). The timing generated by our pipeline is consistent within 0.3 minutes to TOI timing. And the uncertainties are similar (\(\sim 0.45\) minutes). We gather the archival timings (Winn et al. 2008; Johns-Krull et al. 2008; Wong et al. 2014; Bonomo et al. 2017) and obtain a timing baseline longer than 10 years with TESS timing as the most recent (as shown in Figure 6). The timings could not be well fitted with any linear function.

We find a quadratic function is a good fit for the data sets, yielding a constant period decaying model. The period derivative (\(\dot{P}\)) is \(5.8 \times 10^{-9} \pm 9.3 \times 10^{-10}\). The \(\dot{P}\) could be explained by a tidal dissipation model, expressed as ‘equilibrium tide’; Hut (1981; Leconte et al. 2010):

\[
\dot{P} = \frac{27\pi}{Q_p} \left( \frac{M_\ast}{M_p} \right) \left( \frac{R_p}{a} \right)^5 \left[ N(e) \frac{x_p \omega_p}{n} - N_a(e) \right]
+ \frac{27\pi}{Q'_p} \left( \frac{M_\ast}{M_p} \right) \left( \frac{R_\ast}{a} \right)^5 \left[ N(e) \frac{x_\ast \omega_\ast}{n} - N_a(e) \right].
\]

Here \(Q'_p\) is the ‘modified tidal quality factor’, \(\omega_p\) the planet’s rotation rate, \(x_p\) the obliquity. Replacing the \(p\) with \(\ast\) defines...
the stellar parameters, \( N(e) \) and \( N_a(e) \) are defined as:

\[
N(e) = 1 + \frac{15}{2} e^2 + \frac{45}{8} e^4 + \frac{5}{16} e^6 \quad \frac{(1 - e^2)^6}{(1 - e^2)^6}.
\]

and

\[
N_a(e) = 1 + \frac{31}{2} e^2 + \frac{255}{8} e^4 + \frac{185}{16} e^6 + \frac{25}{64} e^8 \quad \frac{(1 - e^2)^{15/2}}{(1 - e^2)^{15/2}}.
\]

The value of \( Q'_\star \) is \(1.6 \times 10^5 \pm 0.2 \times 10^5 \) if assuming the period decaying is due to the stellar tide and the value of \( Q'_p \) is \(1.9 \times 10^4 \pm 0.2 \times 10^4 \) under the assumption that period decaying is due to the planetary tide. The value is derived from Equation 1, with a stellar mass of \(1.213 \pm 0.066 \, M_\odot \), a stellar radius of \(1.377 \pm 0.083 \, R_\odot \), a planet mass of \(11.70 \pm 0.42 \, M_J \), a planet radius of \(1.217 \pm 0.073 \, R_J \), an eccentricity of \(0.27587 \pm 0.00067 \), an orbital semi-major axis of \(4.95 \pm 0.18 \) (in unit of stellar radii), an obliquity of \(70 \pm 15 \) degrees (Hébrard et al. 2008; Bonomo et al. 2017; Stassun et al. 2017).

XO-3b is reported as a candidate giant planet undergoing migration in previous work (Bonomo et al. 2017), due to its large eccentricity and high \( M_p/M_\star \) (larger than \(6 \times 10^{-5} \)). Our timing result provides direct observational evidence to support this scenario.

The apsidal precession could be excited when the tidal torque exists (Ragozzine & Wolf 2009). Distinguishing the difference between tidal dissipation and precession needs to model timings of occultation (Patra et al. 2017; Yee et al. 2020; Turner et al. 2021). XO-3b is also expected to be a candidate presenting precession in previous work (Jordán & Bakos 2008). No clues of a binary companion are reported in XO-3b references. Further investigation on XO-3b is available in the following work (Yang et al. submitted). We note that the period changing originating from precession and Romer effect should be unsigned as the same as from systematic underestimation.

The relation between the planet period derivative and host star acceleration rate is well modeled (Bouma et al. 2020). In our sample, KELT-19Ab shows a maximum stellar acceleration at \(4 \, m \, s^{-1} \, yr^{-1} \) originating from binary companion (Siverd et al. 2018b). This acceleration would cause a period derivative of \(5.32 \, ms \, yr^{-1} \), according to the calculation from (Bouma et al. 2020). We generate the TESS timings in both 2019 and 2020. TOI catalog gives the timing at 2020 which is only 0.14 minutes different from our result (as shown in Figure 2 and caption therein). We find timings can be fitted with both a linear and a quadratic function (as shown in Figure 5). The fitting result of the quadratic function indicates a pe-

![Figure 6. The TTV of XO-3b. The symbols are similar to Figure 3 while the red dashed line presents the fitted quadratic function as described in the text.](image-url)
period derivative of 112±94 ms yr$^{-1}$. Therefore, we conclude that combining TESS and archival timings do not present a significant TTV dominated by stellar acceleration for KELT-19Ab. We regard the Romer effect beyond the detection limit in this work.

5. SUMMARY

We discuss the ephemeris of 31 hot Jupiters, of which TESS timings show significant offsets. The TESS timing comes from the TOI catalog and is validated using our self-generated pipeline. The pipeline obtains the light curve from the raw TESS images and fits the light curve with the planet transit model. The result from our pipeline gives consistent results compared to TOI catalog.

Among the sample, TESS timings present a median offset of 17.8±5.2 minutes, equivalent to an SNR of 3.4σ when compared to the previous ephemeris. WASP-161b and XO-3b give the most significant timing offsets. The ephemeris refinement serves the potential follow-up observations for equipment, e.g., CHEOPS, ongoing James Webb Space Telescope, and Ariel Space Telescope. The refined timing reaches a precision within 1.11 minutes in the next 5 years and 1.86 minutes in the next ten years.

WASP-161b, XO-3b, and KELT-18b present timing offsets larger than 10 σ. These three targets all have an earlier observed timing than the predictions from the previous ephemeris under a constant period assumption. We find WASP-161b presents evidence of period decaying in previous work (Yang et al. submitted).

XO-3b presents a tentative TTV, which could be modeled by a quadratic function. The derived period derivative is 5.8×10$^{-9}$±9.3×10$^{-10}$. Tidal dissipation can explain the TTV with a $Q_*$ of 1.6×10$^5$±0.2×10$^5$ or a $Q_p$ of 1.9×10$^4$±0.2×10$^4$. Apsidal precession could be an alternative explanation to the TTV. Interestingly, all the four targets (WASP-161, XO-3b, WASP-12b, WASP-4b) with significant observed TTVs, show earlier timing than the prediction in a constant period model. Apsidal precession could not explain this since the timing variation caused by precession should be unsigned. Further observations, e.g., occultation timing monitoring, are helpful for confirmation.

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2 https://exoplanetarchive.ipac.caltech.edu/index.html
3 https://github.com/sczesla/PyAstronomy
Figure A1. Timing differences of 31 targets. The symbols are the same as Figure 3 while the legend inside image is dismissed for clarity.
Figure A1. (Continued)
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Figure A1. (Continued)
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