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TESS Transit Timing of Hundreds of Hot Jupiters

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Abstract

We provide a database of transit times and updated ephemerides for 382 planets based on data from the NASA Transiting Exoplanet Survey Satellite (TESS) and previously reported transit times, which were scraped from the literature in a semiautomated fashion. In total, our database contains 8667 transit-timing measurements for 382 systems. About 240 planets in the catalog are hot Jupiters (i.e., planets with mass $>0.3\,M_{\rm Jup}$ and period <10 days) that have been observed by TESS. The new ephemerides are useful for scheduling follow-up observations and searching for long-term period changes. WASP-12 remains the only system for which a period change is securely detected. We remark on other cases of interest, such as a few systems with suggestive (but not yet convincing) evidence for period changes, and the detection of a second transiting planet in the NGTS-11 system. The compilation of light curves, transit times, ephemerides, and timing residuals are made available online, along with the Python code that generated them (visit https://transit-timing.github.io).

Unified Astronomy Thesaurus concepts: Exoplanet astronomy (486); Hot Jupiters (753); Transit timing variation method (1710); Exoplanets (498)

Supporting material: machine-readable tables

1. Introduction

Transiting hot Jupiters are the most intensively studied category of exoplanets. Photometric and spectroscopic observations of transits provide information about the planet's size, mass, orbit, and atmosphere. Because many of the follow-up observations are time-critical, observers need the ability to predict future transit times reliably and precisely. This is especially important when observations need to be scheduled with expensive and oversubscribed facilities such as NASA's James Webb Space Telescope. The uncertainty in transit-time predictions grows approximately in proportion to the time elapsed since the last observation. Thus, the easiest way to improve our ability to predict future transits is to measure new transit times, a process known as "refreshing the ephemerides."

Long-term transit timing of hot Jupiters might also lead to the detection of interesting physical effects, such as planetary mass loss (Valsecchi et al. 2015; Jackson et al. 2016); tidal orbital decay (see, e.g., Maciejewski et al. 2013a; Yee et al. 2019; Patra et al. 2020) and other forms of spin–orbit coupling (Lanza 2020); orbital precession due to a companion planet (Miralda-Escude 2002), the planet's tidal deformation (Wolf & Ragozzine 2009), and general relativity (Jordán and Bakos 2008; Pál & Kocsis 2008); and forces from wide-orbiting companions (Bouma et al. 2019). Short-timescale transit-timing variations can signal the presence of nearby planets (Agol et al. 2005; Holman & Murray 2005), although these are rarely detected for hot Jupiters (Steffen et al. 2012).

The NASA Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) offers an opportunity to measure new and precise transit times for essentially all of the known hot Jupiters orbiting stars brighter than about 13th magnitude. We have taken this opportunity to create a transit time database for 278 planets that have been observed during the first few years of the TESS mission. These planets are mainly hot Jupiters, though we also selected other types of planets for which we expected the signal-to-noise ratio (S/N) of TESS observations to be high. We also searched the literature for all previously reported transit times to allow for improvement in the orbital ephemerides; in this step we included an additional 104 planets that are well suited for TESS observations but for which TESS data are not yet available.

The paper is organized as follows. Section 2 describes our target selection. Section 3 describes our largely automated analysis of TESS data. Section 4 explains how we assembled lists of transit times drawn from the literature. Section 5 describes the process we used to refine the transit ephemerides and search for transit-timing variations. Section 6 discusses systems of special interest. Section 7 summarizes the results.

2. Sample Selection

One of the most comprehensive and carefully curated catalogs of transiting planet properties is TEPCat, which is maintained by John Southworth.[3] For each system in TEPCat, we estimated the S/N with which TESS would be able to detect a single transit. The noise estimates were based on the charts provided in the TESS Data Release Notes showing the combined differential photometric precision on 1 hr timescales (CDPP_1) as a function of apparent magnitude in the TESS bandpass. For each system, we looked up the TESS apparent magnitude and the corresponding value of CDPP_1, and calculated

$$\mathrm{S/N} = \frac{(R_p/R_\star)^2}{\mathrm{CDPP}_1/\sqrt{T_{\rm hr}}}, \tag{1}$$

[3] https://www.astro.keele.ac.uk/jkt/tepcat/; Southworth (2011)

Table 1
Target List

System	TIC	TESS Magnitude	S/N
CoRoT-01	36352297	13.05	31.66
CoRoT-02	391958006	11.67	111.23

(This table is available in its entirety in machine-readable form.)

where R_p and $R_\star$ are the planetary and stellar radii, respectively, and $T_{\rm hr}$ is the total transit duration in hours.

We identified 421 systems for which $S/N > 25$. We decided to exclude the 102 systems in this list that involved brown dwarfs or for which no improvement was possible because the transits were first discovered using TESS data. We also decided to include all of the transiting planets detected in the HAT, WASP, CoRoT, NGTS, and Qatar surveys regardless of S/N, which led to the addition of 62 systems with $S/N < 25$. Thus, our sample consists mainly of hot Jupiters (mass $>0.3\,M_{\rm Jup}$ and period <10 days), although it also includes some smaller and wider-orbiting planets for which TESS data are expected to be useful. The final list of 381 planetary systems with 382 planets is provided in Table 1. Figure 1 displays the distribution of their transit depths, orbital periods, and apparent magnitudes. Naturally, almost all of the systems are short-period giant planets around bright stars.

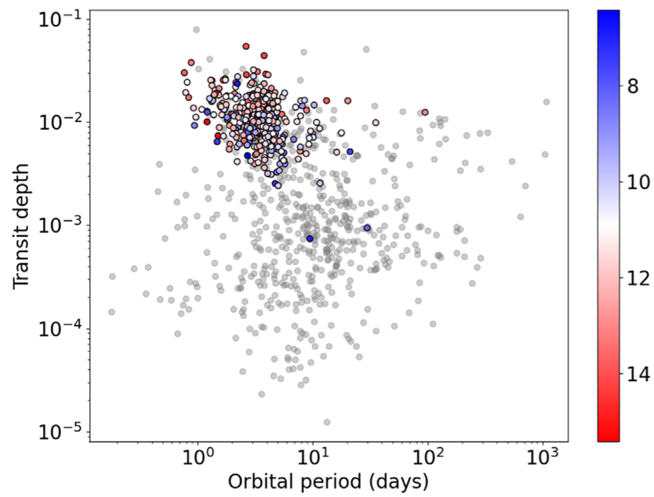

Figure 1. Transit depth and orbital period for all of the known transiting planets (gray), and the systems in our sample (colored points, with the color conveying the TESS apparent magnitude).

Table 2
TESS Data Processed for Each Target

System	Source	Cadence (s)	Sector
CoRoT-01	SPOC	120	33
CoRoT-01	SPOC	120	6

(This table is available in its entirety in machine-readable form.)

3. TESS Data Analysis

TESS data were available for 278 of the selected systems as of 2021 November, the somewhat arbitrary cutoff date for this project. We wrote an automated data reduction code to download the TESS data and process the light curves. We used routines from the LIGHTKURVE Python package (Lightkurve Collaboration et al. 2018) to download any available light curves. Whenever possible, we used the PDC-MAP version of the light curves prepared by the Science Processing Operations Center (Jenkins et al. 2016). When these were not available, we used the light curves from the MIT Quick-Look Pipeline (QLP; Huang 2020). We used light curves with 2 minute time sampling ("cadence") whenever possible. Otherwise, we used the data with 30 minute cadence. The only exceptions were HATS-42 (Sector 33, 34), HATS-61 (Sector 31), HATS-70 (Sector 33, 34), WASP-182 (Sector 27), WASP-143 (Sector 35), HATS-38 (Sector 35), HATS-55 (Sector 34), HATS-64 (Sector 35), KELT-19 (Sector 33), WASP-110 (Sector 27), HATS-32 (Sector 29), WASP-160 (Sector 33), HAT-P-64 (Sector 32), for which we used the data with a 10 minute cadence, a relatively new mode of data collection for TESS. In Table 2, we specify the TESS data that we processed for each target, indicating the source and cadence of the light curves as well as the TESS sector number.

For each system, and for each sector of TESS data, we identified the time intervals centered on predicted transit times and spanning four full transit durations. Initially, because of the accumulated uncertainty in the published ephemerides, the predicted transit times were not always accurate and the intervals were not well centered on the transit midpoints. After performing the first iteration of our entire analysis and refreshing the ephemerides, we repeated everything with the updated predictions for the transit times, to ensure that the intervals in this step were centered on the transits.

We counted the number of available data points during each interval. If it was smaller than 75% of the expected number based on the transit duration and the nominal cadence (2, 10, or 30 minutes), we omitted the interval from further consideration. This removed transits for which there were significant gaps in the time coverage due to observing interruptions or other problems. Figure 2 shows WASP-12 as an illustrative example. The groups of red points are the transit intervals.

To remove photometric trends on timescales longer than the transit duration, whether due to stellar variability or instrumental systematics, we fitted a polynomial to the data in each transit interval that were obtained outside of the transit. The degree of the polynomial was either 1, 2, or 3, with the decision based on minimizing the Bayesian Information Criterion (BIC; Schwarz 1978), $\mathrm{BIC} = \chi^2 + k \log n$, where k is the number of free parameters, and n is the number of data points. In most cases, a linear model (degree 1) was selected. We then "rectified" the data for each transit interval by dividing the flux time series by the polynomial function that had been fitted to the out-of-transit data.

Next, we phase-folded the light curve, initially using the orbital period from TEPCat, and subsequently using the updated orbital period from the first iteration of our analysis. We fitted a Mandel & Agol (2002) model, for which the free parameters were the planet-to-star radius ratio $R_p/R_\star$, the orbit-to-star radius ratio $a/R_\star$, the impact parameter $b \equiv a\cos I/R_\star$ (where I is the orbital inclination), the midtransit time, and either one or two limb-darkening coefficients. We used the BIC to decide whether to fit a linear or quadratic limb-darkening profile; in almost all cases, a linear model was chosen. In a few cases with 30 minute sampling and an especially low S/N, we used a linear law with a fixed coefficient of 0.6.

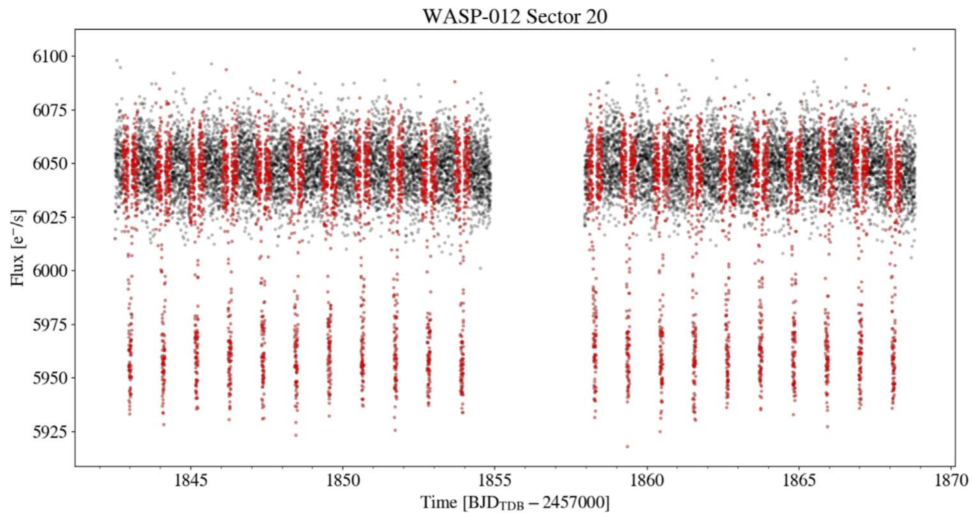

Figure 2. TESS light curve of WASP-12b. The groups of red points are the transit intervals, which are centered on the predicted transit times and extend for four transit durations.

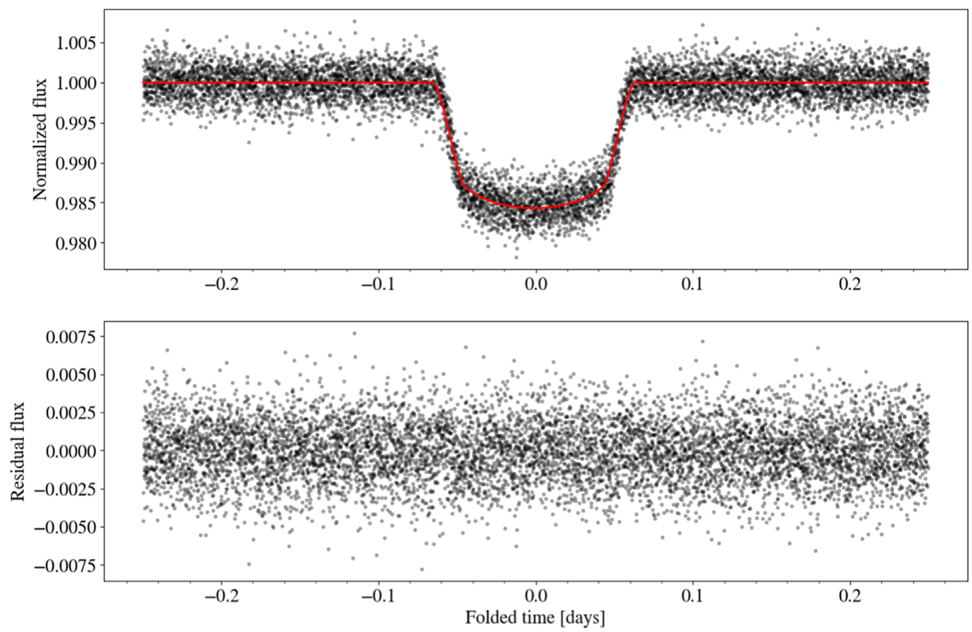

Figure 3. Folded light curve of WASP-12b.

For given values of $a/R_\star$ and b, the transit timescale is proportional to the orbital period (see, e.g., Equation (19) of Winn 2010). To establish this timescale, we used the orbital period reported by TEPCat. Although our aim was to improve on the precision in the period, the uncertainty in the previously reported period was already so small as to be irrelevant for the determination of the basic transit parameters. We sought the best-fitting model parameters by minimizing the usual χ^2 statistic using the Nelder–Mead optimizer within the LMFIT Python library. To minimize the effects of occasional outliers, we removed the data points lying more than 5σ away from the best-fitting model value, where σ is the median absolute deviation (MAD) of the residuals. We iterated this process until there were no more 5σ outliers.

Having established good values for the parameters describing the shape of the transit light curve, we proceeded to analyze each individual transit rather than the phase-folded light curve. We held fixed the parameters $R_p/R_\star$, $a/R_\star$, b, and the parameter or parameters of the limb-darkening law. The only free parameters were the transit time and the coefficients of the detrending polynomial. Figure 3 illustrates the phase-folded light curve of WASP-12 along with the best-fit transit model, and Figure 4 shows the individual transits.

To identify and reject transits for which the data quality was unusually poor, we calculated the MAD of the photometric data for each transit as well as the MAD of all the photometric data for multiple transits that were observed in a given sector. If a particular transit had an MAD greater than 1.5 times the overall MAD, we omitted the transit from further consideration. (This test was only performed when three or more transits were observed per sector.) If any transits were rejected in this step, we reconstructed the phase-folded light curve, rederived the geometric transit parameters and refitted the individual transits.

We employed a Markov Chain Monte Carlo method to estimate the transit times and their uncertainties. The transition

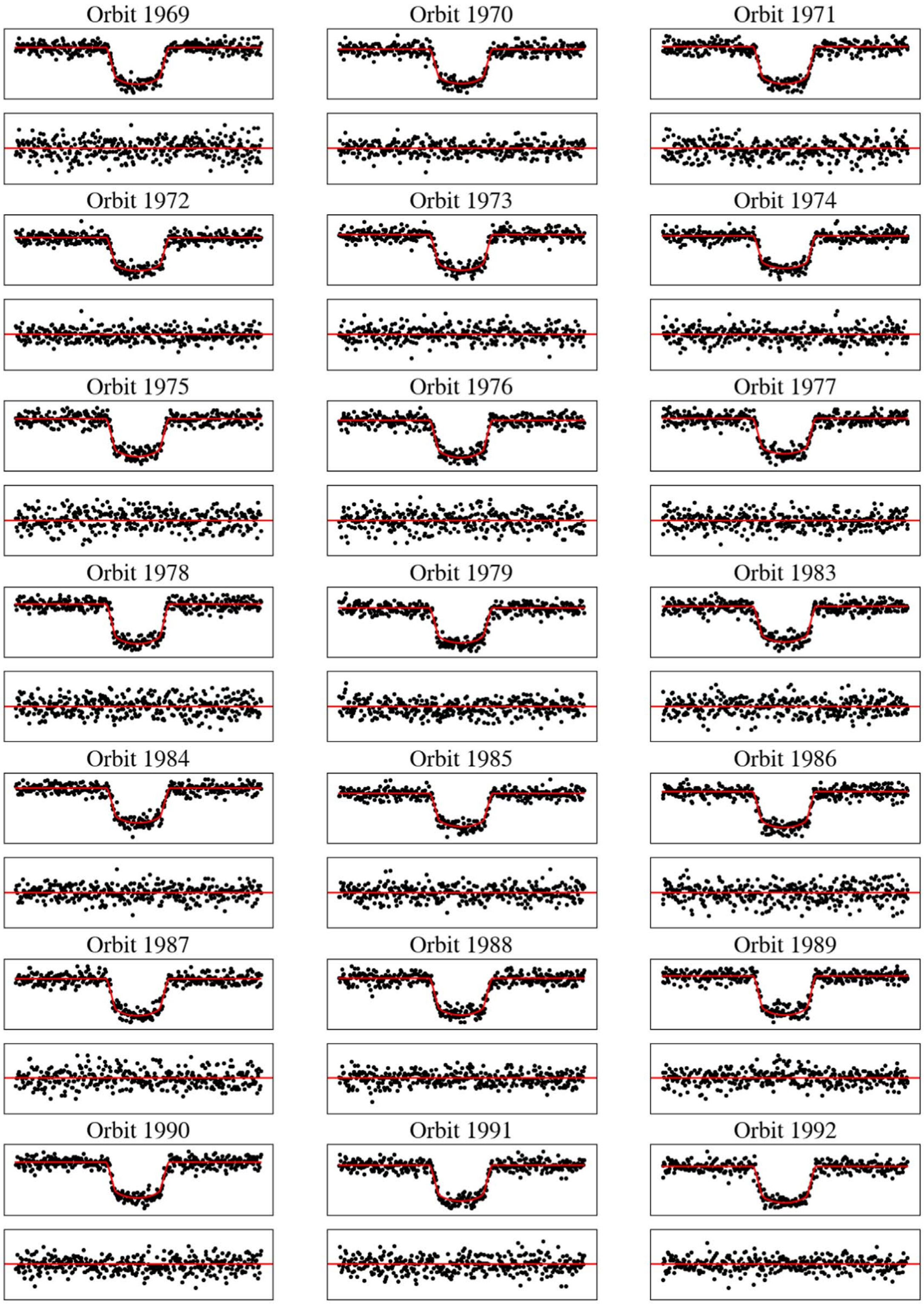

Figure 4. Individual transits of WASP-12b. The red curves are the best-fitting models.

distribution was proportional to $\exp(-\chi^2/2)$ with

$$\chi^2 = \sum_{i=1}^{N}\left(\frac{f_{\mathrm{obs},i} - f_{\mathrm{calc},i}}{\sigma_i}\right)^2, \tag{2}$$

where $f_{\mathrm{obs},i}$ is the observed flux at time t_i, $f_{\mathrm{calc},i}$ is the calculated flux at time t_i, and σ_i is the standard deviation of the out-of-transit data.

The 30 minute data were handled separately. When fitting models to the 30 minute data, we computed the model with 2 minute sampling and averaged the model into 30 minute bins before comparing the model with the data. We noticed that the 30 minute data produced by the QLP tended to have higher levels of systematic effects, including occasional bursts of apparent flux variability of unknown origin. We visually

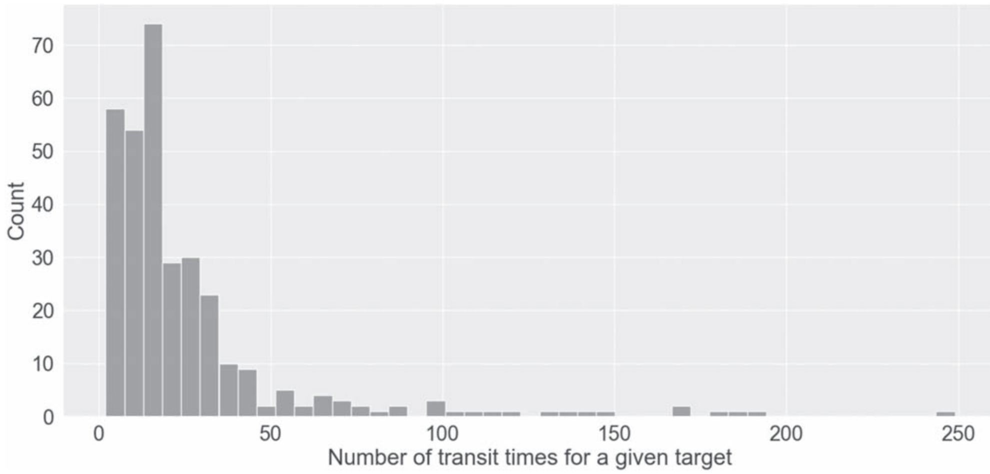

Figure 5. Histogram of the number of transit times available for a given target after sigma clipping has been applied when fitting a linear model to timing data.

identified about 10 cases in which these systematic effects occurred during transits, and omitted these cases from our subsequent analysis. In a few other cases, the S/N of the TESS transit detections proved to be too low for reliable transit timing; these, too, were omitted from further consideration. In particular, we omitted K2-237 (Sector 12), MASCARA-4 (Sector 10, 11), KPS-1 (Sector 14), and WASP-8 (Sector 29) light curves from our analysis.

4. Literature Search

A semiautomated procedure was used to search the extensive literature on transiting planets to find all the previously reported times for all the systems in our sample. First, we queried the NASA Astrophysics Data System database by object for each planet in our sample. We downloaded the `.bib` file associated with the search result, which is a text file that includes citation information for all of the papers that refer to the object in question. Some targets have alternative names; we tried using all the names known to us. We extracted the arXiv ID of each paper from the "eprint" entries in the `.bib` file.

The next step was to download the `.tex` file containing the body of text for each paper. We constructed the URL of the arXiv version of the paper by concatenating `https://arxiv.org/e-print/` and the arXiv ID (1911.09131, for example). We used the REQUESTS Python library to download the `.tex` files. Afterwards, we used the TARFILE Python library to expand the tar packages that arrived from arXiv. Usually, in addition to the main `.tex` file, each package included supplementary materials (such as tables of transit times). There were only a few cases of papers for which there was no arXiv version; these were handled separately by downloading the published papers.

After the `.tex` files had been downloaded, our code searched the source files and noted all cases in which (i) the name of the target appears at least once, and (ii) at least one number appears that is greater than 2,000,000 (allowing for the possible presence of commas), which is plausibly a timestamp expressed as a Julian Date. For these cases, we used the arXiv Python library to download the PDF versions of the manuscripts. In some papers, transit times were reported as an abbreviated Julian Date, such as JD − 2,400,000. Our automated procedure captured these cases as long as the constant that was subtracted was mentioned somewhere in the paper and was greater than 2,000,000. Any papers that did not report the offset might have been missed, although we expect such cases to be rare based on our manual investigation of cases of special interest and our experience with the literature.

At this stage, we needed to inspect the manuscripts to collect all of the transit times pertaining to the object in question, and exert judgment over whether the times had been measured well and reported clearly. We did not attempt to automate this step because of a host of practical issues, among them the need to establish whether the time system was $\mathrm{HJD_{UTC}}$, $\mathrm{BJD_{TDB}}$, or something else. The basic rules we used at this stage were:

1. When necessary, we converted the reported times to the $\mathrm{BJD_{TDB}}$ system using the time utilities code of Eastman et al. (2010). Whenever the time system was reported as HJD without further specification, we assumed the time system was $\mathrm{HJD_{UTC}}$ and converted the time accordingly. When the label was BJD without further specification, we assumed the time system was $\mathrm{BJD_{TDB}}$.
2. When the reported uncertainties were asymmetric, with different upper and lower error bars, for simplicity we adopted the larger error bar and assumed the uncertainty is symmetric.
3. In some cases, the only reported transit times were based on fitting data from multiple transits and assuming a constant orbital period. While not ideal for our purposes, we did include these transit times in our compilation and identified them as such in Table 4.

For 57 out of the 382 planets in our sample, no TESS data were available and there were no transit times in the literature beyond the ephemeris from the paper reporting the discovery of the object. Obviously, we were not able to improve on our knowledge of these systems, but for completeness we still included them in Table 4, reproducing the ephemerides provided by TEPCat.

We considered using additional transit times from the Exoplanet Transit Database, which compiles data from both professional and amateur astronomers, though we ultimately decided to use only the transit times reported in the professional literature.

Table 4 provides 8667 transit times for 382 planets, based on new TESS observations as well as data from about 500 papers in the literature. For completeness, this table includes the cases for which only TESS data are available, for which only earlier

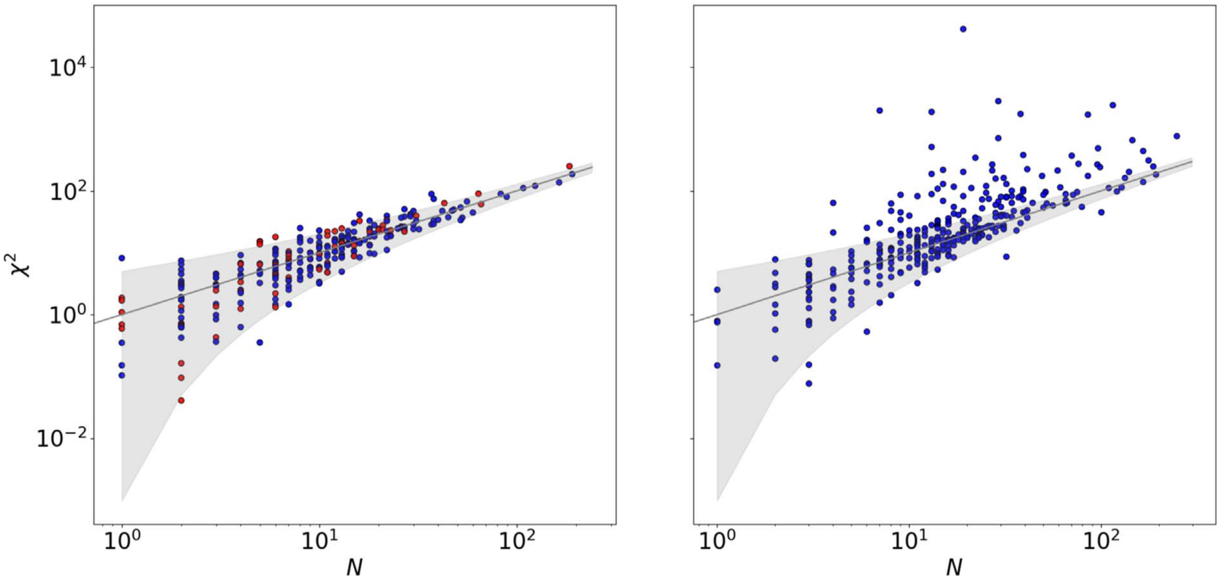

Figure 6. Distribution of χ^2 based on constant-period models fitted to the transit times of all the planets in our sample. The gray shaded area encompasses the region between the 2.5% and 97.5% levels of the chi-square distribution. (Left) Using TESS data only. Red points are cases for which at least some of the data had 30 minute sampling. (Right) Using TESS data and previously reported data from the literature.

data are available, and for which both types of data are available. Figure 5 shows the distribution of the number of transit times available for a given system. The median number of transit times per planet is 16.

5. Transit-timing Analysis

5.1. TESS Transit Times

First, we considered only the TESS transit times. For each system with TESS data, we used least-squares linear regression to fit a constant-period model to the TESS transit times:

$$T_n = T_0 + nP, \tag{3}$$

where P is the period and n is the number of transits that have occurred since a designated reference transit. To reduce the covariance between the fitted values of T_0 and P, we chose the reference transit to be the observed transit closest to the median time of all the observed transits.

Assuming the model is correct and that the deviations between the data and the model are independently and normally distributed zero-mean random variables with variance σ_i^2, the χ^2 statistic should be distributed as

$$f(\chi^2) = \frac{(\chi^2)^{N_{\rm dof}/2-1}}{2^{N_{\rm dof}/2}\,\Gamma(N_{\rm dof}/2)}\exp(-\chi^2/2), \tag{4}$$

where $N_{\rm dof}$ is the number of degrees of freedom and $\Gamma(N_{\rm dof}/2)$ is the gamma function. The χ^2 distribution has a mean of $N_{\rm dof}$ and a variance of $2N_{\rm dof}$. Here, $N_{\rm dof}$ is the number of data points minus two. Figure 6 (left panel) shows the minimum value of χ^2 for each system as a function of the number of degrees of freedom for that system. In almost all cases, χ^2 falls between the 2.5% and 97.5% levels of the chi-square distribution. We interpret this result as evidence that most systems in our sample do not exhibit short-term transit timing variations, and as a validation of our method for assigning uncertainties.

5.2. All Available Transit Times

We also fitted the constant-period model to the entire collection of transit times for each system, from both TESS and the literature. We had two goals: to identify systems showing evidence for period changes, and to provide values and uncertainties for T_0 and P that are appropriate for predicting future transit times.

At first, we fitted the constant-period model taking all the data and the reported uncertainties at face value, and recorded the minimum value of χ^2. Any system for which the minimum value of χ^2 was found to exceed $N_{\rm dof} + 3\sqrt{2N_{\rm dof}}$ was flagged as a candidate for transit-timing variations. However, there were many cases in this category for which only one or two data points deviated strongly from the best-fit model, at seemingly random epochs. Because the previously reported transit times are from heterogeneous sources and are based on data sets with highly variable quality—and likely include some outright errors in the data analysis or in our transcription—we needed to make decisions about how to handle large outliers in the timing data.

First, to avoid missing anything obviously interesting, we visually inspected all of the timing residuals regardless of χ^2, to look for any patterns in the residuals such as a gradual trend or an oscillation, as opposed to isolated outliers. To allow users of the database to perform similar visual inspection, we have provided online[4] the entire library of figures showing the light curves and the timing residuals for each system. The cases that were flagged in this step as potentially interesting are discussed below.

Next, out of a general concern about systematic errors in light-curve fitting and the neglect of time-correlated noise, we repeated the constant-period fit after imposing a minimum uncertainty in each transit time of 0.0003 days (26 s), and attaching zero weight to isolated $>5\sigma$ outliers. Figure 6 (right panel) shows the resulting distribution of χ^2 versus $N_{\rm dof}$. Even after these adjustments, only about three-quarters of the

[4] https://transit-timing.github.io

Table 3
Ephemerides

System	N_{data}	χ^2	σ_0	P (days)	Uncertainty (days)	T_0	Uncertainty (days)	Time System	Reference
CoRoT-01	67	63.83	0	1.508968772	8.3×10^{-8}	2,456,268.99119	0.00011	BJD_{TDB}	This work

Note. N_{data} is the number of transit times that were fitted, χ^2 is the sum of squared residuals when using the timing uncertainties reported in the literature, σ_0 is the error term that must be added in quadrature to the timing uncertainties of each of the transit times to achieve $\chi^2 = N_{dof}$, and T_0 and P are the timing parameters and uncertainties obtained by fitting the data after adding σ_0 in quadrature to the timing uncertainties of each of the transit times.

(This table is available in its entirety in machine-readable form.)

systems had a minimum χ^2 between the 2.5% and 97.5% levels of the theoretical distribution, indicating that either there are genuine transit-timing variations or that the uncertainties in some of the data points have been underestimated.

For the purpose of assigning realistic uncertainties to future predicted transit times, we refitted the data after adding another parameter σ_0 representing the level of either systematic timing errors or transit-timing variations. This term was added in quadrature to the reported uncertainty for each of the transit times whenever we had $\chi^2 > N_{dof}$. The value of σ_0 for each system was determined by the condition $\chi^2 = N_{dof}$. For each target, we report the value of χ^2 obtained with $\sigma_0 = 0$, as well as the value of σ_0 that gives $\chi^2 = N_{dof}$. Table 3 gives the results.

For the 57 targets for which no TESS data were available and multiple independently derived transit times have not been reported in the literature, Table 3 simply reproduces the ephemerides reported in TEPCat, for the convenience of having the information for many systems in one place.

For three targets—WASP-161 b, XO-6 b, and HAT-P-19 b—there were some major outliers in the timing diagrams based on transit times reported in the literature that caused us to suspect problems with the data. After analyzing TESS data of XO-6 b, Ridden-Harper et al. (2020) have also arrived at a similar conclusion that there might be unknown timing errors in its literature data. Table 4 includes all of the available transit times, including these outliers. However, Table 3 reports ephemerides for WASP-161 b and XO-6 b derived from TESS data only. In the case of HAT-P-19 b, we excluded a single outlier ($T_0 = 2{,}458{,}699.53657 \pm 0.00043$ BJD_{TDB} reported in Baştürk et al. 2020) when deriving the ephemeris.

6. Cases of Special Interest

6.1. Features in Light Curves

Although our goal was transit timing, we also looked out for any unexpected features in the TESS light curves. For the following systems, we noticed additional fading events besides those due to the known transiting planets:

1. *NGTS-11* shows four dips, all with an amplitude of about 0.3%, at TESS JDs 1389.8, 1402.57, 2117.83, and 2130.6 (sectors 3 and 30).[5] See Figures 7 and 8, and 9. These characteristics are compatible with an orbital period of 12.77 days and a planet radius of 4.7 $R_\oplus$, assuming the stellar radius is 0.832 $R_\odot$ (Gill et al. 2020). The previously reported planet in this system has a period of 35.5 days and a radius of 9.2 $R_\oplus$. After noticing these extra dips, we also saw that this object appears in the latest list of TESS Objects of Interest with the identifier TOI 1847.02.
2. *HATS-25* shows a dip near TESS JD 2315 (sector 37). We checked the TESS images for this system. The extra dip is also seen in a light curve based on seemingly blank pixels in the image. We hypothesize that the extra dip is due to a problem with the automated subtraction of a model for the background light in the image.
3. *WASP-77* shows a closely spaced pair of dips between TESS JD 2151.0 and 2151.5 (sector 37). Inspection of the images also showed that these dips appear in light curves constructed from pixels far from the star. Thus, the dips almost certainly do not belong to WASP-77.
4. The light curve of WASP-83 shows a brightening event at TESS JD 1590.575. A similar brightening event can be seen in the light curve of every pixel in rows 1368 and 1369. The time of the event becomes progressively later with column number. Clearly, these events are unrelated to WASP-83. Perhaps they are the effect of a moving object (such as an asteroid) that passed through the field or interfered with background subtraction.

For KELT-9 and MASCARA-4, the transit signals do not have the usual mirror symmetry around the time of minimum light. This was already known from prior data (Ahlers et al. 2020a, 2020b). The reason for the asymmetry is the combination of two properties: (i) the stars are rapidly rotating, leading to the latitudinal variation in emergent intensity known as gravity darkening, and (ii) the planets' orbits are misaligned with respect to the stellar equator.

The TESS data for HAT-P-11 show occasional anomalies during transits characteristic of spot crossings, when the planet moves in front of a relatively dark patch on the star's photosphere. Such anomalies were seen in profusion in the NASA Kepler data for this object by Sanchis-Ojeda & Winn (2011) and others.

The TESS light curves for the following systems showed rapid oscillations that are characteristic of stellar pulsations: HAT-P-32, HAT-P-49, KELT-8, WASP-33, WASP-178, and possibly KELT-24 and WASP-7. Because we did not attempt to model or filter out these oscillations, the transit times for these systems are subject to unusually large systematic uncertainties and the reported ephemerides should be used with caution. For WASP-178, in particular, the oscillations are due to blending of the star with the nearby pulsating star ASASSN-V J150908.07-424254.1. We did not include TESS transit times for this target in our work.

6.2. Long-term Period Changes

To look for evidence of long-term period changes in each system, we fitted a model in which the period is changing at a

[5] The TESS JD is defined as BJD minus 2,457,000.

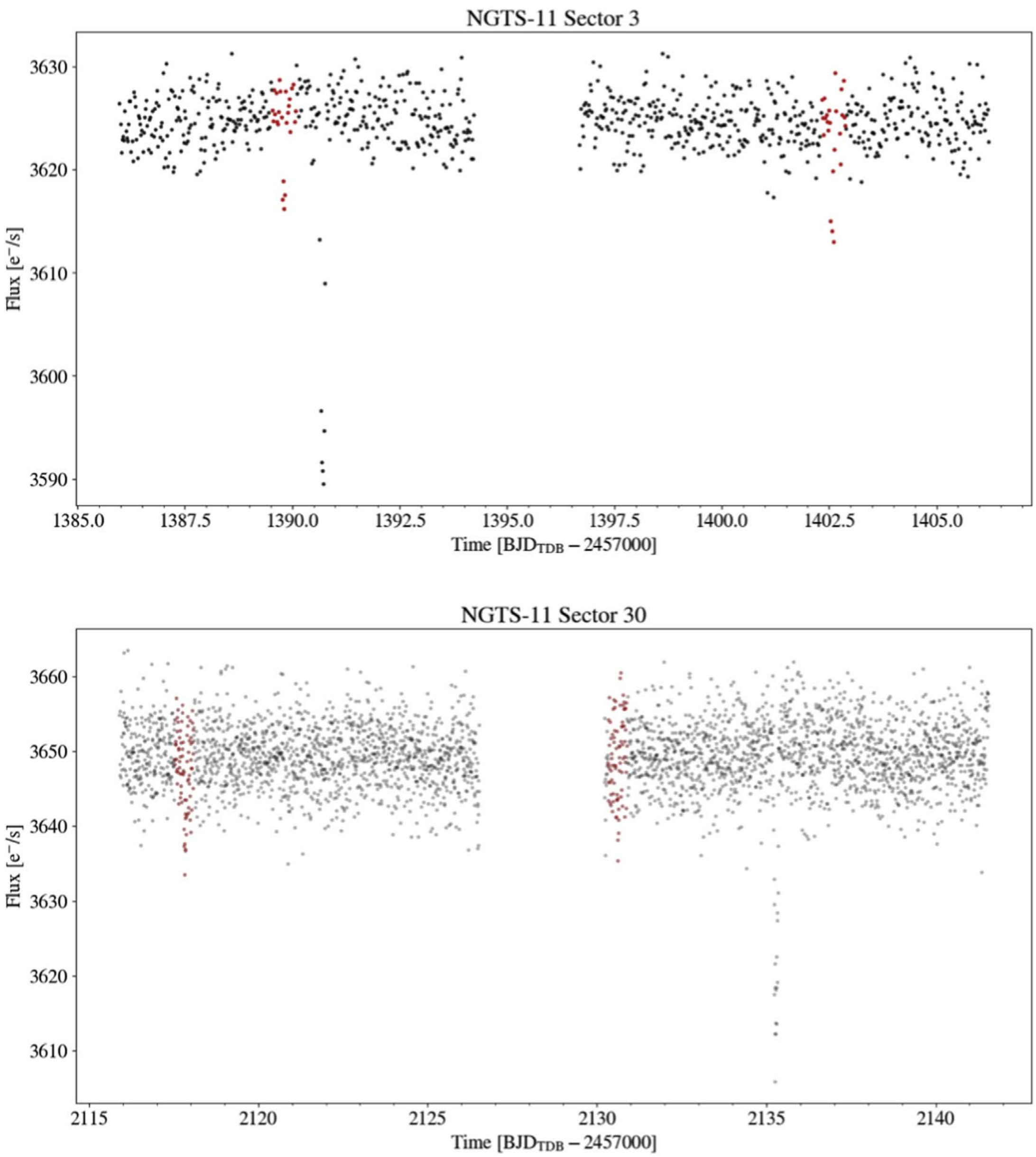

Figure 7. NGTS-11 TESS light curves. The transits of NGTS-11 c are shown in red.

steady rate:

$$T_n = T_0 + nP + \frac{n^2}{2P}\frac{dP}{dt}. \quad (5)$$

and flagged any cases for which dP/dt was found to be at least 3σ away from zero. These cases are discussed in this section, along with a few other notable systems.

1. *WASP-12 b* is a 1.5 $M_{\rm Jup}$ planet in a 1.1 day orbit around a star that appears to be a late-F main-sequence star, but could also be a subgiant (Hebb et al. 2009; Weinberg et al. 2017). The transit period is slowly decreasing with time (Maciejewski et al. 2016; Patra et al. 2017). The interval between occultations (secondary eclipses) is also decreasing with time (Yee et al. 2019). Thus, the orbit appears to be shrinking, possibly due to tidal orbital decay. TESS transit timing for this system was performed by Turner et al. (2021), who found $dP/dt = -32.53 \pm 1.62$ ms yr^{-1}. We found $dP/dt = -30.27 \pm 1.11$ ms yr^{-1} (see Figure 10).
2. *WASP-4 b* is a 1.2 $M_{\rm Jup}$ planet on a 1.3 day orbit around a G7V star (Wilson et al. 2008). The transit period was found to be decreasing in an earlier analysis of TESS data (Bouma et al. 2019). Most or all of the observed change in the transit period is due to the long-term acceleration of the star toward the Sun, probably due to the gravitational pull of a wide-orbiting companion (Bouma et al. 2020). We found $dP/dt = -5.81 \pm 1.58$ ms yr^{-1} (see Figure 11) which is compatible with the result reported by Bouma et al. (2019) and is based on an additional sector of TESS data.
3. *WASP-45 b* is a 1.0 $M_{\rm Jup}$ planet in a 3.1 day orbit around a K2V star (Anderson et al. 2012). The best-fit model gives $dP/dt = -262.57 \pm 28.35$ ms yr^{-1} (see Figure 12). However, the pattern of timing residuals is not obviously quadratic, and the early times show scatter far in excess

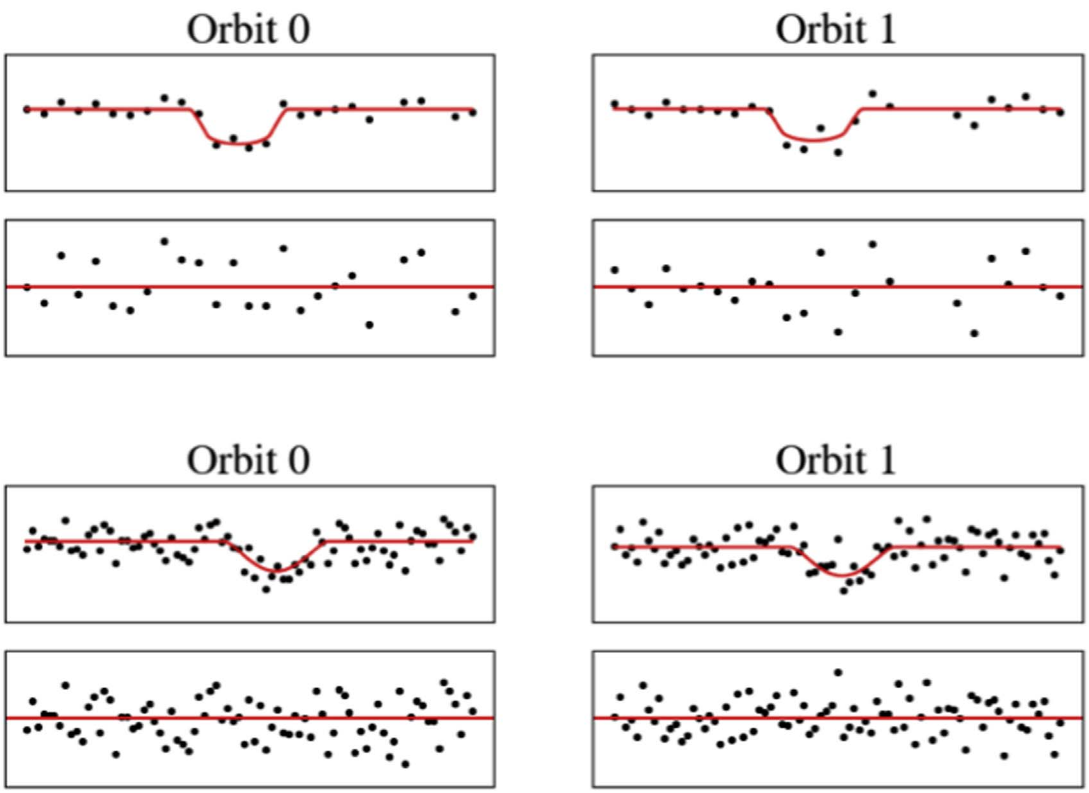

Figure 8. NGTS-11 c individual transits (upper panel: TESS sector 3; lower panel: TESS sector 30).

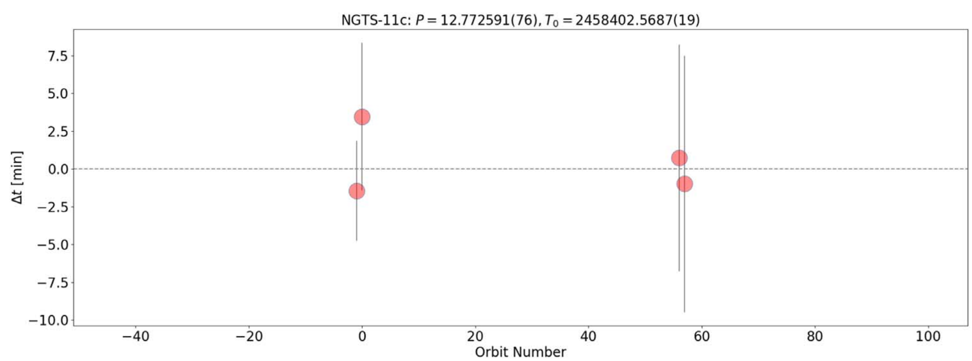

Figure 9. Timing residuals of NGTS-11 c. The points are based on TESS data.

of the formal uncertainties. By themselves, the TESS data show no evidence for a period change. We consider this a mediocre candidate for a period change; more data are needed.

4. *CoRoT-2 b* is a 3.3 $M_{\rm Jup}$ planet in a 1.7 day orbit around a G7V star (Alonso et al. 2008; Bouchy et al. 2008). The star is active and rapidly rotating, with spots covering ∼10% of its visible surface (Guillot & Havel 2011). TESS data are not yet available, but our compilation of previous measurements gave $dP/dt = -103.76 \pm 6.33$ ms yr^{-1} (see Figure 13). This, too, does not yet seem like a compelling candidate for a period change, because of the large scatter around the quadratic trend and because the starspots can cause errors in the determination of transit times.
5. *TrES-1 b* is a 0.76 $M_{\rm Jup}$ planet in a 3.0 day orbit around a K0V star (Alonso et al. 2004). Including the TESS data, we found $dP/dt = -18.36 \pm 3.73$ ms yr^{-1}. Visually, the timing residuals do not show any particular pattern (see Figure 14), and as usual, the data drawn from the literature include sporadic outliers, so it is difficult to take the 3σ detection too seriously. Still, this system might be worth further attention.
6. *TrES-5 b* is a 1.8 $M_{\rm Jup}$ planet in a 1.5 day orbit (Mandushev et al. 2011). Including the TESS data, we found $dP/dt = -17.47 \pm 3.79$ ms yr^{-1}. The timing residuals are shown in Figure 15. A recent study by Maciejewski et al. (2021) concluded that the orbital period of the planet could be varying on a long timescale. The authors found that the most likely explanation of the observations is the line-of-sight acceleration of the system's center of mass due to the orbital motion induced by a massive, wide-orbiting companion. This system is worth watching further.
7. *WASP-161 b* is a 2.5 $M_{\rm Jup}$ planet in a 5.4 day orbit around an F6V star (Barkaoui et al. 2019). The only previously reported timing data was from Barkaoui et al. (2019), who computed an ephemeris but did not provide

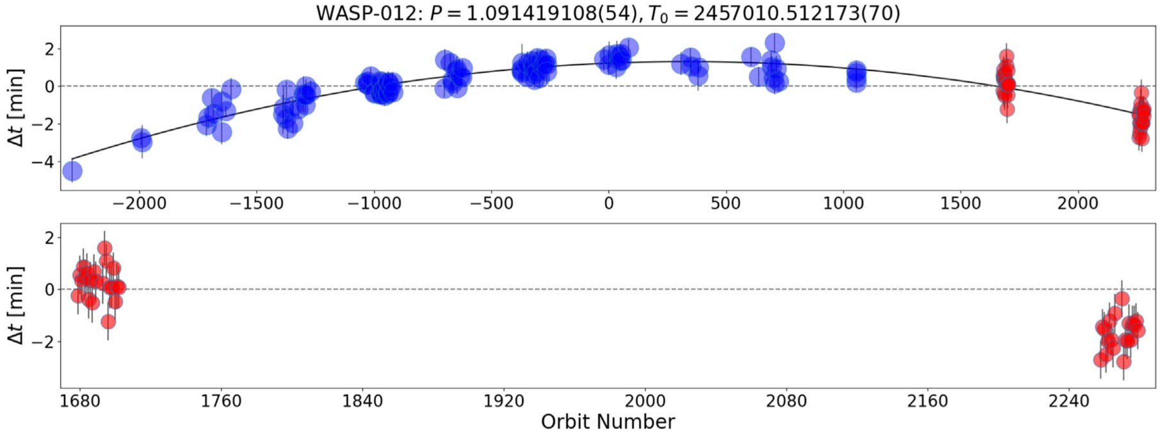

Figure 10. Top panel: Timing residuals of WASP-12 b. Blue points are based on previously reported transit times drawn from the literature. Red points are based on TESS data. The black curve shows the residuals of the best-fitting model in which the period changes uniformly with time. Bottom panel: close-up view of the TESS data points.

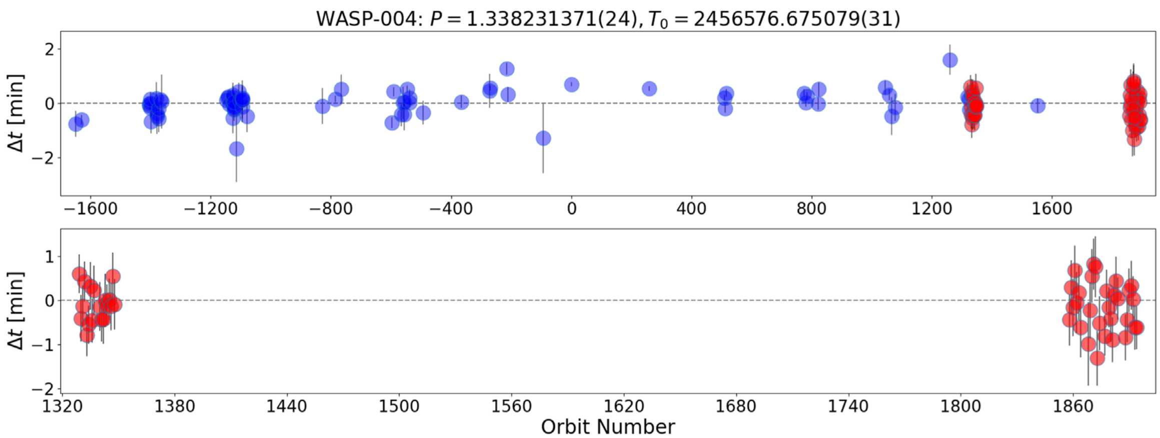

Figure 11. Top panel: Timing residuals of WASP-4 b. Blue points are based on previously reported transit times drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

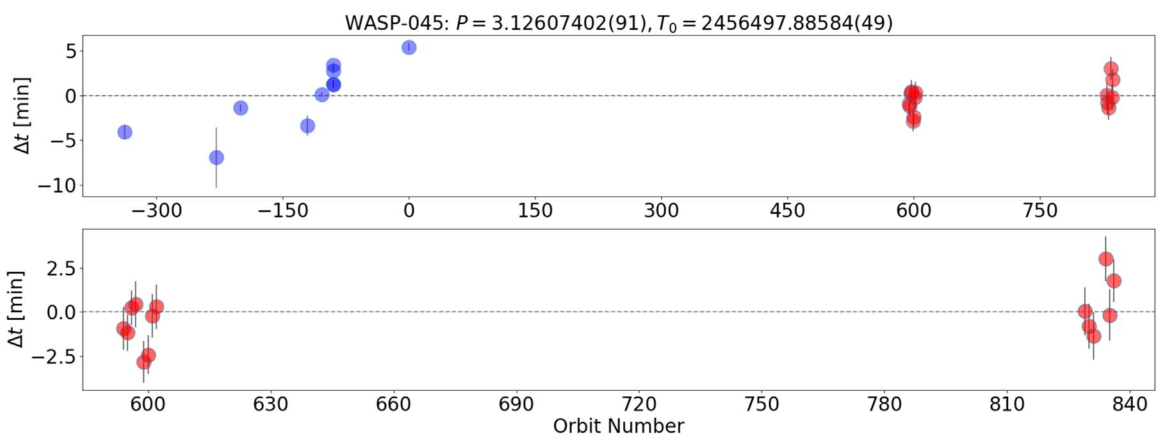

Figure 12. Top panel: Timing residuals of WASP-45 b. Blue points are based on previously reported transit times drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

individual transit times. The reference epoch of their ephemeris was $2{,}457{,}416.5289 \pm 0.0011$ HJD, which we converted to $\mathrm{BJD_{TDB}}$ before including it in our timing study. However, using the TESS data alone, we would have predicted the transit referenced by Barkaoui et al. (2019) to have occurred more than an hour earlier (see Figure 16). The best-fit model has $dP/dt = -15.5 \pm 0.35$ s per year (not ms yr^{-1}). Because the timing residuals have a single outlier, an error in determining or reporting the transit time seems at least as plausible as a genuine timing variation of such a large amplitude.

8. *WASP-99 b* is a 2.8 M_{Jup} planet in a 5.8 day orbit around an F8V star (Hellier et al. 2014). The best-fit model has $dP/dt = -305.85 \pm 104.98$ ms yr^{-1}, but this is another

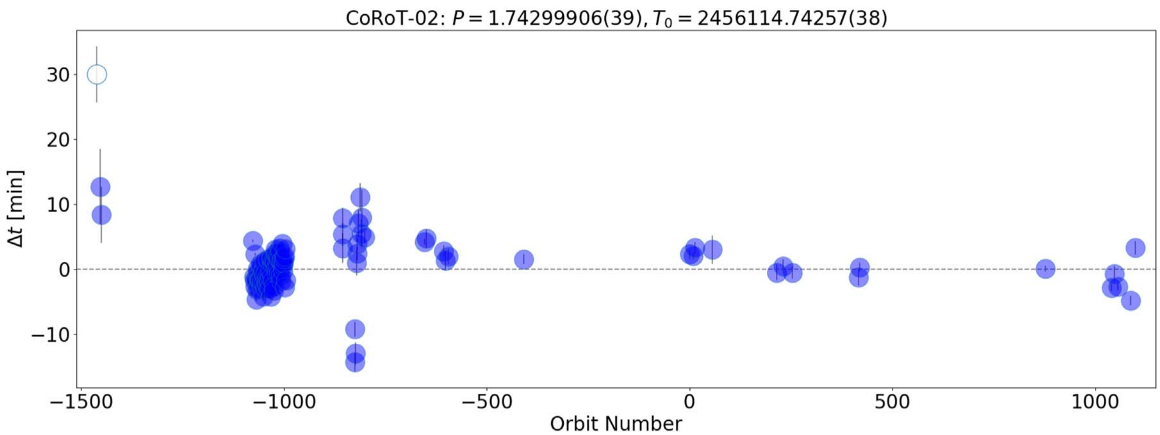

Figure 13. Timing residuals of CoRoT-2 b. Blue points are based on previously reported transit times drawn from the literature. The white point is a 5σ outlier that was not included when performing the fits.

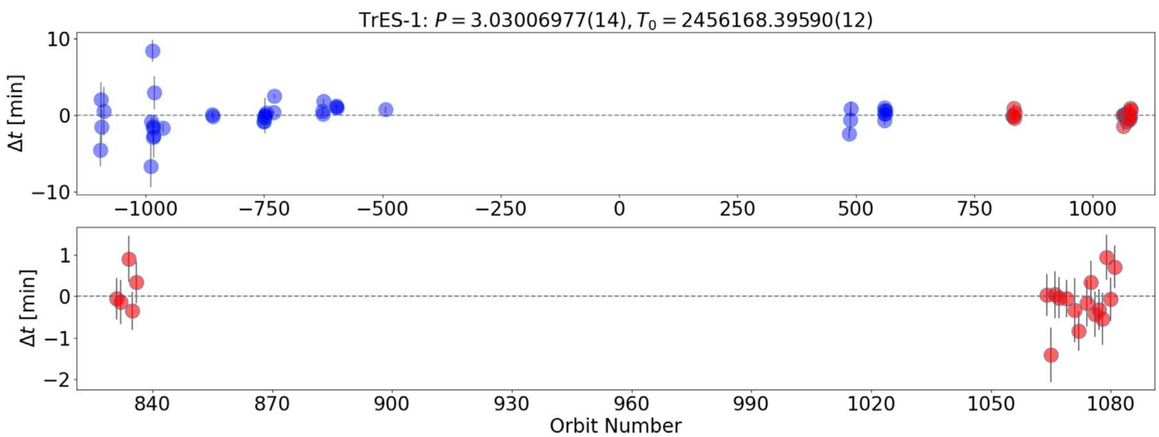

Figure 14. Top panel: Timing residuals of TrES-1 b. Blue points are based on previously reported transit times drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

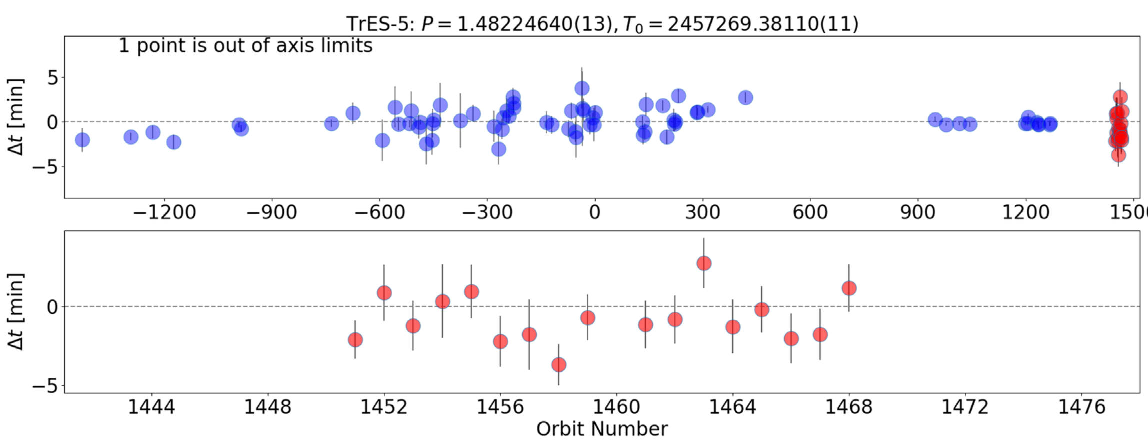

Figure 15. Top panel: Timing residuals of TrES-5 b. Blue points are based on previously reported transit times drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

case in which the literature provide only a single transit time, based on a fit to data from multiple transits and the assumption of a constant period (Figure 17). This makes any conclusions vulnerable to any problems with that single datum.

9. *WASP-19 b* is a 1.1 $M_{\rm Jup}$ planet in a 0.78 day orbit around a G8V star (Hebb et al. 2010). It is predicted to be one of the most favorable targets in the search for evidence of tidal orbital decay. The timing residuals are shown in Figure 18. The best-fit quadratic model gives $dP/dt = -3.54 \pm 1.18$ ms yr^{-1}, which just barely makes our 3σ criterion. Ordinarily, we would not call attention to such a weak detection. However, given that it is based on voluminous and generally high-quality data, and given the prior expectation that the orbit should be decaying especially rapidly, this is most certainly a system worth

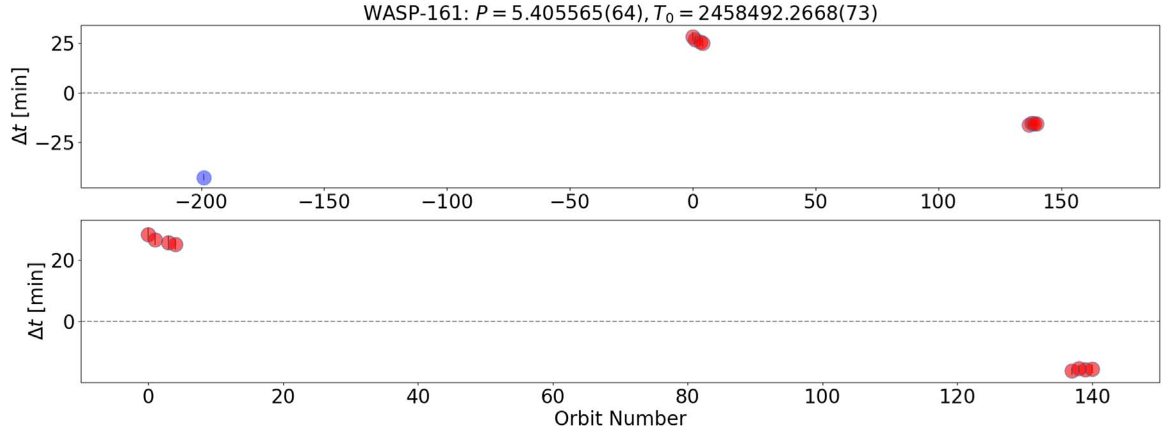

Figure 16. Top panel: Timing residuals of WASP-161 b. The blue point is based on a previously reported transit time drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

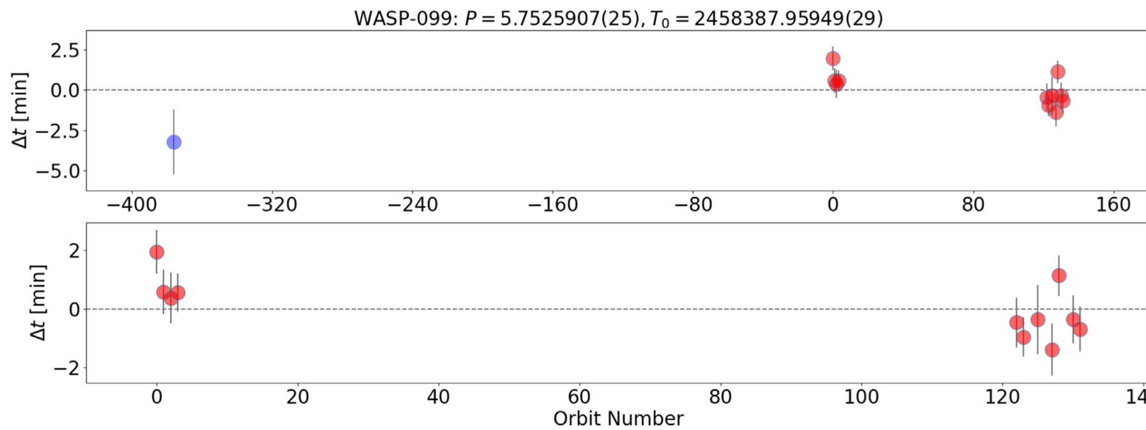

Figure 17. Top panel: Timing residuals of WASP-99 b. The blue point is based on a previously reported transit time drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

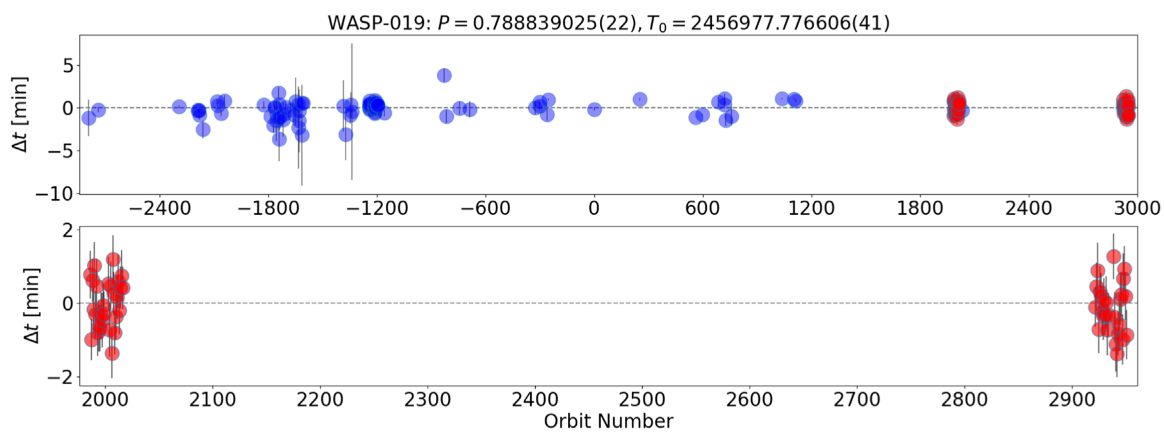

Figure 18. Top panel: Timing residuals of WASP-19 b. Blue points are based on previously reported transit times drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

watching carefully. We hope that TESS keeps revisiting this system every few years.

10. *XO-3 b* is a 13 $M_{\rm Jup}$ planet on a 3.2 day orbit around an F5 star, with an eccentric and misaligned orbit (Johns-Krull et al. 2008; Hébrard et al. 2010). The period derivative for this system was found to be $dP/dt = -182.08 \pm 12.96$ ms yr^{-1}. However, the earliest timing residuals show a lot of scatter, characteristic of ground-based light curves with small telescopes (see Figure 19). Nevertheless, this system is notable because the combination of the TESS data and two transit times measured precisely with data from the Spitzer Space Telescope (Wong et al. 2014) appear to be incompatible with a constant period. Additional visits to this system by TESS should clarify the situation.

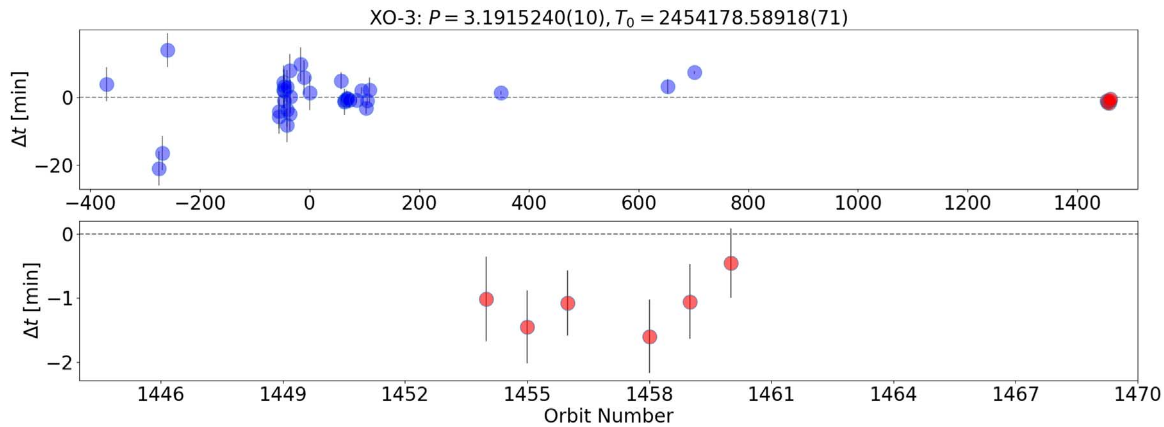

Figure 19. Top panel: Timing residuals of XO-3 b. Blue points are based on previously reported transit times drawn from the literature. Red points are based on TESS data. Bottom panel: close-up view of the TESS data points.

6.3. Short-term Transit-timing Variations

There are only two convincing cases of short-term transit-timing variations in our sample. The first case is Kepler-448, an F star with a transiting $1.2\,R_{\rm Jup}$ planet on an 18 day orbit, for which transit-timing variations revealed an outer giant planet on an eccentric orbit (Masuda 2017). TESS has only observed a single transit, so the new data do not add much information. The second case is WASP-148, a G dwarf with two known planets, one of which is a transiting $0.29\,M_{\rm Jup}$ planet on an 8.8 day orbit, and the other of which is a nontransiting planet with a minimum mass of $0.4\,M_{\rm Jup}$ and a period of 34.5 days. The transit-timing variations of the inner planet, including the TESS data, have been analyzed by Maciejewski et al. (2020).

7. Summary and Discussion

By analyzing TESS data and compiling data from the literature, we improved the precision with which the orbital period is known for 246 planets (Figure 20). We hope that this database of transit times will be useful to anyone interested in observing these systems in the future, as well as anyone searching for long-term period changes, or constraining population-level properties from the incidence (or lack) of transit-timing variations. Nevertheless, any automated procedure applied to hundreds of systems is bound to fumble in some cases. Users of the database are encouraged to inspect the light curves and timing residual diagrams provided online[4] before trusting the ephemerides to plan observations with expensive facilities such as the James Webb Space Telescope.

To facilitate future studies of this nature, we encourage astronomers to report transit times in the $\mathrm{BJD_{TDB}}$ time system, and to report measurements of *individual* transit times in addition to the ephemerides derived from fitting all the transit times.

We note that Klagyivik et al. (2021) have used TESS data to time the transits of nine planets discovered by the CoRoT survey. In addition, after this work was nearly complete, we became aware of two other groups, Kokori et al. (2022) and Shan et al. (2021), who have also been performing transit timing en masse. Since these works were not yet published as of the time of writing this article, we refrained from a detailed comparison between our numerical results and theirs, but we can make some general comparisons.

Kokori et al. (2022) reported ephemerides for 180 planets based on data from the literature as well as new photometric data collected by the ExoClock network, which is a community of amateur astronomers. This team did not utilize TESS data in their study.

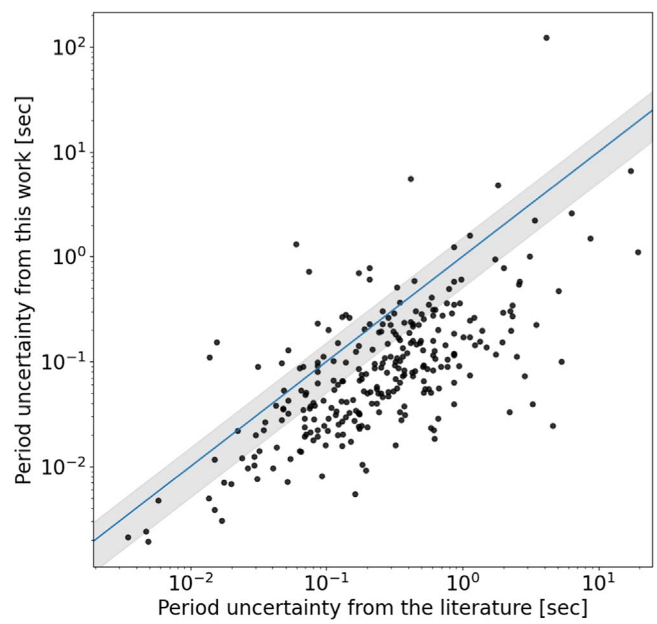

Figure 20. Orbital period error based on fitting literature data only vs. orbital period error derived in our work. The gray area encapsulates the region between 0.5 times the identity line and 1.5 times the identity line. The identity line is shown in blue.

Shan et al. (2021) identified 31 hot Jupiters for which an ephemeris taken from the literature failed to predict the TESS transit times to within the statistical uncertainty. This is different from our approach, which was based on analyzing all available transit times whenever possible, rather than relying on a previously reported ephemeris. Their list includes WASP-161 and WASP-99, which we discussed in Section 6. We did not consider these to be compelling cases for period changes because of the paucity of data points. Apart from those two cases, we did not flag any of the same systems as candidates for period changes.

8. Code

The code is available on GitHub at https://github.com/transit-timing/tt and archived on Zenodo at doi:10.5281/zenodo.5904270.

We are grateful to Filip Walter for compiling and providing the Exoplanet Transit Database in a convenient format, although we ultimately did not include those data in our analyses. We thank Sarah Millholland, Vadim Krushinsky, and Luke Bouma for helpful comments on the draft of this paper. We would also like to thank Betsy Pu for her help with the development of our project's website. This work was supported by the Heising-Simons Foundation and the NASA TESS mission. This work relied on the NASA Astrophysics Data System and the arXiv. We also acknowledge the use of the Extrasolar Planets Encyclopedia at exoplanet.eu (Schneider et al. 2011); the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program (NASA Exoplanet Archive 2021). The authors are pleased to acknowledge that the work reported in this paper was substantially performed using the Princeton Research Computing resources at Princeton University which is a consortium of groups led by the Princeton Institute for Computational Science and Engineering and Office of Information Technology's Research Computing.

Appendix

Table 4 provides a database of transit times for each of the 382 planets included in this work. The table includes the cases for which only TESS data are available, for which only earlier data are available, and for which both types of data are available. The references in Table 4 are: Fukui et al. (2016), Morvan et al. (2020), Bouchy et al. (2010), Barbieri et al. (2007), Ricci et al. (2015), Delrez et al. (2018), Oberst et al. (2017), Burke et al. (2010), Gillon et al. (2006), Sozzetti et al. (2009), Casasayas-Barris et al. (2019), Sada & Ramón-Fox (2016), Murgas et al. (2014), Hébrard et al. (2008), Sanchis-Ojeda et al. (2011), Mallonn et al. (2019), Anisman et al. (2020), Demangeon et al. (2018), Masuda (2017), Huang et al. (2015), Christiansen et al. (2017), Wakeford et al. (2020), West et al. (2016), Alexoudi et al. (2018), Sun et al. (2018), Patra et al. (2020), Southworth et al. (2010), Collins et al. (2017), Triaud et al. (2013), Maciejewski et al. (2015), Bruno et al. (2018a), Johnson et al. (2011), Penev et al. (2016), Saha et al. (2021), Holman et al. (2007), Baştürk et al. (2020), Bakos et al. (2011), Montalto et al. (2015), Wang et al. (2014), Obermeier et al. (2020), Gibson et al. (2013a), Labadie-Bartz et al. (2019), Rodríguez Martínez et al. (2020), Southworth et al. (2011), Hartman et al. (2011c), Močnik et al. (2017), Mancini et al. (2018), Jiang et al. (2013), Wilson et al. (2008), Moyano et al. (2017), Lendl et al. (2012), Gandolfi et al. (2012), Mancini et al. (2014a), Maciejewski et al. (2013b), Fulton et al. (2011), Colón et al. (2010), Rauer et al. (2010), Burdanov et al. (2018), Adams et al. (2011), Bakos et al. (2010), Delrez et al. (2014), Gibson et al. (2009), Bryant et al. (2020), Brahm et al. (2018), Kipping et al. (2010), Quinn et al. (2012), Faedi et al. (2016), Zhang et al. (2018), Narita et al. (2010), Lee et al. (2011), Edwards et al. (2019), Hellier et al. (2014), Smalley et al. (2012), Sokov et al. (2018), West et al. (2009b), Cortés-Zuleta et al. (2020), Diaz et al. (2007), Maciejewski et al. (2016c), Southworth et al. (2018), Nascimbeni et al. (2013), Holman et al. (2006), O'Donovan et al. (2006), Turner et al. (2013), Maciejewski et al. (2020), Chan et al. (2011), Southworth et al. (2015a), West et al. (2009a), Zellem et al. (2020), Hartman et al. (2011a), Skaf et al. (2020), Damasso et al. (2015), Chen et al. (2021), Su et al. (2021), Smith et al. (2013), Street et al. (2010), Maxted et al. (2016), Enoch et al. (2011b), Mandushev et al. (2007), Smith et al. (2012b), Garai et al. (2020), Smith et al. (2012a), Narita et al. (2008), Pont et al. (2007), Kozłowski et al. (2017), Mansfield et al. (2020), Bakos et al. (2012), Louden & Hartman (2021), Anderson et al. (2010), Brahm et al. (2016), Patra et al. (2017), Dragomir et al. (2011), Wong et al. (2014), Johnson et al. (2009), Wilkins et al. (2017), Lendl et al. (2019), Wang et al. (2018a), Dragomir et al. (2013), Mancini et al. (2017), Lendl et al. (2014), Anderson et al. (2011a), Dittmann et al. (2012), Anderson et al. (2008), Petrucci et al. (2018), Christiansen et al. (2010), Smalley et al. (2011), Deming et al. (2013), Jiang et al. (2016), Bakos et al. (2015a), Dorval et al. (2020), Bakos et al. (2020), Collier Cameron et al. (2010), McCullough et al. (2006), McLeod et al. (2017), Wong et al. (2016), Christiansen et al. (2011), Huitson et al. (2017), Montalto et al. (2012), Narita et al. (2007), Bayliss et al. (2018a), Hébrard et al. (2013), Faedi et al. (2013), Lewis et al. (2013), Nielsen et al. (2019), Pál et al. (2008), Mallonn et al. (2015a), Barros et al. (2012), Mislis et al. (2015), Szabo et al. (2010), Jordán et al. (2013), Torres et al. (2010), Kuhn et al. (2016), Shporer et al. (2007), Anderson et al. (2011d), Bakos et al. (2009b), Wang et al. (2018b), Gillon et al. (2009a), Collins et al. (2014), de Val-Borro et al. (2016), Maxted et al. (2013b), Johnson et al. (2018), Nikolov et al. (2013), Anderson et al. (2018a), Seidel et al. (2020), Smith et al. (2014), Rabus et al. (2009), Southworth et al. (2012b), Jordán et al. (2020), Temple et al. (2017), Spake et al. (2016), Maciejewski et al. (2021), Anderson et al. (2012), Wang et al. (2017), Neveu-VanMalle et al. (2014), Southworth et al. (2016), Kipping et al. (2011), Pál et al. (2010), Ranjan et al. (2014), Ramón-Fox & Sada (2013), Barbieri et al. (2009), Raetz et al. (2015), Evans et al. (2018), Hartman et al. (2011b), Bruno et al. (2018b), Bakos et al. (2016), Mannaday et al. (2020), Kovács et al. (2010), Hoyer et al. (2012), Öztürk & Erdem (2019), Lister et al. (2009), Mohler-Fischer et al. (2013), Temple et al. (2019a), Kirk et al. (2018), Lee et al. (2012), Hellier et al. (2012), Stefansson et al. (2017), Winn et al. (2008), Talens et al. (2018), Bryan et al. (2012), Lendl et al. (2017), Hartman et al. (2019), Skillen et al. (2009), Alsubai et al. (2017), Seeliger et al. (2014), Southworth et al. (2013), Lam et al. (2017), Todorov et al. (2012), Jordán et al. (2014), Sarkis et al. (2018), Wang et al. (2021), Guo et al. (2020), Baluev et al. (2015), Hellier et al. (2015), Szabó et al. (2010), Ricci et al. (2017), Gillon et al. (2011), Albrecht et al. (2011), Anderson et al. (2018b), Hellier et al. (2011), Mancini et al. (2014b), Wakeford et al. (2017), Gill et al. (2020), Southworth et al. (2009), Southworth et al. (2012a), Tripathi et al. (2010), Barros et al. (2011), Lund et al. (2017), Howard et al. (2012), Juncher et al. (2015), Wong et al. (2015), Nutzman et al. (2011), Chen et al. (2020), Bouma et al. (2020), Zhou et al. (2019a), Gillon et al. (2009c), Siverd et al. (2017), Brahm et al. (2019), Anderson et al. (2017), Stevenson et al. (2014), Püsküllü & Soydugan (2017), Nikolov et al. (2015), Fukui et al. (2014), Irwin et al. (2008), Bonomo et al. (2017a), Gibson et al. (2008), Gillon et al. (2009b), Fischer et al. (2016), McCormac et al. (2020), Gibson et al. (2013b), Raetz et al. (2019), Mancini et al. (2015b), Tregloan-Reed et al. (2015), Konacki et al. (2004), Deeg et al. (2010), Hartman et al. (2015a), Bayliss et al. (2013), McDonald & Kerins (2018), Petrucci et al. (2015), Močnik et al. (2020), Schröter et al. (2012), Winn et al. (2007c), Kreidberg et al. (2015),

Table 4
Transit Times

System	Orbit Number	Transit Time	Uncertainty (days)	Time System	#	Reference
CoRoT-01	−1412	2,454,138.32761	0.00047	BJD	1	2009A&A506369B

Note. The # column indicates if the transit time is based on an individual transit event or a fit of multiple transits simultaneously assuming a constant period.
(This table is available in its entirety in machine-readable form.)

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