ExoClock Project. III. 450 New Exoplanet Ephemerides from Ground and Space Observations

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Abstract

The ExoClock project has been created to increase the efficiency of the Ariel mission. It will achieve this by continuously monitoring and updating the ephemerides of Ariel candidates, in order to produce a consistent catalog of reliable and precise ephemerides. This work presents a homogenous catalog of updated ephemerides for 450 planets, generated by the integration of ∼18,000 data points from multiple sources. These sources include observations from ground-based telescopes (the ExoClock network and the Exoplanet Transit Database), midtime values from the literature, and light curves from space telescopes (Kepler, K2, and TESS). With all the above, we manage to collect observations for half of the postdiscovery years (median), with data that have a median uncertainty less than 1 minute. In comparison with the literature, the ephemerides generated by the project are more precise and less biased. More than 40% of the initial literature ephemerides had to be updated to reach the goals of the project, as they were either of low precision or drifting. Moreover, the integrated approach of the project enables both the monitoring of the majority of the Ariel candidates (95%), and also the identification of missing data. These results highlight the need for continuous monitoring to increase the observing coverage of the candidate planets. Finally, the extended observing coverage of planets allows us to detect trends (transit-timing variations) for a sample of 19 planets. All the products, data, and codes used in this work are open and accessible to the wider scientific community.

Unified Astronomy Thesaurus concepts: Ephemerides (464); Transits (1711); Amateur astronomers (34); Photometry (1234); Open source software (1866)

Supporting material: machine-readable tables

1. Introduction

The number of exoplanets discovered already exceeds 5000 and continues to increase daily. The characterization of exoplanets will be the main goal of future space missions. The Ariel mission aims to observe the atmospheres of 1000 planets in 2029, in order to investigate their nature (Tinetti et al. 2018). Ariel will observe thousands of transits, and to increase the mission efficiency, it is necessary to have precise ephemerides. Proper planning is important to avoid wasting the precious observing time of Ariel and other future space missions.

For various reasons, the accuracy of predicting transit times is impeded. For example, the uncertainties of the initial ephemerides causes degeneracies over time in the precision of the predicted transit time (e.g., Mallonn et al. 2019b). The insufficient number of available data for each planet is another factor that generates biases in calculating the ephemerides (e.g., Benneke et al. 2017; Mallonn et al. 2019b).

To overcome the above problems and create a complete catalog of precise ephemerides for a large number of planets, it is essential to use all the available data resources. These resources consist of data from the literature, data obtained by telescopes from the ground, and finally data from space telescopes. The ExoClock project (Kokori et al. 2021, 2022) is an open, integrated platform, with the aim of continuously monitoring the ephemerides of the Ariel candidate targets (Edwards & Tinetti 2022). The organization of the project is thoroughly described in Kokori et al. (2021), and the first large-scale catalog of updated ephemerides for 180 planets was produced in Kokori et al. (2022), by combining observations from ground-based telescopes and the literature.

The benefits of using small, ground-based telescopes to observe transiting exoplanets have previously been emphasized (e.g., Beck et al. 2019; Mallonn et al. 2019b; Zellem et al. 2020; Edwards et al. 2021a), and their use in large-scale studies has already been proven in Kokori et al. (2022). While small telescopes are efficient, maximum effectiveness is achieved by utilizing all of the available resources, including other ground-based networks, data from the literature, and also data from space resources. Space telescopes are effective in observing challenging transits that are not easily accessible from ground-based telescopes. Moreover,

TESS (Ricker et al. 2014) has been scanning the sky since 2019, and will continue to provide light curves for many known exoplanets, which can be used for updates to the ephemerides (Ivshina & Winn 2022). Therefore, to produce a complete catalog of ephemerides for all planets, it is important to use data from both space- and ground-based telescopes.

In this study, we integrate data from the ExoClock network, midtime points from the literature, data from the Exoplanet Transit Database (ETD; Poddaný et al. 2010), and data from space telescopes (Kepler—Koch et al. 2010a; K2—Howell et al. 2014; and TESS—Ricker et al. 2014). The integration of ∼18,000 midtime points, in total, allows the generation of a complete analysis of ephemerides for 450 planets. There are several benefits of this integrated analysis: biases are minimized, better precision is achieved, and long-term phenomena can be identified for each planet, which may be indicative of trends (e.g., transit-timing variations, or TTVs). The integrated design and approach of the ExoClock project highlights where there are gaps in the available data. The ExoClock network of ground-based telescopes can then be flexibly directed to make observations to address such gaps and extend the coverage.

In all aspects of the research cycle, the ExoClock project operates with an Open Science Framework (European Commission 2016; Dai et al. 2018). Open science advances the progress of scientific research by encouraging collaborations and reproducibility. During all stages of the scientific process, the project follows open science practices; the data, tools, and codes used for the analysis are all open and accessible to anyone. All data used in this study are open and publicly available (e.g., the data obtained from the ExoClock network and the data from space telescopes). Additionally, open science means the cocreation of scientific research through collaborations between various scientific communities as well as citizen involvement (European Commission 2016). In this respect, the project is open to contributions from any interested person or community. The collaborative perspective helps to ensure the most effective use of resources. Such collaborations are important to avoid instances of overlapping and wastes of observing time—and, to a further extent, they also foster innovation in science.

2. Data

In this study, we integrated light curves from the ExoClock network, the ETD, and the MAST Archive (for the Kepler, K2, and TESS space missions), and midtransit times from the literature, to update the ephemerides of 450 exoplanets. All the light curves were acquired before the end of 2021, and the literature midtransit times were published by the end of 2021. We analyzed all the light curves, regardless of their source, using the stellar and planetary parameters included in the Exoplanet Characterization Catalog (ECC), a dedicated catalog prepared and maintained within the ExoClock project (Kokori et al. 2021), and the open-source Python package PyLightcurve (Tsiaras et al. 2016). For every light curve, PyLightcurve performs the following operations:

1. calculates the limb-darkening coefficients (LDCs) using the ExoTETHyS package (depending on the filter used for the observation; Morello et al. 2020);
2. converts the time formats to barycentric Julian date (BJD_{TDB});
3. finds the maximum likelihood model for the data (an exposure-integrated transit model together with a trend model—linear with airmass, linear with time, or quadratic), using the Nelder–Mead minimization algorithm included in the SciPy package (Virtanen et al. 2020);
4. removes outliers that deviate from the maximum likelihood model by more than 3 times the standard deviation (STD) of the normalized residuals;
5. scales the uncertainties by the rms of the normalized residuals, to take into account any extra scatter; and
6. finally, performs a Markov Chain Monte Carlo optimization process using the emcee package (Foreman-Mackey et al. 2013).

After this analysis, the quality of each light curve was evaluated individually, with the light curves that fulfilled one or more of the criteria below being excluded:

1. the autocorrelation and Shapiro statistic indicate non-Gaussian normalized residuals at a 3σ level or more;
2. the transit signal-to-noise ratio ($S/N = Depth/\sigma_{Depth}$) is lower than 3;
3. the Rp/Rs differs by more than 3σ from the literature value (for the ExoClock and ETD observations) or the weighted average of the mission (for the space observations); and
4. the $O - C$ value is not in agreement (3σ) with the other observations obtained during the same observing period (~a month).

The final list of 450 planets includes those planets for which we collected data points at three or more different epochs and for which we could determine an ephemeris of better or equal quality to the initial ephemeris. Table 1 summarizes the observations that were used to produce the ephemerides of the 450 planets in this work. In addition, Figures 1 and 2 show the distributions of the precision and the coverage of the transit midtime points that were used. As coverage, we define the percentage of years (since the first observation in the database) for which at least one observation exists. We need to note here that 99% of the observations used have transit midtime uncertainties lower than 10 minutes, and that the median coverage of all sources combined together is 50%, while individual sources do not reach more than 29%.

2.1. ExoClock—Summary and Quality of Data

Currently, the ExoClock network consists of 540 participants —80% of whom are amateur astronomers—and 450 telescopes, with sizes ranging between 6 and 40 inches, of which 80% are smaller than 17 inches. Figure 3 shows the distribution of the observations used in this work among the different telescope sizes. The large majority of the observations come from small- and medium-scale telescopes and amateur observers (73%), who are the key part of our network. The ExoClock network is organized in such a way as to maximize the coverage of the planets and to ensure the high quality and homogeneity of the results. To achieve this, we have defined a prioritization system, we provide a personal scheduler for each telescope, we support the observers with the data analysis (by means of educational material, user-friendly software, and regular meetings) and, finally, we perform the light curve modeling and evaluation (as described above) on the ExoClock website. For more details on the organization of the ExoClock project and the ExoClock network, we refer the interested reader to Kokori et al. (2021).

2.2. Data from Space Telescopes

For the first time in the ExoClock project, we have integrated light curves from space telescope observations. More specifically, we have included light curves from Kepler, K2, and TESS (from before the end of 2021). First, we downloaded the long-cadence light curves for the targets on the ExoClock target list. We then identified the transits inside those light curves and isolated them, including a baseline of one transit duration before and one after the event. Finally, the analysis and evaluation of each light curve were conducted as described above, using a quadratic detrending function. As some of the space-based light curves contained gaps, we only considered those light curves that were at least 80% complete, both in transit and out of transit—i.e., the total exposure time was more than 0.8 times the transit duration before, during, and after the transit.

From the analysis of the space-based light curves, and especially from the TESS light curves, it became clear that, for a nonnegligible number of planets, the parameters in the ECC (as derived from the literature) were producing transits of shorter or longer duration than the actual observations. For these planets, we let the reduced semimajor axis (a/R_s) vary, in order to account for the differences in the duration. The ECC has been updated accordingly, and the planets for which the a/R_s was adjusted have been marked. Table 6 includes the adjusted a/R_s values, which are marked with an asterisk. With the exception of Kepler-396 c, Kepler-854b, and TOI-201b, which did not have values for their inclinations (i) in the discovery papers, we decided to fix i to the literature values, as a/R_s and i are strongly correlated when they are both free parameters. In a future work, we plan to provide analysis for both parameters, but the scope of this work is to provide a set of parameters that will produce a reliable duration. Between a/R_s and i, we decided to leave a/R_s free, as it is more flexible for the determination of the duration (only small changes are required, and there is no upper limit, as with i).

Finally, we need to note here that the modeling of the Kepler light curves did not produce Gaussian residuals. This was most probably due to the fixed LDCs used. However, we decided not
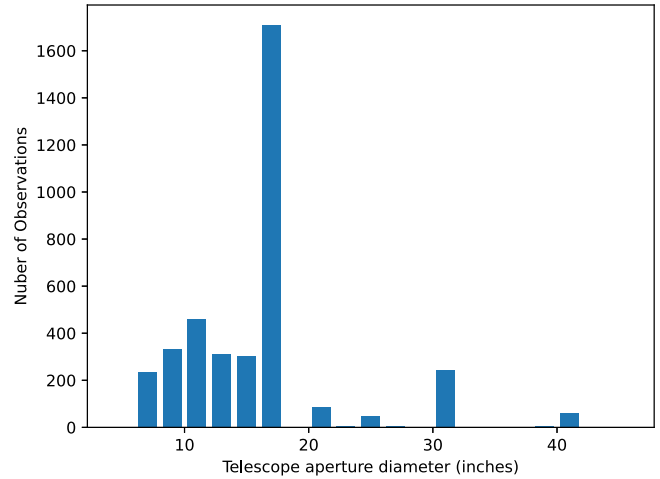
Table 1
Summary of the Observations Used in This Work

	ExoClock	ETD	Kepler	K2	TESS	Literature	Total
Data Points	2911	184	5763	371	6499	2442	18170
Years	2007–2021	2001–2021	2009–2013	2014–2018	2018–2021	2004–2020	2001–2021
Planets	302	40	21	49	371	340	450
Median $\sigma_{T_{mid}}$	1.3 minutes	1.7 minutes	0.5 minutes	0.6 minutes	1.1 minutes	0.6 minutes	0.8 minutes
Median Coverage	20%	18%	29%	17%	20%	17%	50%

Note. As coverage, we define the percentage of years (since the first observation in the database) for which at least one observation exists.
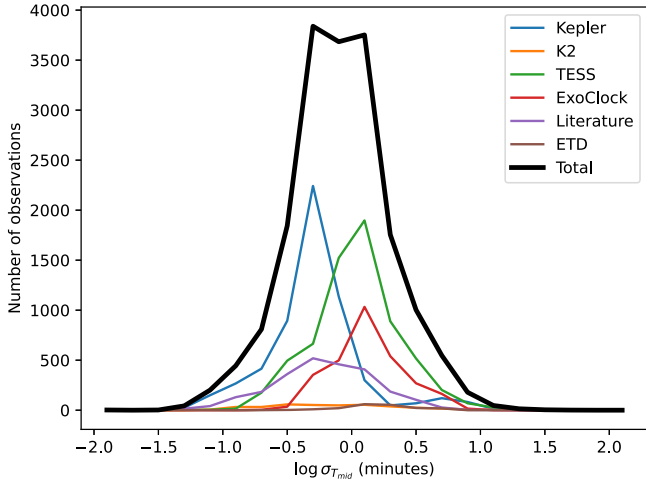
Figure 1. The distribution of the transit midtime uncertainties among the different sources.

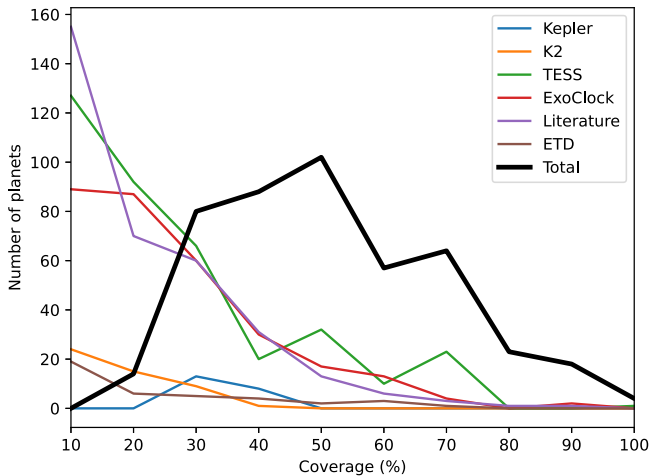**Figure 2.** The distribution of the coverage among the different sources. As coverage, we define the percentage of years (since the first observation in the database) for which at least one observation exists.

Figure 3. The number of observations received from the ExoClock network, as a function of the telescope size.

to allow the LDCs to vary, in order to maintain a homogeneous analysis pattern for all observations.

2.3. ETD

The ETD (Poddaný et al. 2010), which has been run by the Czech Astronomical Society since 2009, is currently the largest database of transit follow-up observations, with more than 10,000 transit light curves for more than 350 exoplanetary systems. The collaboration between ExoClock and ETD started

in 2020, and it is described in Kokori et al. (2022). In this study, we included 184 observations for 40 planets provided by the ETD network. In order to maintain homogeneity and reliability in our analysis, the ETD observations were analyzed and evaluated through the ExoClock website, using the same methodology and validation criteria as for the ExoClock network data. The collaboration with ETD is critical to avoiding duplications and wasting resources. We aim to continue our collaboration and gradually integrate more data from ETD in future publications. Such data can increase the coverage of certain planets in the period before ExoClock observations.

2.4. Midtime Points from the Literature

As we did not reanalyze the original light curves, we could not apply the same criteria as for the ExoClock, ETD, and space light curves. From the available data, we excluded midtransit time values that referred only to ephemerides, rather than to individual transits (with the exception of the discovery papers). We also excluded midtransit time values with uncertainties greater than 5 minutes, and midtransit time values that originated from Kepler, K2, TESS, and ETD, to avoid duplications.

3. Results

3.1. Ephemerides

Here we present the updated ephemerides for 450 of the 570 planets that are currently on the ExoClock target list. To calculate the new ephemerides, we used all the available data from all the sources described in the previous section. First, we
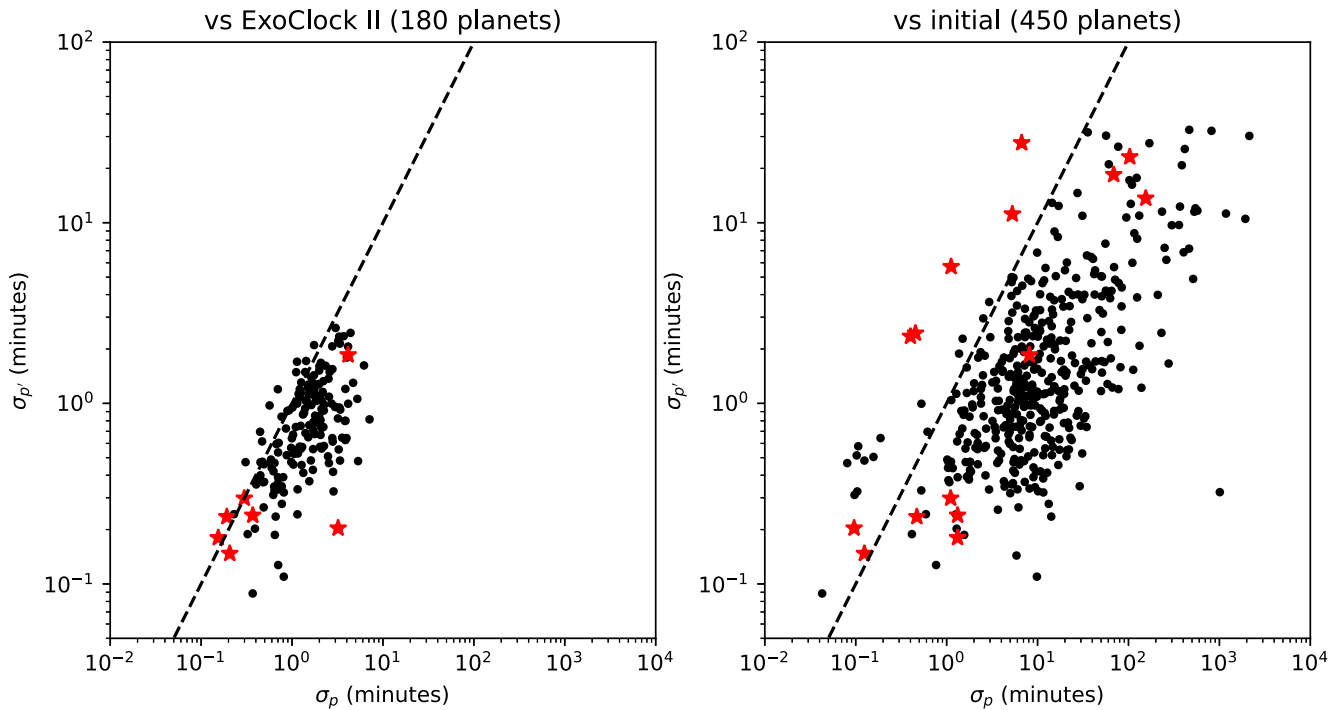
Figure 4. Comparisons of the 2029 prediction uncertainties between this work and ExoClock II (left) and the ephemerides used at the beginning of the project (right). The red stars indicate the planets for which TTV signals have been found. In both panels, the dashed lines show the $\sigma_{p'} = \sigma_p$ lines.

calculated an updated zero-epoch point, as the weighted average of the available epochs. We then fitted a line on the epoch versus midtransit time data, using the emcee package (Foreman-Mackey et al. 2013). After the first fit, we scaled up the uncertainties by the rms of the normalized residuals, to account for excess noise, and performed the fit again. Table 7 provides all the new ephemerides and references to the literature values that were used.

Figure 4 shows the uncertainties in the 2029 predictions, before and after the updates presented in this work (σ_p and $\sigma_{p'}$, respectively), while Table 2 lists five categories of the status of the ephemerides. "Significantly improved" refers to those ephemerides that were giving 2029 predictions with uncertainties greater than the target uncertainty of one-twelfth of the transit duration, D, ($\sigma_p > D/12$), as described in Kokori et al. (2021). The term "drifting" refers to the ephemerides that were giving 2029 predictions that were drifting more than the target uncertainty ($|p - p'| > D/12$). Of the remaining ephemerides, the term "improved" refers to those ephemerides for which the 2029 prediction uncertainties have been improved by more than 1 minute ($\sigma_{p'} < \sigma_p - 1$), while "no change" refers to those ephemerides for which the 2029 prediction uncertainties have not changed by more than 1 minute ($|\sigma_{p'} - \sigma_p| < 1$). Finally, in this work, we introduce the "TTVs" flag, which refers to ephemerides that deviate from linear behavior.

3.2. Deviations from Linear Ephemerides

For all the planets, we calculated the generalized Lomb–Scargle periodogram on the linear ephemeris residuals, to identify deviations from the linear ephemeris. We concluded that periodograms are more reliable in detecting such deviations, since other diagnostics—such as the reduced chi square, the autocorrelation, or Gaussianity tests on the residuals—are strongly affected by red noise, discontinuity, and low numbers of data, respectively. This is due to the sparsity of the

Table 2
Categories of Ephemerides in Comparison with the Previous ExoClock Publication and the Values at the Beginning of the Project

	Versus ExoClock II (180 planets)	Versus Initial (450 planets)
Significantly Improved	0.0%	31.8%
Drifting	1.1%	12.9%
Improved	31.7%	41.1%
No Change	63.3%	10.0%
TTVs	3.9%	4.2%

data and to red noise in the timing measurements. The TTVs flag has been given to those planets with periodograms that had peaks with a False Alarm Probability (FAP) lower than 0.13%. We estimated the FAP for each planet as follows. First, we produced periodograms (Pa) for 100,000 series of white noise with the same sampling, then we produced periodograms (Pb) for 100,000 series where we varied the midtime data within their uncertainties. Finally, the FAP for each period was defined as the percentage of Pb that had greater power than the 99.87% (3σ) upper limit of the Pa periodograms. The detected periodicities were categorized as short-term or long-term, based on the time span of all the available data. The long-term periodicities are those that are close to or longer than the total time span of the data used.

4. Data Release C

The third data release of the ExoClock project includes two data products: the Catalog of Observations (ExoClock, ETD, and space observations) and the catalog of ExoClock ephemerides. All data products and their descriptions can be found through the Open Science Framework repository: 10.17605/OSF.IO/P298N.

Table 3
Distribution Characteristics of the Ephemerid Drift S/Ns

	Versus ExoClock II (180 planets)	Versus Initial (450 planets)	Normal Distribution
STD	1.50	37.00	1.00
Kurtosis	1.75	262.02	0.00
68th Percentile	1.28	1.79	0.995
95th Percentile	3.42	5.23	1.959
99th Percentile	5.13	25.96	2.576

Note. Those between this work and the previous ExoClock publication are shown in the first column and those between this work and the ephemerides at the beginning of the project are shown in the second column. Planets with TTVs have been excluded. In the ideal case of a normal distribution, these parameters should be close to the values in the third column.

4.1. Catalog of Observations

The Catalog of Observations contains all the light curves and literature midtime points that are summarized in Table 1. In the online repository, each light curve is accompanied by:

1. metadata regarding the planet, the source, the observation, the instrument, and the data format;
2. the pre-detrended light curve, filtered for outliers and converted to BJD_{TDB} and flux formats, with scaled uncertainties;
3. the fitting results, including the detrending method used and its parameters;
4. the detrended light curve, enhanced with the detrending model, the transit model, and the residuals; and
5. the fitting diagnostics on the residuals.

4.2. Catalog of ExoClock Ephemerides

The new catalog of ExoClock ephemerides contains the updated ephemerides for the 450 planets studied in this work (see also Table 7), accompanied by metadata regarding the planet and flags concerning the detection of TTVs.

5. Discussion

5.1. Follow-up Efficiency

From the comparison between the ephemerides in ExoClock II and this work, we conclude that the biases in the ephemerides produced by ExoClock are decreasing. This is based on the fact that the number of significantly improved or drifting ephemerides is very small (Table 2, first column). Moreover, the drifts found between ExoClock II and this study are closer to a normal distribution, as seen in the first column of Table 3. These values highlight the reliability of the produced ephemerides and support the view that the ExoClock project is working effectively toward achieving its goal.

5.2. Need for Continuous Monitoring

As indicated in Table 2 (second column), approximately 45% of the initial ephemerides have large uncertainties or drifts (the "significantly improved" or "drifting" categories). This is similar to the percentage reported in ExoClock II, indicating that a significant number of the ephemerides derived in the discovery papers (including the TESS discoveries) need to be corrected to be appropriate for the efficient planning of Ariel.

Moreover, as shown in Tables 2 and 3 (first columns), although the ExoClock ephemerides have reduced biases, they are not completely bias-free. Our sample of 180 planets in ExoClock II is not large enough to determine the coverage needed to produce completely bias-free ephemerides, but we can see that coverages of 60% or more are necessary to avoid unexpected drifts larger than 5 minutes in our 2029 predictions. Finally, as discussed in the previous section, some planets show long-term trends. Such trends can only be identified when the coverage is close to 100%. For all these reasons, follow-up observations are important, and continuous monitoring is essential.

The most important factor for increasing the coverage involves continuing to integrate all the available resources and prioritizing the follow-up observations accordingly.

5.3. Follow-up Capabilities

From the large number of observations so far obtained by the ExoClock network, and with the TESS light curves analyzed in this study, we can more precisely estimate the capabilities of these resources and plan efficiently for the future. In Appendices C and D, we provide detailed calculations of the S/N calibrations that we performed on both the ExoClock and TESS data to produce the equations below.

The minimum telescope aperture diameter (in inches) necessary to observe a planet with the ExoClock network (D_{min}) is given by:

$$D_{min} = \frac{0.135 + 10^{-2.99+0.2R}}{5.1d} \sqrt{\frac{7200 + t_{14}}{900\pi t_{14}}}, \qquad (1)$$

where R is the magnitude of the host star in the R Cousins filter, d is the relative transit depth, and t_{14} is the total duration of the transit in seconds.

By placing an upper limit of a 40 inch aperture on the ExoClock network, we estimate that we can follow up 88% of the currently known Ariel candidates. Figure 5 shows the distribution of available planets per magnitude and telescope size, where we can see that even with telescopes up to 16 inches, 75% of the targets can be observed.

For the TESS observations, the transit S/N that can be achieved is given as:

$$S/N_{transit}^{TESS} = \frac{0.65d\sqrt{t_{14}/90} \times 10^3}{0.135 + 10^{-2.43+0.2G_{RP}+0.0039G_{RP}^2}}, \qquad (2)$$

where G_{RP} is the magnitude of the host star in the GAIA Rp filter, d is the relative transit depth, and t_{14} is the total duration of the transit in seconds.

By placing a lower limit of $S/N = 3$ on the TESS observations, we estimate that we can follow up 90% of the currently known Ariel candidates. By combining the two resources, we can reach up to 95% of the candidates. For the remaining targets, we plan to use other facilities, such as CHEOPS (Benz et al. 2021) and Twinkle (Edwards et al. 2019), or combined multiple ground-based observations.

With this calibration of our ground-based network and TESS, we are in a good position to achieve the most productive use of both resources. We can avoid wasting valuable space telescope time—at facilities like CHEOPS or Twinkle—on following up targets that can be efficiently monitored from the ground, while at the same time we can readily identify the most difficult targets that will definitely require observations from space.
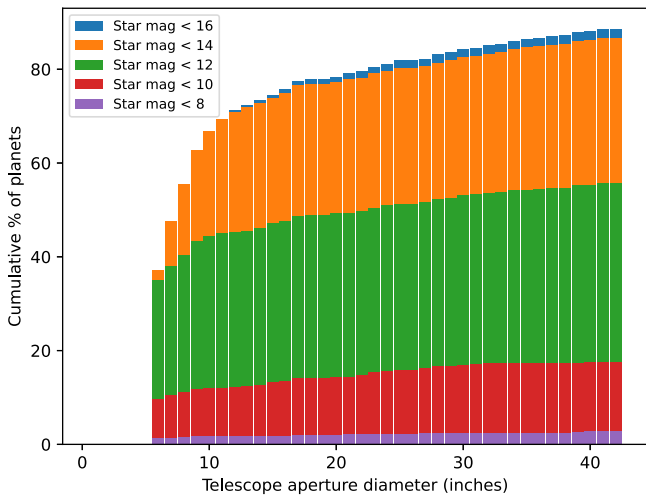
Figure 5. The distribution of the available planets per magnitude and telescope aperture diameter.

5.4. TTV Signals

Our analysis reveals 19 planets with statistically significant signals in the residuals of their linear ephemeris fit (Table 4). Eleven of these planets—namely, HD106315c, HD108236b, K2-19b, KOI-94 c, KOI-94d, KOI-94e, Kepler-18d, Kepler-396 c, TOI-216.01, TOI-216.02, and TOI-431b—have one or more additional transiting planets in their planetary systems. Hence, it is no surprise that they show TTVs, due to the interactions with other planets in the systems. It is beyond the scope of this work to study the dynamics of these systems, but we are flagging them in the ExoClock project, so that observers will continue to monitor them, to help with future dynamic analysis. For the remaining eight planets, we investigate the different scenarios below. In addition to the periodograms for the residuals of the linear ephemeris fit, we also apply a quadratic ephemeris fit and study the periodograms of these residuals, too (Figure 6).

HAT-P-7b. An attempt to detect a third body in the system, either an additional planet or companion star, has been made using radial velocity data over a 2 yr span of observations. Analysis from radial velocity data has suggested the presence of a companion star, but the results were controversial (Winn et al. 2009a). A possible detection of another Saturn-sized planet in the system has also been suggested by Ballard et al. (2011), but the significance for the detection was low.

Our results show a significant signal for a long-term periodicity of approximately 2243 epochs, or 4950 days, which is close to, but still lower than, the total time span of the data used. Moreover, we found a significant quadratic term of $6.95 \pm 0.52 \times 10^{-10}$, and after removing it, the long-term periodicity disappeared. The above results suggest that the signal is not yet periodic, but that it has a positive curvature at the moment. This means that the planet is not decaying, leaving the possibilities of a third-body or orbital precession open.

KOI-12b. Masuda (2017) has suggested the presence of a second planet, based on the same data (Kepler).

Our results indicate a few significant short-term periodicities, between approximately 20 and 200 epochs. Moreover, we found a nonsignificant quadratic term of $-2.49 \pm 0.97 \times 10^{-7}$, and after removing it, the signals from the short-term periodicities remain strong. From the above, we cannot reach a clear conclusion, because the multiple short-term periodicities

Table 4
Planets Identified with Deviations from a Linear Ephemeris

Planet	Short-term	Long-term	Data Points
HAT-P-7b	No	Yes (2243.1 E)	652
HD106315c	Yes (multiple)	Yes (multiple)	8
HD108236b	Yes (multiple)	Yes (multiple)	9
K2-19b	Yes (multiple)	Yes (multiple)	16
KOI-12b	Yes (71.3 E)	No	73
KOI-94 c	Yes (15.0 E)	No	54
KOI-94d	Yes (13.0 E)	No	25
KOI-94e	Yes (7.4 E)	Yes (38.0 E)	8
Kepler-18d	Yes (17.6 E)	No	82
Kepler-396 c	Yes (multiple)	Yes (44.8 E)	14
Qatar-1b	Yes (327.0 E)	No	265
TOI-216.01	Yes (14.4 E)	Yes (50.2 E)	15
TOI-216.02	Yes (35.1 E)	Yes (111.0 E)	26
TOI-431b	Yes (multiple)	No	21
TrES-3b	Yes (multiple)	Yes (4138.1 E)	231
WASP-4b	Yes (multiple)	No	111
WASP-12b	Yes (multiple)	Yes (5173.5 E)	308
WASP-19b	Yes (multiple)	Yes (4465.2 E)	119
WASP-56b	Yes (multiple)	No	25

Note. "Long-term" refers to variations with periodicities that are close to or longer than the total time span of the data used. In brackets, we indicate the peak periodicity in epochs (E), while the "multiple" label refers to cases where more than one periodicity is significant.

could be caused by stellar activity. More data are required to narrow down the possible scenarios.

Qatar-1b. The first TTV analysis for the Qatar-1 system was carried out by von Essen et al. (2013). The authors claimed that there are possible TTVs on Qatar-1b, either due to a weak perturbator in resonance with Qatar-1b or to a massive body similar to a brown dwarf. The follow-up TTV studies by Maciejewski et al. (2015) and Collins et al. (2017) did not detect any signals of an additional planet in the system, while Püsküllü et al. (2017) found weak evidence of TTVs. It was also reported by Covino et al. (2013) that the orbital period of the planet in the Qatar-1 system is much shorter than the rotation period of the star, so the tides produce the decay of the orbit. The most recent analysis, by Su et al. (2021), concluded that no TTV frequencies could be identified.

Our data cover a time span that is double compared to previous studies, and our results indicate a statistically significant short-term periodicity, at approximately 327 epochs, or 465 days. Moreover, we found a nonsignificant quadratic term of $1.13 \pm 0.72 \times 10^{-10}$, and after removing it, the short-term periodicity was not affected. The above results suggest that the signal is periodic, and in combination with the low eccentricity of the planet, this means that a perturbator scenario is favored.

TrES-3b. So far, studies have concluded that there is no evidence of TTVs for Tres-3b (Kundurthy et al. 2013; Püsküllü et al. 2017). Christiansen et al. (2011) mentioned that a long-term variability in the light curve of Tres-3b may be due to star spots. Additionally, the lack of periodic TTVs implies that another planetary body is absent, according to the study by Mannaday et al. (2020). Finally, precession can be ruled out, due to the very low value of eccentricity, whereas the possibility of slow orbital decay cannot (Mannaday et al. 2020).

Our results show multiple significant short-term periodicities, as well as one prominent long-term periodicity, at
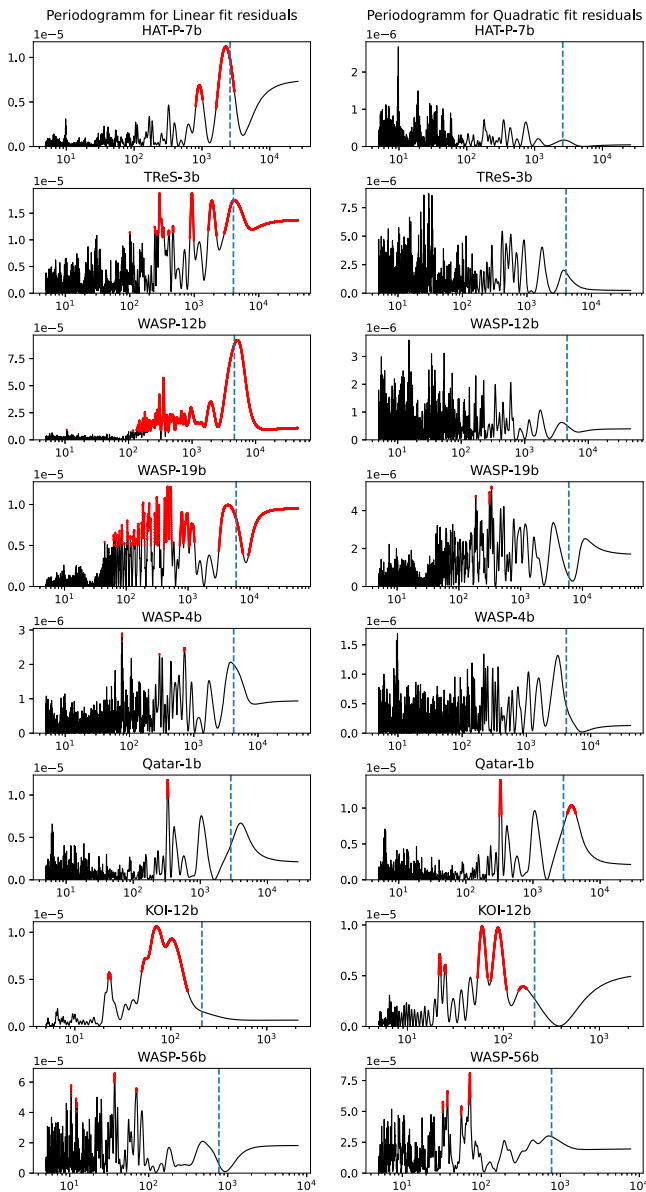
Figure 6. Periodograms for the fitting residuals (linear and quadratic) for the eight planets with TTVs, but without transiting companions. The red parts indicate periods with FAPs lower than 0.13%, and the vertical lines indicate the total time span of the data used.

Southworth et al. (2019) stated that the TTV variations have a smaller magnitude than had previously been detected, and orbital decay or a third body in the system are both problematic hypotheses. More recently, it has been suggested that the line-of-sight acceleration is the most probable reason for the TTVs (Bouma et al. 2020a). Finally, Baluev et al. (2020) have confirmed the existence of quadratic TTVs in the system, without making a new proposal for the origins.

We found a significant quadratic term of $-1.29 \pm 0.22 \times 10^{-10}$, although a long-term periodicity is not shown. In addition, the short-term periodicities disappeared after removing the quadratic term. The above results suggest that timing data alone do not provide any indications toward an interpretation. To further investigate this behavior, other types of data or a longer time span will be required.

WASP-12b. WASP-12b is one of the very first exoplanets to have a verified nonlinear ephemeris, due to orbital decay (Maciejewski et al. 2016a). It is also possible that the planet is undergoing apsidal precession, as the data indicate that its orbit might be slightly eccentric (Yee et al. 2020). According to Weinberg et al. (2017), the measured rate of orbital decay would only be reasonable if WASP-12b were a subgiant that experiences evolutionary changes causing a rapid orbital decay to the planet. The TTVs that were reported later support this idea, but additional data are needed to confirm this (Maciejewski et al. 2018). More recent data show that the orbit is decaying, with occultation times occurring about 4 minutes earlier after 10 yr (Yee et al. 2020). WASP-12b is likely to be engulfed by its host star several million years from now (Yee et al. 2020).

Our results show multiple significant short-term periodicities, as well as one prominent long-term periodicity, at approximately 5173 epochs, or 5650 days. The long-term signal is longer than the total time span of the data. Moreover, we found a significant quadratic term of $-5.24 \pm 0.17 \times 10^{-10}$, and after removing it, both the short-term and the long-term periodicities disappeared. The above suggest that the signal is not yet periodic, with a negative curvature at the moment. In combination with the low eccentricity of the planet, this means that the orbital decay scenario is favored.

WASP-19b. A nonlinear ephemeris has previously been reported (Mancini et al. 2013a; Espinoza et al. 2019a). Petrucci et al. (2020) conducted the first empirical study of orbital decay, using 74 complete transit light curves covering a 10 yr period. Their results did not show any signs of orbital decay or periodic variations that could indicate the existence of additional bodies.

Our results show multiple significant short-term periodicities, as well as one prominent long-term periodicity, at approximately 4465 epochs, or 3520 days. The long-term signal is longer than the total time span of the data. Moreover, we found a significant quadratic term of $-0.87 \pm 0.13 \times 10^{-10}$, and after removing it, the majority of the short-term periodicities and the long-term periodicity disappeared. The above results suggest that the signal is not yet periodic, with a negative curvature at the moment. In combination with the low eccentricity of the planet, this means that the orbital decay scenario is favored.

WASP-56b. A search for TTVs in the WASP-56 system was recently carried out in a study by Wang et al. (2021), but statistically significant trends (at levels of 3σ) were not found.

approximately 4138 epochs, or 5400 days. The long-term signal is longer than the total time span of the data. Moreover, we found a significant quadratic term of $-1.68 \pm 0.34 \times 10^{-10}$, and after removing it, both the short-term and the long-term periodicities disappeared. The above results suggest that the signal is not yet periodic, with a negative curvature at the moment. In combination with the low eccentricity of the planet, this means that the orbital decay scenario is favored.

WASP-4b. From the initial observations of WASP-4b, it was assumed that TTVs might be present (Wilson et al. 2008). However, a follow-up study by Petrucci et al. (2013) concluded that the system does not show significant TTV trends. Baluev et al. (2015) proposed that TTVs probably exist in the WASP-4 system, with a magnitude of 10–20 s and an unknown nature. Additionally, a significant quadratic term in the $O - C$ diagram was reported in the study by Bouma et al. (2019), with the most probable explanation being the planet's orbital decay.

Our results indicate a few significant short-term periodicities, between approximately 10 and 100 epochs. Moreover, we found a nonsignificant quadratic term of $-2.09 \pm 0.82 \times 10^{-8}$, and after removing it, the signals from the short-term periodicities above 50 epochs became stronger. From the above, we cannot reach a clear conclusion, as the multiple short-term periodicities could be caused by stellar activity. With more data in the future, we will be able to narrow down the possible scenarios.

6. Conclusion

In this study, we present a homogeneous analysis of the ephemerides of 450 planets that are currently known candidates for the Ariel mission. The ephemerides resulted from the integration of data from the ExoClock network, midtime points from the literature, data from the ETD, and data from space telescopes (the Kepler, K2, and TESS missions).

The results show that the ephemerides produced by the ExoClock project are less biased, and hence more reliable for future predictions, compared to the initial ephemerides reported in the literature, although continuous monitoring is also necessary, as 40% of the initial ephemerides for new planets require refinement in order for the goals of the project to be achieved. The integrated approach of the project allows us to monitor up to 95% of the Ariel candidates, while identifying missing data and prioritizing observations for specific targets. The ExoClock network effectively facilitates the effort of obtaining such high-priority observations, while observations of more difficult targets can be requested from other space telescopes, like CHEOPS and Twinkle.

The ExoClock project, after 3 yr of continuous operation, development, and interaction, between several communities of academics and nonacademics, has became a sustainable platform for providing reliable ephemerides for the Ariel candidate planets. The dynamic evolution of the project is now being achieved; new ideas can be implemented, with a focus on more specific targets of special interest (such as the ones flagged for TTVs). We plan to continue operating ExoClock within the Open Science Framework, with the twofold objective of monitoring the ephemerides and fostering the democratization of science.

Appendix A
Supplementary Information

Here, we append extra information regarding the data sources and results. More specifically, Table 5 includes a list of the amateur private observatories contributing to this work, which is followed by a description of the ASTEP telescope. Table 6 includes a list of the parameters used in the analysis of the individual light curves and their respective references, where the asterisks indicate orbital parameters (a/R_s or i) that were adjusted, based on TESS data, to match the observed durations. Table 7 provides all the new ephemerides and references to the literature values used.

ASTEP (Antarctic Search for Transiting ExoPlanets) is a 40 cm telescope that is installed at the Concordia Station, Dome

Table 5
Amateur Private Observatories Contributing to This Work

Observer(s)	Observatory
Richard Abraham	The Green Observatory, UK
Vikrant Kumar Agnihotri	Cepheid Observatory, Rawatbhata, India
Raniero Albanesi	157 Frasso Sabino
Enrique Arce-Mansego	Vallbona Observatory, Valencia, Spain
Matthieu Bachschmidt	Gonachon, France
Giorgio Baj	Observatory M57, Saltrio, Italy
David Bennett	Rickford Observatory
Paul Benni	Acton Sky Portal, Acton, MA, USA
Leon Bewersdorff	Observatory Kipshoven, Germany
Patrick Brandebourg	Observatoire du Guernet, Bretagne, France
Luboš Brát	ALTAN Observatory
Stephen M. Brincat	Flarestar Observatory (MPC: 171), San Gwann, Malta
Sebastien Brouillard	Observatoire de Saint-Véran—Paul Felenbok, France
Mauro Caló	Cavallino Observatory, Tuscany, Italy
Fran Campos	Puig d'Agulles Observatory, Vallirana, Spain
Alfonso Carreno	Observatorio Zonalunar (MPC: J08)
Roland Casali	Alto2000 Observatory, Italy
Giovanni Battista Casalnuovo	Filzi School Observatory, Laives, Italy
Jean-François Coliac	OABAC—Observatoire pour l'Astronomie des Binaires et l'Astronomie Collaborative
Giuseppe Conzo	Explorer Orbanic Observatory, Croatia
Mercedes Correa	Sirius B, Spain
Gilles Coulon	Sadr Chili
Martin Valentine Crow	Burnham Observatory, Burnham on Crouch, UK
Ivan Anthony Curtis	ICO, Adelaide, South Australia
Dominique Daniel	LMJ-OBS, Carpentras, France
Bruno Dauchet	Saint Véran Observatory, France
Simon Dawes	William James II Observatory, Bexleyheath, UK
Marc Deldem	Les Barres Observatory, Lamanon, France
Dimitrios Deligeorgopoulos	Artemis Observatory, Evrytania, Greece
Nicolas Esseiva	Observatoire de la Perdrix
Rafael González Farfán	Uraniborg Observatory, Écija, Sevilla, Spain
Salomon Louw Ferreira	PESCOPE
Davide Gabellini	Hypatia Observatory, Italy
Trevor Gainey	Kismet Observatory, Berkshire, UK
Josep Gaitan	MAS MOIXA (MPC: C86)
Alberto García-Sánchez	Observatorio Rio Cofio, Robledo de Chavela, Spain
Joe Garlitz	Elgin Observatory GJP
Christophe Gillier	CALA Observatory, France
Juanjo Gonzales	Cielo Profundo J01
Ferran Grau Horta	Observatori de Ca l'Ou, Sant Martí Sesgueioles, Spain
Tim Haymes	Tim Haymes Southside Observatory, north Oxfordshire, UK
Ken Hose	Quarryview Observatory / HQR
Francois Hurter	Albireo Observatory, Switzerland
Jens Jacobsen	Egeskov Observatory
Kevin Johnson	Holbrook Observatory, East Sussex, UK
Adrian Jones	I64, Maidenhead, UK
Aziz Ettahar Kaeouach	High Atlas Observatory, Oukaimeden, Morocco
Bernd Koch	Soerth B72, Germany
Didier Laloum	Observatoire Privé du Mont, 40280 Saint-Pierre-du-Mont, France
Massimiliano Mannucci	Osservatorio Astronomico Margherita Hack, Firenze, Italy
Antonio Marino	Telescopio Remoto Colacevich, c/o Osservatorio Astronomico di Capodimonte di Napoli

Table 5
(Continued)

Observer(s)	Observatory
Giuseppe Marino	Osservatorio GAC "Luigi Sturzo," Italy
Jean-Claude Mario	Observatoire de la Cabergue
Fernando Antonio Martínez-Bravo	Chile
Paolo Arcangelo Matassa	P.M.P.H.R. Deep Sky (MPC: K81), Atina (FR), Italy
Philip Michel	Verulamium Private Observatory, St Albans, UK
Mike Miller	Georgetown Observatory, Georgetown, TX, USA
David Molina	Anunaki Observatory, Madrid
Thomas Mollier	Tomastro Observatory, France
Mario Morales-Aimar	Observatorio de Sencelles, Spain
Fabio Mortari	Hypatia Observatory, Italy
Gabriel Murawski	MGAB Observatory
Jean-Louis Naudin	Gatinais French Observatory (GFO)
Ramon Naves	Montcabrer (MPC: 213)
David Néel	Le Cat Etoiles, France
Alphonso Noschese	Elianto Observatory
Yenal Öğmen	Green Island Observatory IAU B34
Osamu Ohshima	Ohshima Tamashima Observatory
Zlatko Orbanic	Explorer Orbanic Observatory, Croatia
Christian Pantacchini	Observatoire de Benayes, France
Nikolaos I. Paschalis	Nunki Observatory, Skiathos, Greece
Valère Perroud	Observatoire de Duines, France
Mark Phillips	Forthimage Observatory, Edinburgh, Scotland
Jean-Bernard Pioppa	La Roque Esclapon, France
Jean Plazas	Ribot Observatory
Jeff Purcell	Omaha, NE, United States
Manfred Raetz	Privat Observatory Herges-Hallenberg, Germany
François Regembal	HRT Observatory, Spain
Jose Angel Carrion Rodrigo	OAO Observatorio Aras de los Olmos
Lionel Rousselot	Vierzon Observatory, France
Xesco Rubia	Stupa Observatori, Centelles, Catalonia, Spain
Nello Ruocco	Osservatorio Astronomico Nastro Verde, Sorrento, Italy
Mark Salisbury	POST, UK
Fabio Salvaggio	WBRO (K49), Italy
John Savage	Z42, Rushay Farm Observatory, Dorset, UK
Danilo Sedita	Osservatorio Sedita Castrofilippo, Italy
Alvaro Fornas Silva	Centro Astronómico Alto Turia (CAAT)
Nick Sioulas	NOAK Observatory L02, Greece
Vojtěch Školník	Broumov NM Observatory, Czech Republic
Miroslav Smolka	Motešice Observatory, SK
Dimitris Stouraitis	Galileo Observatory, Greece
Thiam-Guan Tan	Perth Exoplanet Survey Telescope, Australia
Geoffrey Thurston	I67, Hartley Wintney, UK
Fernando Pablo Tifner	MPC: I32
Andrea Tomacelli	Telescopio Remoto Colacevich UAN, c/o Osservatorio Astronomico di Capodimonte di Napoli
Alberto Tomatis	Alto Observatory, Italy
Pierre Valeau	Observatoire de l'Aiguillon sur Mer, France
Jean-Pascal Vignes	Deep Sky Chile, Chile
Alberto Villa	Oss Astr G. Galilei, Libbiano (MPC: B33)
Antoni Vives Sureda	Anunnaki Observatory
Kuldip Vora	Cepheid Observatory, Rawatbhata, India
Martin Vrašťák	Žilina-Mojš, LSO, Slovakia
David E. Wright	Yorick Observatory, Hampshire, UK
Roberto Zambelli	Roberto Zambelli Observatory
Martin Zíbar	Chlumčany

Table 6
Parameters Used in the Analysis of the Individual Light Curves and the Respective References, where the Asterisks Indicate Orbital Parameters (a/R_s or i) That Were Adjusted, Based on TESS Data, to Match the Observed Durations

| Planet | Ephemeris (Before This Update) | Stellar Parameters | Transit Parameters | | |
	T_0 (BJD$_{TDB}$) P (days)	T_{eff} (K) $\log(g)$ (cgs)	R_p/R_s e	a/R_s ω (deg)	i (deg)
55Cnce	$2{,}455{,}962.0727^{+0.0007}_{-0.0007}$ $0.736545^{+9e-07}_{-9e-07}$ Sulis et al. (2019)	$5234.0^{+30.0}_{-30.0}$ $4.45^{+0.08}_{-0.08}$ Demory et al. (2011)	$0.0187^{+0.0004}_{-0.0004}$ ... Sulis et al. (2019)	$3.47^{+0.07}_{-0.07}$ ...	$83.6^{+0.6}_{-0.6}$
CoRoT-11b	$2{,}454{,}597.6797^{+0.0003}_{-0.0003}$ $2.99433^{+1.1e-05}_{-1.1e-05}$ Gandolfi et al. (2010)	$6440.0^{+120.0}_{-120.0}$ $4.22^{+0.23}_{-0.23}$ Gandolfi et al. (2010)	$0.107^{+0.0005}_{-0.0005}$ ... Gandolfi et al. (2010)	$6.89^{+0.08}_{-0.08}$ ...	$83.17^{+0.15}_{-0.15}$
CoRoT-19b	$2{,}455{,}257.4418^{+0.0006}_{-0.0006}$ $3.89713^{+2e-05}_{-2e-05}$ Guenther et al. (2012)	$6090.0^{+70.0}_{-70.0}$ $4.07^{+0.03}_{-0.03}$ Guenther et al. (2012)	$0.0786^{+0.0004}_{-0.0004}$ ... Guenther et al. (2012)	$6.7^{+0.1}_{-0.1}$ ...	$88.0^{+0.7}_{-0.7}$
CoRoT-2b	$2{,}457{,}347.04314^{+0.00012}_{-0.00012}$ $1.742997^{+1.1e-07}_{-1.1e-07}$ Kokori et al. (2022)	$5696.0^{+70.0}_{-70.0}$ $4.42^{+0.12}_{-0.12}$ Chavero et al. (2010)	$0.1667^{+0.0006}_{-0.0006}$ ... Alonso et al. (2008b)	$6.7^{+0.03}_{-0.03}$ ...	$87.84^{+0.1}_{-0.1}$
EPIC211945201b	$2{,}458{,}113.9399^{+0.0004}_{-0.0004}$ $19.49213^{+1e-05}_{-1e-05}$ Chakraborty et al. (2018)	$6025.0^{+100.0}_{-100.0}$ $4.25^{+0.1}_{-0.1}$ Chakraborty et al. (2018)	$0.0407^{+0.0003}_{-0.0003}$ ... Chakraborty et al. (2018)	$23.1^{+0.5}_{-0.5}$ ...	$87.9^{+0.06}_{-0.06}$

Note. Table 6 is published in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content. A complete listing of all references used is provided in the table notes.

References: Alonso et al. (2008b), Anderson et al. (2008), Burke et al. (2008), Johns-Krull et al. (2008), McCullough et al. (2008), Noyes et al. (2008), Pál et al. (2008), Pollacco et al. (2008), Torres et al. (2008), Wilson et al. (2008), Bakos et al. (2009), Barbieri et al. (2009), Carter et al. (2009), Charbonneau et al. (2009), Christian et al. (2009), Gillon et al. (2009a), Hartman et al. (2009), Hebb et al. (2009), Hellier et al. (2009a), Hellier et al. (2009b), Johnson et al. (2009b), Joshi et al. (2009), Latham et al. (2009), Lister et al. (2009), Shporer et al. (2009b), Skillen et al. (2009), West et al. (2009a), West et al. (2009b), Anderson et al. (2010), Bakos et al. (2010), Bouchy et al. (2010), Buchhave et al. (2010), Chavero et al. (2010), Dunham et al. (2010), Gandolfi et al. (2010), Hebb et al. (2010), Hellier et al. (2010), Kipping et al. (2010), Koch et al. (2010b), Kovács et al. (2010), Latham et al. (2010), Maxted et al. (2010a), Maxted et al. (2010b), Narita et al. (2010), Pál et al. (2010), Queloz et al. (2010), Smalley et al. (2010), Southworth et al. (2010), Street et al. (2010), Torres et al. (2010), Alsubai et al. (2011), Anderson et al. (2011a), Bakos et al. (2011), Barros et al. (2011), Beky et al. (2011), Borucki et al. (2011), Buchhave et al. (2011), Chan et al. (2011), Christiansen et al. (2011), Cochran et al. (2011), Demory et al. (2011), Enoch et al. (2011a), Enoch et al. (2011b), Faedi et al. (2011), Fortney et al. (2011), Fukui et al. (2011), Gillon et al. (2011), Hartman et al. (2011a), Hartman et al. (2011b), Hartman et al. (2011c), Hellier et al. (2011), Howard et al. (2011), Johnson et al. (2011), Kipping et al. (2011), Knutson et al. (2011), Mandushev et al. (2011), Maxted et al. (2011), Nutzman et al. (2011), Santerne et al. (2011), Simpson et al. (2011), Smalley et al. (2011), Southworth et al. (2011), Triaud et al. (2011), Anderson et al. (2012), Bakos et al. (2012), Barros et al. (2012), Beatty et al. (2012), Berta et al. (2012), Bonfils et al. (2012), Bryan et al. (2012), Guenther et al. (2012), Hartman et al. (2012), Hellier et al. (2012), Howard et al. (2012), Lendl et al. (2012), Quinn et al. (2012), Sato et al. (2012), Siverd et al. (2012), Smalley et al. (2012), Smith et al. (2012), Southworth et al. (2012c), Bayliss et al. (2013), Boisse et al. (2013), Faedi et al. (2013), Faigler et al. (2013), Gibson et al. (2013a), Gillon et al. (2013), Gómez Maqueo Chew et al. (2013), Hébrard et al. (2013), Mancini et al. (2013b), Masuda et al. (2013), Maxted et al. (2013a), Mohler-Fischer et al. (2013), Nascimbeni et al. (2013a), Penev et al. (2013), Pepper et al. (2013), Smith et al. (2013), Southworth et al. (2013), Triaud et al. (2013), Weiss et al. (2013), Anderson et al. (2014a), Anderson et al. (2014b), Biddle et al. (2014), Bieryla et al. (2014), Brown et al. (2014), Collins et al. (2014), Delrez et al. (2014), Endl et al. (2014), Gillon et al. (2014), Hartman et al. (2014), Hellier et al. (2014), Jordán et al. (2014), Knutson et al. (2014b), Lendl et al. (2014), Maciejewski et al. (2014), Morello et al. (2014), Neveu-VanMalle et al. (2014), Nikolov et al. (2014), Smith et al. (2014), Southworth et al. (2014), Wang et al. (2014a), Wang et al. (2014b), Wong et al. (2014), Zhou et al. (2014), Almenara et al. (2015), Anderson et al. (2015a), Bakos et al. (2015a), Bakos et al. (2015b), Berta-Thompson et al. (2015), Bieryla et al. (2015), Bourrier et al. (2015), Brahm et al. (2015), Ciceri et al. (2015), Damasso et al. (2015a), Damasso et al. (2015b), Esteves et al. (2015), Fulton et al. (2015), Hartman et al. (2015a), Hartman et al. (2015b), Hartman et al. (2015c), Hellier et al. (2015), Huang et al. (2015a), Juncher et al. (2015), Lillo-Box et al. (2015), Mancini et al. (2015a), Motalebi et al. (2015), Narita et al. (2015), Smith (2015), Southworth et al. (2015a), Sozzetti et al. (2015), Triaud et al. (2015), Wong et al. (2015), Addison et al. (2016), Barros et al. (2016), Brahm et al. (2016a), Brahm et al. (2016b), Ciceri et al. (2016), Crossfield et al. (2016), Dai et al. (2016), de Val-Borro et al. (2016), Delrez et al. (2016), Eastman et al. (2016), Espinoza et al. (2016), Evans et al. (2016), Fischer et al. (2016), Fukui et al. (2016), Grziwa et al. (2016), Hartman et al. (2016), Hay et al. (2016), Hirano et al. (2016), Holczer et al. (2016), Hoyer et al. (2016), Johnson et al. (2016), Kuhn et al. (2016), Maciejewski et al. (2016b), Mancini et al. (2016a), Mancini et al. (2016b), Mann et al. (2016), Maxted et al. (2016), Močnik et al. (2016), Morton et al. (2016), Rabus et al. (2016), Rodriguez et al. (2016), Santerne et al. (2016), Sedaghati et al. (2016), Sinukoff et al. (2016), Southworth & Evans (2016), Southworth et al. (2016), Spake et al. (2016), Turner et al. (2016b), West et al. (2016), Wong et al. (2016), Zhou et al. (2016), Alsubai et al. (2017), Anderson et al. (2017), Beatty et al. 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(2018), Henning et al. (2018), Hirano et al. (2018), Johnson et al. (2018a), Johnson et al. (2018b), Jones et al. (2018), Mayo et al. (2018), Raynard et al. (2018), Rodriguez et al. (2018a), Rodriguez et al. (2018b), Siverd et al. (2018), Soto et al. (2018), Temple et al. (2018), Van Eylen et al. (2018), Wang et al. (2018a), Wang et al. (2018b), Yu et al. (2018a), Yu et al. (2018b), Yu et al. (2018c), Alsubai et al. (2019a), Alsubai et al. (2019b), Barkaoui et al. (2019), Beatty et al. (2019), Bouma et al. (2019), Cañas et al. (2019), Crossfield et al. (2019), Espinoza et al. (2019b), Esposito et al. (2019), Günther et al. (2019), Hartman et al. (2019), Hedges et al. (2019), Hellier et al. (2019a), Hellier et al. (2019b), Hellier et al. (2019c), Johns et al. (2019), Jones et al. (2019), Kipping et al. (2019), Korth et al. (2019), Kossakowski et al. (2019), Kostov et al. (2019), Lendl et al. (2019), Luque et al. (2019), Mallonn et al. (2019b), Ment et al. (2019), Nielsen et al. (2019), Quinn et al. (2019), Rice et al. (2019), Rodriguez et al. (2019a), Rodriguez et al. (2019b), Shporer et al. (2019), Smith et al. (2019), Sulis et al. (2019), Temple et al. (2019a), Temple et al. (2019b), Turner et al. (2019), Vanderspek et al. (2019), Vines et al. (2019), Wang et al. (2019a), Wang et al. (2019b), Winters et al. (2019), Zhou et al. (2019a), Zhou et al. (2019b), Badenas-Agusti et al. (2020), Bouma et al. (2020b), Brahm et al. (2020), Burt et al. (2020), Carleo et al. (2020), Cloutier et al. (2020), Crouzet et al. (2020), Dalba et al. (2020), Davis et al. (2020), Demory et al. (2020), Dorval et al. (2020), Dreizler et al. (2020), Gilbert et al. (2020), Hartman et al. (2020), Huang et al. (2020), Jenkins et al. (2020), Jordán et al. (2020), Kanodia et al. (2020), Maciejewski (2020), Mann et al. (2020), Nielsen et al. (2020a), Nielsen et al. (2020b), Rodriguez et al. (2020), Schanche et al. (2020), Shporer et al. (2020), Stefansson et al. (2020), Teske et al. (2020), Addison et al. (2021), Bakos et al. (2021), Cabot et al. (2021), Cointepas et al. (2021), Daylan et al. (2021), de Leon et al. (2021), Demangeon et al. (2021), Hedges et al. (2021), Hobson et al. (2021), Kossakowski et al. (2021), Lacedelli et al. (2021), Lindor et al. (2021), Luque et al. (2021), Martin et al. (2021), Moutou et al. (2021), Murgas et al. (2021), Newton et al. (2021), Osborn et al. (2021a), Osborn et al. (2021b), Rodriguez et al. (2021), Sozzetti et al. (2021), Gan et al. (2022), Khandelwal et al. (2022), Kokori et al. (2022), Montalto et al. (2022).

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

Table 7
Updated Ephemerides and Data Sources

Planet	T_0 (BJD$_{TDB}$) P (days)	References for Literature Data Used
55Cnce	2,459,370.807543 ± 0.000093 0.73654625 ± 0.00000015	Winn et al. (2011a)
CoRoT-11b	2,456,019.96220 ± 0.00037 2.99427803 ± 0.00000049	Gandolfi et al. (2010)
CoRoT-19b	2,455,701.71540 ± 0.00048 3.8971379 ± 0.0000016	Guenther et al. (2012)
CoRoT-2b	2,457,683.44158 ± 0.00016 1.74299705 ± 0.00000015	Alonso et al. (2008b), Öztürk & Erdem (2019)
EPIC211945201b	2,458,094.44793 ± 0.00024 19.4921498 ± 0.0000077	

Note. Table 7 is published in its entirety in a machine-readable format. A portion is shown here for guidance regarding its form and content. A complete listing of all references used is provided in the table notes.

References: Alonso et al. (2004), Charbonneau et al. (2006), McCullough et al. (2006), O'Donovan et al. (2006), Holman et al. (2006), Bakos et al. (2007a), Bakos et al. (2007b), Burke et al. (2007), Charbonneau et al. (2007), Cameron et al. (2007), Gillon et al. (2007a), Gillon et al. (2007b), Holman et al. (2007), Kovács et al. (2007), Mandushev et al. (2007), Narita et al. (2007), O'Donovan et al. (2007), Shporer et al. (2007), Torres et al. (2007), Winn et al. (2007a), Winn et al. (2007b), Alonso et al. (2008a), Alonso et al. (2008b), Anderson et al. (2008), Bean & Seifahrt (2008), Burke et al. (2008), Gibson et al. (2008), Gillon et al. (2008), Hébrard et al. (2008), Irwin et al. (2008), Johnson et al. (2008), McCullough et al. (2008), Miller-Ricci et al. (2008), Narita et al. (2008), Noyes et al. (2008), Pál et al. (2008), Pollacco et al. (2008), Ribas et al. (2008), Wilson et al. (2008), Winn et al. (2008a), Winn et al. (2008b), Bakos et al. (2009), Barbieri et al. (2009), Cáceres et al. (2009), Carter et al. (2009), Christian et al. (2009), Gibson et al. (2009), Gillon et al. (2009a), Gillon et al. (2009b), Hartman et al. (2009), Hebb et al. (2009), Hellier et al. (2009a), Hellier et al. (2009b), Johnson et al. (2009a), Joshi et al. (2009), Knutson et al. (2009), Latham et al. (2009), Lister et al. (2009), Nutzman et al. (2009), Pál et al. (2009), Rabus et al. (2009), Raetz et al. (2009a), Raetz et al. (2009b), Shporer et al. (2009a), Shporer et al. (2009b), Skillen et al. (2009), Southworth et al. (2009), Sozzetti et al. (2009), West et al. (2009a), Winn et al. (2009b), Winn et al. (2009c), West et al. (2009b), Agol et al. (2010), Anderson et al. (2010), Bakos et al. (2010), Bouchy et al. (2010), Buchhave et al. (2010), Burke et al. (2010), Christiansen et al. (2010), Colón et al. (2010), Dittmann et al. (2010), Gandolfi et al. (2010), Gibson et al. (2010), Hebb et al. (2010), Hrudkova et al. (2010), Kipping et al. (2010), Kovács et al. (2010), Maciejewski et al. (2010), Maxted et al. (2010b), Mislis et al. (2010), Narita et al. (2010), Queloz et al. (2010), Smalley et al. (2010), Southworth et al. (2010), Street et al. (2010), Torres et al. (2010), Tripathi et al. (2010), Alsubai et al. (2011), Anderson et al. (2011a), Anderson et al. (2011b), Bakos et al. (2011), Barros et al. (2011), Beaulieu et al. (2011), Beky et al. (2011), Berta et al. (2011), Buchhave et al. (2011), Chan et al. (2011), Christiansen et al. (2011), Dragomir et al. (2011), Enoch et al. (2011a), Enoch et al. (2011b), Faedi et al. (2011), Fukui et al. (2011), Fulton et al. (2011), Gillon et al. (2011), Hartman et al. (2011a), Hartman et al. (2011b), Hartman et al. (2011c), Hellier et al. (2011), Johnson et al. (2011), Kipping et al. (2011), Maciejewski et al. (2011a), Maciejewski et al. (2011b), Maciejewski et al. (2011c), Mandushev et al. (2011), Maxted et al. (2011), Nascimbeni et al. (2011a), Nascimbeni et al. (2011b), Nutzman et al. (2011), Pál et al. (2011), Sanchis-Ojeda et al. (2011), Simpson et al. (2011), Smalley et al. (2011), Triaud et al. (2011), Winn et al. (2011a), Winn et al. (2011b), Anderson et al. (2012), Bakos et al. (2012), Barros et al. (2012), Beatty et al. (2012), Dittmann et al. (2012), Eibe et al. (2012), Gillon et al. (2012), Guenther et al. (2012), Hartman et al. (2012), Haswell et al. (2012), Hellier et al. (2012), Howard et al. (2012), Hoyer et al. (2012), Knutson et al. (2012), Lee et al. (2012), Lendl et al. (2012), Montalto et al. (2012), Quinn et al. (2012), Sada et al. (2012), Sato et al. (2012), Siverd et al. (2012), Smalley et al. (2012), Smith et al. (2012), Southworth et al. (2012a), Southworth et al. (2012b), Southworth et al. (2012c), Stevenson et al. (2012), Todorov et al. (2012), Barros et al. (2013), Bean et al. (2013), Becker et al. (2013), Blecic et al. (2013), Boisse et al. (2013), Ciceri et al. (2013), Covino et al. (2013), Deming et al. (2013), Dragomir et al. (2013), Faedi et al. (2013), Fraine et al. (2013), Fukui et al. (2013), Gómez Maqueo Chew et al. (2013), Gibson et al. (2013a), Gibson et al. (2013b), Gillon et al. (2013), Hébrard et al. (2013), Harpsøe et al. (2013), Hoyer et al. (2013), Huitson et al. (2013), Kundurthy et al. (2013), Lendl et al. (2013), Lewis et al. (2013), Line et al. (2013), Maciejewski et al. (2013a), Maciejewski et al. (2013b), Mancini et al. (2013a), Mancini et al. (2013b), Mancini et al. (2013c), Maxted et al. (2013a), Maxted et al. (2013b), Mohler-Fischer et al. (2013), Nascimbeni et al. (2013b), Nikolov et al. (2013), Penev et al. (2013), Pepper et al. (2013), Sing et al. (2013), Smith et al. (2013), Southworth et al. (2013), Tregloan-Reed et al. (2013), Triaud et al. (2013), Turner et al. (2013), von Essen et al. (2013), Wang et al. (2013), Addison et al. (2014), Anderson et al. (2014a), Anderson et al. (2014b), Beatty et al. (2014), Bieryla et al. (2014), Brown et al. (2014), Cáceres et al. (2014), Chen et al. (2014), Collins et al. (2014), Delrez et al. (2014), Fukui et al. (2014), Gillon et al. (2014), Granata et al. (2014), Hartman et al. (2014), Hellier et al. (2014), Jordán et al. (2014), Knutson et al. (2014a), Lendl et al. (2014), Mancini et al. (2014a), Mancini et al. (2014b), Mancini et al. (2014c), Murgas et al. (2014), Neveu-VanMalle et al. (2014), Pearson et al. (2014), Seeliger et al. (2014), Smith et al. (2014), Southworth et al. (2014), Stevenson et al. (2014), Van Grootel et al. (2014), Wang et al. (2014b), Zhao et al. (2014), Zhou et al. (2014), Anderson et al. (2015a), Anderson et al. (2015b), Bakos et al. (2015a), Bakos et al. (2015b), Berta-Thompson et al. (2015), Bieryla et al. (2015), Brahm et al. (2015), Dragomir et al. (2015), Fulton et al. (2015), Hartman et al. (2015a), Hartman et al. (2015b), Hartman et al. (2015c), Hellier et al. (2015), Hinse et al. (2015), Huang et al. (2015b), Juncher et al. (2015), Kammer et al. (2015), Kreidberg et al. 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(This table is available in its entirety in machine-readable form.)

C, Antarctica, which operates during the polar winter, from March to September (Fressin et al. 2005; Daban et al. 2010; Mékarnia et al. 2016). The continuous night and excellent atmospheric conditions make it well suited to high-precision time-series photometry, such as that for exoplanet transit observations. The telescope was installed in 2010 and upgraded in 2022. The project is a collaboration between Laboratoire Lagrange (CNRS UMR 7293), the University of Birmingham, and the European Space Agency.

Appendix B
Transit S/N Calculation

For a light curve with a standard deviation of std, a total observing time of T, individual points with exposure times of t_e, and overheads of t_o, the uncertainty of the relative flux (σ_F) that can be achieved is:

$$\sigma_F = \frac{\text{std}}{\sqrt{T/(t_e + t_o)}}. \quad (B1)$$

In the case of a transit (assuming that it is square), the transit depth (d) is the difference between the out-of-transit relative flux (F_{oot}) and the in-transit relative flux (F_{int}). Hence, the uncertainty on the transit depth (σ_d) is:

$$\sigma_d = \sqrt{\sigma_{F_{\text{oot}}}^2 + \sigma_{F_{\text{int}}}^2} = \sqrt{\text{std}^2 \frac{(t_e + t_o)}{T_{\text{oot}}} + \text{std}^2 \frac{(t_e + t_o)}{T_{\text{int}}}}$$
$$= \text{std} \sqrt{(t_e + t_o)\left(\frac{1}{T_{\text{oot}}} + \frac{1}{T_{\text{int}}}\right)} = \text{std} \sqrt{\frac{(t_e + t_o)(T_{\text{oot}} + T_{\text{int}})}{T_{\text{oot}} T_{\text{int}}}}. \quad (B2)$$

Hence, the square-transit S/N is:

$$\text{S}/\text{N}_{\text{square-transit}} = \frac{d}{\sigma_d} = \frac{d}{\text{std}} \sqrt{\frac{T_{\text{oot}} T_{\text{int}}}{(t_e + t_o)(T_{\text{oot}} + T_{\text{int}})}}. \quad (B3)$$

Finally, due to the fact that in reality the transits are not squares, and because we are also fitting light curves for extra parameters, there is an additional x-factor for estimating the final transit S/N:

$$\text{S}/\text{N}_{\text{transit}} = x\text{S}/\text{N}_{\text{square-transit}}$$
$$= x \frac{d}{\text{std}} \sqrt{\frac{T_{\text{oot}} T_{\text{int}}}{(t_e + t_o)(T_{\text{oot}} + T_{\text{int}})}}. \quad (B4)$$

From simulations, which we verified with current ExoClock and TESS observations, the x-factor is equal to 0.85 for linear or airmass detrending and equal to 0.65 for quadratic detrending. We need to note that for linear and airmass detrending, the x-factor is stable, regardless of the length of the out-of-transit observations. However, for quadratic detrending, in order to maintain the x-factor of 0.65, we need to observe one transit duration before and one after the transit, otherwise the x-factor becomes lower. For example, an observation of a 3 hr long transit, with 1 hr of observations before and after, has an x-factor of 0.5, instead of 0.65.

Appendix C
Transit S/N Predictions for ExoClock

To predict the transit S/N, we need to have predictions for all the values included in Equation (B4). The most uncertain one is the std, which we predicted from the performance of the current telescopes. Figure 7 (left) shows the std of the current observations made using an R Cousins filter, normalized to a 1 s exposure and a telescope size of 1 inch, as a function of the R_C magnitude. We have modeled this behavior as follows:
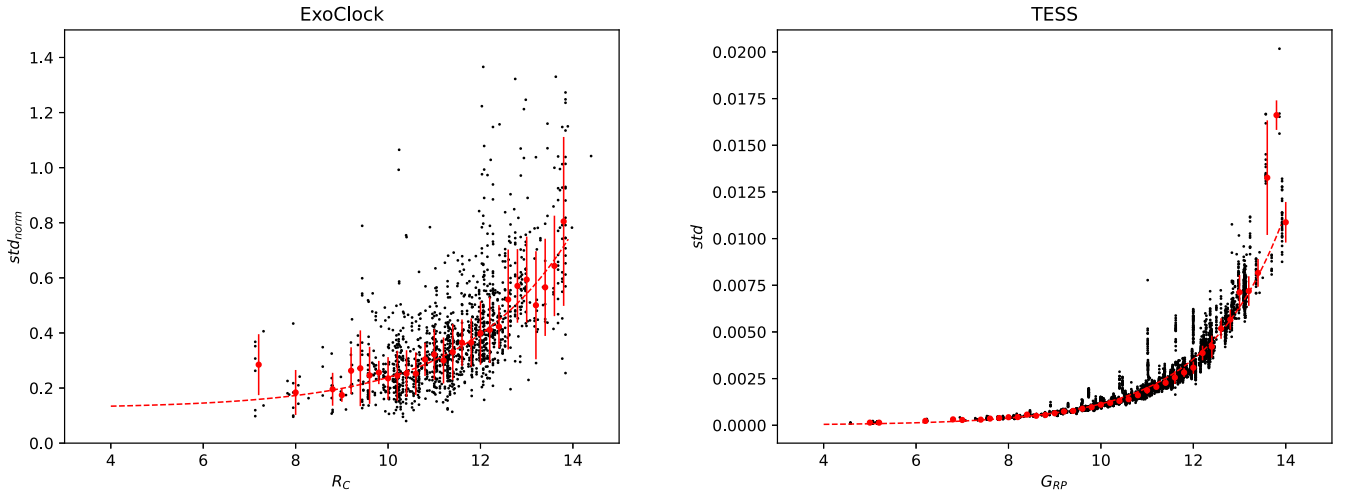
$$\text{std}_{\text{norm}}^{\text{ExoClock}} = 0.135 + 10^{-2.99+0.2R}. \quad (C1)$$

Hence, the predicted std for a light curve obtained by a telescope of diameter D with an exposure time of t_e will be:

$$\text{std}^{\text{ExoClock}} = \frac{\text{std}_{\text{norm}}^{\text{ExoClock}}}{\sqrt{\pi (D/2)^2 t_e}} = \frac{0.135 + 10^{-2.99+0.2R}}{\sqrt{\pi (D/2)^2 t_e}}, \quad (C2)$$

and the predicted transit S/N will be:

$$\text{S}/\text{N}_{\text{transit}}^{\text{ExoClock}} = x \frac{d\sqrt{\pi (D/2)^2 t_e}}{0.135 + 10^{-2.99+0.2R}}$$
$$\sqrt{\frac{T_{\text{oot}} T_{\text{int}}}{(t_e + t_o)(T_{\text{oot}} + T_{\text{int}})}}. \quad (C3)$$

Figure 7. The standard deviations of the light curves as a function of magnitude, for the ExoClock (left; normalized for a 1 inch telescope and a 1 s exposure) and the TESS (right) light curves, together with the models derived. The red errorbars indicate the medians and standard deviations of the data, in bins of 0.2 mag.

The ExoClock scheduler calculates the minimum telescope size necessary to observe a transit, based on the following assumptions:

1. the targeted S/N_{transit} is 6;
2. the detrending model is expected to be the airmass model, hence $x = 0.85$;
3. the observation includes 1 hr before and 1 hr after the transit, hence $T_{\text{oot}} = 7200$ s;
4. the observation includes the full transit, hence $T_{\text{int}} = t_{14}$, in seconds; and
5. the overheads and the exposure time are equal, hence $t_e = t_o$.

Hence, the minimum telescope size is:

$$6 = 0.85 \frac{d\sqrt{\pi (D_{\min}/2)^2 t_e}}{0.135 + 10^{-2.99+0.2R}} \sqrt{\frac{7200 t_{14}}{(t_e + t_e)(7200 + t_{14})}}$$

$$D_{\min} = \frac{0.135 + 10^{-2.99+0.2R}}{5.1d} \sqrt{\frac{7200 + t_{14}}{900 \pi t_{14}}}.$$

(C4)

Appendix D
Transit S/N Predictions for TESS

As far as the TESS observations are concerned, the calculation is less complicated, as many of the parameters are fixed. The std can be predicted from the performance of the telescope. Figure 7 (right) shows the std of the current observation, as a function of the G_{RP} magnitude. For TESS, there is no need to normalize to the telescope size and the exposure time, as these are fixed. We have modeled this behavior as follows:

$$\text{std}^{\text{TESS}} = (0.135 + 10^{-2.43+0.2G_{\text{RP}}+0.0039G_{\text{RP}}^2}) \times 10^{-3}. \quad \text{(D1)}$$

Moreover, for TESS, the detrending model is the quadratic ($x = 0.65$), the exposure time is 2 minutes ($t_e = 120$), overheads are negligible ($t_o = 0$), and the observations are continuous, so we can select the out-of-transit observations to be equal to one transit duration before and one transit duration after the transit ($T_{\text{oot}} = 2t_{14}$, in seconds), while the in-transit observing time is equal to a full transit duration ($T_{\text{int}} = t_{14}$, in seconds). Hence, the predicted transit S/N will be:

$$S/N_{\text{transit}}^{\text{TESS}} = \frac{0.65 d\sqrt{t_{14}/90}}{0.135 + 10^{-2.43+0.2G_{\text{RP}}+0.0039G_{\text{RP}}^2}} \times 10^3. \quad \text{(D2)}$$

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