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Confirming long-period transiting exoplanets with TESS and CHEOPS

The case of HD 22946 d

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Abstract. Due to the limited observing duration of the Transiting Exoplanet Survey Satellite (TESS) primary mission, which observed the majority of the near-ecliptic sectors for only 27 days, planets on long periods produce only single transits. However, thanks to its extended mission, TESS re-observed the same fields 2 years later, and in many cases was able to re-detect a second transit. These duotransit cases require follow-up in order to uncover the true orbital period due to the gap, which causes a set of aliases. The Characterising Exoplanet Satellite (CHEOPS) space observatory can be used to follow-up duotransit targets and to determine their true orbital periods and other characteristics. We investigated the HD 22946 planetary system with a similar aim. Based on the combined TESS and CHEOPS observations, we successfully determined the true orbital period of the planet d to be 47.42489 ± 0.00011 d, and derived precise radii of the planets in the system. Planet d, as a warm sub-Neptune, is very interesting because there are only a few similar confirmed exoplanets to date.

Key words: methods: observational – techniques: photometric – planets and satellites: fundamental parameters

1. Introduction

Nowadays the Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al., 2014) is the most active transiting-exoplanet searching program. However, due to the nature of its observing strategy, TESS is limited in its ability to discover long-period exoplanets. During its two-year primary mission, TESS observed the majority of the sky for about 27 consecutive days. This means that planets with periods longer than $\sim 27\,\mathrm{d}$ would only have been observed to transit once, if at all. These single transit detections are known as monotransits and their orbital periods are unknown (Osborn et al., 2022).

Thanks to its extended mission, TESS re-observed the same fields two years later, and in many cases was able to detect a second transit. The result was a sample of duotransits, this means, long-period ($P_{\mathrm{orb}} > 27\,\mathrm{d}$) planetary candidates with two observed transits separated by a large gap, typically two years. From the two non-consecutive transits, the orbital period of the planet remains unknown, but there now exists a discrete set of allowed period aliases. These aliases (P_{n}) can be calculated according to

$$P_{\mathrm{n}} = \frac{T_{\mathrm{diff}}}{n}, \tag{1}$$

where T_{diff} is the time between the two transit events and $n \in \{1, 2, 3, \ldots, n_{\mathrm{max}}\}$. The maximum value, n_{max}, is determined by the non-detection of a third transit in the TESS data. Follow-up photometric or spectroscopic observations are required to recover their true orbital periods. The follow-up of monotransits requires a blind survey approach, whereas the period aliases of a duotransit allow more targeted follow-up observations.

2. Photometric follow-up of TESS duotransits with CHEOPS

There is a dedicated Characterising Exoplanet Satellite (CHEOPS) Guaranteed Time Observing (GTO) program, called Duos, to recover the orbital periods of TESS duotransits, focusing on small planets that cannot be observed from the ground. Many duotransits produce transits on the order of $500-2500\,\mathrm{ppm}$. These are also some of the most interesting objects, often being super-Earths or sub-Neptunes. CHEOPS is a European Space Agency (ESA) mission dedicated to the photometric follow-up of known exoplanets (Benz et al., 2021). The effective aperture diameter of CHEOPS ($\sim 30\,\mathrm{cm}$) is about three times larger than that of TESS ($\sim 10\,\mathrm{cm}$), allowing it to achieve a higher per-transit signal-to-noise ratio. Furthermore, CHEOPS performs targeted photometric observations. It is therefore very well-suited to the follow-up of small, long-period planets from TESS. Detecting long-period planets is important. For example, the increased distance from their host stars means that, when compared with close-in planets,

Table 1. Orbital period aliases of the planet HD 22946 d. Only the period aliases with a probability of $p > 1\%$ are listed here, as calculated by the `MonoTools` package from TESS data alone, i.e. before CHEOPS observations.

Alias No.	Period alias (P_n) [d]	Probability (p) [%]
1	39.5206	17.420
2	41.8454	20.078
3	44.4607	20.341
4	47.4248	18.113
5	50.8122	13.445
6	54.7209	7.061
7	59.2809	2.756
8	64.6701	~ 1.0

they may retain more of their primordial characteristics, such as unevaporated atmospheres (Owen, 2019).

We focus on a sample of targets, which are suitable for future characterisation observations, for example, with Ariel (Tinetti et al., 2021). In any of these cases, stellar magnitude is the most important parameter, and we use this as the key metric to rank targets, with an upper limit of $V = 11.5$ mag. In order to not compete with ground-based facilities performing similar programs, we also place an upper limit on the transit depth of our targets at 2500 ppm. There is a chance that this sample includes false positives (FPs). The best way to reduce such cases is to target unconfirmed long-period planets with a radius upper limit of $R_\mathrm{p} = 10\,\mathrm{R}_\oplus$ that are in multi-planet systems, for which there is very low FP probability. This means that the investigation is performed mainly on a limited sample of multi-planet systems, for example on TOI-2076, HIP 9618 or HD 15906. We discovered 5 planet candidates in the TESS data using our specialised duotransit pipeline (Tuson, 2022). This pipeline was created to search for TESS duotransits suitable for CHEOPS follow-up. The pipeline concatenates the TESS Presearch Data Conditioning Simple Aperture Photometry (PDCSAP) light curves from the primary and extended mission, detrends the light curve using a mean sliding window, and then runs a box least squares (BLS) transit search (Kovács et al., 2002) on the detrended light curve with parameters optimized for duotransit detections.

3. Confirming HD 22946 d with TESS and CHEOPS

As an illustrative example, in this section we briefly summarise confirmation of the planet HD 22946 d, which was published in Garai et al. (2023). HD 22946 is a bright ($G = 8.13$ mag) late F-type star with three transiting planets. The planetary system was discovered and validated only recently by Cacciapuoti et al. (2022). As TESS recorded several transits during observations in sector numbers 3, 4, 30, and 31, the discoverers easily derived the orbital periods of the two inner planets, b and c. The orbital period of planet d was not found by the discoverers. The authors determined its presence through a single transit found in sector number 4 and obtained its parameters from this single transit event. As Cacciapuoti et al. (2022), we also initially recognised a transit-like feature in the sector number 4 data through visual inspection of the light curve. Given $65-80\%$ of single transits from the TESS primary mission will re-transit in the extended mission sectors (Cooke et al., 2021), we subsequently visually inspected the light curve once the TESS year 3 data were available and found a second dip in the sector number 30 data with near-identical depth and duration. Given the high prior probability of finding a second transit, the close match in transit shape between events, and the high quality of the data, we concluded that this signal is a bona fide transit event and that the transits in sector numbers 4 and 30 are very likely caused by the same object, that is, by planet d.

In order to determine each possible period alias and to schedule CHEOPS observations of planet d, we first performed a period analysis of the available TESS data. For this purpose, we used the `MonoTools` package (Osborn et al., 2022). The package calculates probability distribution across all allowed aliases for a given transit model. The probabilities are estimated based on two major assumptions, namely that short-period orbits are highly favoured over long-period ones (Kipping, 2018), and that planets in multi-planet systems have low eccentricities (Van Eylen & Albrecht, 2015). The software `MonoTools` forecasted that a transit of planet d with the orbital period alias No. 2 (see Tab. 1) would take place on 25th October 2021. This forecasted event was observed with CHEOPS, but the expected transit of planet d did not happen; only the transit of planet b was recorded that time. After this observation, we were able to exclude the period alias No. 2 from the list of possible aliases. The next forecast predicted a transit of planet d on 28th October 2021, which means that, in this case, the alias No. 4 (see Tab. 1) was preferred as its true orbital period. This forecasted event was also observed with CHEOPS. This time, the transit of planet d was successfully detected together with a transit of planet c (see Fig. 1), confirming that the period alias No. 4 is the true orbital period of planet d.

With this gathered knowledge about the true orbital period of planet d, we were able to combine TESS and CHEOPS photometric observations and radial-velocity measurements in order to improve the orbital and planetary parameters of the HD 22946 system. Cacciapuoti et al. (2022) expected an orbital period of $P_{\rm orb} = 46 \pm 4\,{\rm d}$ for planet d. We confirmed this prediction, finding an orbital period for planet d of $P_{\rm orb} = 47.42489 \pm 0.00011\,{\rm d}$. According to the radius valley at $\sim 1.5-2.0\,{\rm R}_\oplus$ (Fulton et al., 2017), which separates super-Earths and sub-Neptunes and based on the refined planet radii ($R_{\rm p,b} = 1.362 \pm 0.040\,{\rm R}_\oplus$, $R_{\rm p,c} = 2.328 \pm 0.039\,{\rm R}_\oplus$, $R_{\rm p,d} = 2.607 \pm 0.060\,{\rm R}_\oplus$), we find that planet b is a super-Earth, and planets c and d are similar in size and are sub-Neptunes, in agreement with the discoverers. For further details see Garai et al. (2023).

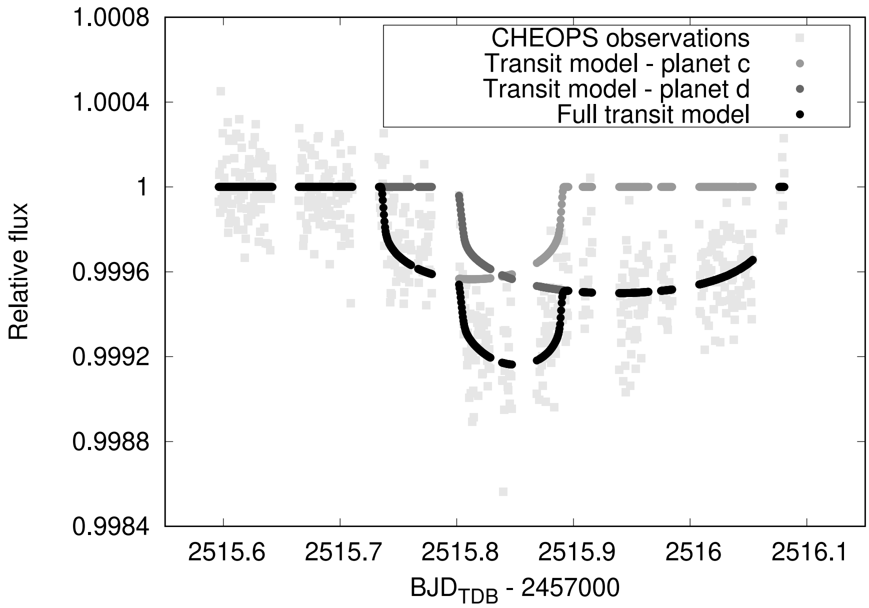

Figure 1. CHEOPS observations of HD 22946 on 28th October 2021. The observed light curve is overplotted with the best-fitting model. The individual transit models of planets c and d are also shown in addition to the summed model.

4. Conclusions

Due to the nature of its observing strategy, TESS is biased towards the discovery of short-period planets. We demonstrated how CHEOPS can be used to follow-up TESS duotransits to expand the sample of long-period planets. Through the CHEOPS GTO Duos program, we have contributed to the discovery of 6 planets with orbital periods longer than 20 d, radii smaller than 5 $R_\oplus$, and host stars brighter than $G = 12$ mag (Osborn et al., 2022, 2023; Tuson et al., 2023; Ulmer-Moll et al., 2023; Garai et al., 2023). There are only ~ 18 other planets confirmed by TESS in this parameter space, illustrating the power of the TESS and CHEOPS synergy for the discovery of small, long-period planets transiting bright stars. Planet d as a warm sub-Neptune is very interesting, because there are only a few similar confirmed exoplanets to date. Thanks to the synergy of TESS and CHEOPS missions, there is a growing sample of planets, such as HD 22946 d. Such objects are worth investigating in the near future, for example in order to investigate their atmosphere, composition, and internal structure.

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References

Benz, W., Broeg, C., Fortier, A., et al., The CHEOPS mission. 2021, *Experimental Astronomy*, **51**, 109, DOI: 10.1007/s10686-020-09679-4

Cacciapuoti, L., Inno, L., Covone, G., et al., TESS discovery of a super-Earth and two sub-Neptunes orbiting the bright, nearby, Sun-like star HD 22946. 2022, *Astronomy and Astrophysics*, **668**, A85, DOI: 10.1051/0004-6361/202243565

Cooke, B. F., Pollacco, D., Anderson, D. R., et al., Resolving period aliases for TESS monotransits recovered during the extended mission. 2021, *Monthly Notices of the RAS*, **500**, 5088, DOI: 10.1093/mnras/staa3569

Fulton, B. J., Petigura, E. A., Howard, A. W., et al., The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets. 2017, *Astronomical Journal*, **154**, 109, DOI: 10.3847/1538-3881/aa80eb

Garai, Z., Osborn, H. P., Gandolfi, D., et al., Refined parameters of the HD 22946 planetary system and the true orbital period of planet d. 2023, *Astronomy and Astrophysics*, **674**, A44, DOI: 10.1051/0004-6361/202345943

Kipping, D., The Orbital Period Prior for Single Transits. 2018, *Research Notes of the American Astronomical Society*, **2**, 223, DOI: 10.3847/2515-5172/aaf50c

Kovács, G., Zucker, S., & Mazeh, T., A box-fitting algorithm in the search for periodic transits. 2002, *Astronomy and Astrophysics*, **391**, 369, DOI: 10.1051/0004-6361:20020802

Osborn, H. P., Bonfanti, A., Gandolfi, D., et al., Uncovering the true periods of the young sub-Neptunes orbiting TOI-2076. 2022, *Astronomy and Astrophysics*, **664**, A156, DOI: 10.1051/0004-6361/202243065

Osborn, H. P., Nowak, G., Hébrard, G., et al., Two warm Neptunes transiting HIP 9618 revealed by TESS and Cheops. 2023, *Monthly Notices of the RAS*, **523**, 3069, DOI: 10.1093/mnras/stad1319

Owen, J. E., Atmospheric Escape and the Evolution of Close-In Exoplanets. 2019, *Annual Review of Earth and Planetary Sciences*, **47**, 67, DOI: 10.1146/annurev-earth-053018-060246

Ricker, G. R., Winn, J. N., Vanderspek, R., et al., Transiting Exoplanet Survey Satellite (TESS). 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **9143**, *Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave*, ed. J. Oschmann, Jacobus M., M. Clampin, G. G. Fazio, & H. A. MacEwen, 914320

Tinetti, G., Eccleston, P., Haswell, C., et al., Ariel: Enabling planetary science across light-years. 2021, *arXiv e-prints*, arXiv:2104.04824, DOI: 10.48550/arXiv.2104.04824

Tuson, A., A Search for Long-Period Transiting Exoplanets with TESS and CHEOPS. 2022, in *European Planetary Science Congress*, EPSC2022–499

Tuson, A., Queloz, D., Osborn, H. P., et al., TESS and CHEOPS discover two warm sub-Neptunes transiting the bright K-dwarf HD 15906. 2023, *Monthly Notices of the RAS*, **523**, 3090, DOI: 10.1093/mnras/stad1369

Ulmer-Moll, S., Osborn, H. P., Tuson, A., et al., TOI-5678b: A 48-day transiting Neptune-mass planet characterized with CHEOPS and HARPS. 2023, *Astronomy and Astrophysics*, **674**, A43, DOI: 10.1051/0004-6361/202245478

Van Eylen, V. & Albrecht, S., Eccentricity from Transit Photometry: Small Planets in Kepler Multi-planet Systems Have Low Eccentricities. 2015, *Astrophysical Journal*, **808**, 126, DOI: 10.1088/0004-637X/808/2/126