HD 22946 d: a 47-day transiting warm sub-Neptune confirmed by TESS and CHEOPS

Z. Garai[1,2,3], H.P. Osborn[4,5], A. Tuson[6], S. Ulmer-Moll[4,7], and The CHEOPS Consortium

[(1)] *HUN-REN–ELTE Exoplanet Research Group, 9700 Szombathely, Szent Imre h. u. 112, Hungary, zgarai@gothard.hu;*
[(2)] *ELTE Gothard Astrophysical Observatory, 9700 Szombathely, Szent Imre h. u. 112, Hungary;*
[(3)] *Astronomical Institute, Slovak Academy of Sciences, 05960 Tatranská Lomnica, Slovakia;*
[(4)] *Space Research and Planetary Sciences, Physics Institute, University of Bern, Gesellschaftsstrasse 6, 3012 Bern, Switzerland;*
[(5)] *Department of Physics and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA;*
[(6)] *Astrophysics Group, Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, UK;*
[(7)] *Observatoire de Genéve, Université de Genéve, Chemin Pegasi, 51, 1290 Versoix, Switzerland*

Introduction

- Long-period planets in multi-planet systems often escape detection, especially when their orbital periods are longer than the typical observing duration of photometric surveys. However, detecting such planets is also important (Owen 2019, Dobos et al. 2021).
- Due to the limited observing duration of the TESS (Ricker at al. 2014, 2015) 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 two 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 (Osborn et al. 2023, Ulmer-Moll et al. 2023, Tuson et al. 2023).
- HD 22946 is a bright ($G = 8.13$ mag) late F-type star around which three transiting planets were identified via TESS photometry (Fig. 1; Cacciapuoti et al. 2022), but the true orbital period of the outermost planet d was unknown until now. We aim to use the CHEOPS space observatory (Benz et al. 2021) to uncover the true orbital period of HD 22946 d and to refine the orbital and planetary properties of the system, especially the radii of the planets.

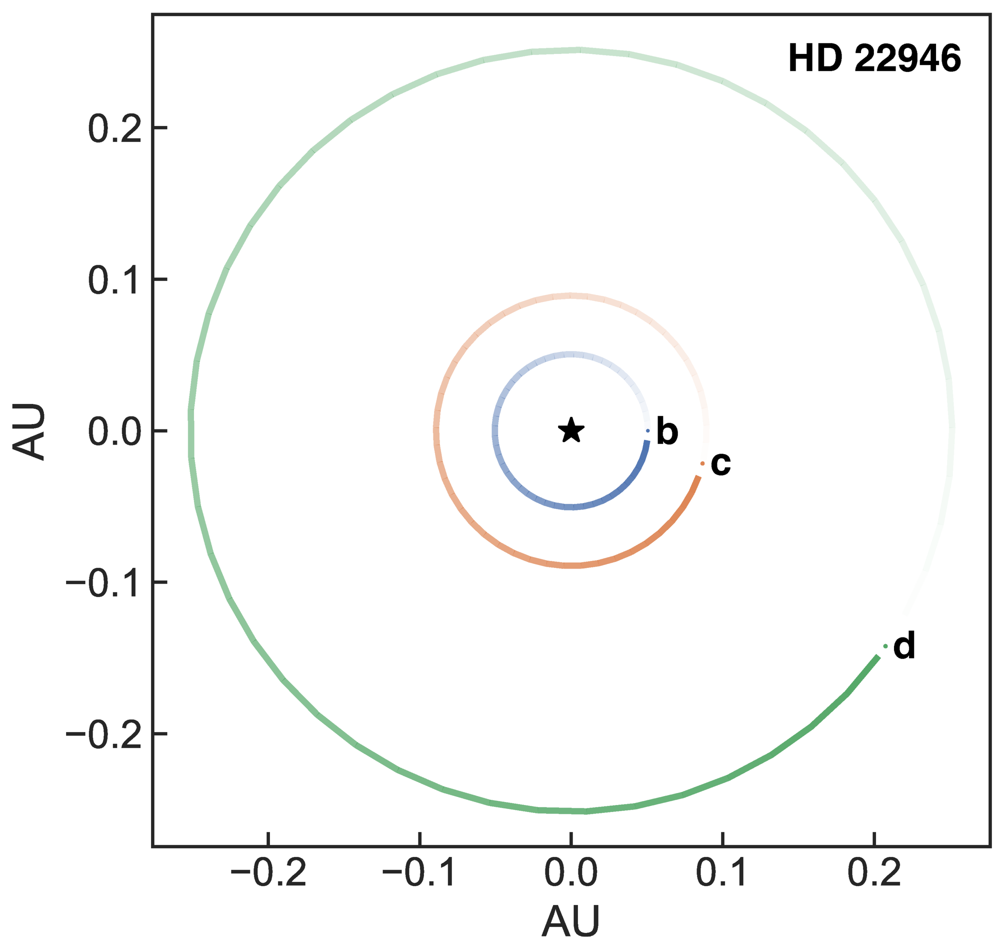

Fig. 1. Visualisation of the HD 22946 multi-planet system. The model was generated using the Allesfitter software (Guenther & Daylan 2019, 2021). The true orbital period of the outermost planet d was unknown until now.

Search for transits of planet d in TESS data

- 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 Cacciapuoti et al. (2022). The authors determined its presence through a single transit found in the TESS sector number 4 and obtained its parameters from this single transit event. As in 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 (Fig. 2).
- Given 65 - 80% of single transits from the TESS primary mission will re-transit in the extended mission sectors (Cooke et al. 2019, 2021), we subsequently visually inspected the light curve once the TESS year 3 data were available and found a second transit of planet d in the sector number 30 data (Fig. 3).

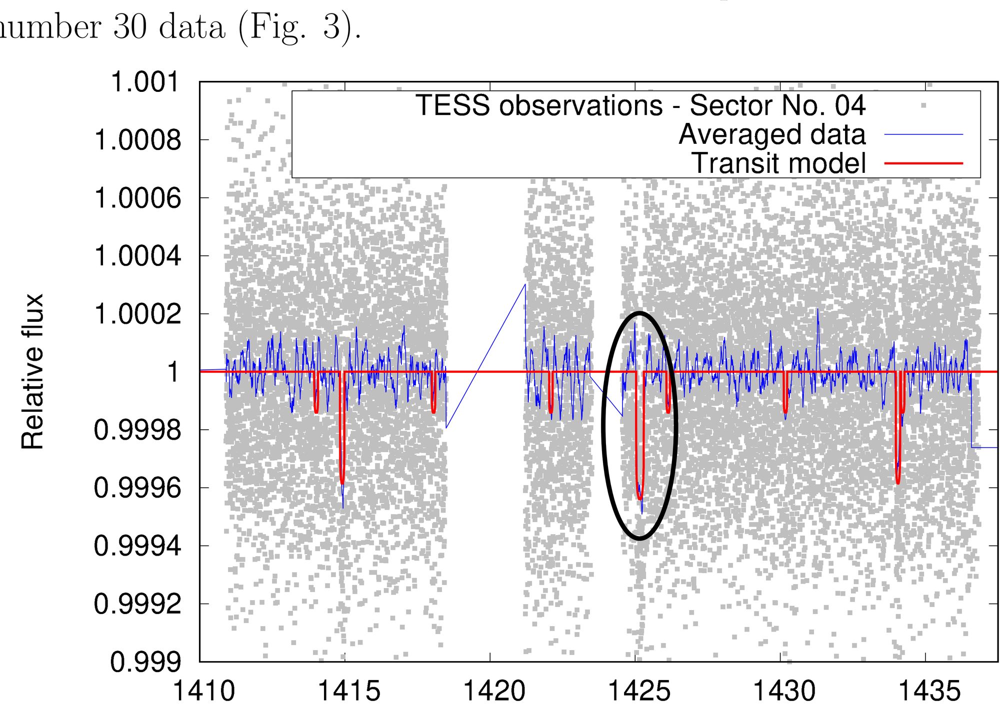

Fig. 2. TESS observations of HD 22946 from the sector number 4. The detrended light curve is overplotted with the best-fitting transit model. The transit of planet d is highlighted in black.

Period aliases of planet d from TESS data

- With two identified transits (Figs. 2 and 3), the orbital period of planet d is still unknown, but there now exists a discrete set of allowed period aliases. 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 software (Osborn et al. 2022).

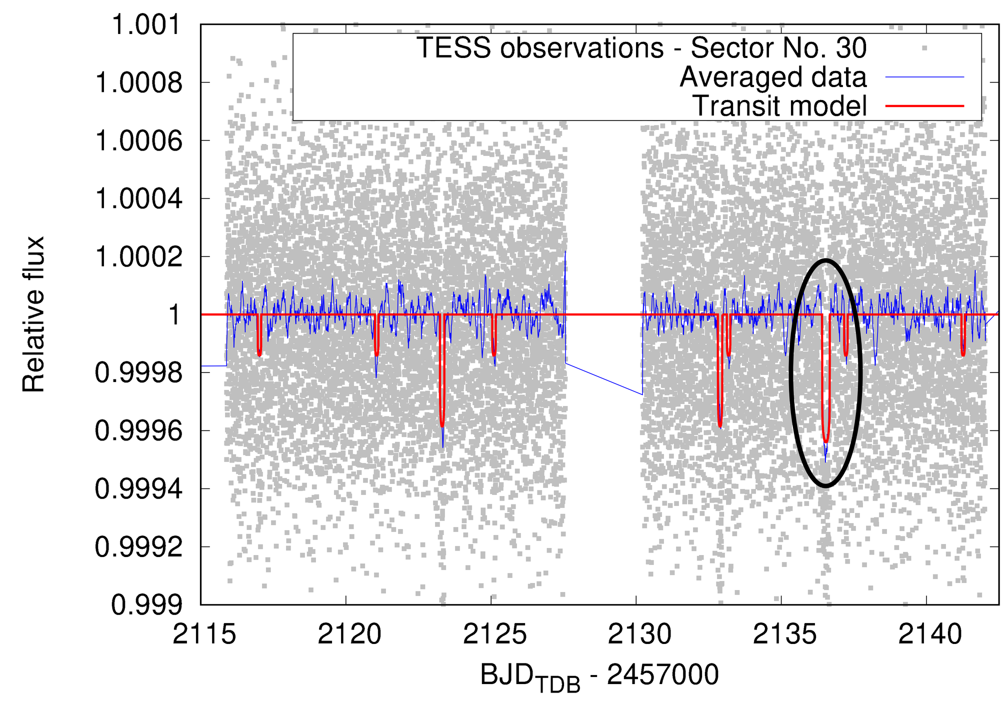

Fig. 3. TESS observations of HD 22946 from the sector number 30. The detrended light curve is overplotted with the best-fitting transit model. The transit of planet d is highlighted in black.

- The MonoTools software calculates probability distribution across all allowed aliases for a given transit model (Fig. 4). The probabilities are estimated based on two major assumptions, namely that short-period orbits are highly favoured over long-period ones, and that planets in multi-planet systems have low eccentricities (Kipping et al. 2013, Van Eylen & Albrecht 2015, Kipping 2018).

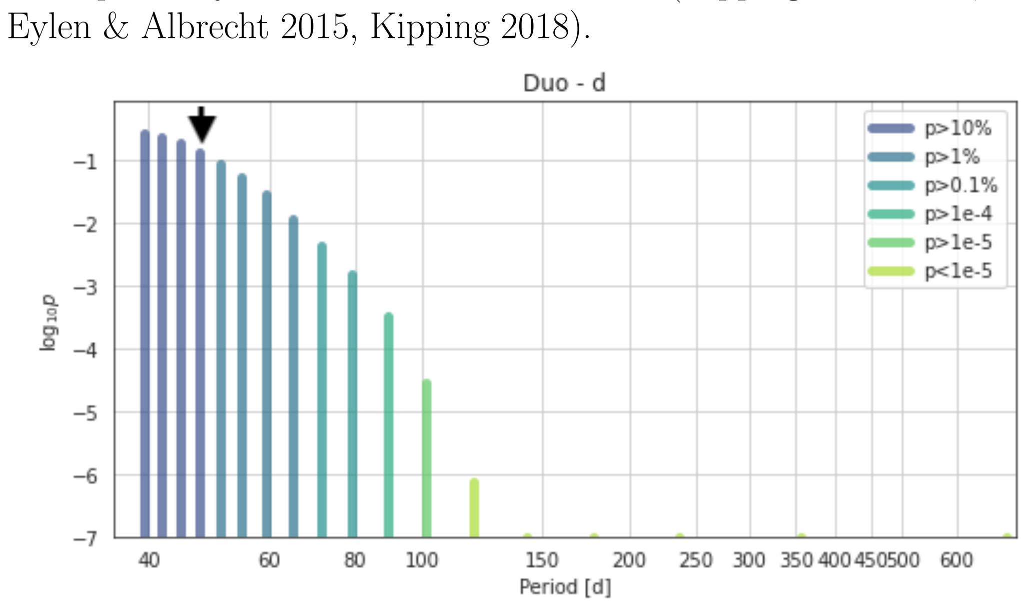

Fig. 4. Orbital period aliases of planet d and their probabilities, calculated by the MonoTools software from TESS data alone, i.e. before CHEOPS observations. The true orbital period is indicated with the black arrow.

CHEOPS observations

- The software MonoTools forecasted that a transit of planet d with the orbital period alias of $P_n = 41.8454$ d would take place on 25 Oct. 2021. This forecasted event was observed with CHEOPS, but the expected transit of planet d did not happen. The next forecast predicted a transit of planet d on 28 Oct. 2021. This time, the transit of planet d was successfully detected (Fig. 5), confirming that the period alias of $P_n = 47.4248$ d is the true orbital period of planet d.

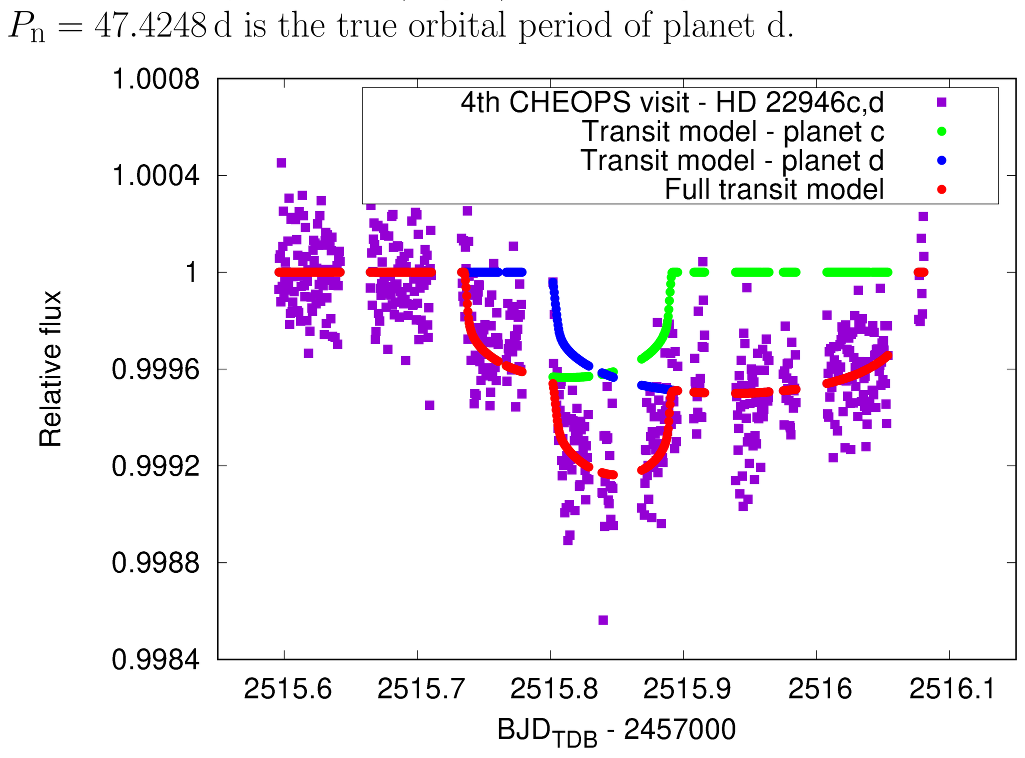

Fig. 5. CHEOPS observations of HD 22946 on 28th October 2021. The detrended light curve is overplotted with the best-fitting transit model. The individual transit models of planets c and d are also shown in addition to the summed model.

Search for transit time variations

- Although Cacciapuoti et al. (2022) already performed such an analysis and found no obvious sign of transit time variations (TTVs) in the system, we repeated this procedure, but in this case using the CHEOPS data, as well (Fig. 6). We can see that the observed-minus-calculated (O-C) values are scattered around O-C = 0.0 d, which means that no significant TTVs are present in the system.

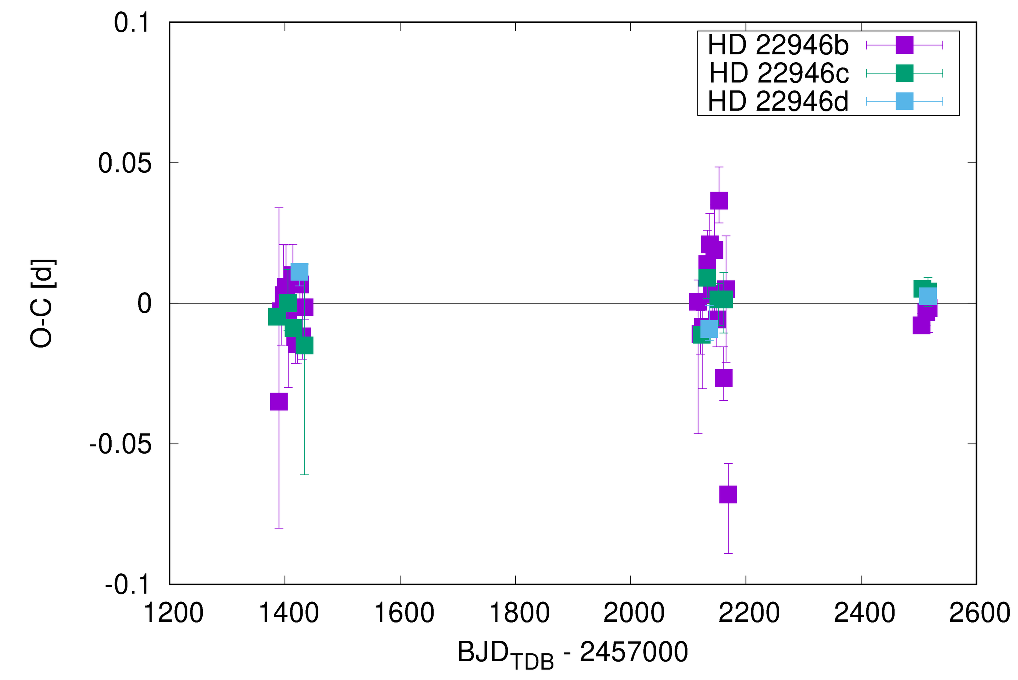

Fig. 6. O-C diagram of mid-transit times of the planets in the HD 22946 system, obtained using the Allesfitter software.

Final results

- The photometric data were supplemented with ESPRESSO (Pepe et al. 2014) radial velocity (RV) data (Fig. 7). Finally, a combined model was fitted to the entire dataset in order to obtain final planetary and system parameters.

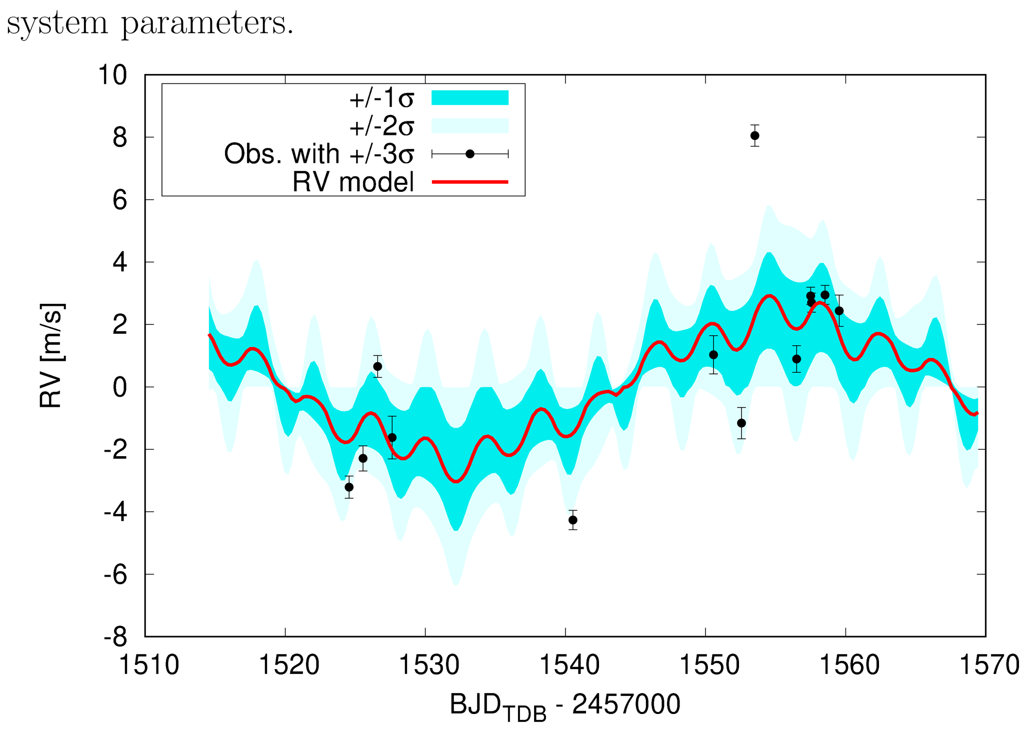

Fig. 7. RV observations taken at ESPRESSO fitted with a spectroscopic orbit (red line). The 1σ and 2σ uncertainties of the model are plotted as coloured areas. The uncertainties of the individual RV data points correspond to a 3σ interval.

- Based on the combined TESS and CHEOPS observations, we successfully determined the true orbital period of planet d to be 47.42489 ± 0.00011 d, and derived precise radii of the planets in the system, namely 1.362 ± 0.040 $R_\oplus$, 2.328 ± 0.039 $R_\oplus$, and 2.607 ± 0.060 $R_\oplus$ for planets b, c, and d, respectively.
- Due to the low number of RVs, we were only able to determine 3σ upper limits for these respective planet masses, which are 13.71 $M_\oplus$, 9.72 $M_\oplus$, and 26.57 $M_\oplus$. We estimated that another 48 ESPRESSO RVs are needed to measure the true masses of all planets in HD 22946.
- We can confirm the conclusion of the discoverers that the planetary system consists of a super-Earth, and planets c and d are sub-Neptunes.
- Planet d, as a warm sub-Neptune, is very interesting because there are only a few similar confirmed exoplanets to date. Such objects are worth investigating in the near future, for example in terms of their composition and internal structure

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