Discovery of TOI-1260d and the characterisation of the multi-planet system *

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We report the discovery of a third planet transiting the star TOI-1260, previously known to host two transiting sub-Neptune planets with orbital periods of 3.127 and 7.493 days, respectively. The nature of the third transiting planet with a 16.6-day orbit is supported by ground-based follow-up observations, including time-series photometry, high-angular resolution images, spectroscopy, and archival imagery. Precise photometric monitoring with CHEOPS allows to improve the constraints on the parameters of the system, improving our knowledge on their composition. The improved radii of TOI-1260b, TOI-1260c are $2.36 \pm 0.06R_{\oplus}$, $2.82 \pm 0.08R_{\oplus}$, respectively while the newly discovered third planet has a radius of $3.09 \pm 0.09R_{\oplus}$. The radius uncertainties are in the range of 3%, allowing a precise interpretation of the interior structure of the three planets. Our planet interior composition model suggests that all three planets in the TOI-1260 system contains some fraction of gas. The innermost planet TOI-1260b has most likely lost all of its primordial hydrogen-dominated envelope. Planets c and d were also likely to have experienced significant loss of atmospheric through escape, but to a lesser extent compared to planet b.

Key words: planets and satellites: detection – planets and satellites: individual: TOI-1260b, c, d – stars: individual: TOI-1260 – techniques: photometric – techniques: radial velocities – planets and satellites: composition

1 INTRODUCTION

Precise characterization of the bulk properties of transiting extrasolar planets allows constraining their possible interior composition. This information is used to infer planet formation processes, as it can be used to demonstrate, for example, transport of material in the protoplanetary disk. Additionally, planets orbiting close to their stars suffer from atmospheric erosion processes (see, e.g. Lampón et al. 2021) that further shape their chemical evolution. The CHaracterising ExOPlanet Satellite (CHEOPS) was launched in 2019 to allow the precise characterization of known planetary systems in order to better understand the processes of planetary formation and evolution (Benz et al. 2021). Since the end of commissioning activities in April 2020, CHEOPS has successfully characterised several planetary systems (e.g. Lendl et al. 2020; Hooton et al. 2022), including the discovery of new planets(e.g. Leleu et al. 2021; Delrez et al. 2021), improving our knowledge of planetary sciences.

In this paper we report the discovery of a third planet orbiting the system TOI-1260, which was previously known to host two

^{*} This article uses data from CHEOPS program CH_PR100031.

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planets (Georgieva et al. 2021, Hereafter G21). The nature of the third planet is supported by ground-based follow-up observations, including time-series photometry, high-angular resolution images, spectroscopy, and archival imagery. Precise photometric monitoring with CHEOPS allows to improve the constraints on the parameters of the system, improving our knowledge on their possible composition. In particular, the study of multiplanet systems with sub-Neptune or super-Earths planets is very interesting for planet formation models, as they share the same disk and have evolved in the same timescales, yet with different outcomes (e.g. Kubyshkina et al. 2019b). The study of small planets allows exploring the effect of physical processes resulting in the observed variation of core compositions and envelope sizes (Modirrousta-Galian et al. 2020). Furthermore, multiplanetary systems provide excellent opportunity to study the dependence of planet formation, evolution and habitability on factors such as stellar insolation, age and spectral type (e.g. Weiss et al. 2018a,b; Leleu et al. 2021).

The planetary system around TOI-1260 was first discovered with the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014), a space-borne NASA mission launched in 2018 to survey the sky for transiting exoplanets around nearby and bright stars. It builds on the legacy of the NASA's Kepler space telescope (Borucki et al. 2010) launched in 2009, which was the first exoplanet mission to perform a large statistical survey of transiting exoplanets. One of the goals of the TESS prime mission is to discover 50 exoplanets with radii smaller than $4R_{\oplus}$ (e.g. Armstrong et al. 2020; Delrez et al. 2021; Lam et al. 2021; and see also the overview of the planet yield during the Prime Mission in Guerrero et al. 2021). Coordinated mass measurements via precise high-resolution spectroscopic follow-up enable accurate inferences about the bulk composition and atmospheric characterization of small exoplanets. To date, there are more than 100 exoplanets smaller than $4R_{\oplus}$ in the public domain, with many more in the TESS pipeline.

CHEOPS and TESS missions complement each other in their aims, with TESS carrying the weight of the detection efforts, organizing the community for the ground-based support observations, and CHEOPS providing accurate measurements of the planetary radius, allowing detailed characterization of the planetary interiors (e.g. Lacedelli et al. 2022; Wilson et al. 2022).

The paper is structured as follows. Section 2 describes the TESS observations and transit analysis. The CHEOPS observations and its transit analysis is described in Section 3. The HARPS-N data and the spectral analyses are described in Section 4. Section 5 outlines the the model and result of the joint analysis of the TESS, CHEOPS photometry and HARPS-N RVs. Section 6 discusses the results of the global fit, the interior structure of the planets, planet atmospheric evolution model and the possible origin of the planetary system. Finally, the conclusion of our work is presented in Section 7.

2 TESS PHOTOMETRY

TOI-1260 was observed by TESS during sector 14 (between 18 Jul 2019 and 15 Aug 2019 on camera 4, CCD 3) and sector 21 (between 21 Jan 2020 and 18 Feb 2020 on camera 2, CCD 2) in 2-minute short cadence mode. This data set was previously analyzed in G21. The target was further observed in sector 41 (between 23 Jul 2021 and 20 Aug 2021) in 2-minute and 20-second cadence mode. The TESS data were process by the Science Process Operation Centre (SPOC Twicken et al. 2010; Morris et al. 2017). SPOC extracted TESS light curves using a Simple Aperture Photometry (SAP) and known instrumental systematics are corrected in the Presearch Data

Conditioning (PDCSAP) light curves (Smith et al. 2012; Stumpe et al. 2012, 2014). The TESS PDCSAP light curves were downloaded from Mikulski Archive for Space Telescopes (MAST¹) and were used for subsequent analyses.Figure 1 shows the PDCSAP light curves of TOI-1260.

3 CHEOPS PHOTOMETRY

We performed follow-up photometric observations with CHEOPS to refine the radii of the two inner planets and to confirm the presence of the outer planet, scheduling 9 visits between 26 Dec 2020 and 4 Mar 2021.

The discovery paper of TOI-1260b and c (G21) reported a possible third planet, on the basis of a single transit in sector 21, with a number of period aliases in the range 20.3 d < P < 56.3 d. The paper discussed the possibility of the third planet having a period of 16.6 days. At the time, only one clear single transit were observed in the TESS light curves. The 16.6-day signal in the radial velocity (RV) data was not significant due to the period being close to a harmonic of the stellar rotation period. The nature of the 16.6-day signal was uncertain. However, their results encouraged our efforts to confirm the suspected third planet in the system. We used our code to identify possible additional transit signatures in the existing data (the code is described in Osborn et al. 2022). This identified a unique period of 16.6 d, meaning that the transit fell in the gap in sector 14. The available data at that time was used to constrain the possible ephemeris of the putative third planet in the system. The visits that we programmed with CHEOPS lasted between 8.25 and 16.8 hours to cover the transits of planet b and c, as well as to confirm the presence of the third planet candidate. The details of each observation runs are listed in Table 1.

Observations obtained in each visit were processed by the CHEOPS data reduction pipeline (DRP; Hoyer et al. 2020). The pipeline calibrated each image by applying bias, gain, non-linear effects, dark current, and flat field corrections. It also corrects individual calibrated frames from environmental effects such as smearing trails, bad pixels, background, and stray-light pollution. The DRP then performed aperture photometry on the calibrated and corrected images to extract the photometric fluxes. Next, the DRP pipeline provides four sets of light curves by performing aperture photometry on the calibrated images using different aperture sizes (R_{ap}) . These apertures are RINF ($R_{ap} = 22.5$ "), DEFAULT ($R_{ap} = 25$ "), RSUP $(R_{ap} = 30^{\circ})$, and a further aperture OPTIMAL which is optimised for each visit. We used the root-mean-squared (RMS) values of the light curve extracted by different aperture in each visit to assess the the light curves. Apart from the first visit of planet c, the RINF aperture of each visit gives the lowest RMS. Thus the corresponding light curves were use for subsequent analysis. For the first visit of planet c, we used the light curve reduced from the OPTIMAL aperture for subsequent analysis.

It is known that the rotation of the CHEOPS field-of-view along with the orbit of the spacecraft can result in varying background, contaminants, or other non-astronomical sources (e.g. Wilson et al. 2022). This may induce noises in the data and cause short trm trends in the photometric light curve. Fortunately, the DRP pipeline provides basis vectors for CHEOPS which is used to correct and detrend these variabilities in the light curves. For our dataset, we use the opensource Python package pycheops (Maxted et al. 2021) to evaluate

¹ https://archive.stsci.edu/tess

the data produced by DRP and found that the light curves showed periodic flux variation that is in phase with the orbit of the spacecraft.

For each visit, we performed simultaneous transit fitting and detrending of a combinations of standard basis vectors used in the decorrelation of CHEOPS data (i.e. background, contamination, smear, x and y centroid positions, and first, second, and third-order harmonics of the roll angle). The Bayesian Information Criterion (BIC) and minimum χ^2 of the model in each visit were assessed separately to select the basis vectors required to optimally detrend each set of light curve. We also used the *addglint* function to remove internal reflection from resulting from the spacecraft rotation cycle in each visit. The detrended CHEOPS light curves were used for our joint model described in Section 5.

4 HOST STAR CHARACTERISATION

TOI-1260 was observed between 14 Jan 2020 and 13 Jun 2020, a campaign in which 33 high resolution spectra (R= 115000) were reported by G21 using the HARPS-N spectrograph (Cosentino et al. 2012). The HARPS-N Data Reduction Software (DRS) pipeline (Cosentino et al. 2014) was used to extract the spectra.

To retrieve the fundamental parameters of TOI-1260, stellar effective temperature, T_{eff} , iron abundance relative to hydrogen, [Fe/H], and the surface gravity, $\log g$, we modelled the HARPS-N co-added high resolution spectrum with the spectral analysis package SME (Spectroscopy Made Easy; Valenti & Piskunov 1996; Piskunov & Valenti 2017), version 5.22. With atomic and molecular line data from VALD (Rvabchikova et al. 2015), the MARCS 2012 (Gustafsson et al. 2008) atmosphere grids, and a chosen set of fundamental parameters, SME calculate synthetic stellar spectra which is fitted to the observations. The models were also checked with the Atlas12 (Kurucz 2013) grids. We followed the modelling procedure explained in (Persson et al. 2018). In summary, we modelled $T_{\rm eff}$ and log g with the H_{α} line wings and the Ca₁ λ =6102 Å, 6122 Å, and 6162 Å triplet, respectively. The model was checked with the Na1 doublet at λ =5888 Å and 5895 Å. The abundances and projected stellar rotational velocity, $V \sin i_{\star}$, were modelled from unblended lines between λ =6000 Å and 6600 Å. The results, listed in Table 2, were checked with the empirical SpecMatch-Emp code (Hirano et al. 2018) which were in very good agreement with SME. The full set of host star parameters are listed in Table 2.

As recently described in Schanche et al. (2020), we can use a modified version of the infrared flux method (IRFM; Blackwell & Shallis 1977) to determine the stellar angular diameters and effective temperatures of stars through known relationships between these properties, and estimates of the apparent bolometric flux, via a Markov-Chain Monte Carlo (MCMC) approach. We perform synthetic photometry of TOI-1260 by building spectral energy distributions (SEDs) from stellar atmospheric models with the stellar parameters, derived via the spectral analysis detailed above, as priors. To compute the apparent bolometric flux, these fluxes are compared to the observed data taken from the most recent data releases for the following bandpasses; Gaia G, GBP, and GRP, 2MASS J, H, and K, and WISE W1 and W2 (Skrutskie et al. 2006; Wright et al. 2010; Gaia Collaboration et al. 2021) with the stellar atmospheric models taken from the ATLAS Catalogues (Castelli & Kurucz 2003). We convert the stellar angular diameter to the stellar radius of TOI-1260 using the offset corrected Gaia EDR3 parallax (Lindegren et al. 2021) and obtain $R_{\star} = 0.672 \pm 0.010 \, R_{\odot}.$

Together with R_{\star} , we used the effective temperature and the metallicity to then derive the isochronal mass M_{\star} and age t_{\star} . Rather than directly adopting [Fe/H] as a proxy for the stellar metallicity, we estimated the α -element abundance by averaging out the [Mg/H] and [Si/H], obtaining $\left[\alpha/\text{Fe}\right] = 0.13 \pm 0.13$. Using Eq. (3) from Yi et al. (2001), we finally computed the metallic content of the star ($[M/H] = 0 \pm 0.15$ dex) from [Fe/H] and [α /Fe]. To make our M_{\star} and t_{\star} estimates more robust we employed two different evolutionary models, namely PARSEC² v.1.2S (Marigo et al. 2017) and CLES (Code Liègeois d'Évolution Stellaire Scuflaire et al. 2008). In detail, we interpolated the input set ([M/H], $T_{\rm eff}$, and R_{\star}) within pre-computed grids of PARSEC isochrones and tracks through the isochrone placement technique described in Bonfanti et al. (2015, 2016) and we derived a first best-fit pair of mass and age. The code further accounted for $v \sin i$ and $\log R'_{HK}$ as outlined in Bonfanti et al. (2016) to improve the convergence. Instead, the second pair of mass and age was inferred by directly fitting the input set into the evolutionary track built by CLES according to the Levenberg-Marquadt minimisation criterion (Salmon et al. 2021). After carefully checking the consistency of the results outputted by the two codes through the χ^2 -test described in Bonfanti et al. (2021a), we finally merged the respective output distributions ending up with $M_{\star} = 0.679^{+0.095}_{-0.057} M_{\odot}$ and $t_{\star} = 6.7^{+5.1}_{-5.2}$ Gyr. The host star mass and radius derived in this work are consistent within ~ 1 -sigma and we adopt values from this work for subsequent analyses.

5 JOINT LIGHT CURVE AND RADIAL VELOCITY ANALYSIS

A global analysis of the observational data was performed using the exoplanet toolkit (Foreman-Mackey et al. 2021). The toolkit implements the probabilistic programming package PyMC3 (Salvatier et al. 2016) to perform a Bayesian inference using a Hamiltonian Monte Carlo (HMC; Duane et al. 1987) method.

We first removed the out of transit variability in the TESS light curve by first masking the transits in the light curve, then binning the light curve into 1-hour steps. A Gaussian Process (GP) regression model with a simple harmonic oscillator (SHO) kernel, implemented by celerite2 (Foreman-Mackey et al. 2017; Foreman-Mackey 2018), was then applied to remove the light curve variations.

The joint analysis was subsequently carried out on the "flattened" TESS light curve from the aforementioned best-fit GP photometry model, CHEOPS light curve, and the HARPS-N RV data. The toolkit uses starry (Luger et al. 2019) to model the limb darkened transit light curves. To account for the limb darkening parameters of the star, we used the quadratic limb darkening coefficients (u_1, u_2) parameterised by Kipping (2013) in the model for each photometric instrument. Uniform priors were used for the planet orbital periods $(P_{\rm b}, P_{\rm c} \text{ and } P_{\rm d})$, mid-transit times $(T0_{\rm b}, T0_{\rm c} \text{ and } T0_{\rm d})$, planet-to-star radius ratios $(R_{p,b}/R_{star}, R_{p,c}/R_{star})$ and $R_{p,d}/R_{star})$ and impact parameters (b_b, b_c, b_d) . We account for the instrument zero-point offset between the TESS (σ_{TESS}) and CHEOPS (σ_{CHEOPS}) light curves by fitting a mean to the light curves of the two separate instruments. Gaussian priors were used for the stellar mass M_{star} and radius R_{star} based on the results in Section 4. The Keplerian orbits of the three transiting planets are defined by their orbital periods. The planets' respective semi-major axes (a_b, a_c, a_d) can be derived using Kepler's third law and the scaled semi-major axes $(a_b/R_{\text{star}}, a_c/R_{\text{star}}, a_c/R_{\text{star}})$ $a_{\rm d}/R_{\rm star}$) were subsequently derived from the fitted stellar radius.

² PAdova and TRieste Stellar Evolutionary Code: http://stev.oapd. inaf.it/cgi-bin/cmd

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Table 1. List of CHEOPS observations of TOI-1260. The file key is the unique identifier which corresponds to the dataset used.

File Key	Observation Start	Observation End	Duration [h]	Exposure Time [s]	N _{frames}
CH_PR100031_TG018501_V0200	2020-12-26 23:21	2020-12-27 08:04	8.72	60.0	296
CH_PR100031_TG018502_V0200	2021-01-18 09:34	2021-01-28 18:34	9.00	60.0	270
CH_PR100031_TG018503_V0200	2021-02-02 09:51	2021-02-02 18:15	8.40	60.0	285
CH_PR100031_TG018504_V0200	2021-02-17 10:49	2021-02-17 19:14	8.42	60.0	291
CH_PR100031_TG036501_V0200	2021-01-22 21:31	2021-01-23 04:58	7.45	60.0	273
CH_PR100031_TG036502_V0200	2021-02-01 05:58	2021-02-01 14:13	8.25	60.0	254
CH_PR100031_TG036504_V0200	2021-02-13 18:18	2021-02-14 02:33	8.25	60.0	281
CH_PR100031_TG036505_V0200	2021-02-16 22:17	2021-02-17 06:32	8.25	60.0	280
CH_PR100031_TG038201_V0200	2021-03-04 03:50	2021-03-04 19:10	15.34	60.0	522

Table 2. Stellar parameters of TOI-1260.

Parameter [Unit]	Value.	Note
Identifiers	TIC 355867695	
RA (ICRS Ep. 2016.0)	157.14401106413	1
Dec (ICRS Ep. 2016.0)	+65.85418726790	1
π [mas]	13.6226 ± 0.0147	1
$\mu_{\alpha} [\text{mas yr}^{-1}]$	-177.340 ± 0.012	1
$\mu_{\delta} [\mathrm{mas \ yr^{-1}}]$	-81.693 ± 0.013	1
Effective temperature $T_{\rm eff}$ [K]	4227 ± 85	2
[Fe/H] abundance	-0.1 ± 0.07	2
[Si/H] abundance	-0.02 ± 0.15	2
[Mg/H] abundance	0.09 ± 0.15	2
$[\alpha/\text{Fe}]$ abundance	0.13 ± 0.13	2
[M/H] abundance	0 ± 0.15	2
$\log g [\mathrm{cgs}]$	4.57 ± 0.05	2
Stellar rotation velocity $v \sin i [\text{km s}^{-1}]$	1.5 ± 0.7	2
Stellar rotation period $P_{\rm rot}$ [d]	30.63 ± 3.81	2
Chromospheric activity $\log R'_{\rm HK}$	-4.86	3
Stellar mass $M_{\text{star}} [M_{\odot}]$	$0.679^{+0.095}_{-0.057}$	2
Stellar radius $R_{\text{star}} [R_{\odot}]$	0.672 ± 0.010	2
Stellar density ρ_{star} [g cm ⁻³]	3.43 ± 0.08	2
Bolometric luminosity $[L_{\odot}]$	0.129 ± 0.004	2
Stellar age [Gyr]	$6.7^{+5.1}_{-5.2}$	2

[1] Gaia Collaboration et al. (2021), [2] this work, [3] Suárez Mascareño et al. (2015)

The TOI-1260 star is moderately active where activity-induced variations were reported by G21. The activity-induced variations in the RVs were modeled by a GP model alongside the three-planet Keplerian model. We chose a RotationTerm GP kernel (Foreman-Mackey 2018), which consists of a mixture of two SHO terms to describe the stellar rotation. A uniform prior was used for the log rotation period (log P_{rot}) parameter and the radial velocity semi-amplitudes (K_b , K_c , K_c) in the RV dataset. Finally, we included jitter (σ_{HARPS}) and mean velocity offset or systemic offset (γ_{HARPS}) parameters for the RV fit. The host star mass and radius were sampled using a Gaussian prior which is based on our results in Section 4. We note that the best-fit stellar rotation period from our GP model is 30.63 ± 3.81 days. This gives a rotation rate of $2\pi R_{star}/P_{rot} = 1.1$ km s⁻¹ which is consistent with our V sin i value from Section 4.

The fitted parameters were first optimised with the scipy.optimize.minimize function, integrated in the exoplanet package, to find the respective maximum a posteriori parameters. These estimates were used to initialise parameters in the sampling space via a "No U-Turn Sampling" (NUTS; Hoffman & Gelman 2011), a gradient-based HMC sampler implemented in PyMC3. We initiated 4 sampling chains where each chain has

2000 tuning steps and 2000 draw iterations. The Gelman-Rubin statistic (Gelman & Rubin 1992) of the sample is ≤ 1.003 , indicating the chains are converged.

The phase-folded TESS and CHEOPS transit light curves and the corresponding best-fit transit models are shown in Figure 2. The HARPS-N RVs and best-fit three planet RV model is shown in Figure 3. The phase-folded RVs for each planet and their respective best-fit models are shown in Figure 4.

We studied the case where planet eccentricities are allowed to float in the model and found that there are no difference between the zero and non-zero eccentricities models. Hence we adopted the zero eccentricity model. The resulting median parameters and their $1-\sigma$ uncertainties are listed in Table 3. The posterior distributions of fitted parameters are shown in the corner plot in Figure A1.

TOI-1260 is a multiplanet system that consists of three transiting exoplanets where the innermost planet TOI-1260b has a radius and mass of 2.41 ± 0.05 R_{\oplus} and 8.56 ± 1.54 M_{\oplus} , respectively. TOI-1260c has a radius and mass of 2.74±0.07 R_{\oplus} and 13.20±4.23 M_{\oplus} , respectively, while the outermost planet TOI-1260d has a radius of 3.12 ± 0.08 R_{\oplus} and a mass of 11.84 ± 7.79 M_{\oplus} , respectively. With the addition of the CHEOPS photometry as well as TESS data

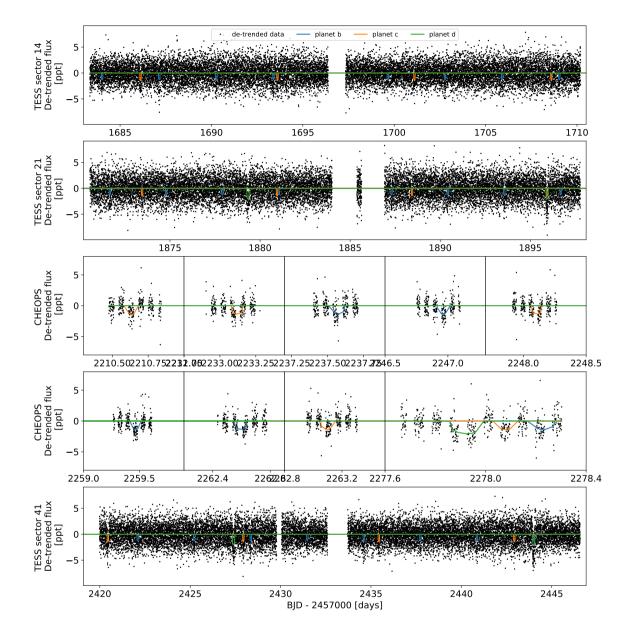


Figure 1. Time-series light curves of TOI-1260. From top to bottom: The TESS PDCSAP light curves from Sectors 14, 21, and 41 are shown in the first, second, and last panels, respectively. The TESS light curves were detrended using a Gaussian Process model described in Section 5. The CHEOPS light curves are shown in the third and fourth rows.

from more recent sectors, this work has significantly improved the precision of the radius measurements of TOI-1260b and c compared to previous work. The radii of all three transiting planets are measured with a precision of better than 3%. We note that the mass precision of planets b and c in our work is does not improve despite the inclusion of planet d in the Keplerian model. This may be due to the methodology

used to model the stellar activity induced variation in the RV data. In G21, the author applies a multi-dimensional GP approach and used activity indicators as prior to constraining the GP model which reduced the flexibility of the GP to model the RVs and may have resulted in a smaller semi-amplitude precision. Nevertheless, the

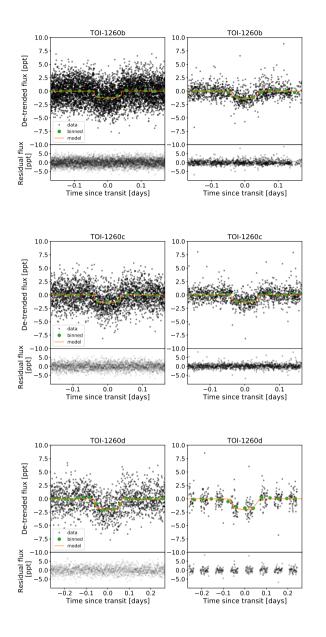


Figure 2. Phase folded light curves of TOI-1260b (top), TOI-1260c (middle), TOI-1260d (bottom). The TESS data are shown in the left panels and the CHEOPS data are shown in the right panels. Residuals of each transit are shown below each phase-folded light curves. The phase binned data are denoted by green points and the orange line shows the best-fitted transit models for each planet.

mass determination of planets b and c are consistent within 1-sigma with values derived in G21.

The mass precision of the planets is the main source of uncertainty in the determination of the planetary bulk densities in the system. This work highlights the need to strategically obtain more RVs for the system in order to understand the effect of stellar activity on the RVs of the system and better constrain the planetary masses.

6 DISCUSSION

The follow-up photometric observations of TOI-1260 allows the precise characterisation of the two inner transiting planets and confirms the planetary nature of the transiting outer planetary companion. Figure 5 shows the mass-radius diagram of known exoplanets with masses below 30 M_{\oplus} and radii less than 4 R_{\oplus} . We proceed now with the discussion of the interior composition and atmospheric evolution of the planetary system.

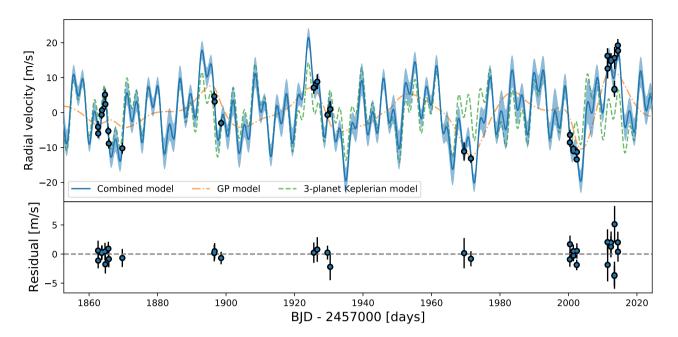


Figure 3. *Top:* Time-series HARPS-N RVs of TOI-1260. The RVs were modelled using a three-planet Keplerian RV model and a GP simultaneously to model the activity-induced RV variations (see Section 5). The green dash line shows the 3-planet Keplerian model and the orange dash-dot line shows the GP model that accounts for activity induced RV variations. The blue solid line shows the median three-planet Keplerian + GP model. The 1-sigma credible intervals of the best fit Keplerian + GP model is indicated by the blue shaded region.

Bottom: Residuals of the RV data.

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Table 3. System	parameters obtained from th	e joint light curves and radial	velocities analysis.	s. The median values and 1	-sigma uncertainty are reported.

Parameter [Unit]	Planet b	Planet c	Planet d
Fitted parameters			
Period P [day]	3.127463 ± 0.000005	7.493134 ± 0.000020	16.608164 ± 0.000083
Epoch T0 [BJD-2457000]	2065.564269 ± 0.000396	2068.270505 ± 0.000577	2062.017406 ± 0.001309
Planet-to-Stellar radius ratio [Rp/Rs]	0.0329 ± 0.0006	0.0377 ± 0.0007	0.0425 ± 0.0009
Impact paramater b	0.20 ± 0.12	0.75 ± 0.02	0.53 ± 0.05
Radial velocity semi-amplitude K [m s ⁻¹]	4.93 ± 0.83	5.67 ± 1.77	3.90 ± 2.54
Eccentricity e	0 (adopted)	0 (adopted)	0 (adopted)
Angle of periastron ω [°]	0 (adopted)	0 (adopted)	0 (adopted)
Derived parameters	-	-	-
Transit duration T14 [hr]	2.06 ± 0.02	1.97 ± 0.03	3.19 ± 0.07
Transit depth [ppm]	1082 ± 37	1421 ± 55	1808 ± 78
Scaled semi-major axis a/Rs	11.73 ± 0.35	20.99 ± 0.63	35.69 ± 1.06
Orbital semi-major axis a [au]	0.0367 ± 0.0011	0.0657 ± 0.0020	0.1116 ± 0.0033
Inclination i [deg]	89.03 ± 0.61	87.97 ± 0.11	89.14 ± 0.10
Planet radius R_p $[R_{\oplus}]$	2.41 ± 0.05	2.76 ± 0.07	3.12 ± 0.08
Planet mass $M_p[M_{\oplus}]$	8.56 ± 1.54	13.20 ± 4.23	11.84 ± 7.79
Planet density $\rho_p [g \ cm^{-3}]$	3.35 ± 0.64	3.45 ± 1.14	2.14 ± 1.42
Planet surface gravity $\log g_p$	3.16 ± 0.09	3.23 ± 0.15	3.08 ± 0.30
Equilibrium dayside temperature [K]	871 ± 24	651 ± 18	499 ± 14
Stellar insolation $[S_{\oplus}]$	95.58 ± 0.07	29.81 ± 0.05	10.32 ± 0.07
TESS instrument offset σ_{TESS} [ppm]	64.0 ± 8.6		
CHEOPS instrument offset σ_{TESS} [ppm]	48.8 ± 14.7		
HARPS jitter σ_{HARPS} [m s ⁻¹]	0.22 + /-0.79		
Systemic radial velocity γ_{HARPS} [m s ⁻¹]	10.73 ± 2.63		
Limb darking parameter $u_{1,\text{TESS}}$	0.21 ± 0.18		
Limb darkening parameter $u_{2,\text{TESS}}$	0.53 ± 0.26		
Limb darking parameter $u_{1,CHEOPS}$	0.92 ± 0.18		
Limb darking parameter $u_{2,CHEOPS}$	-0.33 ± 0.21		
GP RotationTerm parameters			
GP rotation period $R_{rot,GP}$ [day]	30.63 ± 3.81		
$\sigma_{ m GP}$	6.62 ± 1.45		
Q0	0.83 ± 1.48		
dQ	1.94 ± 3.67		
f	0.70 ± 0.23		
Stellar mass $M_{\rm s}$ [M_{\odot}]	0.67 ± 0.06		
Stellar radius $R_{\rm s} [R_{\odot}]$	0.67 ± 0.01		
Stellar density ρ_s [g cm ⁻³]	3.12 ± 0.33		

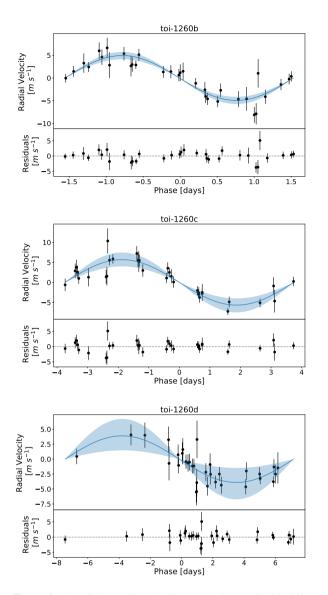


Figure 4. Phase-folded radial velocities and residuals of TOI-1260b (top), TOI-1260c (middle), TOI-1260d (bottom). The best-fit RV models are indicated by the solid blue line and the corresponding 1-sigma credible interval is shown by the blue shaded region.

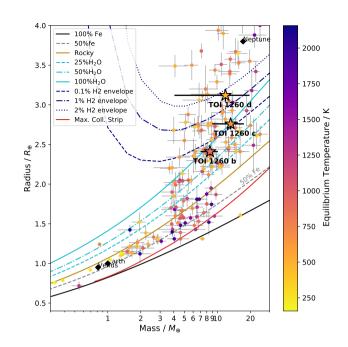


Figure 5. Mass-radius diagram showing low mass planets in the range of 0.4-30 M_{\oplus} which have mass and radius precision measured to better than 30% and 15%, respectively. TOI-1260b, TOI-1260c, TOI-1260d, are indicated by the star symbols. All exoplanets are colour-coded according to their the equilibrium dayside temperatures as shown in the colour bar. The different lines plotted are the theoretical mass-radius relations corresponding to the planet interior compositions (Zeng et al. 2019).

6.1 Interior composition of the planets

The TOI-1260 system has three sub-Neptune transiting exoplanets where planets b, c and d have masses of 8.56 \pm 1.54 M_{\oplus} , 13.20 \pm 4.23 M_{\oplus} and 11.84 ± 7.79 M_{\oplus} , respectively, and their radii are $2.41 \pm 0.05 R_{\oplus}$, $2.76 \pm 0.07 R_{\oplus}$, and $3.12 \pm 0.08 R_{\oplus}$, respectively. This means that the three sub-Neptunes TOI-1260 b, c and d have bulk densities of 3.35 \pm 0.64 g cm^{-3}, 3.45 \pm 1.14 g cm^{-3}, and 2.14 ± 1.42 g cm⁻³, respectively. Figure 5 shows the distribution of known exoplanet with precise mass and radius measurements in the mass-radius diagram, alongside some theoretical mass-radius relations for different planet interior compositions. The interior of TOI-1260 b is likely to be consisted of up up 50% rocky core and a 50% H₂O layer. In the case of TOI-1260 c, the sub-Neptune planet is likely a water world or it could be composed of a water-rich core with a small fraction of H2 atmosphere. For the outermost planet TOI-1260 d, its interior is likely to consist of a water-rich or Earth-like rocky core with up to $\sim 2\%$ of H2 atmosphere.

The interior compositions of exoplanet correlates with the compositions of their host stars (Adibekyan et al. 2021a). This is because they were formed from accretion of the same disk material. Therefore, using physical parameters of the host star in addition to the planet's mass and radius provides a better constrain to the planet's interior composition. Using the values of radius, mass, and stellar properties derived in Section 5, we performed an analysis of the internal structure of the three planets in the TOI-1260 system. Our method is based on a global Bayesian model that fits the observed properties of the star (mass, radius, age, effective temperature, and the photospheric abundances [Si/Fe] and [Mg/Fe]) and planets (planetstar radius ratio, the RV semi-amplitude, and the orbital period). The hidden parameters in the Bayesian model are, for each planet, the masses of solids (everything except the H or He gas), the mass fractions of the core, mantle and water, the mass of the gas envelope, the Si/Fe and Mg/Fe mole ratios in the planetary mantle, the S/Fe mole ratio in the core, and the equilibrium temperature. All details on the methods are presented in Leleu et al. (2021).

The Bayesian analysis relies on a forward models that computes the expected planetary radius and bulk internal structure as a function of the hidden parameters. In the forward model, we assume a fully differentiated planet made of a core (composed of Fe and S), a mantle (composed of Si, Mg, Fe, and O), a pure water layer, and a H and He layer. The temperature profile is adiabatic, and the equations of state (EoS) used for these calculations are taken from Hakim et al. (2018) and Fei et al. (2016) for the core materials, from Sotin et al. (2007) for the mantle materials, and Haldemann et al. (2020) for water. The thickness of the gas envelope is determined as a function of the gas mass fraction, the equilibrium temperature, the mass and radius of the solid planet, and the age (assumed to be equal to the stellar age), using the semi-analytical model of Lopez & Fortney (2014). Importantly, the radius of the high-Z part of the planet (core, mantle and water layer) is computed independently of the thickness of the gas layer. This implies in particular that the compression effect of the gas envelope onto the core, as well as the effect of the temperature at the basis of the gas envelope are not included in the mode.

The Bayesian analysis is done assuming the following priors: the mass fractions of the planetary cores, mantles, and water layers have uniform positive priors (the mass fractions of water being limited to a maximum value of 0.5). The prior on the gas mass is uniform in log, and the bulk Si/Fe and Mg/Fe mole ratios in the planet are

assumed to be equal to the values determined for the atmosphere of the star, given above 3 .

The posterior distribution of the main planetary hidden parameters are presented in Fig. 6. All planets have some fraction of gas, the mass of gas increasing for decreasing equilibrium temperatures (see Fig. 7). The fraction of water, on the other hand, is essentially unconstrained.

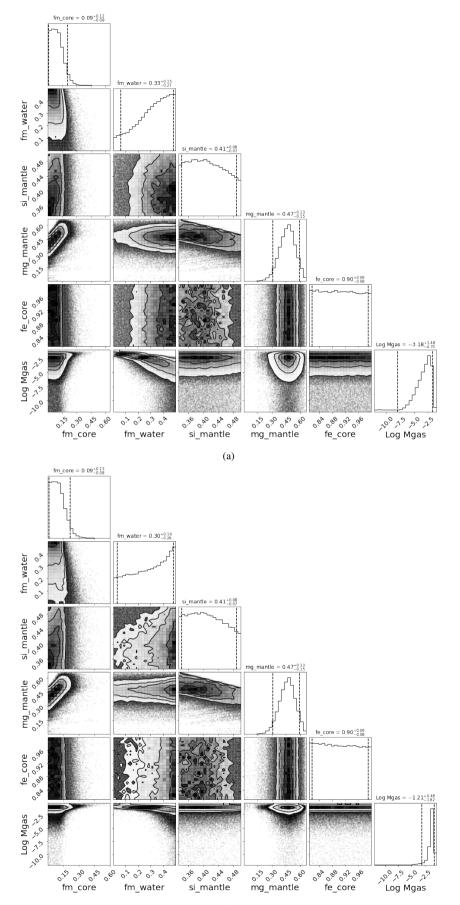
6.2 Atmospheric evolution

We considered the stellar and planetary parameters derived in our paper, as well as the present-day planetary atmospheric mass fractions presented in Section 6.1, to reconstruct the evolution of the stellar rotation rate and of the planetary atmospheres. In particular, we constrain the evolution of the stellar rotation period, which we use as proxy for the evolution of the stellar high-energy emission affecting atmospheric escape, and the predicted initial atmospheric mass fraction of the detected planets $f_{\text{atm}}^{\text{start}}$, that is the mass of the planetary atmosphere at the time of the dispersal of the protoplanetary disk, which we assume being at 5 Myr.

We reach these results by using the Planetary Atmospheres and Stellar RoTation RAtes (PASTA; Bonfanti et al. 2021b) code, which is an updated version of the original code presented by Kubyshkina et al. (2019c,a). In short, PASTA constraints the evolution of planetary atmospheres and of the stellar rotation rate combining a model predicting planetary atmospheric escape rates based on hydrodynamic simulations (this has the advantage over other commonly used analytical estimates to account for both XUV-driven and corepowered mass loss; Kubyshkina et al. 2018), a model of the stellar high-energy (X-ray plus extreme ultraviolet; XUV) flux evolution (Bonfanti et al. 2021b), a model relating planetary parameters and atmospheric mass (Johnstone et al. 2015b), and stellar evolutionary tracks (Choi et al. 2016). PASTA works under two main assumptions: 1) planet migration did not occur after the dispersal of the protoplanetary disk; 2) the planets hosted at some point in the past or still host a hydrogen-dominated atmosphere. PASTA returns realistic uncertainties on the free parameters (i.e. the planetary initial atmospheric mass fractions at the time of the dispersal of the protoplanetary disk, and the indexes of the power law controlling the stellar rotation period that is used as proxy for the stellar XUV emission) by implementing the atmospheric evolution algorithm in a Bayesian framework (Cubillos et al. 2017), using the system parameters with their uncertainties as input priors. All details of the algorithm can be found in Bonfanti et al. (2021b). The only difference with respect to the analysis of the systems considered by Bonfanti et al. (2021b) is that here we fit the planetary atmospheric mass fractions given in Section 6.1 instead of the planetary radii. This enables the code to be more accurate by avoiding the continuous conversion of the atmospheric mass fraction into planetary radius, given the other system parameters (see e.g. Delrez et al. 2021).

Figure 8 shows the results obtained from PASTA. As a proxy for the evolution of the stellar rotation period, Figure 8 displays the posterior distribution of the stellar rotation period at an age of 150 Myr ($P_{rot,150}$), also in comparison to that of stars member of young open clusters and of comparable mass extracted from Johnstone et al. (2015a). The posterior distribution is slightly shifted towards slower rotation compared to that of the open cluster stars, indicating that the

³ It should be noted however that Adibekyan et al. (2021b) has found that despite an existing correlation between the abundances of planets and host stars, the relation is not always strictly one-to-one.



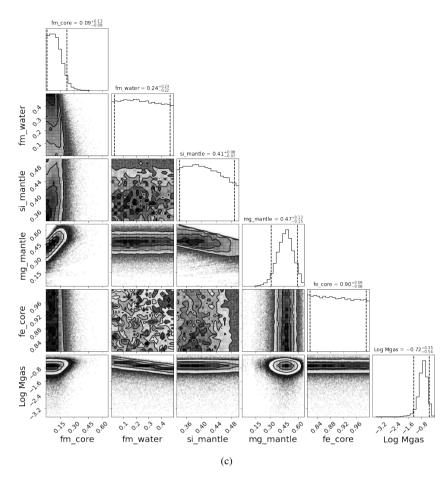


Figure 6. Corner plot showing the results on the interior composition models of (a) TOI-1260 b, (b) TOI-1260 c and (c) TOI-1260 d. The vertical dashed lines and the 'error bars' given at the top of each columns represent the 5 % and 95 % percentiles.

planets were likely subject to somewhat less XUV radiation than the average.

Figure 8 shows also the posterior distribution of the initial atmospheric mass fraction for planets b (in linear scale), c (in logarithmic scale), and d (in logarithmic scale) in comparison to the present-day atmospheric mass fraction (Section 6.1). The posterior distribution for planet b is flat, indicating that the planet has most likely lost (almost) entirely its primordial hydrogen-dominated envelope through escape at some point in the past, which is why PASTA is unable to constrain the initial atmospheric mass fraction. Figure 8 indicates that also planets c and d have gone through significant evolution through escape that has significantly eroded the primordial atmospheric content, which was however small in comparison to the planetary masses. Therefore, we conclude that both planets (i.e. c and d) accreted a small hydrogen envelope during the formation process compared to their masses. This may have been the result of several physical mechanisms, such as late planet formation compared to the age of the protoplanetary disk, early dispersal of the protoplanetary disk, low gas content of the disk.

As the isochronal age is loosely constrained, we performed additional evolution runs by artificially making the star much younger or older, further imposing tighter constraints on the stellar age. Despite the different evolutionary time scales, we did not find significant changes in the $f_{\rm atm}^{\rm start}$ of the planets. This is because (1) atmospheric mass loss is significant only during the first Myrs of evolution and (2) $f_{\rm atm,c}^{\rm start}$ and $f_{\rm atm,d}^{\rm start}$ are always found to be rather small, indicating that the constraints given by system parameters prevent those planets to host a massive initial atmosphere regardless of the age of the system.

The current stellar XUV fluxes impinging on each planet are $F_{\rm XUV,b} = 2.87 \cdot 10^4 \text{ erg/(cm}^2 \text{ s})$, $F_{\rm XUV,c} = 8.97 \cdot 10^3 \text{ erg/(cm}^2 \text{ s})$, and $F_{\rm XUV,d} = 3.10 \cdot 10^3 \text{ erg/(cm}^2 \text{ s})$. The correspondent massloss rate values expected for the planets right now are $\dot{M}_b = 10^{10}$ g/s, $\dot{M}_c = 1.59 \cdot 10^9$ g/s, and $\dot{M}_d = 7.43 \cdot 10^8$ g/s. Assuming that the stellar XUV flux does not change over time in the future, which is a reasonable assumption given the old age of the star, these values imply that in the next Gyr the planets are respectively going to lose 0.6%, 0.06%, and 0.03% of their mass. From Fig. 7 these values then imply that planet b is going to lose entirely its hydrogen-dominated envelope, while planets c and d are going to keep it. As the results of planet b are consistent with no hydrogen atmosphere at all, it is unlikely that the position of these planets in the period-radius diagram (e.g. Fulton et al. 2017) is going to change in the future.

7 CONCLUSIONS

We presented the follow-up observations of the TOI-1260 system using CHEOPS and TESS. The addition of the recent photometric dataset allow us to refine the physical parameters of the planetary system and discover a third additional transiting planet. For planets TOI-1260 b and c, we found that the radii are $2.36 \pm 0.06 R_{\oplus}$, $2.82 \pm 0.08 R_{\oplus}$, respectively, and the masses $8.52 \pm 1.45 M_{\oplus}$ and $13.29 \pm$

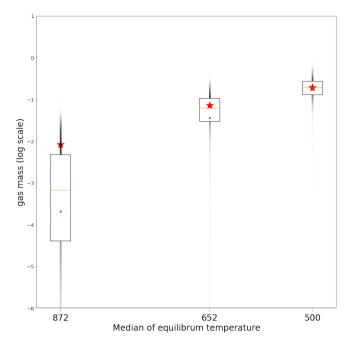


Figure 7. Gas fraction in the planets as a function of their equilibrium temperature. The box show the 25 % and 75 % percentiles, the orange line represents the median of the posterior distribution, the green triangle is the mean, and the red stars is located at the mode of the posterior distribution. Finally, the opacity of the thick vertical black line is proportional to the posterior distribution.

 $3.94~M_\oplus$. The newly discovered TOI-1260-d has bulk properties $3.01\pm0.09~R_\oplus$ and $11.8\pm7.5~M_\oplus.$

The detailed characterization of the planetary parameters allows us to derive constraints of their internal composition and evolution that we related to the formation processes in the system and its future evolution.

The TOI-1260 system presents an exciting opportunity for comparative exoplanetology using JWST transmission spectroscopy. Moses et al. (2013) predicted that sub-Neptune sized exoplanets such as those in the TOI-1260 system can harbour a large diversity of atmospheric compositions. Multi-planet systems such as TOI-1260 give us the opportunity to test whether such diversity can exist within different sub-Neptunes in the same system. All three of the planets in the TOI-1260 system appear to be favourable for atmospheric categorisation with JWST, with transmission spectroscopy metrics (TSMs Kempton et al. 2018) of 43.6, 36.1 and 40.4 for planets b, c, and d, respectively. Figure 9 shows how this compares to similar multiplanet systems as a function of planetary radius and semi-major axis. In addition, due to its high northern declination TOI-1260 is particularly favourable for JWST visibility, with observations possible for 196 days each year (Bourque et al. 2021).

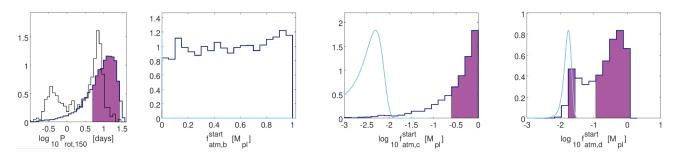


Figure 8. Posterior probability density functions (PDFs) of the stellar rotation period when TOI-1260 was 150 Myr old ($P_{rot,150}$) and of the initial atmospheric mass fraction (f_{atm}^{start}) of the hosted exoplanets. The purple areas show the 68%-HPD (highest posterior density) interval. *Leftmost panel.* $P_{rot,150}$ PDF (dark blue histogram) to be compared with the rotation period distribution of stars of comparable masses that belong to coeval open clusters (black histogram; data taken from Johnstone et al. 2015a). *Other panels.* Atmospheric mass fractions PDFs of planet b (linear scale) and of planet c and d (log scale). The light blue curve is the present-day atmospheric content, as inferred from our internal structure analysis. See text for details.

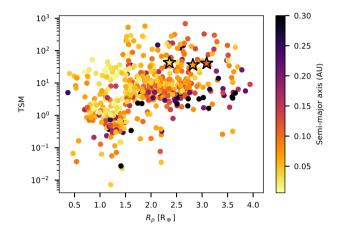


Figure 9. Unscaled transmission spectroscopy metrics (TSM) of all multiplanet systems with host stars of K-type and later as a function of planetary radius, with orbital separation visible in the colour scale. The three planets in the TOI-1260 system are marked with stars.

ACKNOWLEDGEMENTS

CHEOPS is an ESA mission in partnership with Switzerland with important contributions to the payload and the ground segment from Austria, Belgium, France, Germany, Hungary, Italy, Portugal, Spain, Sweden, and the United Kingdom. The CHEOPS Consortium would like to gratefully acknowledge the support received by all the agencies, offices, universities, and industries involved. Their flexibility and willingness to explore new approaches were essential to the success of this mission.

KGI is the ESA CHEOPS Project Scientist and is responsible for the ESA CHEOPS Guest Observers Programme. She does not participate in, or contribute to, the definition of the Guaranteed Time Programme of the CHEOPS mission through which observations described in this paper have been taken, nor to any aspect of target selection for the programme.

K.W.F.L. acknowledge support by DFG grants RA714/14-1 within the DFG Schwerpunkt SPP 1992, "Exploring the Diversity of Extrasolar Planets".

YA, MJH and JAE acknowledge the support of the Swiss National Fund under grant 200020_172746.

CMP, MF and IYG gratefully acknowledge the support of the Swedish National Space Agency (DNR 65/19, 174/19, 174/18).

SH gratefully acknowledges CNES funding through the grant

837319.

ACC and TW acknowledge support from STFC consolidated grant numbers ST/R000824/1 and ST/V000861/1, and UKSA grant number ST/R003203/1.

We acknowledge support from the Spanish Ministry of Science and Innovation and the European Regional Development Fund through grants ESP2016-80435-C2-1-R, ESP2016-80435-C2-2-R, PGC2018-098153-B-C33, PGC2018-098153-B-C31, ESP2017-87676-C5-1-R, MDM-2017-0737 Unidad de Excelencia "María de Maeztu"- Centro de Astrobiolog'ia (INTA-CSIC), as well as the support of the Generalitat de Catalunya/CERCA programme. The MOC activities have been supported by the ESA contract No. 4000124370.

S.C.C.B. acknowledges support from FCT through FCT contracts nr. IF/01312/2014/CP1215/CT0004.

XB, SC, DG, MF and JL acknowledge their role as ESA-appointed CHEOPS science team members.

ABr was supported by the SNSA.

This project was supported by the CNES.

LD is an F.R.S.-FNRS Postdoctoral Researcher. The Belgian participation to CHEOPS has been supported by the Belgian Federal Science Policy Office (BELSPO) in the framework of the PRODEX Program, and by the University of Liège through an ARC grant for Concerted Research Actions financed by the Wallonia-Brussels Federation.

This work was supported by FCT - Fundação para a Ciência e a Tecnologia through national funds and by FEDER through COMPETE2020 - Programa Operacional Competitividade e Internacionalização by these grants: UID/FIS/04434/2019; UIDB/04434/2020; UIDP/04434/2020; PTDC/FIS-AST/32113/2017 & POCI-01-0145-FEDER-032113; PTDC/FIS-AST/28953/2017 & POCI-01-0145-FEDER-028953; PTDC/FIS-AST/28987/2017 & POCI-01-0145-FEDER-028987. O.D.S.D. is supported in the form of work contract (DL 57/2016/CP1364/CT0004) funded by national funds through FCT. B.-O.D. acknowledges support from the Swiss National Science Foundation (PP00P2-190080).

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (project FOUR ACES; grant agreement No 724427). It has also been carried out in the frame of the National Centre for Competence in Research PlanetS supported by the Swiss National Science Foundation (SNSF). DE acknowledges financial support from the Swiss National Science Foundation for project 200021_200726. DG gratefully acknowledges financial support from the CRT foundation under Grant No. 2018.2323 "Gaseousor rocky? Unveiling the nature of small worlds".

M.G. is an F.R.S.-FNRS Senior Research Associate.

This work was granted access to the HPC resources of MesoPSL financed by the Region IIe de France and the project Equip@Meso (reference ANR-10-EQPX-29-01) of the programme Investissements d'Avenir supervised by the Agence Nationale pour la Recherche.

ML acknowledges support of the Swiss National Science Foundation under grant number PCEFP2_194576.

GSc, GPi, IPa, LBo, VNa and RRa acknowledge the funding support from Italian Space Agency (ASI) regulated by "Accordo ASI-INAF n. 2013-016-R.0 del 9 luglio 2013 e integrazione del 9 luglio 2015 CHEOPS Fasi A/B/C".

PM acknowledges support from STFC research grant number ST/M001040/1.

This work was also partially supported by a grant from the Simons Foundation (PI Queloz, grant number 327127).

IR acknowledges support from the Spanish Ministry of Science and Innovation and the European Regional Development Fund through grant PGC2018-098153-B- C33, as well as the support of the Generalitat de Catalunya/CERCA programme.

S.G.S. acknowledge support from FCT through FCT contract nr. CEECIND/00826/2018 and POPH/FSE (EC).

GyMSz acknowledges the support of the Hungarian National Research, Development and Innovation Office (NKFIH) grant K-125015, a PRODEX Institute Agreement between the ELTE Eötvös Loránd University and the European Space Agency (ESA-D/SCI-LE-2021-0025), the Lendület LP2018-7/2021 grant of the Hungarian Academy of Science and the support of the city of Szombathely.

V.V.G. is an F.R.S-FNRS Research Associate.

S.S. has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 833925, project STAREX). R.L. acknowledges funding from University of La Laguna through the Margarita Salas Fellowship from the Spanish Ministry of Universities ref. UNI/551/2021-May 26, and under the EU Next Generation funds. This paper includes data collected with the TESS mission, obtained from the MAST data archive at the Space Telescope Science Institute (STScI). Funding for the TESS mission was provided by the NASA Explorer Program. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5–26555.

DATA AVAILABILITY

TESS data are publicly available in the Space Telescope Science Institute (STScI) at https://mast.stsci.edu. CHEOPS data generated and analysed in this article will be made available in the CHEOPS mission archive (https://cheops.unige.ch/ archive_browser/). No new HARPS RV data were generated for this work.

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APPENDIX A: EXTRA MATERIAL

We present in Figure A1 the posterior distribution of the fitted parameters.

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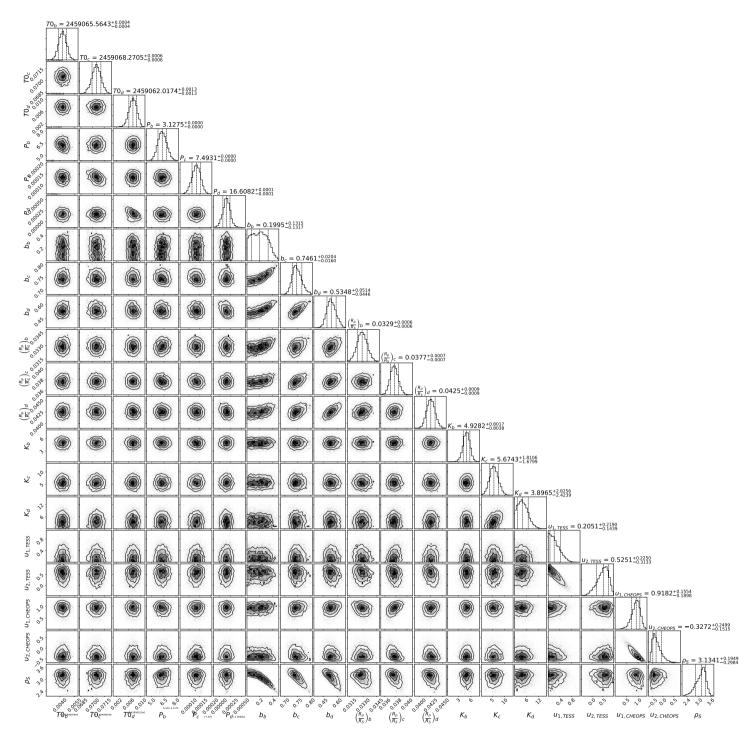


Figure A1. Corner plot showing the posterior distribution of the fitted parameters.