Transit detection of the long-period volatile-rich super-Earth \( \nu^2 \) Lupi d with CHEOPS

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Exoplanets transiting bright nearby stars are key objects for advancing our knowledge of planetary formation and evolution. The wealth of photons from the host star gives detailed access to the atmospheric, interior and orbital properties of the planetary companions. \( \nu^2 \) Lupi (HD 136352) is a naked-eye (\( V = 5.78 \)) Sun-like star that was discovered to host three low-mass planets with orbital periods of 11.6, 27.6 and 107.6 d via radial-velocity monitoring\(^1 \). The two inner planets (b and c) were recently found to transit\(^2 \), prompting a photometric follow-up by the brand new Characterising Exoplanets Satellite (CHEOPS). Here, we report that the outer planet d is also transiting, and measure its radius and mass to be \( 2.56 \pm 0.09 \, R_\oplus \) and \( 8.82 \pm 0.94 \, M_\oplus \), respectively. With its bright Sun-like star, long period and mild irradiation (\( \sim 5.7 \) times the irradiation of Earth), \( \nu^2 \) Lupi d unlocks a completely new region in the parameter space of exoplanets amenable to detailed characterization. We refine the properties of all three planets: planet b probably has a rocky mostly dry composition, while planets c and d seem to have retained small hydrogen–helium envelopes and a possibly large water fraction. This diversity of planetary compositions makes the \( \nu^2 \) Lupi system an excellent laboratory for testing formation and evolution models of low-mass planets.

CHEOPS\(^3 \) is the new European mission dedicated to the study of known exoplanets around bright stars (\( V \leq 12 \)). Unlike previous exoplanet detection missions, such as CoRoT\(^4 \), Kepler\(^5 \) and TESS\(^6 \), CHEOPS is a follow-up mission, designed to collect ultrahigh-precision photometry of a single star at a time. For this purpose, it relies on a 30 cm effective aperture telescope, equipped with a single frame-transfer back-illuminated CCD detector providing a broad 330–1,100 nm bandpass\(^7 \). CHEOPS was launched on 18 December 2019 into a 700-km-altitude Sun-synchronous dusk–dawn orbit and started routine science operations in April 2020. For very bright stars (\( V \approx 6 \)), CHEOPS demonstrated that it can achieve an outstanding photometric precision of about 10 ppm per 1 h interval\(^8 \).

\( \nu^2 \) Lupi is one of the first scientific targets observed by CHEOPS. This system of three low-mass planets orbiting one of the closest (14.7 pc) G-type main-sequence stars was discovered using radial velocities (RVs) obtained with the HARPS spectrograph\(^1 \). It was then observed by TESS during Sector 12 of its primary mission (21 May–18 June 2019), which revealed that the two inner planets are transiting\(^2 \). These 28-day-long observations did not cover any inferior conjunction of the outer planet d. However, the transiting configuration of the two inner planets increased the probability that it is also transiting, to about 20% for typical mutual inclinations of \( \pm 1^\circ \).
Table 1 | Properties of the ν² Lupi planetary system

| Parameters                                      | Values     |
|------------------------------------------------|------------|
| Star                                           | ν² Lupi    |
| Effective temperature, T_eff (K)               | 5.664 ± 0.61 |
| log surface gravity, log g, (cgs)              | 4.39 ± 0.11 |
| Microturbulence, ξ (km s⁻¹)                    | 0.85 ± 0.02 |
| Metallicity, (M/H) (dex)                       | −0.24 ± 0.05 |
| Radius, R, (Rₖ)                                | 1.058 ± 0.019 |
| Mass, M, (Mₖ)                                  | 0.87 ± 0.04 |
| Density, ρ, (ρₖ)                               | 0.734 ± 0.053 |
| Age (Gyr)                                       | 12.3 ± 1.2 |
| Rotation period, Pₚ (d)                        | 23.8 ± 3.1 |
| Luminoity, L, (Lₖ)                             | 1.038 ± 0.059 |

| Planets                                         |           |
|------------------------------------------------|------------|
| Orbital period, P (d)                          | 11.5779 ± 0.000016 |
| Mid-transit time, Tₜ (BJD₀ − 2,450,000)        | 8,944.3726 ± 0.0005 |
| Planet-to-star radius ratio, R/Rₖ               | 0.0144 ± 0.00027 |
| Transit depth, dₗ (ppm)                        | 208 ± 8 |
| Transit impact parameter, b (Rₖ)               | 0.52 ± 0.04 |
| Transit duration, W (h)                        | 3.93 ± 0.03 |
| Orbital inclination, i (°)                     | 88.49 ± 0.17 |
| Orbital eccentricity, e                       | 0 (fixed, <0.17) |
| RV semi-amplitude, K (m s⁻¹)                   | 1.46 ± 0.12 |
| Orbital semi-major axis, a (au)                | 0.0964 ± 0.0028 |
| Scale parameter, a/Rₖ                          | 19.60 ± 0.45 |
| Stellar irradiation, Sₗ (Sₖ)                   | 111.6 ± 7.3 |
| Equilibrium temperature, T_eq (K)              | 905 ± 14 |
| Radius, R, (Rₖ)                                | 1.664 ± 0.043 |
| Mass, M, (Mₖ)                                  | 4.72 ± 0.42 |
| Mean density, ρ, (ρₖ)                          | 1.02 ± 0.13 |

a From ref. 1.  b BJD₀, barycentric Julian date in barycentric dynamical time. c 2σ upper limits derived from our global analysis allowing all orbits to be eccentric. d σeff = Teq √(1 − Aₚ)³/₄, assuming an efficient heat redistribution (∆T = 1/4) and a null Bond albedo (Aₚ = 0).

(Ref. 1). ν² Lupi is one of only three naked-eye stars known to host several transiting planets, the other two being HD 219134 (Refs. 9,10) and HR 858 (Ref. 11). The multitransiting nature of these systems, combined with the brightness of their stars, make them targets of paramount importance for comparative exoplanetology studies.

The primary objective of our follow-up of ν² Lupi with CHEOPS was to refine the properties of the two inner planets, most notably their radii but also their ephemerides, since being able to predict precise transit times is essential to enable follow-up observations with heavily subscribed facilities.

Six observation runs (visits) were obtained with CHEOPS between 4 April and 6 July 2020 (Supplementary Table 1), targeting four transits of planet b and three of planet c (the last visit contained one transit of each planet). The data were processed with the CHEOPS data reduction pipeline 11 (DRP, Methods) and the resulting individual light curves are shown in Supplementary Fig. 1.

During the fifth visit (8–9 June 2020), we serendipitously detected a ~500 ppm transit-like flux drop, which started during the targeted transit of planet c, and lasted for the rest of the visit (Supplementary Fig. 1, bottom left panel). We carefully checked the data for systematics and found this signal to be very robust (Methods). Furthermore, the star does not show any comparable photometric variability in either the CHEOPS or TESS data (Supplementary Fig. 4). This flux drop occurred at 1.3σ of an inferior conjunction of ν² Lupi d, as predicted by the RV orbital solution of ref. 1, and we show in Methods that it most probably originates from a transit of this outer planet. This makes ν² Lupi d the first long-period (>100 d) planet detected to transit a naked-eye star.

To determine the system parameters, we performed a global analysis of our six CHEOPS light curves together with other available photometric and RV data. This includes first a custom TESS light curve, which we extracted from the target pixel files following
corrected light curves, phase-folded for each planet, are presented together with the best-fit transit models in Fig. 1 for CHEOPS and Supplementary Fig. 5 for TESS. Finally, the phase-folded RVs are shown in Supplementary Fig. 6, together with the best-fit RV model for each planet. To test our results, we explored the orbital stability of the system for masses and eccentricities around our derived solution and found it to be very stable (Methods).

As mentioned above, the exquisite precision of our CHEOPS photometry (~15 ppm with a 10 min binning) makes it sensitive to stellar granulation and oscillations. To characterize this stellar signal, we analysed the power spectral density (PSD) of the photometric residuals obtained after subtracting our best-fit transit and instrumental models (Methods and Supplementary Fig. 10). We measured for the stellar oscillations a frequency at maximum power \( \nu_{\text{max}} = 2,710 \pm 77 \) Hz and a flicker index \( \alpha_e = 1.14 \pm 0.22 \) (slope of the PSD associated with granulation) that are in agreement with the values expected from our derived stellar parameters and with the trends observed for Kepler stars (Supplementary Fig. 11). This asteroseismic detection is in good agreement with, and even exceeds, the expectations of ref. \(^1\), thus spectacularly demonstrating the potential of CHEOPS for asteroseismology.

With a radius of \( 1.664 \pm 0.043 \) \( R_\text{\textbullet} \) and a stellar irradiation of \( 111.6^{+5.8}_{-5.0} \) \( S_\odot \), \( \nu^{2} \) Lupi b lies near the inner edge of the well known radius valley \(^{18} \), while planets c (2.916\( ^{+0.075}_{-0.078} \) \( R_\odot \), 35.1\( ^{+2.1}_{-2.2} \) \( S_\odot \)) and d (2.562\( ^{+0.079}_{-0.079} \) \( R_\odot \), 57.4\( ^{+3.3}_{-3.3} \) \( S_\odot \)) are located on the other side (Fig. 2b). This gap in the planetary radius distribution separates predominantly rocky planets from larger volatile-rich (hydrogen, helium, water) sub-Neptunes. The \( \nu^{2} \) Lupi planets seem to fit this picture well: planet b has an Earth-like bulk density of \( 1.02^{+0.13}_{-0.10} \) \( \rho_\odot \) while planets c and d have significantly lower densities of \( 0.453^{+0.044}_{-0.043} \) \( \rho_\odot \) and \( 0.522^{+0.073}_{-0.078} \) \( \rho_\odot \) respectively, implying that they contain water and/or gas (Fig. 2c). Several theories have been put forward to explain the radius valley, such as photoevaporation \(^{20,22} \), core-powered mass loss \(^{25,26} \) or combined formation and evolution effects \(^{27} \). With three transiting planets spanning the valley, the \( \nu^{2} \) Lupi system provides a valuable opportunity to test these scenarios.

To go one step further, we performed a detailed Bayesian analysis (Methods) to derive the joint posterior distribution of the present-day internal structures of the three planets \(^{24,25} \) (Fig. 3 and Supplementary Figs. 12–14), assuming four layers (iron–sulfur core, silicate mantle, water layer, gas envelope). The innermost planet is found to be mostly dry (water mass equal to \( 0.70^{+0.04}_{-0.03} \) \( M_\odot \)), whereas the two outer planets have a similarly massive water layer (2.81\( ^{+2.52}_{-1.23} \) \( M_\odot \) for planet c, 2.31\( ^{+2.09}_{-1.11} \) \( M_\odot \) for planet d) and a small but non-negligible amount of gas (0.13\( ^{+0.03}_{-0.03} \) \( M_\odot \) for planet c, 0.058\( ^{+0.039}_{-0.036} \) \( M_\odot \) for planet d). The dichotomy between the derived amounts of water is consistent with a formation by migration, where the innermost planet would start its formation inside the ice line (located a few AU from the star for typical proto-planetary disks) whereas the two outer planets would have spent at least part of their formation time outside the ice line, and therefore accreting icy bodies.

With regard to the derived amounts of gas, planetary atmospheric evolution calculations \(^{25,26} \) indicate that the innermost planet b was subject to substantial atmospheric loss, while planets c and d did not suffer strong evaporation (Methods and Supplementary Fig. 15). The two outer planets are indeed sufficiently massive and far away from the host star to be only slightly affected by mass loss throughout their evolution. Therefore, the current low gas content returned by our internal structure modelling for these two planets is probably of primordial origin. In the standard core-accretion model, planets start to accrete substantial amounts of gas when they reach the critical mass, which is of the order of \( \sim 10 \) \( M_\oplus \) but also depends strongly on different parameters, in particular the accretion rate of solids.

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**Fig. 1** CHEOPS transit photometry of the \( \nu^{2} \) Lupi planets. a, Corrected and phase-folded CHEOPS transit photometry of \( \nu^{2} \) Lupi b, c and d. The blue dots show the unbinned measurements, with error bars corresponding to the quadratic sum of the formal photometric errors and the fitted extra jitter term. Open circles show the light curves binned into 20 min intervals. The best-fit transit models from our global analysis are shown as orange lines. b, Corresponding residuals. In both panels, the light curves corresponding to planets c and d are shifted vertically for clarity.
The structure of the two outer planets, as observed today, being probably primordial, these two objects provide a very important anchor for planet formation models, as this indicates that neither of them reached the critical mass during their formation. These two planets, by giving access to both the core mass and gas-to-core ratio for two objects in the same system, will provide strong constraints on the understanding of the formation of subcritical planets. Since the presence of large gas envelopes hinders habitability, the ν² Lupi system, with its two subcritical outer planets, also provides an interesting case study for numerical models targeting the emergence of habitable worlds.

A thorough characterization of the system will require atmospheric measurements with, for example, the upcoming James Webb Space Telescope (JWST) or future ground-based extremely large telescopes. On the basis of the transmission spectroscopy metric (TSM) of ref. 29, the three planets are attractive targets, with TSM values of 125, 214 and 117 for planets b, c and d, respectively (Methods and Fig. 2d). In particular, ν² Lupi d is the best target found so far around a Sun-like star for atmospheric studies in the low-temperature regime (<500 K). It is also a potentially promising object to search for moons or rings (Methods). Our transit detection of this exciting planet with CHEOPS thus further increases the importance of ν² Lupi as a cornerstone system for comparative exoplanetology studies of small worlds.

**Methods**

CHEOPS observations and data reduction. Six observation runs (visits) were obtained with CHEOPS between 4 April and 6 July 2020. The log of these observations is presented in Supplementary Table 1. Each visit lasted between 11 and 12.8h, so as to cover transits of planets b and c (duration of ~3.9 and ~3.2h, respectively) together with a substantial out-of-transit baseline. Due to CHEOPS low Earth orbit (altitude ~700 km), the data show some gaps corresponding to Earth occultations or passages through the South Atlantic Anomaly, resulting in observing efficiencies between 49 and 60%. Due to the target's brightness (V = 5.78), we used a short exposure time of 1.7s and co-added on board 26 exposures, yielding a cadence of 44.2s. For a detailed description of CHEOPS’ instrumentation, technicalities of its observations, and on-board processing, see ref. 1.
The data were automatically processed with the CHEOPS DRP\(^\text{T}\) (version 12), a detailed description of which can be found in ref. 11. In short, the DRP calibrates the raw images (event flagging, bias and gain corrections, linearization, dark current and flat-field corrections), corrects them for environmental effects (smearing trails, depointing, background and stray light) and performs aperture photometry to extract target fluxes for various apertures. For all the visits, we found a minimal light curve root mean squared (r.m.s.) with the default aperture of 25 pixels. The resulting light curves are shown in Supplementary Fig. 1 (upper panels for each visit). Owing to the extended and irregular shape of the CHEOPS point spread function\(^4\) and the fact that the field rotates around the target along the spacecraft’s orbit, nearby background stars can introduce a time-variable flux contamination in the photometric aperture, in phase with the spacecraft roll angle. The DRP also estimates this contamination by using the Gaia DR2 catalogue\(^5\) to simulate CHEOPS images of the field of view. For our \(\nu\) Lupi observations, this contamination was very small, varying between 0.025 and 0.030% of the target’s flux.

In the light curve of the fifth visit (8–9 June 2020), we serendipitously detected a ~500 ppm transit-like flux drop, which started during the targeted transit of planet c, and lasted for the rest of the visit (Supplementary Fig. 1, bottom left panel). We carefully checked the data for systematics and found this signal to be very robust. As shown in Supplementary Fig. 2, it does not show any correlation with the size of the photometric aperture, or with any instrumental or environmental parameter (background, position of the target’s point spread function centroid on the CCD, various voltages and temperatures, dark current and so on). Neither can the signal be ascribed to cosmic rays or telegraphic pixels (noisy unstable pixels whose state randomly flips between a normal behaviour and an arbitrary high response). Having ruled out any systematics as the origin of this signal, we then turned towards another possible culprit, \(\nu\) Lupi d. This planet is the third one detected in HARPS RVs by ref. 1, which reported an orbital period of \(-107.6\) d and a minimum mass \((M_\text{sin} i)\) of \(-8.6 M_\oplus\). Ref. 1 did not find any evidence for a transit of planet d in the TESS data but also noted that this was totally expected, since the 28-d-long observations actually did not cover any inferior conjunction of the planet, as predicted from the RVs. On the basis of the orbital solution of ref. 1, the inferior conjunction that is the nearest in time to the fifth CHEOPS visit was predicted to be \(2,459,023.21 \pm 0.33\) BJD. The transit-like signal that we detected started around \(2,459,009.59\) BJD, thus at \(1.3\) h. We demonstrate below (Origin of the CHEOPS single transit event) that it most probably originates from a transit of \(\nu\) Lupi d.

**TESS observations and data reduction.** \(\nu\) Lupi was observed by TESS\(^6\) during Sector 12 of its primary mission, from 21 May until 18 June 2019. During these 28 days, TESS saved and downlinked images of \(\nu\) Lupi every 2 min, resulting in a total of 20,119 photometric measurements. Ref. 7 recently reported the detection of two transits of planet b and one of planet c in these data. As mentioned above, these observations did not cover any transit of planet d.

Following an approach similar to that used by ref. 1, we extracted our own custom light curve from the TESS pixel files, to conduct a careful treatment of spacecraft systematics. Using the lightcurve Python package\(^8\), we retrieved the calibrated 2 min target pixel image files from the Mikulski Archive for Space Telescopes (https://archive.stsci.edu) using the default-quality bitmask. We extracted light curves for 20 different apertures centred on the target, which were then background corrected by subtracting the sky contribution determined using a custom background mask (Supplementary Fig. 3). We chose the photometric aperture minimizing the 1 h combined differential photometric precision metric\(^9\), in this case a circular aperture with a radius of 4.6 pixels. We corrected the extracted fluxes for the contamination from other faint sources in the aperture, on the basis of their magnitudes from the TESS Input Catalog\(^2\). We note that, despite the large pixel scale of TESS (21 arcsec per pixel), \(\nu\) Lupi is so much brighter than other nearby stars that the contamination (\(\text{flux}_{\text{contaminant}} / \text{flux}_{\text{target}}\)) is only 0.95% in this case.

As can be seen in the upper panel of Supplementary Fig. 4, the resulting light curve suffers from instrumental systematics, mostly related to the pointing jitter of the spacecraft. To correct for these systematics, we retrieved the engineering quaternion measurements for camera 1 (which observed \(\nu\) Lupi), which are 2-cadence vector time series that describe the spacecraft attitude on the basis of observations of a set of guide stars (https://archive.stsci.edu/missions/tess/engineering/). For each of the three vector components, we computed the means and s.d.s of the measurements within each 2 min science image. We also retrieved the various cotrending basis vectors (CBVs, https://archive.stsci.edu/tess/bulk_downloads/bulk_downloads_chr.html) computed by the presearch data conditioning module\(^8,10\) of the TESS Science Processing Operations Center pipeline\(^11\). We then decorrelated our light curve against the quaternion and CBV time series using Bayesian linear regression, while masking the in-transit points in the fit. We tested many different combinations of regressors and kept the one minimizing the Bayesian information criterion\(^12\), which notably comprised the first and second-order quaternion time series as well as the high-frequency (band 3) CBVs. At the end of the process, 1,000 samples were drawn from the

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**Fig. 3 | Internal structures of the \(\nu\) Lupi planets.** Present-day internal structures returned by our Bayesian analysis\(^23,24\) (Methods), assuming four layers (iron–sulfur core, silicate mantle, water layer, and H–He envelope). For each planet, a ternary diagram shows the mass fractions of the iron core, silicate mantle and water layer. The yellow (respectively, dark violet) colours represent zones of highest (respectively, lowest) posterior probability distribution, and the grey area (lower left part) represents the zone that is excluded by the assumed prior (water mass fraction smaller than 50% so that it cannot be larger than the icy fraction inside planetary solid building blocks; see Methods and references therein). Next to each ternary diagram, we also show an illustration representing the radius fractions of the core + mantle (dark grey), water layer (blue) and gas envelope (magenta), corresponding to the medians of the posterior distributions.

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posterior distribution of the regression coefficients to estimate the uncertainty of the model, which was then added quadratically to the error bars of the corrected data points. The resulting decorrelated light curve is shown in the second panel of Supplementary Fig. 4. In the first case, a combined differential photometric precision improved from 62 to 37 ppm h⁻¹, which is comparable with the precision achieved by ref. 1 for HR 858, a similarly bright star. We used this decorrelated light curve in our subsequent global analysis.

Archival RVs. In our global analysis, we also included 246 previously published³⁶ RV measurements that were obtained between 27 May 2004 and 4 August 2017 with the HARPS spectrograph on the ESO 3.6 m telescope (La Silla, Chile). Among these, the last six measurements were acquired after an instrument upgrade and we thus treated them as an independent dataset in our analysis. These RV data are shown in the upper panel of Supplementary Fig. 6. For details of the instrument, observations and data reduction, see ref. 3⁶ for CLES and ref. 1 for PARSEC. Ref. 2 also published 169 RV measurements obtained with the UCLES spectrograph on the 3.9 m Anglo-Australian Telescope (Siding Spring, Australia), as well as 43 RV measurements obtained with the HiRES spectrograph on the 10 m Keck I telescope (Mauna Kea, HI, USA). However, these data have significantly larger uncertainties than the HARPS data (mean measurement uncertainties of 1.27 and 1.17 m s⁻¹ for UCLES and HiRES versus 0.42 m s⁻¹ for HARPS) and show a significantly larger scatter (5.7 and 4.5 m s⁻¹ for UCLES and HiRES versus 2.7 m s⁻¹ for HARPS—Fig. 1 of ref. 1). After some preliminary analyses of the RV data (see below), it appeared that including the UCLES and HiRES data did not improve the fit, which is mostly dominated by the precise HARPS data. Thus, we only included the HARPS data in our final global analysis.

Host star properties. The main stellar parameters are presented in the upper part of Table 1. The spectroscopic parameters (T₂₅, log g, ξ, and [Fe/H]) were taken from ref. 1. These parameters were derived with the same methodology as used in CLES-MOOG, which was recently described in detail in ref. 1. The uncertainties were updated following the discussion in ref. 1 about precision versus accuracy errors. In summary, the method starts with the measurement of equivalent widths of iron lines using the ARES code⁴⁰. Then a minimization process is applied to find the ionization and excitation equilibrium and converge to the best set of spectroscopic parameters. This process makes use of a grid of Kurucz model atmospheres⁴¹ and the radiative transfer code MOOG⁴².

Stellar atmospheric abundances of several refractory elements are given in Supplementary Table 2. They were computed using the same tools and models of atmospheres as for the determination of the stellar atmospheric parameters (see above). In our analysis, we followed the classical curve-of-growth method under assumption of local thermodynamic equilibrium⁴³. Our results show that the star is enhanced in α-elements (Mg, Si, Ti and Ca) relative to iron. Using the stellar parameters derived above and Gaia, 2MASS and WISE broadband photometry, we determined the radius of v¹ Lupi via the infrared flux method⁴⁴, which, via the comparison of observed fluxes with synthetic photometry of atmospheric models, allows for the calculation of stellar effective temperature and angular diameter, and thus stellar radius when combined with the parallax. Following the removal of Gaia G, Gp and Gp, 2MASS J, H and K and WISE W1 and W2 fluxes and relative uncertainties⁴⁵,⁴⁶,⁴⁷, we employed a Markov chain Monte Carlo (MCMC) approach to compare the observed photometry with synthetic values derived by the stellar atmospheric models. The optical and infrared photometric bandspasses, taking the stellar parameters determined above as normal priors on the spectral energy distributions used. Via this method, we derived $R_\star = 1.058 ± 0.019 R_\odot$ which is in agreement (1.8σ) with the value reported in previous work⁴⁸ (1.012 ± 0.018 R_\odot), with differences potentially arising from differing methods used to derive $R_\star$ or the careful treatment of stellar metallicity conducted in our study.

We derived the stellar age and mass from stellar models calibrated to reproduce the aforementioned infrared flux method radius, metallicity accounting for alpha enrichment, and effective temperature. Two sets of stellar parameters were computed with different stellar evolution codes, respectively (against any relevant external parameter) or GPs (celerite⁶⁹, george⁷⁰).

We first performed individual analyses of each of our light curves, to select for each of them the best correlated noise model, based on Bayesian evidence. We explored a large range of models for the CHEOPS light curves, consisting of first- to fourth-order polynomials in the recorded external parameters (most importantly time, background level, position of the point spread function centroid, spacecraft roll angle), as well as GPs against time, roll angle or a combination of the two. In this process, we only selected a more complicated model over a simpler one if the difference in its Bayesian log evidence ($\Delta \ln Z$) was greater than two $\sigma$⁷¹. We found that GP models and functional forms of the form (see below for a detailed study of the power spectrum of the residuals and characterization of the stellar noise). If not properly accounted for, such stellar noise can introduce biases in the inferred transit parameters⁷². In our analysis, we modelled the stellar noise using a GP with a stochastically driven damped simple harmonic oscillator kernel⁷³, with a quality factor of $\nu / 2\pi$. In this particular case, the simple harmonic oscillator kernel indeed has a similar PSD to stellar granulation⁷⁴, to a first approximation. Since this stellar variability is seen in all the CHEOPS light curves, a single common simple harmonic oscillator GP was fitted across the six CHEOPS visits in our combined analysis (shown in green in the upper panels of Supplementary Fig. 1). On top of this, we noticed in the photometric residuals some higher-frequency correlated noise, which we attribute to the careful treatment of stellar granulation and oscillations (see below for a detailed study of the power spectrum of the residuals and characterization of the stellar noise). If not properly accounted for, such stellar noise can introduce biases in the inferred transit parameters⁷². 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from wide uniform priors, except the stellar density, for which we used the normal prior mentioned previously.

We performed several global analyses: one assuming circular orbits (e set to zero) for all three planets, and a ‘reference model’ (‘reference model’), one allowing the orbits of all three planets to be eccentric (hereafter the ‘eccentric model’) and three more analyses allowing the orbit of one planet to be eccentric while assuming circular orbits for the other two. A comparison between the Bayesian evidences of these models is provided in Supplementary Table 4. The reference model is the one with the highest Bayesian evidence. The eccentric model is marginally disfavoured compared with the reference model ($\Delta \ln Z = -3.6$). The models allowing the orbit of only one of the planets to be eccentric are statistically indistinguishable from the reference model ($\Delta \ln Z$ between $-0.9$ and $-1.7$). However, given that the reference model is the simplest model and it has the highest Bayesian evidence, it appears to be the best model given the data at hand. We thus adopted it as our nominal solution.

The posterior distributions of the main fitted parameters of our global analysis are shown in Supplementary Fig. 7, while Table 1 presents our results for the most relevant physical parameters of the system. The best-fit models for the individual light curves are shown in Supplementary Figs. 1 (CHEOPS) and 4 (TESS). The unbinned CHEOPS light curves, which span a duration of 44.2 days, have residual r.m.s. between 47 and 53 ppm. When binning into 10 min and 1 h intervals, we reach r.m.s. values between 14 and 17 ppm and between 5 and 7 ppm, respectively. For comparison, the residual r.m.s. of the unbinned (2-min cadence) TESS light curve is 1.49 ppm. This r.m.s. decreases to 80 and 30 ppm when binning into 10 min and 1 h intervals, respectively. The corrected light curves, phase-folded per planet, are shown in Fig. 1 (CHEOPS) and Supplementary Fig. 5 (TESS) together with the best-fit transit models. The phase-folded RVs are shown in Supplementary Fig. 6, together with the best-fit RV model for each planet.

**Refinement of the system parameters.** To assess the improvement brought by the CHEOPS data to the RVs of planet b and c, we compared our previous TESS-only photometric measurements, we also analysed both datasets individually, in a homogeneous way, using the same methods and priors as above. For this exercise, we assumed eccentric orbits for the planets to allow a direct comparison with the results of ref. 1. We first made a combined analysis of the TESS light curve and the RVs. The results of this analysis are compared with those of ref. 1 in Supplementary Table 5 (second and third columns) for some key parameters. Our results are consistent, but our uncertainties are significantly larger, for example by factors of 1.7 and 2.1 for the planet-to-star radii ratios of planet b and c, respectively. These larger uncertainties are probably related to our modelling of the residual systematics with a GP that is fitted simultaneously with the transits, while ref. 1 performed a full detrending of the TESS light curve before the transit fitting. We consider our approach to be more robust, as it accounts for the possible covariances between the nuisance and transit parameters, thus ensuring a proper propagation of the uncertainties on the derived transit parameters.

We then performed a combined analysis of our six CHEOPS visits together with the RVs. The results are reported in the fourth column of Supplementary Table 5. They are in good agreement with those of our TESS data analysis and also provide tighter constraints on the transit parameters. The planet-to-star radius ratios are measured with relative precisions of 2.8% and 2.1% for planets b and c, respectively, a factor of 2 more precise than the measurements returned by our global TESS data analysis. This significant refinement stems from both the higher photometric precision of CHEOPS and the larger number of transits observed (four transits of planet b observed with CHEOPS versus two with TESS; three transits of planet c observed with CHEOPS versus only one with TESS).

Of course, the best constraints are obtained when combining all the data (TESS + CHEOPS + RVs) together (last column of Supplementary Table 5). Thanks to the longer temporal baseline, the transit ephemerides are significantly refined, thus enabling efficient follow-up observations. The mid-transit times of planets b and c in May 2021 (middle of the next observing window) now have uncertainties of only 10.1 and 2.6 min, respectively. This is a major improvement when compared with the previous respective uncertainties of 86 and 106 min obtained when using the TESS was not compatible with the expected transit ephemerides (for example, the planet b’s transit ephemerides and impact parameters) are only slightly refined when comparing with the results of our CHEOPS data analysis, which demonstrates that they are mostly constrained by CHEOPS. The planetary radii derived from our global analysis are slightly larger than those reported in ref. 1. This is due to the combined effect of both our slightly larger planet-to-star radii ratios and stellar radius (Host star properties). We note however that the planetary radii are still consistent within the uncertainties.

**Transit timing variations.** The identification of mean-motion resonance (MMR) configurations or the detection of significant TTVs in multoplanet systems can yield valuable information about their formation and evolution2,3. In particular, the TTV signal is enhanced when the planets are in, or close to, an MMR $5:2$, and the lower the order of the MMR the stronger the TTV amplitude. Looking at the period commensurability, that is the ratio of the periods of planet pairs in the system, is the first step to identify a possible MMR. In the $i$ Lp sysytem, both pairs of planets b–c and c–d show a period commensurability close to a third-order MMR, that is a 5:2 MMR for the b–c pair and a 4:1 MMR for the c–d pair.

The common method to identify TTVs is to plot the so-called O–C (observed—calculated) diagram, where O are the observed (measured) transit times and C are transit times computed from a linear ephemeris. To compare the expected TTV signals, we simulated the system's dynamics for the parameters in Table 1 to integrate the orbits of the three planets for 3.5 yr (that is, the nominal duration of the CHEOPS mission) with the TRADES $^{45}$–$^{46}$ program, which allows us to compute the simulated transit times for each planet. We then extracted the semi-amplitude of the O–C diagram of each planet, assuming the simulated transit times to be the reference O and subtracting the model times C calculated from the MMRs based on $P$ and $T_0$ in Table 1. We found that the expected TTV semi-amplitudes are rather small: around 20 s for planets b and d, and around 40 s for planet c.

To explore our current dataset for possible TTVs, we ran another global analysis with Jupiter, additionally including a free TTV offset parameter for every transit of planet b (six transits) and planet c (four transits), while keeping the orbital period $P$ and $T_0$ fixed to the values given in Table 1. For the TTV offsets, we assumed uniform priors between $-15$ and $+15$ min. We assumed the same priors as previously (Supplementary Table 3) for the other physical and nuisance parameters, as well as circular orbits. This analysis returned uncertainties on the individual transit times of $-4.5$ min for planet b and $-1.2$ min for planet c, which did not allow us to detect any significant TTVs.

**Origin of the CHEOPS single transit event.** In all of the above, we assumed that the single transit event caught by CHEOPS was caused by $i$ Lp d. However, one might ask whether this transit may instead be caused by an additional as yet unobserved planet. Using the TESS transit ephemerides, phase-folded RVs, and the high photometric precision of CHEOPS and the larger number of transits observed in the TESS data, this significant refinement stems from both the higher photometric precision of CHEOPS and the larger number of transits observed in Supplementary Fig. 4, meaning that they can be used to exclude some orbital periods. To assess the constraints brought by the photometry on the orbital period of the transiting object, we performed a combined fit of all of the CHEOPS and TESS data with Jupiter. We assumed the same normal priors as used previously for the stellar density and nuisance parameters and wide uniform priors for the planet parameters (Supplementary Table 3). For the third transiting planet corresponding to the CHEOPS single transit event, we assumed a uniform prior between $30$ and $1,000$ d for the orbital period, and a uniform prior between $2,459,009.6$ and $2,459,010.0$ BJD for the mid-transit time. The posterior distributions of the fitted parameters for the third planet are shown in Supplementary Fig. 8. A wide range of orbital periods is compatible with the photometry, with a 3σ upper limit of $624$ d. The few blank vertical stripes seen in the corner plot for some orbital periods (for example around $185$ d and $379$ d) correspond to periods that can be excluded on the basis of the TESS data.

To assess the possibility of a fourth unknown planet in the system, we also searched for some additional signals in the HARPS RVs. We computed the $\ell$ periodogram, which searches for several periodic signals simultaneously and thus is less prone to show spurious peaks due to aliasing than a regular periodogram. As a result, we found that the derived $P (122.26 \pm 0.83 \pm 0.83$ d) and $T_0 (2,455,590.75 \pm 4.32 BD)$ posterior distributions are completely incompatible with the photometry: all the posterior samples that are compatible with a transit during the fifth CHEOPS visit would have also produced a transit in the TESS data. Furthermore, a dynamical stability analysis reveals that a fourth planet with a period of $123$ d would make the system unstable (Orbital stability). This candidate signal at $123$ d can thus be discarded. For the $485$ d signal, we find that $0.02\%$ of the derived $P (481.72 \pm 17.95 \pm 17.95$ d) and $T_0 (2,455,772.22 \pm 2.08 \pm 2.08$ BD) posterior samples are compatible with the photometry. By way of comparison, this is 20 times less than the corresponding percentage of $0.4\%$ obtained for $i$ Lp d. As a result of these analyses, we concluded that planet $e$ is not responsible for the CHEOPS single transit event (‘4 planets—$e$ transiting’ model) and that planet d was thus not detected in transit in the photometry. For the second one, we assumed the opposite, that is that planet $d$ is responsible for the CHEOPS single transit event and that planet $e$ is not detected in the photometry (‘4 planets—d
were built following the same procedure as presented above, but we increased the number of pixels to 15 × 15. We then explored eccentricities in the range of 0.0–0.6 and masses ranging from 1 to 15 M_⊕. We ran two suites of simulations: (1) planets b, c, and d were forced to be coplanar, and (2) they were given eccentric orbits using the eccentricities derived from our global eccentric analysis. For each pixel (or equivalently, each combination of ε_{b–c}, ε_{c–d}), we ran 20 different initial conditions by randomly varying the orbital angles, and then averaged the results. That is, each stability map contained 4,500 scenarios. We found that such a four-planet system would be fully unstable for times shorter than 10^6 orbits of the outermost planet. On the basis of these results, a fourth planet at 123 d can thus be discarded.

**Tidal interactions.** The planets are close enough to their host star to experience notable tidal interactions. To investigate this aspect, we quantified the influence of tides by means of the constant-time-lag model, in which a planet is considered as a purely viscous fluid that responds to tidal deformations due to gravitational effects. In this context, the tidal dissipation of a given planet is defined by the product of the potential Love number of degree 2 and the constant time lag, k_2 Δt. For terrestrial exoplanets, a range of possibilities centred on Earth's dissipation factor k_2 Δt ≈ 0.1–10, is generally adopted, so as to explore a range of possible tidal contributions to the system. This assumption is valid for the innermost planet in the system, v¹ Lupi b, which has an Earth-like mean density (Table 1). This is not the case for v¹ Lupi c and d, whose lower densities suggest that they are probably volatile rich and have small gaseous envelopes (Internal planetary structures). Hence, we assumed a tidal dissipation factor similar to Jupiter's value of k_2 Δt ≈ 2.5 ± 0.1, and explored a range of 1–100 times this value. We then performed a suite of simulations with the N-body code Posidonius, which includes the effects of tides, rotational flattening and general relativity, using the same prescriptions as given in ref. 14.

We found that the innermost planet b evolved rapidly into a pseudorotational state: that is, into a tidally locked configuration where its orbital rotational and rotational periods become synchronized to an odd periodicity close to zero, so that its orbital axis became aligned with the spin axis of the star. This state was reached within a short timescale, at a maximum 10^5–10^6 yr. This process is slower for the two outermost planets, which should reach pseudorotational states after 10^7–10^8 yr for planet c and 10^4–10^5 yr for planet d. Considering the circularization of the orbits, we found that this should be reached after 10^6–10^7 yr for planet c and after 10^5–10^6 yr for planet d. For planet d, the circularization time exceeds 10^7 yr. Dynamical tidal processes thus do not seem to be very efficient in this system.

Considering that the estimated age of the system is 12.3 ± 1.7 Gyr (Table 1), we conclude that circularization may be complete for planet b, but still ongoing for planets c and d. However, while eccentric orbits are not fully discarded from our global analysis, we found the model with circular orbits for all three planets to be marginally favoured. If this is the case, this would mean that planets c and d dissipated more energy than was explored in this study, hinting that other processes such as tidal inertial waves in the convective region of the planets might be affecting the system. In this case, enhancement of the tidal dissipation rates would imply a more rapid synchronization of the planets' spins with their orbiters, and faster circularization of their orbits.

**Characterization of the stellar signal seen in CHEOPS photometry.** To precisely characterize the stellar noise detected in the CHEOPS light curves, we removed the best-fit solution from the HNPSD of the resulting residuals (Supplementary Fig. 10, grey curve). We clearly observe the bump of the stellar acoustic modes at high frequency, and the characteristic increase of the PSD towards the lower frequencies associated with the signature of stellar granulation.

To characterize this stellar signal, we first performed a GP regression in the time-domain based on the model described in ref. 16 (dash-dotted line in Supplementary Fig. 10). This GP model consists of a sum of three kernels chosen such that their respective PSDs correspond to a Gaussian-like envelope to describe the oscillation bump, a Harvey-like function to describe the granulation component and a stochastic term to describe the high-frequency (photon) noise. Using this approach, we inferred a characteristic amplitude and frequency for the granulation of 49 ± 2 ppm and 1.026 ± 0.030 Hz, respectively, and a f_{\text{rms}} of 2.710 ± 0.077 Hz. The latter is in agreement (1.8σ) with the f_{\text{rms}} of 2.414 ± 0.056 Hz expected from the stellar parameters given in Table 1.

Considering that there is still some debate as to which model best describes the granulation signature (see for example refs. 15,25 and references therein), we tested another model based on simple power laws27–29. Making the approximation that the power background follows frequency power functions, this model is defined as log(P(ν)) = α_1 log(ν) + β, with ν the frequency, α_1 the flicker index measured between two cutoff frequencies ν (ν/ν) and β a constant. Using again an MCMC approach, we found that this power-law has α_1 = 1.14 ± 0.22 between 1.996 ± 0.06 Hz and f_ν = 830 ± 130 Hz (red dotted line in Supplementary Fig. 10). Based on Kepler observations, it has been shown that this flicker index and the corresponding cutoff frequencies are strongly correlated with the stellar fundamental parameters25, particularly with the stellar mass, radius and surface gravity (Supplementary Fig. 11). Comparing the flicker index we
inferred for v\textsuperscript{2} Lupi (red dot with error bars) with results obtained previously for Kepler stars (grey and black dots), we observe that it follows the expected trends well. Moreover, this first CHEOPS measurement opens the way to studies of granulation signatures on bright stars that were not covered by Kepler.

**Internal planetary structures.** We performed a Bayesian analysis to infer the possible interior structures of the three transiting planets\textsuperscript{12,13}. We assumed the planet to be made of four different layers: a central core made of iron and sulfur, a silicate mantle (containing Si, Mg and Fe), a water layer and a layer made of pure H and He. Compared with previous similar models\textsuperscript{3,4,5}, the physical models used here have been improved\textsuperscript{6}, namely with a new equation of state for the water layer\textsuperscript{7,8,9,10,11}, and the equation of state for the iron core\textsuperscript{12} (which can also contain some sulfur). The equation of state for the silicate mantle\textsuperscript{13} depends on the mole fractions of Si, Mg and Fe, and the gas envelope model\textsuperscript{14} gives the thickness of the gas envelope as a function of age, planetary mass and so on. In this analysis, we did not include the compression effect of the gas envelope on the innermost layers of the planet (core, mantle and water layer). The validity of this hypothesis can be checked a posteriori, as the mass of gas is small for the three planets (see below).

The transit and RV data provide measurements of the planetary radii and masses needed to constrain the evolution algorithm in a Bayesian framework employing an MCMC tool\textsuperscript{110,111}. The framework uses the system parameters with their uncertainties as inputs (that is priors). It then computes millions of forward planetary evolutionary tracks, varying the input parameters according to the shape of the prior distributions, and evaluates the fit of the defined ranges, the planetary atmospheric mass fractions obtained as described in the previous section. The fit is done for the three planets simultaneously. The results are posterior distributions of the free parameters, which are the rotation period of the star when it was young and the planetary initial atmospheric mass fractions. The modifications to the original tool are fitting for the planetary atmospheric mass fractions, instead of the planetary radii, and employing the stellar rotation period as a step parameter for the MCMC model, instead of the index of the power law controlling the stellar rotation period within the first 2 Gyr. The former modification enables the code to be more accurate by avoiding continuously converting the atmospheric mass fraction into planetary radius, given the other system parameters. The latter modification avoids biasing the MCMC calculations towards faster-rotating stars.

Supplementary Figure 15 shows the resulting posterior probability distribution functions for the rotation period of the host star at the age of 150 Myr and for the initial atmospheric mass fraction of each of the three planets. In this figure, the stellar rotation period at an age of 150 Myr is also compared with the distribution functions for the rotation period of stars with masses between 0.75 and 1 M\textsubscript{\odot}, that is members of open clusters of comparable age\textsuperscript{112}. Our result suggests that v\textsuperscript{2} Lupi evolved as a medium rotator, with a most probable rotation period at an age of 150 Myr ranging between 1 and 10 d and peaking at about 7 d, in agreement with the rotation period observed for most of the stars that are members of open clusters of similar age.

The posterior distribution obtained for the initial atmospheric mass fraction of v\textsuperscript{2} Lupi is flat, evidencing that the planet has completely lost its primary hydrogen-dominated atmosphere at some unknown point in time during the evolution. Therefore, the framework is unable to identify how much atmosphere was lost before the planet stopped accreting. For both v\textsuperscript{2} Lupi c and v\textsuperscript{2} Lupi d, the posterior distribution of the initial atmospheric mass fraction presents one strong, rather narrow peak close to the one that is obtained for the current atmospheric mass fraction through the interior structure modelling (see previous section). These results suggest that both planets experienced little atmospheric evolution through mass loss. This indicates that both planets accreted only a small atmospheric envelope that was later enriched in water by processes of gravitational instability. On the basis of the evolution simulations, we estimate the current mass-loss rates of v\textsuperscript{2} Lupi c and v\textsuperscript{2} Lupi d to be of the order of 3.2×10\textsuperscript{−4} and 1.8×10\textsuperscript{−4} g cm\textsuperscript{−2} s\textsuperscript{−1}, respectively.

**Potential of the system for atmospheric characterization.** To assess quantitatively the potential of the system for atmospheric characterization, we used the TSM of ref.\textsuperscript{113}. This metric is proportional to the expected transmission spectroscopy signal-to-noise ratio and is defined as

$$TSM = \frac{R^2 T_m}{M_{\star} R_{\star}^3} \times 10^{-m/50}$$

where \(m\) is the apparent magnitude of the planet in the J band. The scale factor depends on the radius of the planet and allows a one-to-one scaling between the TSM values and the signal-to-noise ratios estimated in ref.\textsuperscript{113} assuming 10 h of observations with the SPHERE/GPI or the NIF/CHARMS spectrograph (NIRISS) aboard the JWST. Using the system parameters derived from our global analysis (Table 1), we obtained TSM values of 125, 214 and 117 for v\textsuperscript{2} Lupi c, b and d, respectively. To provide context, Fig. 2d compares these TSM values with those of the currently known population of small (\(R_{\star} < 4 R_{\oplus}\)) transiting exoplanets as a function of their \(T_{\text{eq}}\). The size of the symbols is proportional to the host star effective temperature. To identify the top atmospheric characterization targets among the exoplanet population, ref.\textsuperscript{113} recommends a threshold of 92 for planets with 1.5 \(R_{\oplus} < R_{\star} < 2.75 R_{\oplus}\), such as v\textsuperscript{2} Lupi b and d, and a threshold of 84 for planets with 2.75 \(R_{\oplus} < R_{\star} < 4 R_{\oplus}\), such as v\textsuperscript{2} Lupi c. All three v\textsuperscript{2} Lupi planets are above these suggested thresholds, thus opening up promising perspectives for complementary exoplanetary studies. We note that the TSM is only intended as a general metric for the ranking of transmission spectroscopy targets and that atmospheric observations of the v\textsuperscript{2} Lupi planets may turn out to be challenging in practice. With a K-band magnitude of 4.16, v\textsuperscript{2} Lupi is close to the JWST saturation limit for spectroscopy of \(K \approx 4\) (ref.\textsuperscript{114}). Still, higher-efficiency readout modes for observations of bright stars are currently being investigated\textsuperscript{115}. In particular, a new
mode\textsuperscript{31} was proposed for the Near Infrared Camera (NIRCam) that would allow us to measure spectra of targets up to $K \approx 1$–2 between 1 and 2 μm. With its rocky and mostly dry composition, \textit{v} Lupi b might not be an ideal target for atmospheric characterization. Still, its high temperature ($\sim$900 K) opens the interesting possibility that its surface is molten and sustains a secondary atmosphere in equilibrium with the underlying magma\textsuperscript{32}. High-resolution ultraviolet spectroscopy with the Hubble Space Telescope could be used to detect the strong electronic transitions from metal effluents in this envelope. In contrast, the nature of \textit{v} Lupi c makes it a particularly promising target. Among the three planets, this is the one with the lowest bulk density. Measuring the hydrogen and helium content of its gas envelope, and its mass loss, would bring useful constraints to simulations of the planet evolution. High-resolution ground-based spectroscopy in the near infrared will allow measurement of the absorption lines from metastable helium in the upper atmosphere\textsuperscript{33}. Interestingly, \textit{v} Lupi c, in an analogous irradiation conditions to GI 3470 (Fig. 2), a warm Neptune that was found to be markedly evaporating\textsuperscript{34} (at a rate of about \textit{10}$^{-3}$ g s$^{-1}$) and whose atmosphere has already been intensively studied using both space\textsuperscript{35,36} and ground-based\textsuperscript{37} facilities. While the smaller present-day size of \textit{v} Lupi c probably makes it less efficient at capturing the stellar energy and evaporate, its lower density could favour the formation of a large exosphere of neutral hydrogen, sustained by the photodissociation of water from its massive reservoir \textsuperscript{38}. At only 14.7 pc, the Lyman α line of a G-type star such as \textit{v} Lupi will show reduced absorption by the interstellar medium and could readily be used to search for the absorption signature of this exosphere with the Hubble Space Telescope\textsuperscript{39}. Above temperature ($\sim$500 K), the only target more favourable than \textit{v} Lupi d according to the TSM is \textit{K} 98–59 d, a low-density super-Earth traniting an M-dwarf star\textsuperscript{40}. Despite a somewhat small gas envelope, the long-period and eccentric orbit ($e \sim 0.5$, \textit{P} = 254 d) makes it the only target more promising than \textit{v} Lupi d according to the TSM is \textit{K} 98–59 d, a low-density super-Earth traniting an M-dwarf star\textsuperscript{40}. Despite a somewhat small gas envelope, the long-period and eccentric orbit ($e \sim 0.5$, \textit{P} = 254 d) makes it the only target more promising.
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Author contributions

L.D. led the data analysis, with support from L.B., M.I.H., S.H., A. Brandeker, A.D.P., N.H., M.O. and T.G.W. L.D. also coordinated the interpretation of the results and writing of the manuscript. D.E. designed and coordinated, with support from A.D., the CHEOPS Early Science programme, within which these observations took place. Y.A. led the analysis of the internal structures, with support from J.H., A. Bonfanti and I.F. performed the atmospheric evolution simulations. B.G. carried out the TVT simulations. F.J.P. studied the orbital stability and tidal interactions. S. Salmon, Y.A., A. Bonfanti, G.S., V.V.G. and T.G.W. performed the stellar characterization. S. Sulis analysed the stellar granulation and oscillations. B.V. assessed the possibility of the potential for atmospheric characterization. S.C. evaluated the possibility of the Lups d having moons or rings. The other authors provided key contributions to the development of the CHEOPS mission. All authors read and commented on the manuscript, and helped with its revision.

Competing interests

The authors declare no competing interests.

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