TOI-1442 b and TOI-2445 b: two ultra-short period super-Earths around M dwarfs

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ABSTRACT

Context. Exoplanets with orbital periods of less than one day are known as Ultra-short period (USP) planets. They are relatively rare products of planetary formation and evolution processes, but especially favourable for characterisation with current planet detection methods. At the time of writing, 120 USP planets have already been confirmed.

Aims. We aim to confirm the planetary nature of two new transiting planet candidates announced by the NASA’s Transiting Exoplanet Survey Satellite (TESS), registered as TESS Objects of Interest (TOIs) TOI-1442.01 and TOI-2445.01.

Methods. We use the TESS data, ground-based photometric light-curves and Subaru/IRDIS spectrograph radial velocity (RV) measurements to validate both planetary candidates and to establish their physical properties.

Results. TOI-1442 b is a hot super-Earth with an orbital period of $P = 0.4090682 \pm 0.0000004 \text{ d}$, a radius of $R_p = 1.15 \pm 0.06 \text{ R}_\oplus$, equilibrium temperature of $T_{\text{eq}} = 1357_{-42}^{+49} \text{ K}$, and a mass $M_p \leq 18 \text{ M}_\oplus$ at 3$\sigma$. TOI-2445 b is also a hot super-Earth/mini-Neptune with an orbital period of $P = 0.3711286 \pm 0.0000004 \text{ d}$, a radius of $R_p = 1.33 \pm 0.09 \text{ R}_\oplus$, equilibrium temperature of $T_{\text{eq}} = 1330_{-61}^{+64} \text{ K}$, and a mass $M_p < 38 \text{ M}_\oplus$ at 3$\sigma$. Their physical properties align with current empirical trends and formation theories of USP planets. More RV measurements will be useful to constrain the planetary masses and mean densities, as well as the predicted presence of outer planetary companions. These targets are amenable for atmospheric characterisation via emission spectroscopy with the James Webb Space Telescope.

Key words. planetary systems – planets and satellites: individual: TOI-1442 b, TOI-2445 b – techniques: photometric – techniques: spectroscopic – methods: observational

1. Introduction

The main theories of planetary formation based on our Solar System did not predict the existence of planets on orbits much narrower than that of Mercury. However, since the discovery of the first hot Jupiter (Mayor & Queloz 1995), many exoplanets have been detected with orbital periods of just a few days. Among the close-in planet population, the ultra-short period (USP) planets are defined as the ones that complete their entire orbit in less than one day (Sahu et al. 2006). These extreme cases may provide some of the most revealing insights into the formation and evolution processes of planetary systems. They are also excellent test beds for studying star-planet interactions, such as the effects of tidal forces and atmospheric erosion processes.

All other conditions being equal, USP planets are the easiest to detect and characterise by means of occultations and radial velocity measurements (Gaudi et al. 2005). Despite this strong selection bias, the observed period distribution of exoplanets drops at $P \lesssim 4 \text{ d}$ (see Figure [1]), indicating that planets with shorter orbital periods are increasingly rare. Recent estimates of the occurrence rate of USP planets are $\sim 0.5\%$ (Sanchis-Ojeda et al. 2014; Winn et al. 2018; Zhu & Dong 2021; Uzsoy et al. 2021), which is comparable with the frequency of hot Jupiters (Howard et al. 2012; Fressin et al. 2013; Wang et al. 2015; Zhu & Dong 2021). Additionally, more than 80% of the known USP population have radii $R_p < 2 \text{ R}_\oplus$. There are only eight USP Jupiters with $0.75 < P < 1 \text{ d}$. Both the frequency and the small size of USP planets have suggested that they could be the remnant rocky cores of evaporated hot Jupiters (Valsecchi et al. 2014; Königl et al. 2017). The lack of a metallicity trend for the USP planet host stars, unlike hot Jupiters, limits the maximum relative frequency for this evolutionary path (Fischer & Valenti 2005; Winn et al. 2017). Other proposed pathways include photoevaporation of gaseous sub-Neptunes (Lundkvist et al. 2016; Lee & Chiang 2017), in situ formation (Chiang & Laughlin 2013), and inward migration of rocky planets (Petrovich et al. 2019). The latter hypothesis finds empirical support as several USP planets are part of compact systems showing a broad range of mutual inclinations (Petrovich et al. 2020).

In this paper, we report the discovery of two USP super-Earths around M dwarfs from the Transiting Exoplanet Survey Satellite (TESS) and ground-based follow-up programs. During the preparation of this manuscript, Giacalone et al. (2022) published another paper that also includes validation of TOI-1442 b and TOI-2445 b among other targets. Our analyses are fully...
Fig. 1. Left panel: Orbital period distribution of the confirmed exoplanets with $P < 100 \text{ d}$, based on NASA Exoplanet Archive data as of 2022 January 28. Right panel: Period distribution of the subset of exoplanets with $P < 10 \text{ d}$; the red bar denotes the number of USP planets. Note that selection effects favour the discovery of planets with shorter orbital periods, so that the observed distributions are not necessarily representative of the underlying population. However, the decrease in frequency at $P < 4 \text{ d}$ must be real, as such planets are easier to detect than those with longer periods.

2. Observations

2.1. TESS photometry

TOI-1442 (TIC 235683377) was observed by TESS in 2 min short-cadence integrations during sectors 14 to 26 (2019 July 18 - 2020 July 04) and 40 to 41 (2021 June 25 - 2021 August 20). It was announced on 2019 November 14 as a TESS object of interest (TOI) by the Science Processing Operations Center (SPOC) pipeline at NASA Ames Research Center.

TOI-2445 (TIC 439867639) was observed by TESS in 2 min short-cadence integrations during sectors 4 (2018 October 19 - 2018 November 14) and 31 (2020 October 22 - 2020 November 16). It was announced on 2021 January 6 as a TOI detected also by SPOC.

We downloaded the data from the Mikulski Archive for Space Telescopes (MAST) and extracted the Pre-search Data Conditioned Simple Aperture Photometry (PDCSAP) from the light-curve files (extension: ‘.lc.fits’). The PDCSAP timeseries were computed by the SPOC pipeline (Jenkins et al. 2016), that calibrates the image data, performs quality control (e.g., flags bad data), calculates the flux for each target in the field of view through simple aperture photometry (SAP module, Morris et al. 2020), and corrects for instrumental systematic effects (PDC module, Smith et al. 2012; Stumpe et al. 2014). Figure 2 shows the target pixel files (TPFs) and aperture masks used to extract the SAP flux, created using tpfplotter (Aller et al. 2020).

There are no known contaminants falling within the aperture masks in most sectors, except for a fainter source with $\Delta m > 3$ with respect to TOI-1442 in sectors 15, 18, 21, 26 and 41.

2.2. Ground-based photometry

The TESS Follow-up Observing Program (TFOP) is a network of observatories and researchers aiming to validate the planetary nature of transit-like signals tagged as TOIs, to measure the masses and radii of the planets, as well as the orbital properties and the stellar host parameters. We make use of transit photometry data acquired under the TFOP to confirm that the planetary transits occur on the targeted stars, rule out some false positive scenarios (e.g., blended eclipsing binaries), and refine the planet’s radius measurement. The TFOP data are available to the working group members on the Exoplanet Follow-up Observing Program for TESS (ExoFOP-TESS) website.

2.2.1. MuSCAT

The Multi-colour Simultaneous Camera for studying Atmospheres of Transiting planets (MuSCAT, Narita et al. 2015) is a three-band imager mounted on the 188-cm telescope of National Astronomical Observatory of Japan in Okayama, Japan. MuSCAT is equipped with three $1024 \times 1024$ pixel CCDs with pixel scale of 0’.358 pixel$^{-1}$. The field of view of MuSCAT is

https://github.com/jlillo/tpfplotter
https://exofop.ipac.caltech.edu/tess/
Fig. 2. TESS target pixel file images of TOI-1442 (top 15 panels) and TOI-2445 (last two panels). The pixels highlighted in red denote the aperture mask used to calculate the SAP. The red circles represent neighboring sources listed in Gaia DR2, the target star being marked with a white "x" and identifier 1. The size of the red circles is inversely proportional to the apparent magnitude difference with respect to the target star.
6.1\times 6.1. Each CCD is coupled with an Astrodon Photometrics Generation 2 Sloan filter. The three filter bands are g (400-550 nm), r (550-700 nm) and z (820-920 nm).

We observed a full transit of TOI-2445 b on 2021 February 7 UT with MuSCAT. The exposure times were 30, 20 and 35 s for the g, r and z bands, respectively. After performing dark and flatfield calibrations, we extracted light-curves by aperture photometry with radii of 3\textquoteright, 4\textquoteright, and 3\textquoteright.6 using a custom data reduction pipeline [Fukui et al., 2011]. The resulting photometric dispersion per exposure are 1.4\%, 0.7\% and 0.2\%.

2.2.2. MuSCAT2

MuSCAT2 [Narita et al., 2019] is a four-band imager mounted on the 152-cm Telescopio Carlo Sánchez (TCS) at Teide Observatory in Spain. MuSCAT2 is equipped with four 1024\times 1024 pixel CCDs with pixel scale of 0\textquoteright.353 pixel\textsuperscript{-1}. The field of view of MuSCAT2 is 7\textquoteright.4\times 7\textquoteright.4. The four filter bands are g (400-550 nm), r (550-700 nm), i (700-820 nm) and z (820-920 nm). Three g, r and z filters are identical to those adopted by MuSCAT. The i filter was custom-ordered and manufactured by Asahi Spectra Co., Ltd.

We observed a partial transit of TOI-2445 b on 2021 August 6 UT, and a full transit on 2021 September 14 UT with MuSCAT2. The r filter was not available during the last observation. The exposure times were set between 50 and 100 s, depending on the band, instrument and observing conditions. We extracted photometry with aperture radii of 10\textquoteright.875. The resulting photometric dispersion per exposure are 0.53-0.42\% in g, 0.29\% in r, 0.33-0.25\% in i, and 0.24-0.27\% in z, for the two nights, respectively.

2.2.3. MuSCAT3

MuSCAT3 [Narita et al., 2020] is another four-band imager with g, r, i and z\textsubscript{r} filters, mounted on the 2-m Faulkes Telescope North (FTN) of Las Cumbres Observatory at the Haleakala observatory in Hawaii. The 2048\times 2048 pixel CCDs, with pixel scale of 0\textquoteright.266 pixel\textsuperscript{-1}, were manufactured by Teledyne Princeton Instruments. The field of view of MuSCAT3 is 9\textquoteright.1\times 9\textquoteright.1.

We observed three transits of TOI-1442 b on 2021 May 05, 2021 June 06 and 2021 June 17 UT with MuSCAT3. We discarded the g band data from the first two observations, because of too high scatter. The exposure times were set to 240, 67, 30 and 29 s for the g, r, i and z\textsubscript{r} bands, respectively. We extracted photometry with aperture radii of 2\textquoteright.65, 7\textquoteright.95 and 4\textquoteright.68. The resulting photometric dispersion per exposure are 0.07\% in g, 0.054-0.064\% in r, 0.62-0.94\% in i, and 0.39-0.68\% in z\textsubscript{r}.

2.2.4. TRAPPIST-South

The TRAnsting Planets and Planetesimals Small Telescope-South (TRAPPIST-PlanetSouth, Jehin et al., 2011; Gillon et al., 2011) is a 60-cm telescope at La Silla Observatory in Chile. It is equipped with a thermoelectrically cooled 2K \times 2K pixel FLI Proline PL3041-BB CCD with pixel scale of 0\textquoteright.64 pixel\textsuperscript{-1}, resulting a field of view of 22\textquoteright\times 22\textquoteright.

We observed two transits of TOI-2445 b on 2021 January 8 and 14 in the f+z filter with an exposure time of 50 s. We used the TESS Transit Finder tool, which is a customized version of the Tapir software package [Jensen, 2013], to schedule the photometric time-series. Data calibration and photometric measurements were performed using the PROSE\textsuperscript{4} pipeline [Garcia et al., 2021].

2.2.5. LCOGT 1 m

We observed four full transits of TOI-1442 b from the Las Cumbres Observatory Global Telescope (LCOGT, Brown et al., 2013) 1.0 m network node at McDonald Observatory. Observations on 2020 August 14 and 2020 August 30 were conducted in I-band, and observations on 2020 September 26 and 2020 October 21 were conducted in Sloan i\textsuperscript{'} band. We used the TESS Transit Finder to schedule our transit observations. The 1 m telescopes are equipped with 4096\times 4096 pixel SINISTRO cameras having an image scale of 0\textquoteright.389 per pixel, resulting in a 2\textquoteright\times 2\textquoteright field of view. The images were calibrated by the standard LCOGT BANZAI pipeline (McCully et al., 2018), and photometric data were extracted using AstroImageJ (Collins et al., 2017). The images were focused and have mean stellar point-spread-functions with a FWHM of ∼ 2\textquoteright, and circular photometric apertures with radius ∼ 4\textquoteright were used to extract the differential photometry. The apertures exclude flux from the nearest Gaia EDR3 and TESS Input Catalog neighbor (TIC 1718221659) 13\textquoteright west of the target.

2.2.6. OMM/PESTO

We observed a full transit of TOI-1442 b at Observatoire du Mont-Mégantic, Canada, on 2020 February 9. The observations were made in the i\textsuperscript{'} filter using the 1.6 m telescope of the observatory equipped with the PESTO camera. The light curve extraction via differential photometry was accomplished with AstroImageJ, which was also used for image calibration (bias subtraction and flat field division). The images have typical stellar point-spread-functions with a FWHM of ∼ 2\textquoteright, and circular photometric apertures with radius ∼ 5\textquoteright were used to extract the differential photometry, excluding flux from the nearest Gaia EDR3 neighbour.

2.2.7. MLO/Lewin

We observed a full transit of TOI-2445 b in I-band on 2021 January 10 from the Maury Lewin Astronomical Observatory 0.36 m telescope near Glendora, CA. The telescope is equipped with 3326 \times 2504 pixel SBIG STF8300M camera having an image scale of 0\textquoteright.84 per pixel, resulting in a 23\textquoteright \times 17\textquoteright field of view. The images were calibrated and the photometric data were extracted using AstroImageJ. The images have typical stellar point-spread-functions with a FWHM of ∼ 5\textquoteright, and circular photometric apertures with radius ∼ 7\textquoteright were used to extract the differential photometry, which excluded most of the flux from the nearest Gaia EDR3 neighbour.

2.3. Spectroscopic observations with Subaru/IRD

The InfraRed Doppler (IRD) instrument on the 8.2m Subaru telescope is a fiber-fed spectrograph covering the wavelength range 930-1740 nm with a spectral resolution of R ∼ 70,000 [Yamara et al., 2012; Kotani et al., 2018]. We obtained 20 IRD spectra of TOI-1442 on 11 nights between 2020 September 27 and 2021 October 22 UT. We also obtained 12 IRD spectra of TOI-2445 on 5 nights between 2021 September 9 and 2021 November 12 UT. The exposure times were set to 1200-1800
3. Stellar characterisation

We applied the following procedure to determine the main stellar parameters relevant to the light-curve analysis: First, we derived the effective temperature ($T_{\text{eff}}$), iron abundance ([Fe/H]), and overall metallicity ($[M/H]$) from the telluric-free template IRD spectra by following the same analysis as in Ishikawa et al. (2022). The template spectra were extracted for the purpose of radial velocity measurement described in Section 5. Note that for TOI-2445, we dare to use the spectrum without instrumental-deconvolution. This is because the SNR per frame of TOI-2445 is so low that the noise is amplified during the deconvolution, especially in the $Y$-band.

We used the 47 FeH molecular lines in the Wing-Ford band at 990–1020 nm to estimate $T_{\text{eff}}$. Note that the errors given in Tables 1 and 2 do not include any possible systematic errors but only the standard deviation ($\sigma$) of estimates based on individual FeH lines divided by the square root of the number of lines ($\sigma/\sqrt{N}$). More details can be found in Ishikawa et al. (2022). For elemental abundances, we used 34 and 30 neutral atomic lines for TOI-1442 and TOI-2445, respectively. The atomic species responsible for these lines are Na, Mg, Ca, Ti, Cr, Mn, Fe, and Sr. The analyses are based on the equivalent width comparison of individual absorption lines between the calculated model spectra and the observed ones. The detailed procedures to determine individual elemental abundances and their errors are also described in Ishikawa et al. (2020).

We alternated between $T_{\text{eff}}$ estimation and abundance analysis to obtain $T_{\text{eff}}$ and metallicity that are consistent with each other. Firstly, we derived a provisional $T_{\text{eff}}$ adopting the solar metallicity ([Fe/H] = 0), and then, we determined the individual abundances of the eight elements [X/H] using the $T_{\text{eff}}$. Secondly, we re-determined $T_{\text{eff}}$ adopting the iron abundance [Fe/H], as the input metallicity, and then, we re-determined the abundances using the new $T_{\text{eff}}$. We iterated the estimation of $T_{\text{eff}}$ and [Fe/H] until the final results and the results of the previous step agreed within the error margin. From the final results the abundances of the eight elements, $[M/H]$, was determined by calculating the average weighted by the inverse of the square of their estimated errors.

Second, we performed SED fitting on the photometric magnitudes of Gaia EDR3 (Gaia Collaboration et al. 2021), 2MASS (Skrutskie et al. 2006), and WISE (Cutri et al. 2012), applying the [M/H], prior from the spectral analysis. Hence, we obtained an independent estimate of $T_{\text{eff}}$, along with the stellar radius ($R_*$) and luminosity ($L_*$). Specifically, the SED was calculated from the magnitudes in the Gaia EDR3 G, BP, and RP bands, 2MASS J, H, and K_s bands, and WISE W1, W2, and W3 bands. The BT-Settl synthetic spectra (Allard 2013) were then fitted to the SED with the parameters of $T_{\text{eff}}, [M/H]$, log surface gravity ($\log g_s$), and log($R_*/D$), where $D$ is the distance to the system.

We calculated the posterior probability distributions of these parameters using the Markov Chain Monte Carlo (MCMC) method implemented in the Python package emcee (Foreman-Mackey et al. 2013). In each MCMC step, a synthetic spectrum was calculated by linearly interpolating the model grid for a given set of parameters. A Gaussian prior from IRD was applied for [M/H]. A white noise jitter term, $\sigma_{\text{jitter}}$, was also fitted for each of the Gaia EDR3, 2MASS and WISE data sets such that the magnitude uncertainty was given by $\sqrt{\sigma_{\text{cat}}^2 + \sigma_{\text{jitter}}^2}$, where $\sigma_{\text{cat}}$ is the catalogue uncertainty in magnitude. Using the obtained posteriors of log($R_*/D$) and $T_{\text{eff}}$, we also derived the posteriors of $R_*$ and $L_*$ applying the distance from Bailey-Jones et al. (2021) for $D$.

Finally, we estimated the stellar mass ($M_*$) and radius from [Fe/H], and the absolute $K_s$ magnitude via the empirical relations of Mann et al. (2019) and Mann et al. (2015), respectively.

Tables 1 and 2 report the stellar parameters obtained with the three methods and values adopted from the literature. The parameter values obtained with multiple methods are consistent within 1σ. The log $g_s$ is weakly constrained by SED fitting. The empirical relations provide the most precise determinations of $M_*$, $\rho$, and log $g_s$.

4. Light-curve analysis

4.1. Contamination transit models

In order to confirm the planetary nature of our TOIs, we fitted simultaneously the TESS and ground-based photometric light-curves by modeling planetary transits with third light contamination. Our approach is similar to that described by Parviainen et al. (2019, 2020, 2021).

The transit models were generated with a customised version of PYLIGHTCURVE5 (Tsiaras et al. 2016), which implements the analytic formulae derived by Pall (2008). Conventionally, the model light-curves are normalised so that the out-of-transit flux is unity, and the flux drop during transit corresponds to the fraction of stellar flux occulted by the transiting planet. We fitted the following transit parameters: planet-to-star radius ratio ($p = R_p/R_*$), orbital period ($P$), epoch of transit ($T_0$), total transit duration ($T_{14}$), stellar mean density ($\rho_*$), and two limb-darkening coefficients (LDCs, $q_1$ and $q_2$). We assumed the power-2 law to approximate the stellar limb-darkening profile (Hestroffer 1997), as recommended by Morello et al. (2017), especially for M dwarfs. Additionally, we implemented optimal sampling by means of the transformed LDCs, $q_1$ and $q_2$, derived by Short et al. (2019) following the procedure of Kipping (2013).

Third light generally means any contribution to the flux from sources outside the star-planet system, such as blended or nearby stars which part of the photons hit the selected photometric aperture of the target. In this work, we define the relative third light flux as

$$\beta = \frac{F_3}{F_* + F_3}.$$
where $F_*$ and $F_c$ denote the flux from the target star and contaminating sources, respectively. Thus, the contaminated transit model can be expressed as

$$\hat{F}(t) = (1 - \beta)(1 - \Lambda(t)) + \beta,$$

where $\hat{F}(t)$ is the normalised astrophysical flux, and $1 - \Lambda(t)$ is the pure planetary transit model. We further assumed that the contaminating flux comes from only one blended star, except for the TESS observations, due to the significantly larger pixel scale of TESS compared to that of ground-based detectors. The planet self-blend effect is negligible in the analysed datasets (Kipping & Tinetti 2010; Martin-Lagarde et al. 2020). Both $F_*$ and $F_c$ were computed through ExoTETHyS (Morello et al. 2021), based on a precomputed grid of PHOENIX stellar spectra (Claret 2018). We fitted the photospheric parameters of the contaminating star ($T_{\text{eff}}$ and log $g_*$), a flux scaling factor ($f_\lambda$) to account for, e.g., different distances of the target and contaminating stars, and an independent blend TESS factor ($\beta_{\text{TESS}}$).

### 4.2. Baseline models

In addition to planetary transit and possible third light contamination, other signals are present in the observed light-curves, both of astrophysical and instrumental origin. We modelled the modulations present in the TESS time series by using Gaussian Processes (GPs), which provide a flexible non-parametric method to approximate stochastic trends in various types of datasets (Rasmussen & Williams 2006; Roberts et al. 2012). In the field of Astrophysics, GPs are often used to filter out stellar variability and instrumental systematic effects in photometric time series (Gibson et al. 2012; Evans et al. 2015; Barros et al. 2020). In this paper, we computed the TESS GPs using celerite\(^6\) (Foreman-Mackey et al. 2017) with the Matern-3/2 kernel:

$$k(\tau) = \sigma^2_{\text{GP}} \left[ 1 + \frac{1}{\epsilon} \right] e^{-\frac{\sqrt{3}\tau}{\rho}} \left[ 1 - \frac{1}{\epsilon} \right] e^{-\frac{\sqrt{3}(1+\epsilon)\tau}{\rho}}$$

where $\tau = |t_0 - t_j|$ is the time interval between two points, $\epsilon = 0.01$, $\sigma_{\text{GP}}$ and $\rho_{\text{GP}}$ are characteristic amplitude and timescale of the modulations. The choice of GP Matern-3/2 kernel has proven

### Table 1. Stellar properties of TOI-1442.

| Parameter        | Value                  | Reference\(^a\) |
|------------------|------------------------|-----------------|
| **Astrometric Parameters** |                      |                 |
| $\alpha$ (epoch 2016) | $19.9:10.1142$          | (1)             |
| $\delta$ (epoch 2016) | $+74.10:27.626$         | (1)             |
| $\mu_\alpha$ (mas/yr) | $81.959 \pm 0.020$      | (1)             |
| $\mu_\delta$ (mas/yr) | $462.708 \pm 0.017$     | (1)             |
| Parallax (mas)    | $24.164 \pm 0.015$      | (1)             |
| Distance (pc)     | $41.316 \pm 0.023$      | (2)             |
| **Photospheric Parameters** | Spec. Synth. | SED fit | Emp. Rel. |
| $T_{\text{eff}}$ ($K^b$) | $3345 \pm 13$          | $3263^{+33}_{-22}$ | This work   |
| log $g_*$ (dex)   | $5.27^{+0.17}_{-0.37}$  | $4.91 \pm 0.03$  | This work   |
| [$M/H]$ (dex)     | $0.10 \pm 0.07$         | $0.12 \pm 0.07$  | This work   |
| [$Fe/H]$ (dex)    | $0.03 \pm 0.15$         |                 | This work   |
| **Physical Parameters** | Spec. Synth. | SED fit | Emp. Rel. |
| $M_*$ ($M_\odot$) | $0.2843 \pm 0.0065$     |                 | This work   |
| $R_*$ ($R_\odot$) | $0.3159^{+0.0036}_{-0.0047}$ | $0.3105 \pm 0.0089$ | This work |
| $L_*$ ($L_\odot$) | $0.01020^{+0.0014}_{-0.0012}$ |                 | This work   |
| $\rho_*$ ($\rho_\odot$) | $9.5 \pm 0.8$          |                 | This work   |
| **Magnitudes**    |                        |                 |
| $V$ (mag)         | $15.39 \pm 0.20$        |                 | (3)         |
| $G$ (mag)         | $13.7390 \pm 0.0029$    |                 | (1)         |
| $TESS$ (mag)      | $12.4934 \pm 0.0075$    |                 | (3)         |
| $J$ (mag)         | $10.925 \pm 0.019$      |                 | (4)         |
| $H$ (mag)         | $10.332 \pm 0.019$      |                 | (4)         |
| $K_s$ (mag)       | $10.089 \pm 0.020$      |                 | (4)         |

Notes.\(^{a,b}\) References: (1) Gaia EDR3 (Gaia Collaboration et al. 2021), (2) Bailer-Jones et al. (2021), (3) TIC v8.2 (Stassun et al. 2019), (4) 2MASS (Skrutskie et al. 2006).

\(^{a}\)The error bars account for the random error from the fitting procedure. A systematic error of ~100 $K$ is associated with the absolute calibration of the instruments.

\(^{b}\)This work.

\[^{6}\]https://github.com/ucl-exoplanets/ExoTETHyS

\[^{7}\]https://github.com/dfm/celerite

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and possible changes in orbital inclinations were neglected. We
wavelength-dependent absorption of the planetary atmospheres
observations and passbands; second-order effects such as
transit duration to let them be fully constrained by the transit
priors for all parameters.

We selected uniform priors on the radius ratio and total
results such as the
consistent photospheric parameters.
assumed linear ephemeris with gaussian priors on the orbital
period and epoch of transits, centered on the ExoFOP values, but
their \( \sigma \) widths were conservatively enhanced by a factor of 3. For
stellar mean density, we used our estimates from empirical
relations (Tables 1 and 2) with a factor of 1.5 on the error bars.
The orbital eccentricity was fixed to zero, as is expected for USP
planets.

We detrended the ground-based light-curves by fitting linear
models with maximum two auxiliary parameters, as detailed in
Table 3.

### 4.3. Bayesian priors

We made use of the `emcee` package to compute the posterior
probability distributions of the astrophysical parameters associated
with the contaminated transit models (Section 4.1), along with those of the data detrending parameters (Section 4.2). The
prior distributions were chosen to discard unphysical solutions, and considering our knowledge of the system from ancillary
observations, e.g., the stellar spectra. Table 2 reports the bayesian priors for all parameters.

We selected uniform priors on the radius ratio and total
transit duration to let them be fully constrained by the transit
light-curves themselves. These parameters were shared by all
observations and passbands; second-order effects such as
the wavelength-dependent absorption of the planetary atmospheres
and possible changes in orbital inclinations were neglected. We
also assumed linear ephemeris with gaussian priors on the orbital
period and epoch of transits, centered on the ExoFOP values, but
their \( \sigma \) widths were conservatively enhanced by a factor of 3. For
stellar mean density, we used our estimates from empirical
relations (Tables 1 and 2) with a factor of 1.5 on the error bars.
The orbital eccentricity was fixed to zero, as is expected for USP planets.

The stellar LDCs were computed with ExoTETHyS (Morello
et al. 2020b), based on the photospheric parameters reported
in Tables 1 and 2, then transformed into \( q_1 \) and \( q_2 \) (see Section 4.1). We adopted broad gaussian priors centered on the theoretical
values of \( q_1 \) and \( q_2 \) with widths \( \sigma = 0.1 \), that largely encompass all plausible values derived from stellar models with
consistent photospheric parameters.

To compute the physical contamination model, we fixed the
effective temperature and surface gravity of the target star, and
assumed uniform priors for all the contaminant parameters,
including the blend TESS factor. Finally, we selected uninformative
prior distributions for all data detrending parameters and
normalisation factors. In particular, we adopted log-uniform priors
for the TESS GP parameters, that were shared over all sectors
for the same target. The final `emcee` fit for TOI-1442 had 68 pa-

### Table 2. Stellar properties of TOI-2445.

| Parameter | Value | Reference |
|-----------|-------|-----------|
| \( \alpha \) (epoch 2016.0) | 02:53:15.8792 | (1) |
| \( \delta \) (epoch 2016.0) | +00:03:08.400 | (1) |
| \( \mu_\alpha \) (mas/yr) | 57.557 \pm 0.029 | (1) |
| \( \mu_\delta \) (mas/yr) | -23.693 \pm 0.025 | (1) |
| Parallax (mas) | 20.361 \pm 0.032 | (1) |
| Distance (pc) | 48.968 \pm 0.077 | (2) |

### Photometric Parameters

| Parameter | Spec. Synth. | SED fit | Emp. Rel. |
|-----------|--------------|---------|-----------|
| \( T_{\text{eff}} \) (K) \( ^b \) | 3375\pm10 | Spec. Synth. | This work |
| \( \log g \) (dex) | 5.24\pm0.20 | SED fit | This work |
| \( [M/H] \) (dex) | -0.32\pm0.07 | -0.34\pm0.07 | This work |
| \( [Fe/H] \) (dex) | -0.39\pm0.16 | -0.39\pm0.16 | This work |

### Physical Parameters

| Parameter | Spec. Synth. | SED fit | Emp. Rel. |
|-----------|--------------|---------|-----------|
| \( M_\star \) (\( M_\odot \)) | 0.2448\pm0.0056 | 0.2448\pm0.0056 | This work |
| \( R_\star \) (\( R_\odot \)) | 0.2762\pm0.0055 | 0.2699\pm0.0078 | This work |
| \( L_\star \) (\( L_\odot \)) | 0.00760\pm0.00019 | 0.00760\pm0.00017 | This work |
| \( \rho_\star \) (\( \rho_\odot \)) | 12.5\pm1.1 | 12.5\pm1.1 | This work |

### Notes

- References: (1) Gaia EDR3 (Gaia Collaboration et al. 2021), (2) Bailer-Jones et al. (2021), (3) TIC v8.2 (Stassun et al. 2019), (4) 2MASS (Skrutskie et al. 2006).
- The error bars accounts for the random error from the fitting procedure. A systematic error of \( \sim 100 \) \( \kappa \) is associated with the absolute calibration of the instruments.
parameters, 150 walkers and 300000 iterations. The final \texttt{emcee} fit for TOI-2445 had 48 parameters, 110 walkers and 300000 iterations.

5. Radial velocity analysis

We fitted the IRD RV data using \texttt{radvel}\cite{Fulton2018}. We adopted gaussian priors on the orbital period and epoch of transits, based on the results of the photometric analysis reported in Table 6, and uniform prior with upper bound of 300 m s\(^{-1}\) on the RV semiamplitude (\(K_p\)). We also included the jitter term with uniform prior between 0 and 100. However, the best-fit models do not provide a good match to the observed RV data, as it can be seen in Figure 3. Alternative configurations with a linear trend do not provide significant improvements.

There are at least three possible explanations of such a poor agreement between the RV data and our simple RV models. First, the RV measurements can be dominated by systematic effects, as their overall ranges of variations are comparable with the potential instrumental offsets of \(\sim 10\) m s\(^{-1}\). Second, strong stellar activity could also cause similar offsets. The third and most intriguing scenario is that TOI-1442 and/or TOI-2445 host additional planets with detectable RV signals, but which are not transiting. More RV measurements are required to test these different scenarios.

Nonetheless, the current RV measurements have a good phase coverage, so that we can constrain \(K_p\). We derive 3\(\sigma\) upper limits as half of the variation ranges obtained by subtracting the maximum value plus three times its upper error bar and the minimum value minus three times its lower error bar.

6. Results

6.1. TOI-1442 b

Figure 4 shows the TESS phase-folded light-curve and ground-based light-curves, after data detrending, and best-fit contaminated transit models for TOI-1442 b. Figure 5 shows the posterior distributions and mutual correlations of the transit model parameters. The multiband light-curve analysis constrains the \(T_{\text{c,eff}}\) of a hypothetical blended source to similar or cooler values than \(T_{\text{c,eff}}\). The posterior distribution of \(T_{\text{c,eff}}\) is bimodal with a primary peak towards the lower temperature limit of the PHOENIX stellar models grid (2300 K), and a second peak at \(T_{\text{c,eff}}\sim 3000\) K. Overall, we pose a 3\(\sigma\) upper limit at \(T_{\text{c,eff}}<5000\) K. If such a blend exists, it would not imprint a significant colour-dependent signature, and the dilution factor would be nearly uniform over all passbands. We checked that the differential third light fraction

\[
\Delta\beta_{\text{pass}} = \beta_{\text{pass}} - \beta_{\text{c}},
\]

with \(\beta\) defined as in Equation 5 is consistent with zero within 1.3\(\sigma\) (1-10%) for all passbands, including TESS.

The radius ratio turns out to be \(p = 0.0373^{+0.0039}_{-0.0025}\) with a 3\(\sigma\) upper limit at \(p < 0.0694\). Multiplying these values by \(R_e\) from Table 1 the radius of the planetary candidate is \(R_p = 1.27^{+0.17}_{-0.12} R_\oplus\) with a 3\(\sigma\) upper limit at \(R_p < 2.55 R_\oplus\). The small size of the transiting object around TOI-1442 inferred by multicolour photom-

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Table 3. List of ground-based observations and auxiliary parameters used for detrending.

| Target       | Instrument | UT Date | Passband | Detrending       |
|--------------|------------|---------|----------|-----------------|
| TOI-1442     | MuSCAT3    | 2021 May 05 | r        | AIRMASS         |
| TOI-1442     | MuSCAT3    | 2021 May 05 | i        | AIRMASS         |
| TOI-1442     | MuSCAT3    | 2021 May 05 | z_s      | AIRMASS         |
| TOI-1442     | MuSCAT3    | 2021 Jun 06 | r        | tot_C_cnts     |
| TOI-1442     | MuSCAT3    | 2021 Jun 06 | i        | tot_C_cnts     |
| TOI-1442     | MuSCAT3    | 2021 Jun 06 | z_s      | width_T1       |
| TOI-1442     | MuSCAT3    | 2021 Jun 17 | g        | AIRMASS         |
| TOI-1442     | MuSCAT3    | 2021 Jun 17 | r        | width_T1       |
| TOI-1442     | MuSCAT3    | 2021 Jun 17 | i        | AIRMASS         |
| TOI-1442     | MuSCAT3    | 2021 Jun 17 | z_s      | AIRMASS         |
| TOI-1442     | LCO-McD-1m0| 2020 Aug 14 | I        | –               |
| TOI-1442     | LCO-McD-1m0| 2020 Aug 30 | I        | –               |
| TOI-1442     | LCO-McD-1m0| 2020 Sep 26 | i        | BJD_TDB, Sky/Pixel_T1 |
| TOI-1442     | LCO-McD-1m0| 2020 Oct 21 | i        | AIRMASS         |
| TOI-1442     | PESTO      | 2020 Feb 09 | i        | AIRMASS         |
| TOI-2445     | MuSCAT     | 2021 Feb 07 | g        | BJD_TDB, AIRMASS |
| TOI-2445     | MuSCAT     | 2021 Feb 07 | r        | BJD_TDB, AIRMASS |
| TOI-2445     | MuSCAT     | 2021 Feb 07 | z_s      | BJD_TDB, AIRMASS |
| TOI-2445     | MuSCAT2    | 2021 Aug 06 | g        | –               |
| TOI-2445     | MuSCAT2    | 2021 Aug 06 | r        | –               |
| TOI-2445     | MuSCAT2    | 2021 Aug 06 | i        | –               |
| TOI-2445     | MuSCAT2    | 2021 Aug 06 | z_s      | –               |
| TOI-2445     | MuSCAT2    | 2021 Sep 14 | g        | –               |
| TOI-2445     | MuSCAT2    | 2021 Sep 14 | i        | –               |
| TOI-2445     | MuSCAT2    | 2021 Sep 14 | z_s      | –               |
| TOI-2445     | TRAPPIST-S | 2021 Jan 08 | I + z    | –               |
| TOI-2445     | TRAPPIST-S | 2021 Jan 14 | I + z    | –               |
| TOI-2445     | MLO-Lewin  | 2021 Jan 10 | I        | Y(FITS)_{T1}    |

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\(^a\) \url{https://github.com/California-Planet-Search/radvel}
Table 4. Prior probability distributions of the fitted parameters.

| Parameter      | TOI-1442                                                                 | TOI-2445                                                                 |
|----------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Transit        |                                                                           |                                                                           |
| $p$            | $U(0, 1)$                                                                 | $U(0, 1)$                                                                 |
| $P$ (day)      | $N(0.409072, 0.000011)$                                                   | $N(0.371133, 0.000047)$                                                   |
| $T_0$ (BJD)    | $N(1683.45058, 0.00085)$                                                  | $N(1411.21732, 0.00188)$                                                  |
| $ho_s$       | $N(9.50, 1.27)$                                                           | $N(12.45, 1.67)$                                                          |
| $T_{14}$ (hr)  | $U(0.169, 1.036)$                                                         | $U(0, 1.289)$                                                             |
| Contamination  |                                                                           |                                                                           |
| $T_{\text{eff}}$ (K)$^b$ | 3304                                                                      | 3306                                                                      |
| log $g_s$ (dex)$^c$ | 4.91                                                                      | 4.96                                                                      |
| $T_{\text{eff}}$ (K) | $U(2300, 12000)$                                                         | $U(2300, 12000)$                                                          |
| log $g_s$ (dex) | $U(2.0, 5.5)$                                                             | $U(2.0, 5.5)$                                                             |
| $f_c$          | $U(-1, 1000)$                                                             | $U(-1, 1000)$                                                             |
| $\beta_{\text{TESS}}$ | $U(-0.2, 0.99)$                                                         | $U(-0.2, 0.99)$                                                           |
| LDCs$^r$       |                                                                           |                                                                           |
| $q_{1, \text{TESS}}$ | $N(0.038667, 0.1) \times U(0, 1)$                                        | $N(0.038237, 0.1) \times U(0, 1)$                                        |
| $q_{2, \text{TESS}}$ | $N(0.005047, 0.1) \times U(0, 1)$                                        | $N(0.00067, 0.1) \times U(0, 1)$                                         |
| $q_{1, \text{g}}$ | $N(0.104994, 0.1) \times U(0, 1)$                                        | $N(0.104916, 0.1) \times U(0, 1)$                                        |
| $q_{2, \text{g}}$ | $N(0.0, 0.1) \times U(0, 1)$                                             | $N(0.0, 0.1) \times U(0, 1)$                                             |
| $q_{1, \text{f}}$ | $N(0.126307, 0.1) \times U(0, 1)$                                        | $N(0.123358, 0.1) \times U(0, 1)$                                        |
| $q_{2, \text{f}}$ | $N(0.102417, 0.1) \times U(0, 1)$                                        | $N(0.092309, 0.1) \times U(0, 1)$                                        |
| $q_{1, \text{l}}$ | $N(0.047087, 0.1) \times U(0, 1)$                                        | $N(0.047093, 0.1) \times U(0, 1)$                                        |
| $q_{2, \text{l}}$ | $N(0.0, 0.1) \times U(0, 1)$                                             | $N(0.0, 0.1) \times U(0, 1)$                                             |
| $q_{1, \text{z}}$ | $N(0.031820, 0.1) \times U(0, 1)$                                        | $N(0.031817, 0.1) \times U(0, 1)$                                        |
| $q_{2, \text{z}}$ | $N(0.0, 0.1) \times U(0, 1)$                                             | $N(0.0, 0.1) \times U(0, 1)$                                             |
| $q_{1, \text{I}}$ | $N(0.028676, 0.1) \times U(0, 1)$                                        | $N(0.028607, 0.1) \times U(0, 1)$                                        |
| $q_{2, \text{I}}$ | $N(0.0, 0.1) \times U(0, 1)$                                             | $N(0.0, 0.1) \times U(0, 1)$                                             |
| $q_{1, \text{J+K}}$ | –                                                                        | $N(0.022097, 0.1) \times U(0, 1)$                                        |
| $q_{2, \text{J+K}}$ | –                                                                        | $N(0.0, 0.1) \times U(0, 1)$                                             |
| Baseline       |                                                                           |                                                                           |
| log$_{10}$ $\sigma_{\text{GP}}$ | $U(-10, 6)$                                                              | $U(-10, 6)$                                                              |
| log$_{10}$ $\rho_{\text{GP}}$ | $U(-10, 6)$                                                              | $U(-10, 6)$                                                              |
| $N_{\text{TESS}}$ | $U(1000, 2000)$                                                          | $U(400, 1400)$                                                           |
| $N_{\text{ground}}$ | $U(0.5, 1.5)$                                                            | $U(0.5, 1.5)$                                                            |
| $X_1, X_8$     | $U(-1, 1)$                                                               | $U(-1, 1)$                                                               |

Notes. $U(a, b)$ denotes a uniform prior delimited by $a$ and $b$; $N(\mu, \sigma)$ denotes a normal prior with $\mu$ mean and $\sigma$ width.

(a) Centered on the ExoFOP values as of 2021 November 30. For the normal distributions, the prior $\sigma$ equals three times the nominal error bars. For the uniform distributions, the whole interval equals six times the nominal error bars.

(b) Arithmetic average between spectral synthesis and SED fitting estimates from Tables 1 and 2.

(c) Obtained with empirical relations, from Tables 1 and 2.

(d) Negative contamination values are allowed to avoid bouncing effect at the physical boundary of zero contaminants; they could also be caused by systematic offsets.

(e) Some ground-based detectors share the same LDCs, if they have the same passband (see Table 3).

(f) Normalisation factors, i.e., multiplicative factors for the contaminated transit models. A factor is fitted for each TESS sector and for each ground-based observation.

(g) Coefficients of the linear detrending models for ground-based observation, using up to two auxiliary parameters (see Table 3).

Note that the radius ratio is largely degenerate with the third light contamination parameters. We repeated the light-curve fits assuming that such contamination is negligible, based on the lack of colour dependence from photometry and known blends from the GAIA DR2. This assumption leads to more precise estimates of $p = 0.03405 \pm 0.00077$ and $K_p = 1.15 \pm 0.06 \text{m}$. Our radius measurement is consistent within $1\sigma$ with that obtained independently by Giacalone et al. (2022).

From the RV measurements, we derived a $3\sigma$ upper limit of $K_p < 34 \text{m}$. Using $M_\star$ from Table 1, we infer a $3\sigma$ upper limit on the (projected) planet mass of $M_p \sin i \approx M_\star < 18M_\oplus$.

Table 5 reports the final system parameters.

6.2. TOI-2445 b

Figure 6 shows the TESS phase-folded light-curve and ground-based light-curves, after data detrending, and best-fit contaminated transit models for TOI-2445 b. Figure 7 shows the posterior distributions and mutual correlations of the transit model parameters. The multiband light-curve analysis led to similar results on the possible blend for this target. The posterior distribution of $T_{\text{eff}}$ is bimodal with two similar peaks towards the lower temperature limit of 2300 K and at $\sim 3500$ K. Overall, we pose a $3\sigma$ upper limit at $T_{\text{eff}} < 6300$ K. The differential third light fraction is within less than $1\sigma$ ($1\%$-$10\%$) for all passbands.

Table 6 reports the final system parameters.
The radius ratio is \( p = 0.051^{+0.029}_{-0.006} \) with a 3\( \sigma \) upper limit at \( p < 0.162 \). Multiplying these values by \( R_e \) from Table 2, the radius of the planetary candidate is \( R_p = 1.49^{+0.85}_{-0.32} R_\oplus \) with 3\( \sigma \) upper limit at \( R_p < 5.17 R_\oplus \) (equivalent to \( R_p < 0.46 R_J \)). The small size of the transiting object around TOI-2445 inferred by multicolour photometry confirms that it must be planetary in nature, and it is likely to be another super-Earth or mini-Neptune. However, it could also be a giant planet, given the 3\( \sigma \) upper limit on its radius.

The lack of colour dependence from photometry and known blends from the GAIA DR2 motivated repeating the light-curve fits without contamination even for this planet. The corresponding values were \( p = 0.0453 \pm 0.0018 \) and \( R_p = 1.33 \pm 0.09 R_\oplus \).

Our radius measurement is consistent within 1\( \sigma \) with that obtained independently by Giacalone et al. (2022).

We estimated the equilibrium temperature to be \( T_{\text{eq}} = 1330^{+61}_{-30} \), which is also pointing to a dayside hemisphere covered by molten rocks and metals.

From the RV measurements, we derived a 3\( \sigma \) upper limit of \( K_p < 82 \text{ m s}^{-1} \). Using \( M_\star \) from Table 2, we infer a 3\( \sigma \) upper limit on the (projected) planet mass of \( M_p \sin i \approx M_p < 38 M_\oplus \).

Table 6 reports the final system parameters.
Fig. 4. TESS phase-folded light-curve and ground-based light-curves, after data detrending, and best-fit contaminated transit models for TOI-1442 b.

7. Discussion

Figure 8 shows the radius vs. orbital period distribution of the known USP planets. TOI-1442 b and TOI-2445 b are among the 12 confirmed USP planets with the shortest orbital periods, and likewise their radii are smaller than $2R_{\oplus}$. If we consider the known sample of 13 USP planets around M dwarfs, TOI-1442 b and TOI-2445 b have the third and the fifth shortest periods, respectively. They also have the fourth and fifth highest equilibrium temperatures. All the USP planets around M dwarfs have radii smaller than $2R_{\oplus}$, except K2-22 b (Sanchis-Ojeda et al. 2015). The mass upper limits of $M_p < 18M_{\oplus}$ for TOI-1442 b and $M_p < 38M_{\oplus}$ for TOI-2445 b confirm the sub-giant nature. More RV measurements are desirable to place significant constraints on their masses and mean densities, hence their chemical compositions.

The dispersion in our RV measurements suggests the possible presence of additional non-transiting planets around both stars, although stellar activity or instrumental systematic offsets could also provide alternative explanations. Despite only a small fraction of USP planets have been detected in multiplanet systems, four out of the 11 USP planets previously reported around M dwarfs are members of multiplanet systems. These systems are Kepler-42 (Muirhead et al. 2012), LTT-3780 (Cloutier et al. 2020), LHS-1678 (Silverstein et al. 2021) and LP 791-18 (Crossfield et al. 2019). Another peculiarity of these four systems is that...
their orbits are aligned so that the outer planets are also transiting. The only non-transiting planet discovered in these systems is LHS-1678 d, which has a wide orbit with a period of decades. The new RV measurements will also be useful to assess the architecture of the planetary systems around TOI-1442 and TOI-2445, which is important to validate formation theories for USP planets around M dwarfs and differences with those around later-type stars (e.g., Petrovich et al. 2020).

Both TOI-1442 b and TOI-2445 b are amenable targets to observe their thermal emission spectra with the James Webb Space Telescope (JWST). We estimated their emission spectroscopy metric (ESM) to be 9.0^{+1.1}_{-1.0} and 11.1^{+1.3}_{-1.3}, according to the definition given by Kempton et al. (2018). Planets with ESM > 7.5 and $R_p \lesssim 1.5R_\oplus$ are considered top targets to be observed in eclipse with the JWST/Mid-InfraRed Instrument (MIRI). Such observations can clarify whether these USP planets are bare rock stripped of their primordial atmospheres, or whether they have retained substantial gaseous envelopes, and characterise their surface/gas composition.

8. Conclusions
We confirm the planetary nature of TOI-1442 b and TOI-2445 b, two USP planets with M dwarf stellar hosts. TOI-1442 b has an orbital period of $P = 0.4090682 \pm 0.0000004 \, d$, a radius of
Fig. 6. TESS phase-folded light-curve and ground-based light-curves, after data detrending, and best-fit contaminated transit models for TOI-2445 b.

\[ R_p = 1.15 \pm 0.06 R_{\oplus} \] and equilibrium temperature of \( T_{p,eq} = 1357_{-49}^{+49} K \). TOI-2445 b has an orbital period of \( P = 0.3711286 \pm 0.0000004 \text{ d} \), a radius of \( R_p = 1.33 \pm 0.09 R_{\oplus} \), and equilibrium temperature of \( T_{p,eq} = 1330_{-50}^{+61} K \). We also report 3\( \sigma \) upper limits on their masses of \( M_p < 18 M_{\oplus} \) and \( M_p < 38 M_{\oplus} \), respectively.

These are interesting targets to follow-up with high-precision RV facilities to improve their mass measurements (to constrain their bulk compositions) and possibly detect other planetary companions. They are also amenable targets for emission spectroscopy with JWST.

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Fig. 7. Cornerplot showing the posterior distributions and mutual correlations of the transit model parameters for TOI-2445. The histograms along the diagonal report the median values of the distributions.

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### Table 6. Final system parameters

| Parameter | TOI-1442 | TOI-2445 |
|-----------|----------|----------|
| Stellar   |          |          |
| $T_\text{e}ff$ (K) | 3304 ± 50 | 3306 ± 75 |
| log $g_*$, (dex) | 4.91 ± 0.03 | 4.96 ± 0.03 |
| $[M/H]_*$, (dex) | 0.11 ± 0.07 | −0.33 ± 0.07 |
| $[Fe/H]_*$, (dex) | 0.03 ± 0.15 | −0.39 ± 0.16 |
| $M_*$ ($M_\odot$) | 0.2843 ± 0.0065 | 0.2448 ± 0.0056 |
| $R_*$ ($R_\odot$) | 0.3105 ± 0.0089 | 0.2699 ± 0.0078 |
| $L_*$ ($L_\odot$) | 0.01020 $^{+0.00014}_{-0.00012}$ | 0.00760 $^{+0.00019}_{-0.00017}$ |
| Transit fit |          |          |
| $p$ | 0.03405 ± 0.00077 | 0.0453 ± 0.0018 |
| $P$ (d) | 0.4090682 ± 0.0000004 | 0.3711286 ± 0.0000004 |
| $T_0$ (BT JD) | 1683.45193 $^{+0.00033}_{-0.00034}$ | 1411.21990 $^{+0.00071}_{-0.00083}$ |
| $\rho_*$ ($\rho_\odot$) | 9.09 $^{+0.91}_{-1.06}$ | 12.5 ± 1.6 |
| $T_{14}$ (hr) | 0.644 $^{+0.016}_{-0.013}$ | 0.537 $^{+0.022}_{-0.019}$ |
| (derived) |          |          |
| $a/R_*$ (a) | 4.84 $^{+0.16}_{-0.20}$ | 5.04 $^{+0.20}_{-0.23}$ |
| $b^b$ | 0.29 ± 0.13 | 0.44 $^{+0.09}_{-0.13}$ |
| $i$ (deg) (c) | 86.57 $^{+1.54}_{-1.62}$ | 84.95 $^{+1.53}_{-1.50}$ |
| RVs |          |          |
| $K_p$ (m s$^{-1}$) | < 34 | < 82 |
| Planetary and orbital (derived) |          |          |
| $R_p$ ($R_\oplus$) | 1.15 ± 0.06 | 1.33 ± 0.09 |
| $M_p$ ($M_\oplus$) | < 18 | < 38 |
| $a$ (au) (d) | 0.00699 $^{+0.00043}_{-0.00049}$ | 0.00634 $^{+0.00043}_{-0.00047}$ |
| $T_{p,\text{eq}}$ (K) (e) | 1357 $^{+42}_{-49}$ | 1330 $^{+61}_{-56}$ |

Notes. Values preceded by < report 3σ upper limits.

(a) Orbital semimajor axis relative in units of the stellar radius.

(b) Impact parameter.

(c) Orbital inclination.

(d) Orbital semimajor axis.

(e) Dayside equilibrium temperature, assuming zero albedo and no heat redistribution.
Fig. 8. Planetary radius vs. orbital period for the known USP planets, based on the same data of Figure 1. Planets around M dwarfs are colored in red. The green and orange stars correspond to TOI-1442 b and TOI-2445 b, based on the final results of our analysis.
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