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J. Irwin<sup>19</sup>, J. M. Jenkins<sup>18</sup>, E. Jensen<sup>24</sup>, K. Kawauchi<sup>15</sup>, T. Kotani<sup>14,16,25</sup>, T. Kudo<sup>22</sup>, M. Kunimoto<sup>26</sup>, M. Kuzuhara<sup>14,16</sup>, D. W. Latham<sup>19</sup>, D. Montes<sup>27</sup>, J. C. Morales<sup>2,3</sup>, M. Mori<sup>28</sup>, R. P. Nelson<sup>1</sup>, M. Omiya<sup>14,16</sup>, S. Pedraz<sup>29</sup>,
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 **BSTRACT** One of the main objectives of the *Transiting Exoplanet Survey Satellite* (TESS) mission is the discovery of small rocky planets around relatively bright nearby stars. Here, we report the discovery and characterization of the transiting super-Earth planet orbiting LHS 1478 (TOI-1640). The star value and spectral type m3V with mass and radius estimates of 0.29 ± 0.01 M<sub>6</sub>, necespectively, and a effective temperature of 3381 ± 54 K. It was observed by TESS in four sectors. These data revealed a transit-like feature with a period of 1.949 dogs. We combined the TESS data with three ground-based transit measurements, 57 radial velocity (RV) measurements from CARMENES, and 13 RV measurements from IRD, determining that the signal is produced by a planet with a mass of 2.33<sup>+0.20</sup> M<sub>6</sub> and a radius of 1.24<sup>+0.00</sup> R<sub>6</sub>. Although the planet would be too hot to sustain liquid water on its surface (its equilibrium temperature is about -395 K, suggesting a Venus-like at the forthoroning *Janews Web Space Telescope* and the fact that the host star is rather inactive indicate that this is one of the most favorable known rocky exoplanets for atmospheric characterization.
 Key words. techniques: photometric, radial velocities – planets and satellite: detection, fundamental parameters – stars: low-mass
 1. Introduction
 Stars smaller than the Sun offer a number of advantages at oth effective the goal of detecting those that should enable (e.g., Proxima) hits of the Stary for signals of these planets in her TAPPISF1 = lystem; Gillon et al. 2017). Both are india velocity for signals of the sky for signals of thask for signals of these

Exoplanet surveys with the Doppler technique are typically conducted with ground-based high-resolution spectrometers ( $R = \lambda/\delta\lambda > 50\,000$ ) that are kept in a very stable environment and are calibrated against spectral features of a reference source measured in the laboratory. This is the case for the CARMENES spectrometer (Quirrenbach et al. 2016), which was specifically designed to obtain maximal precision on red dwarf stars. The CARMENES survey has led to numerous new exoplanet discoveries in the super-Earth to Earth-mass regime, in

ing one to derive their mean bulk densities and put constrains on their compositions. Finally, the atmospheres of transiting planets can be studied by performing spectroscopic measurements during transits (the planet blocks more light at certain wavelengths where the molecules in its atmosphere deter more light, producing deeper transits) and secondary eclipses (the spectrum of thermal emission of the planet is also affected by the presence of absorbing molecules, producing a shallower dip in the light curve when the planet goes behind the star). Among these, and thanks to the more favorable radius ratio between the planet and the star, exoplanets transiting red dwarfs are the best ones for atmo-

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spheric characterization. The measured spectrum of an exoplanet can be affected by the presence of spots and active regions in the visible part of the star during transits (Rackham et al. 2018): The less active the star is, the cleaner and easier it is to interpret the measured spectrum of a planet. Due to its properties (transiting, Doppler signal in the few m s<sup>-1</sup> regime) and its host star (small, relatively nearby, and low stellar activity), LHS 1478 b satisfies all the favorable conditions for becoming a prime target for the characterization of rocky terrestrial planets.

In this paper, we validate the transiting exoplanet LHS 1478 b (TOI-1640 b). We provide an overview of the measurements with photometry (initial detection, stellar activity, orbital period, and planet size), imaging (validation against false positives), and RV (confirmation, stellar activity, and measurement of the planet mass) in Sect. 2. Stellar parameters are presented in Sect. 3.1, and a joint analysis to constrain the planet properties is given in Sect. 3.2. We discuss the results in the context of terrestrial planet candidates and further follow-up in Sect. 4 and summarize our work in Sect. 5.

# 2. Data

# 2.1. TESS photometry

LHS 1478 (TOI-1640) was observed by TESS in sectors 18, 19, 25, and 26 of its primary mission. The data were processed through the Science Processing Operations Center (SPOC; Jenkins et al. 2016), and transiting planet search algorithms (Jenkins 2002; Jenkins et al. 2010) detected a signal with a period of  $1.949521 \pm 0.000007$  d and a transit depth of  $2185 \pm 111$  parts-per-million (ppm) in December 2019 based on the data from sector 18. After reviewing the results of the data validation reports (Twicken et al. 2018; Li et al. 2019), the TESS Science Office alerted the community of TOI-1640 on 14 January 2020<sup>1</sup>.

We obtained the photometric light curve, corrected for systematics (PDC; Smith et al. 2012), from the Mikulski Archive for Space Telescopes<sup>2</sup> (MAST) using the lightkurve<sup>3</sup> package (Lightkurve Collaboration et al. 2018). The data are shown in Fig. 1. We performed a period search using the Box-Fitting Least Squares (BLS; Kovács et al. 2002) and the Transit Least Squares (TLS; Hippke & Heller 2019) algorithms (Fig. A.1), and we detected with both of them a signal with a period of 1.949 d and a signal detection efficiency (SDE) > 8 (empirical transit detection threshold from Aigrain et al. 2016). This period is the same as the one reported by the TESS SPOC.

Figure A.2 shows the TESS field of view and aperture size used for each of the four sectors for LHS 1478, generated using tpfplotter<sup>4</sup> (Aller et al. 2020). No sources contaminating the TESS aperture were found in the *Gaia* Early Data Release 3 (EDR3) catalog (Gaia Collaboration et al. 2020) down to a magnitude contrast limit of 6 mag compared to our target. Additionally, the *Gaia* EDR3 renormalized unit weight error (RUWE) value for this target is 1.26, below the critical value of 1.40, which is an indicator that a source is non-single or has a problematic astrometric solution (Lindegren et al. 2020).

### 2.2. High-spatial-resolution imaging

In order to exclude the presence of contaminants close to our target, we observed LHS 1478 with the AstraLux highspatial-resolution camera (Hormuth et al. 2008), located at the 2.2 m telescope of the Calar Alto Observatory (Almería, Spain). This instrument uses the lucky-imaging technique to obtain diffraction-limited images by obtaining thousands of shortexposure frames (below the atmospheric coherence time) to subsequently select those with the highest Strehl ratios (Strehl 1902) and combine them into a final high-spatial-resolution image. We observed this target on the night of 25 February 2020 under good weather conditions with a mean seeing of 1.0 arcsec. We obtained 41 710 frames with 20 ms exposure times for a total exposure of 83.4 s in the Sloan Digital Sky Survey z' filter ("SDSSz"), with a field of view windowed to  $6 \times 6$  arcsec. The data cube was reduced by the instrument pipeline (Hormuth et al. 2008), and we selected the 10% of frames with the highest quality to produce the final high-resolution image. In order to obtain the sensitivity limits of the image, we used the astrasens package<sup>5</sup> with the procedure described in Lillo-Box et al. (2012, 2014). Both the  $5\sigma$  sensitivity curve and the image are shown in Fig. 2. We could exclude sources down to 0.2 arcsec with a magnitude contrast of  $\Delta z' < 4$  mmag, corresponding to a maximum contamination level of 2.5 %.

We additionally estimated the probability of an undetected blended source in our high-spatial-resolution image, called the blended source confidence (BSC), following the steps in Lillo-Box et al. (2014). In short, we used a python implementation of this approach (bsc), which uses the TRILEGAL<sup>6</sup> galactic model (v1.6; Girardi et al. 2012) to retrieve a simulated source population of the region around the corresponding target<sup>7</sup>. This simulated population was used to compute the density of stars around the target position (radius  $\rho = 1 \text{ deg}$ ) and derive the probability of chance alignment at a given contrast magnitude and separation. We applied this to the position of LHS 1478 and used a maximum contrast magnitude of  $\Delta m_{b,max} = 6.7 \text{ mag}$  in the z' passband, corresponding to the maximum contrast of a blended eclipsing binary that could mimic the observed transit depth. Using our high-resolution image, we estimated the probability of an undetected blended source to be 0.2 %. The probability of such an undetected source being an appropriate eclipsing binary is even lower, and thus we concluded that the transit signal is not due to a blended eclipsing binary.

### 2.3. Ground-based photometry

Ground-based transit photometry was obtained to confirm the TESS transit event and to refine the ephemeris of the planet. We used the TESS Transit Finder, a customized version of the Tapir software package (Jensen 2013), to schedule our observations based on the preliminary ephemeris from the SPOC light curve. We obtained a total of three transit detections, which we included in our joint fit. The individual observations are described below.

#### 2.3.1. MEarth-North

LHS 1478 was first observed by the MEarth-North telescope array on 14 January 2020. MEarth-North is located at the Fred Lawrence Whipple Observatory on Mount Hopkins, Arizona, and consists of eight 40 cm telescopes equipped with Apogee U42 cameras and custom RG715 passbands. We reduced the MEarth photometry following the standard procedures outlined

<sup>&</sup>lt;sup>1</sup> https://tess.mit.edu/toi-releases/

<sup>&</sup>lt;sup>2</sup> https://archive.stsci.edu

<sup>&</sup>lt;sup>3</sup> https://github.com/KeplerGO/Lightkurve

<sup>4</sup> https://github.com/jlillo/tpfplotter

<sup>&</sup>lt;sup>5</sup> https://github.com/jlillo/astrasens

<sup>&</sup>lt;sup>6</sup> http://stev.oapd.inaf.it/cgi-bin/trilegal

 $<sup>^{7}</sup>$  This is done in python by using the astrobase implementation by Bhatti et al. (2020).

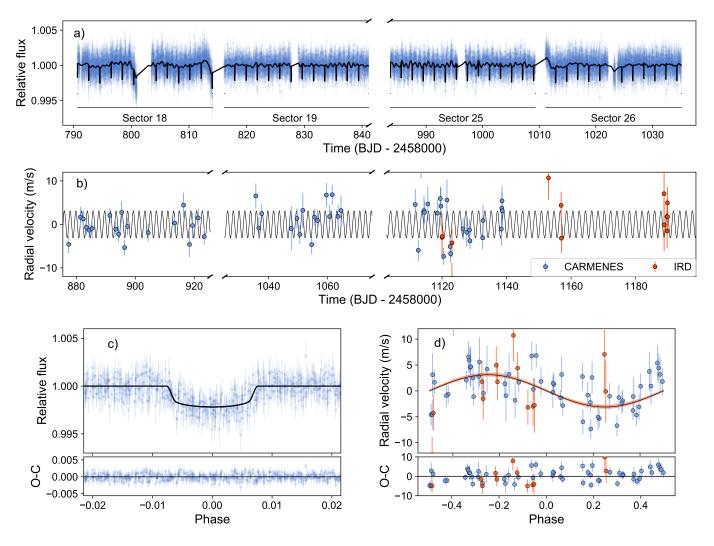


Fig. 1: Data and joint fit results of LHS 1478 with juliet (Sect. 3.2). *Top* (*a*): TESS photometry, with the black line representing the best transit-plus-GP fit. *Middle* (*b*): RV data from CARMENES and IRD, with the jitter term added to the uncertainties. The black line is the best fit Keplerian model. *Bottom left* (*c*): Phased-folded TESS data, with the GP component removed. The black line is the best transit fit. The bottom sub-panel shows the residuals from the transit fit. *Bottom right* (*d*): Phased-folded RV data. The black line is the best fit Keplerian model, and the red shaded area represents the 68 % CI. The bottom sub-panel shows the residuals after removing the Keplerian fit.

by Irwin et al. (2007) and Berta et al. (2012) and using a 6 arcsec 2.3.2. RCO aperture.

LHS 1478 was observed continuously with all eight telescopes from an airmass of 1.4 to 2.0 with 14-second exposures. The observations were taken through intermittent clouds and produced a tentative transit detection amid large residual systematics with a photometric dispersion of 4.2 parts-per-thousand (ppt). Although the combined light curve of the star from all eight telescopes did not yield a reliable transit detection, these data were still used to rule out nearby eclipsing binaries in 101 of 103 sources within 2.5 arcmin and down to a differential magnitude of 8.6 mag. The two uncleared sources are faint ( $\Delta m =$ 3.8–4.0 mag) and are blended with nearby sources. Their wide separations from LHS 1478 (1.8–2.2 arcmin) also make them improbable sources of the TESS transit events. The first reliable ground-based detection of a transit of LHS 1478 was obtained on 31 January 2020 using the Ritchey-Chrétien Optical (RCO) 40 cm telescope located at the Grand-Pra Observatory near Valais Sion, Switzerland. We observed a full transit in the Sloan *i'* passband with an exposure time of 45 s. We used the AstroImageJ software package (Collins et al. 2017) to perform differential photometry using 5.1 arcsec apertures and to detrend against airmass in order to produce the light curve of LHS 1478 depicted in the left panel of Fig. 3. With our reduction, we achieved a photometric precision of 1.1 ppt in three-minute bins. We detected the transit of LHS 1478 with a mid-transit time of  $\approx 8$  min late relative to the SPOC prediction (the transit epoch was derived at the time using TESS data from sectors 18 and 19).

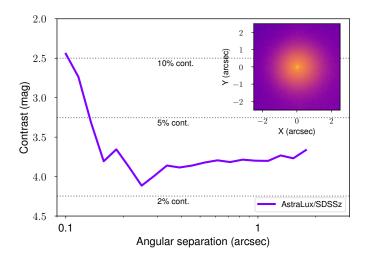


Fig. 2: AstraLux  $5\sigma$  sensitivity curve (main panel) of the high-spatial-resolution image obtained for LHS 1478 (inset) in the SDSSz photometric band.

# 2.3.3. LCOGT

We observed two additional full transits of LHS 1478 on 27 August 2020 and 7 October 2020 from the Las Cumbres Observatory Global Telescope (LCOGT; Brown et al. 2013) 1.0 m network node at McDonald Observatory. The images were calibrated by the standard LCOGT Banzai pipeline (McCully et al. 2018).

Both light curves were obtained in the Pan-STARRS *z*-short passband with exposure times of 40 s and 50 s in the August and October runs, respectively. We used AstroImageJ to perform differential photometry using 5.8 arcsec apertures and to detrend against airmass. The resulting combined and phase-folded light curves are included in the right panel of Fig. 3. With our reduction, we achieve photometric precisions of 0.7 ppt and 0.5 ppt in three-minute bins, which resulted in a high signal-to-noise ratio (S/N) transit detection in each LCOGT light curve. Both LCOGT transit detections were at the time predicted by the refined ephemeris of LHS 1478 from the RCO detection.

#### 2.4. Spectroscopy

## 2.4.1. CARMENES

We obtained a total of 57 spectra of LHS 1478 with CARMENES between 28 January 2020 and 16 October 2020, all taken with exposure times of 1800s. The visual channel (VIS) of CARMENES has a resolving power  $R = 94\,600$  and covers the spectral range from 520 nm to 960 nm. Simultaneous wavelength calibration is performed with Fabry-Pérot etalon exposures, which are also used to track the instrument drift at night. The obtained spectra have a median S/N of  $\sim 48$  per pixel at 746 nm. The spectra were reduced with caracal (Zechmeister et al. 2014; Caballero et al. 2016b), and the corresponding RVs were extracted using serval (Zechmeister et al. 2018) along with selected activity indicators (Sect. 3.1). The RVs were corrected for barycentric motion, instrumental drift, secular acceleration, and nightly zero points (Tal-Or et al. 2019; Trifonov et al. 2020). The root-mean-square uncertainty (rms) and median uncertainty ( $\hat{\sigma}$ ) of the VIS RVs were 4.02 m s<sup>-1</sup> and 2.49 m s<sup>-1</sup>, respectively, and are shown in Fig. 1 and Table A.1. A generalized Lomb-Scargle (GLS) periodogram (Zechmeister & Kürster 2009) of the RV data shows a period at 1.949 d, which is consistent with the transit signal, with a theoretically computed falsealarm probability (FAP) of less than 1 % (Fig. 4).

The RVs measured with the CARMENES near-infrared (NIR) channel have rms and median uncertainties of 19.26 m s<sup>-1</sup> and 9.97 m s<sup>-1</sup>, respectively. We excluded the NIR RVs from the analysis because their scatter is higher than the expected planetary amplitude.

# 2.4.2. IRD spectroscopy

We observed LHS 1478 using the InfraRed Doppler (IRD) instrument at the Subaru 8.2 m telescope (Tamura et al. 2012; Kotani et al. 2018) between September and December 2020. A total of 13 spectra were obtained, with an integration time of 900 s. The IRD instrument is a fiber-fed spectrograph that covers the spectral range from 930 nm to 1740 nm at a resolving power of  $R \sim 70000$ . Simultaneous wavelength calibration is performed by injecting light from a laser-frequency comb into the second fiber. The raw data were reduced into one-dimensional spectra using the IRAF software, as well as with a custom code (Kuzuhara et al. 2018; Hirano et al. 2020) to suppress the bias and correlated noise of the detectors. The typical S/N of the reduced spectra ranged from 60 to 95 per pixel at 1000 nm.

Following Hirano et al. (2020), we analyzed the observed spectra to extract precise RVs. In doing so, we combined multiple frames to obtain a high S/N template for the RV analysis, after removing the telluric lines and the instrumental profile of the spectrograph. The relative RV was then measured with respect to this template for each spectrum. The resulting relative RVs after the correction for the barycentric motion of Earth are listed in Table A.2 and shown in Fig. 1. The internal RV error was typically 3–6 m s<sup>-1</sup> for each frame.

# 3. Analysis

### 3.1. Stellar parameters

The stellar parameters for this target were estimated using the CARMENES VIS stacked stellar template produced by serval. The  $T_{\text{eff}}$ , log g, and iron abundance [Fe/H] were determined through spectral fitting with a grid of PHOENIX-SESAM models following Passegger et al. (2019), using the upper limit  $v \sin i = 2.0 \text{ km s}^{-1}$  from Reiners et al. (2018) and Marfil et al (in prep.), who did not detect any rotational velocity. The luminosity,  $L_{\star}$ , was estimated by integrating the spectral energy distribution with the photometric data used by Cifuentes et al. (2020). The stellar radius,  $R_{\star}$ , was determined via the Stefan-Boltzmann law, and the stellar mass  $M_{\star}$  via the mass-radius relation from Schweitzer et al. (2019). We estimated the overall activity level of the star from the pseudo-equivalent width of the H $\alpha$  line after the subtraction of an inactive stellar template, pEW'(H $\alpha$ ), following Schöfer et al. (2019). We obtained a value of  $+0.040 \pm 0.026$  Å, which indicates that LHS 1478 is a fairly inactive star (Jeffers et al. 2018; Schöfer et al. 2019).

The star has a rotational period of 6.4 d, as listed by Newton et al. (2016), but the detection is deemed inconclusive. We looked at the SAP (Simple Aperture Photometry; Morris et al. 2020) and PDC data from TESS and, after masking the transits and performing a Lomb-Scargle periodogram, we could not detect any signal with a period of 6.4 d. Therefore, we agreed with Newton et al. (2016) in that the signal is a non-detection and may not correspond to the real rotational period for this star.

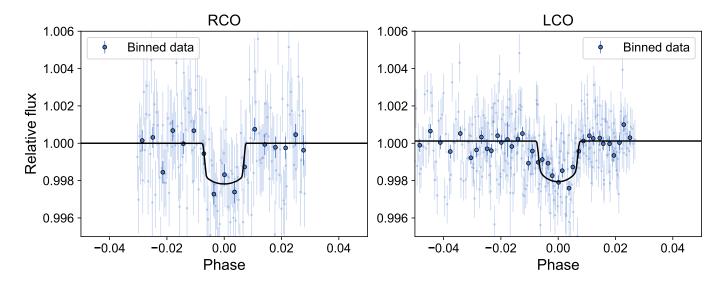


Fig. 3: Phased-folded RCO (*left*) and LCOGT (*right*) data. The black line represents the best transit model from juliet. The small points show the raw data, while the large points show the data binned into ten-minute bins.

Parameter	Value	Reference
Name	LHS 1478	Luy79
Karmn	J02573+765	Cab16
TOI	1640	ExoFOP-TESS
TIC	396562848	Sta18
$\alpha$ (J2000)	02 57 17.51	Gaia EDR3
$\delta$ (J2000)	+76 33 13.0	Gaia EDR3
Sp. type	$m3 V^a$	This work
J [mag]	$9.615 \pm 0.026$	Skr06
G [mag]	$12.2481 \pm 0.0028$	Gaia EDR3
<i>T</i> [mag]	$11.0548 \pm 0.0073$	Sta19
$\varpi$ [mas]	$54.904 \pm 0.018$	Gaia EDR3
<i>d</i> [pc]	$18.214 \pm 0.006$	Gaia EDR3
$T_{\rm eff}$ [K]	$3381 \pm 54$	This work
$\log g [\mathrm{cgs}]$	$4.87\pm0.06$	This work
[Fe/H] [dex]	$-0.13\pm0.19$	This work
$M_{\star}$ $[M_{\odot}]$	$0.236 \pm 0.012$	This work
$R_{\star} [R_{\odot}]$	$0.246 \pm 0.008$	This work
$\rho_{\star}  [\mathrm{g}  \mathrm{cm}^{-3}]^b$	$22.2\pm2.5$	This work
$L_{\star} [10^{-4} L_{\odot}]$	$71.5 \pm 1.2$	Cif20
pEW'(H $\alpha$ ) [Å]	$+0.040 \pm 0.026$	This work
$v \sin i  [\mathrm{km}  \mathrm{s}^{-1}]$	< 2	Mar21
$P_{\rm rot}$ [d]	$[6.4]^{c}$	New16

Table 2: Posterior distributions from the joint fit. The uncertainties represent the 68% CI of the obtained distributions.

Parameter	Value			
Stellar density				
$\rho_{\star}  [\mathrm{g}  \mathrm{cm}^{-3}]^a$	$22.2^{+2.7}_{-2.3}$			
Orbital parameters				
<i>P</i> [d]	$1.9495378^{+0.0000040}_{-0.0000041}$			
<i>T</i> <sup>0</sup> [BJD]	2458786.75425 <sup>+0.00042</sup> -0.00042			
$r_1{}^b$	$0.8111\substack{+0.0079\\-0.0088}$			
$r_2^b$	$0.0462^{+0.0011}_{-0.0010}$			
$p = R_p/R_{\star}$	$0.0462^{+0.0011}_{-0.0010}$			
$b = (a/R_\star)\cos i$	$0.717^{+0.012}_{-0.013}$			
<i>i</i> [deg]	$87.452_{-0.048}^{+0.052}$			
$a/R_{\star}$	$16.119\substack{+0.088\\-0.094}$			
$K [{ m m \ s^{-1}}]$	$3.13^{+0.23}_{-0.25}$			
$t_T$ [h]	$0.705^{+0.011}_{-0.011}$			
Derived planetary parameters				
$M_p [M_{\oplus}]$	$2.33^{+0.20}_{-0.20}$			
$R_p[R_{\oplus}]$	$1.242^{+0.051}_{-0.049}$			
$\rho_p [\mathrm{g}\mathrm{cm}^{-3}]$	$6.67^{+1.03}_{-0.89}$			
<i>a</i> [au]	$0.01848^{+0.00061}_{-0.00063}$			
$T_{\rm eq}  [{\rm K}]^c$	$595^{+10}_{-10}$			

**References.** Luy79: Luyten (1979); Sta18: Stassun et al. (2018); Cab16: Caballero et al. (2016a); Skr06: Skrutskie et al. (2006); *Gaia* EDR3: Gaia Collaboration et al. (2020); Sta19: Stassun et al. (2019); Cif20: Cifuentes et al. (2020); Mar21: Marfil et al. (in prep); New16: Newton et al. (2016).

**Notes.** <sup>(a)</sup> Spectral type estimated from photometry and parallax (with a lowercase "m"), as by Cifuentes et al. (2020). <sup>(b)</sup> Derived from  $M_{\star}$  and  $R_{\star}$ . <sup>(c)</sup> Flagged as a non-detection or an undetermined detection by Newton et al. (2016).

**Notes.** <sup>(a)</sup> Derived from light curve fitting using the relations from Seager & Mallén-Ornelas (2003). <sup>(b)</sup> Parameterization from Espinoza (2018) for p and b. <sup>(c)</sup> Assuming zero Bond albedo.

Time series of three activity indicators were extracted from the spectra with serval: the chromatic index (CRX), differential line width (dLW), and H $\alpha$  (Zechmeister et al. 2018). We found no signs of periodic variations similar to the planet orbital pe-

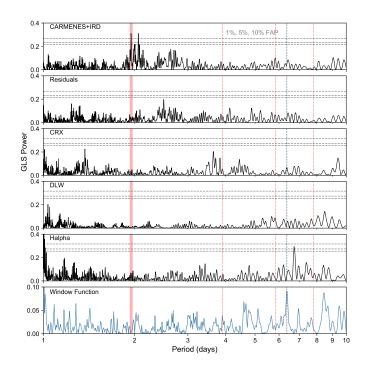


Fig. 4: GLS periodograms for the combined RVs, RV residuals from the fit, the activity indices CRX, dLW, and H $\alpha$ , and the window function. The dotted horizontal lines represent the 1%, 5%, and 10% FAP. The red shaded area is the position of the orbital period of the planet, and the vertical dotted red lines are aliases of that period. The vertical dotted black line represents the 6.4 d stellar rotation period by Newton et al. (2016).

riod or the putative stellar rotational period of 6.4 d (Fig. 4). The only exception is for the H $\alpha$  data, where there is a signal at  $\approx$  6.8 d with an FAP = 5 %. This signal is not seen in any of the other indices or data sets, and, therefore, we could not provide any insight into its origin or relevance. The activity data are not correlated with the RV data either, with a correlation coefficient of |r| < 0.3. A summary of the stellar properties and relevant photometric and astrometric data from *Gaia* EDR3 is shown in Table 1.

#### 3.2. Joint fit

We used juliet (Espinoza et al. 2019) to perform a joint fit of the TESS, RCO, LCOGT, CARMENES, and IRD data. We used the efficient, uninformative sampling scheme from Kipping (2013) together with a quadratic law to parameterize the limb darkening in the TESS data. For the RCO and LCOGT data we used a linear limb-darkening law. We also followed the parameterization presented in Espinoza (2018), with parameters  $r_1$  and  $r_2$ , to fit for p and b, the planet-to-star radius ratio and impact parameter, respectively. The TESS data were fitted separately by sector, each with its own relative flux offset and jitter, but we imposed identical limb-darkening coefficients for the transit curves from all sectors. We fitted the LCOGT data separately for each observing night, but, as with the TESS data, we imposed an identical limb-darkening coefficient for the two nights. The detrending of the TESS data was done by incorporating a Gaussian process (GP) model. We used the celerite Mátern kernel with a hyperparameter amplitude and the GP timescale given by  $\sigma_{\rm GP}$  and  $\rho_{\rm GP}$ , respectively (Foreman-Mackey et al. 2017).

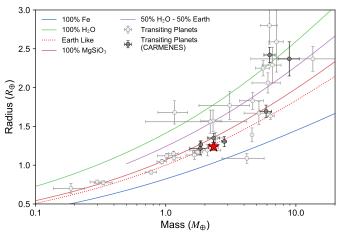


Fig. 5: Mass-radius diagram for LHS 1478 b (red star). The colored lines represent the composition models from Zeng et al. (2016, 2019). Transiting planets around M dwarfs with mass and radius measurements are shown in black circles (detected with CARMENES) and gray circles.

The same GP model was used for each TESS sector. An initial search for the optimal parameters of this system was done with **exostriker** (Trifonov 2019) using all data sets, and the results were used to build the priors for juliet, which are shown in Table A.3. The obtained posterior probabilities are listed in Tables 2 and A.4.

We built our full model, shown in Figs. 1 and 3, from the 68% confidence interval (CI) of the posterior distribution for each parameter. We found that the signal observed in both the photometric and RV data is consistent with a  $2.33^{+0.20}_{-0.20} M_{\oplus}$  and  $1.242^{+0.051}_{-0.049} R_{\oplus}$  planet, with a density of  $6.67^{+1.03}_{-0.89}$  g cm<sup>-3</sup>, orbiting the star with a period of  $1.9495378^{+0.000040}_{-0.000041}$  d. Since there is a brighter star ( $G \approx 10.30$  mag) about

Since there is a brighter star ( $G \approx 10.30 \text{ mag}$ ) about 120 arcsec north of LHS 1478, we checked for possible contamination in the TESS light curve. We analyzed the transit data from TESS and LCOGT, using the GP-detrended data, leaving the dilution factor as a free parameter for the TESS data, and fixing the limb-darkening coefficients to the values interpolated from limb darkening tables (Claret et al. 2013; Claret 2017). The parameters from Table 2 were recovered very well, and the best fit dilution factor is below 1% (and below 13% at 95% confidence). We conclude that the TESS light curve is therefore not contaminated.

A TLS search in the light curve residuals from the TESS data showed two significant periods at 13.9 d and 27.8 d, but they were due to the sampling of the data (Fig. A.3). A GLS periodogram of the residuals of the RV data did not show any significant signals either (Fig. 4). The obtained jitter terms for the RVs are within the expected instrumental jitter intervals for each instrument:~  $1.2 \text{ m s}^{-1}$  for CARMENES VIS (Bauer et al. 2020) and ~ 2–3 m s<sup>-1</sup> for IRD (Hirano et al. 2020).

# 4. Discussion and characterization prospects

Given the measured properties, we made a first exploratory guess of the planet composition. We compared its mass and radius with the models from Zeng et al. (2016, 2019), shown in Fig. 5, plus other transiting planets around M dwarfs from the literature<sup>8</sup>. We

<sup>&</sup>lt;sup>8</sup> Data on transiting M dwarf planets at https://carmenes.caha.es/ext/tmp/.

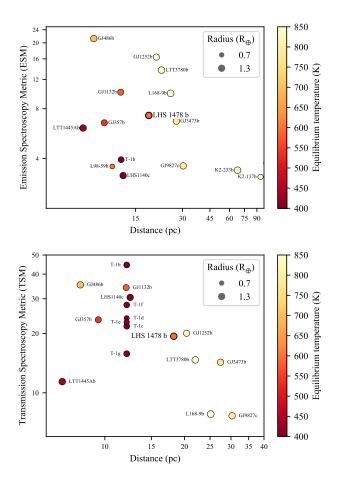


Fig. 6: ESM (*top panel*) and TSM (*bottom panel*) as a function of distance from the Sun for exoplanets with radii of less than  $1.5 R_{\oplus}$  and mass determinations by RVs or TTVs. LHS 1478 b is labeled and marked with a thicker black borderline in both panels.

found that LHS 1478 b is compatible with a bulk composition of  $\sim$ 30 % Fe plus 70 % MgSiO<sub>3</sub>. This makes its composition comparable to Earth's, thus strongly supporting the notion that it is indeed a rocky world.

Atmospheric characterization of rocky planets with (some) properties similar to Earth's is one of the pivotal developments expected in the forthcoming years thanks to the deployment of new ground- and space-based facilities. The potential of a target for detailed characterization is a complicated function of the planet and host star properties, as well as the instrument to be used. In this sense, not all transiting planets that have interesting properties are equally suitable for actual characterization.

As a first approximation of the suitability of LHS 1478 b, we calculated the spectroscopic metrics from Kempton et al. (2018), which were developed to rank the best TESS targets for the instrumentation aboard the *James Webb Space Telescope (JWST)*. We estimated the emission spectroscopy metric (ESM) and the transmission spectroscopy metric (TSM) to be 7.28 and 19.35, respectively. The upper panel of Fig. 6 shows the ESMs of rocky exoplanets with measured masses, either through RVs or TTVs, and puts LHS 1478 b in that context. The ESM of 7.28 is slightly lower than the 7.5 threshold set by Kempton et al. (2018), but it is very close to that of Gl 1132 b, which was considered by the authors as a benchmark rocky planet for emission spectroscopy (after performing a recomputation of the ESM for Gl 1132 b, we

found a value of 10.06, which is less than half of the ESM value of GJ 486 b, recently discovered by Trifonov et al. 2021). The lower panel illustrates TSM values. An acceptable TSM value for this class of planet is around 12 or higher (Table 1 in Kempton et al. 2018), which implies that LHS 1478 b is likely also an appropriate candidate for atmospheric characterization through transmission spectroscopy.

As a second refinement to its suitability for characterization, we assessed the potential chemical species that could be detected in its atmosphere using near-future instrumentation. Molecular features such as water, carbon dioxide, or methane should typically be observable on these kinds of planets if they maintain a substantial atmosphere (Molaverdikhani et al. 2019a,b), but the detectability of such features could also be obscured by the presence of clouds (Molaverdikhani et al. 2020). In order to quantitatively assess the potential of the atmospheric characterization observations of LHS 1478 b with the JWST, we calculated a few atmospheric models and their compositions using the photochemical code ChemKM (Molaverdikhani et al. 2019a) and their corresponding spectra using petitRADTRANS (Mollière et al. 2019). We assumed a stellar radiation environment similar to that measured for the well-studied star GJ 667C (T\_{eff}~\approx 3327\,K). For the model of the planetary atmospheric structure, we adapted a Venus-like temperature profile to make it consistent with the derived brium temperature of the planet (see Table 2). Our photochemical models included 135 species and 788 reactions.

Figure 7 shows simulated realizations of the transmission spectrum of LHS 1478 b, assuming solar metallicities (top panel) and 100-times-enhanced metallicities (bottom panel). The dominant spectral features come from water and methane, as expected, with a less extended  $CO_2$  feature at around  $4.5 \,\mu$ m. The amplitudes of these features are between 50 and 100 ppm, which should be measurable given that the star is rather bright. This was verified using PandExo (Batalha et al. 2017) simulations of the NIRISS/SOSS, NIRSpec/G395M, and MIRI/LRS instruments and modes on board *JWST*.

Hydrogen-dominated atmospheres with temperatures below 900 K are expected to have significant photochemically produced hazes (e.g., He et al. 2018; Gao et al. 2020). If such a scenario applied to LHS 1478 b, it would result in the obscuration of spectral features, particularly in the case of an enhanced metallicity (see the bottom panel of Fig. 7). A relatively flat transmission spectrum thus might be indicative of a metallicity-enhanced atmosphere covered by haze, which might be indistinguishable from the planet having no atmosphere at all. If a (nearly) flat spectrum were observed, ground-based highresolution spectroscopy could then be used to detect unobscured molecular features and break the associated degeneracies (see **Brogi et al.** 2017 and Gandhi et al. 2020 for more details on the possible features that could be detected).

In short, the simulations described in this section indicate that LHS 1478 b, along with GJ 357 b (Luque et al. 2019), GJ 1132 b (Berta-Thompson et al. 2015), and GJ 486 b (Trifonov et al. 2021), belongs to the small family of planets where we can realistically expect to obtain meaningful measurements and constraints with next-generation space telescopes such as *JWST*.

# 5. Conclusions

In this paper we present TESS and ground-based photometric observations, together with CARMENES and IRD Doppler spectroscopy, of the star LHS 1478. We determine LHS 1478 b to have a mass of  $2.33^{+0.20}_{-0.19} M_{\oplus}$ , a radius of  $1.242^{+0.050}_{-0.049} R_{\oplus}$ , and

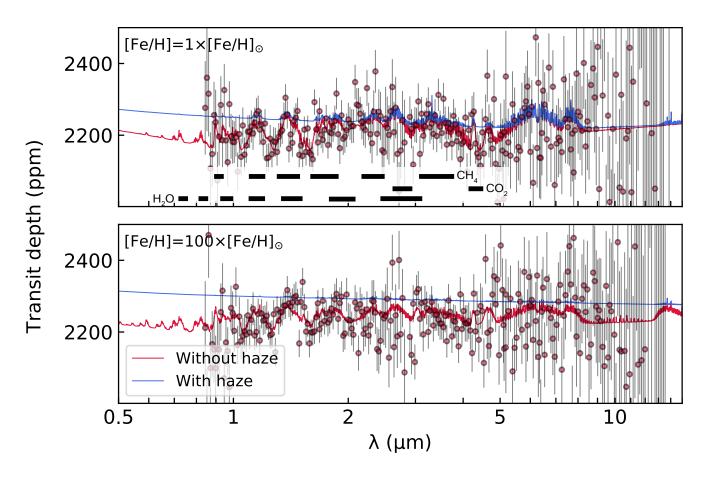


Fig. 7: Synthetic transmission atmospheric spectra of LHS 1478 b with haze opacity (solid blue lines) and without haze opacity (solid red lines). Simulated observations and estimated uncertainties are shown for the *JWST* NIRISS/SOSS (0.6–2.8  $\mu$ m), NIR-Spec/G395M (2.87–5.10  $\mu$ m), and MIRI/LRS (5–12  $\mu$ m) configurations, assuming two transits and binned for *R* = 50 (filled circles with error bars). *Top*: Fiducial models with solar abundance and the location of the strongest molecular features of H<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub>. *Bottom*: Metallicity enhanced by a factor of 100.

a bulk density of  $6.67^{+1.03}_{-0.89}$  g cm<sup>-3</sup>, which is consistent with an Earth-like composition. The star is remarkably inactive, and we see no signs of additional planetary signals in the photometry or the RVs, which thus greatly simplifies the analysis.

The equilibrium temperature of this planet places it in a recently found group of warm rocky planets, together with GJ 357 b, GJ 1132 b, and GJ 486 b, which are ideal for atmospheric studies. The fact that the planetary signal is very isolated in both photometry and RV, with no stellar activity or additional companions contaminating it, together with the proximity of the system to the Sun and the relative brightness of the star make this an ideal target for near-future transit observations with *JWST* and ground-based high-resolution spectrometers.

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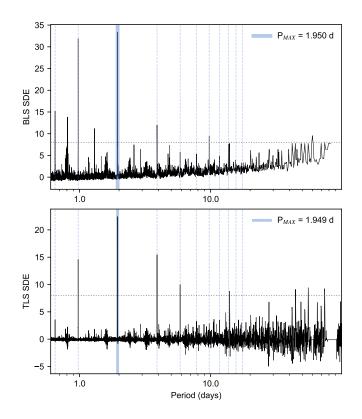


Fig. A.1: BLS (*top panel*) and TLS (*bottom panel*) SDE for the TESS light curve. The vertical blue lines correspond to aliases of the maximum period, highlighted by the blue shaded region. The dashed horizontal line at SDE = 8 in both panels corresponds to the threshold for transit detection from Aigrain et al. (2016).

# Appendix A: Additional figures and tables

Table A.1: RV data and activity indicators from CARMENES VIS.

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8877.420-4.542.0311.0 ± 17.8 $3.3 \pm 2.4$ 0.934 ± 0.0038881.3481.712.402.0 ± 25.8-20.4 ± 4.20.943 ± 0.0048882.3441.311.96-8.3 ± 20.03.4 ± 1.80.925 ± 0.0038883.412-0.621.78-8.0 ± 17.44.0 ± 1.90.925 ± 0.0038884.348-1.281.524.9 ± 14.88.2 ± 1.90.943 ± 0.0038885.346-0.872.33-3.2 ± 23.49.3 ± 2.20.968 ± 0.0048891.3612.121.77-1.9 ± 17.94.6 ± 1.60.949 ± 0.0038895.3642.812.54-50.7 ± 25.3-8.6 ± 2.10.925 ± 0.0048895.3642.812.54-50.7 ± 25.3-8.6 ± 2.10.925 ± 0.0048896.368-5.291.7715.4 ± 18.2-4.6 ± 2.10.937 ± 0.0048901.3650.432.032.02 ± 2.18-1.4 ± 1.90.920 ± 0.0058913.3650.362.24-2.6 ± 2.290.937 ± 0.0048913.3650.432.88-58.1 ± 29.34.8 ± 4.00.920 ± 0.0058913.376-0.223.0013.4 ± 31.9-9.4 ± 3.00.920 ± 0.0058913.376-0.223.0013.4 ± 31.9-9.4 ± 3.00.920 ± 0.0058913.376-0.223.0013.4 ± 31.9-9.4 ± 3.00.920 ± 0.0038913.357-2.781.928.2 ± 2.518.7 ± 2.40.971 ± 0.0039035.6456.602.85-4.32 ± 2.962.8 ± 4.50.916 ± 0.0038913.350 </th <th>BJD</th> <th>RV</th> <th>RV error</th> <th>CRX</th> <th>dLW</th> <th>Нα</th>	BJD	RV	RV error	CRX	dLW	Нα
$\begin{array}{llllllllllllllllllllllllllllllllllll$	-2450000	$(m s^{-1})$	$(m s^{-1})$	$(m s^{-1} N p^{-1})$	$(m^2 s^{-2})$	
$\begin{array}{llllllllllllllllllllllllllllllllllll$	8877 420	-4 54	2.03	$11.0 \pm 17.8$	33 + 24	$0.934 \pm 0.003$
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$\begin{array}{cccccccccccccccccccccccccccccccccccc$		-4.61		$-50.6 \pm 18.2$		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	9055.559	1.72	1.94	$14.1 \pm 18.3$	$-3.1 \pm 2.3$	$0.912 \pm 0.003$
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	9056.575	0.94	2.48	$5.6 \pm 23.8$	$-7.8 \pm 2.3$	$0.917 \pm 0.004$
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	9059.567	6.79	2.78	$27.8 \pm 28.9$	$-4.5 \pm 2.4$	$0.932 \pm 0.004$
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	9060.656	1.85	2.67	$18.2 \pm 26.4$	$1.1 \pm 2.9$	$0.924 \pm 0.004$
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	9061.554			$-18.4 \pm 22.1$		$0.931 \pm 0.004$
$\begin{array}{cccccccccccccccccccccccccccccccccccc$						
$\begin{array}{cccccccccccccccccccccccccccccccccccc$						
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		4.61		$47.2 \pm 35.5$		
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9138.528 $3.79$ $3.83$ $63.5 \pm 38.4$ $-1.3 \pm 4.2$ $0.930 \pm 0.006$ 9138.595 $5.45$ $3.38$ $-105.6 \pm 30.0$ $-7.7 \pm 4.0$ $0.915 \pm 0.006$						
9138.595 5.45 3.38 $-105.6 \pm 30.0$ $-7.7 \pm 4.0$ $0.915 \pm 0.006$						
	/130.072	5.15	7.22	-20.2 ± 44.0	-5.0 ± 5.5	0.713 ± 0.007

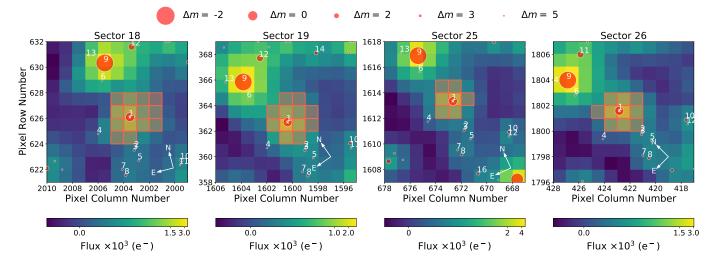


Fig. A.2: TESS target pixel files for all four sectors that observed the target LHS 1478. The red shaded area corresponds to the apertures used to extract the photometry. The nearest sources to the target with up to 6 mag differences in the *Gaia G* passband are marked with red circles. The TESS pixel scale is  $\sim 21$  arcsec.

Table A.2: RV data from IRD.

BJD	RV	RV error
-2450000	$(m s^{-1})$	$(m s^{-1})$
9120.014	-3.25	3.78
9120.024	-3.05	5.27
9123.071	-12.62	3.49
9123.082	-4.52	3.36
9152.992	10.43	5.03
9156.926	4.11	3.16
9157.012	-3.44	3.34
9188.842	6.78	6.78
9188.853	-0.39	5.99
9189.771	1.52	3.97
9189.781	-1.77	4.00
9189.890	4.69	3.60
9189.901	1.49	3.60

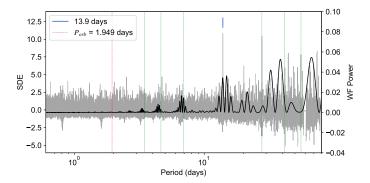


Fig. A.3: TLS of the TESS light curve residuals after subtracting the GP-plus-transit model. The dashed green lines are the aliases of the 13.9 d signal. The black line represents the window function of the data.

Table A.3: Priors used for the juliet run.

Parameter	Prior <sup>a</sup>
$M_{\rm lc}^{b}$ [ppm]	<b>N</b> (0, 0.1)
$\sigma_{\rm lc}{}^{b}$ [ppm]	$\mathcal{LU}(0.1, 1000)$
$q_{1,\text{TESS}}$	$\mathcal{U}(0,1)$
$q_{2,\text{TESS}}$	$\mathcal{U}(0,1)$
$q_{1,LCO,RCO}$	$\mathcal{U}(0,1)$
$\mu_{\rm RV} \ [{\rm m \ s^{-1}}]^c$	$\mathcal{N}(0, 0.2)$
$\sigma_{\rm RV} \ [{\rm m \ s^{-1}}]^c$	$\mathcal{LU}(10^{-4}, 15)$
<i>P</i> [d]	<i>N</i> (1.949, 0.01)
<i>T</i> <sup>0</sup> [BJD-2458000]	N(786, 0.01)
$r_1$	$\mathcal{U}(0,1)$
$r_2$	$\mathcal{U}(0,1)$
$a/R_{\star}$	N(16.1, 0.2)
$K [{ m m \ s}^{-1}]$	$\mathcal{U}(0.2, 10)$
е	Fixed(0)
$\sigma_{\rm GP,  TESS}$ [ppm]	$\mathcal{LU}(10^{-6}, 10^{6})$
$ ho_{ m GP,TESS}$ [d]	$\mathcal{LU}(10^{-3}, 10^3)$

**Notes.** <sup>(a)</sup> N: normal distribution,  $\mathcal{LU}$ : log-uniform distribution,  $\mathcal{U}$ : uniform distribution. <sup>(b)</sup> The same prior distributions were assumed for the photometric data, where "lc" stands for the light curves of TESS sectors 18, 19, 25, 26, the two nights of photometry from LCOGT, and RCO. <sup>(c)</sup> The same prior distributions were assumed for the RV data (CARMENES and IRD).

Table A.4: Posterior distributions for the instrumental parame-
ters. The uncertainties represent the 68 % CI of the obtained dis-
tributions.

Parameter	Value	
Photometric pa	irameters	
$M_{\rm S18} \ [10^{-6} \ {\rm ppm}]$	$3.97^{+57.05}_{-56.47}$	
$\sigma_{ m S18}$ [ppm]	$1.78^{+11.24}_{-1.51}$	
$M_{\rm S19} \ [10^{-6} \ \rm ppm]$	$-16.15^{+52.67}_{-50.37}$	
$\sigma_{ m S19}$ [ppm]	$1.99^{+12.69}_{-1.68}$	
$M_{\rm S25} \ [10^{-6} \ \rm ppm]$	$-75.50^{+51.51}_{-50.25}$	
$\sigma_{ m S25}$ [ppm]	$2.04^{+13.31}_{-1.75}$	
$M_{\rm S26} \ [10^{-6} \ \rm ppm]$	$-12.42^{+53.02}_{-56.05}$	
$\sigma_{ m S26}$ [ppm]	$1.91^{+11.40}_{-1.63}$	
<i>M</i> <sub>LCO1</sub> [10 <sup>-6</sup> ppm]	$-115.66^{+104.37}_{-103.52}$	
$\sigma_{ m LCO1}$ [ppm]	$977.77^{+16.31}_{-30.72}$	
$M_{\rm LCO2} \ [10^{-6} \ {\rm ppm}]$	$-69.46^{+125.09}_{-123.14}$	
$\sigma_{ m LCO2}$ [ppm]	$856.87^{+90.00}_{-107.94}$	
$M_{\rm RCO} \ [10^{-6} \ {\rm ppm}]$	$10.19^{+144.64}_{-143.99}$	
$\sigma_{ m RCO}$ [ppm]	$651.31^{+250.94}_{-641.52}$	
$q_{1,\mathrm{TESS}}{}^a$	$0.29^{+0.21}_{-0.16}$	
$q_{2,\mathrm{TESS}}^{a}$	$0.43^{+0.34}_{-0.29}$	
$q_{1,\mathrm{LCO}}$	$0.51^{+0.26}_{-0.28}$	
$q_{1,\mathrm{RCO}}$	$0.34^{+0.31}_{-0.23}$	
<i>RV</i> parameters		
$\mu_{\text{CARMENES}}$ [m s <sup>-1</sup> ]	$0.04^{+0.17}_{-0.16}$	
$\sigma_{\text{CARMENES}} \text{ [m s}^{-1} \text{]}$	$1.43^{+0.56}_{-0.70}$	
$\mu_{\rm IRD} \ [{ m m s}^{-1}]$	$-0.26^{+0.43}_{-0.44}$	
$\sigma_{ m IRD} \ [{ m m s}^{-1}]$	$2.66^{+1.46}_{-1.91}$	
GP parameters		
$GP_{\sigma,TESS}$ [10 <sup>-6</sup> ppm]	$339.76^{+20.12}_{-19.07}$	
$GP_{\rho,TESS}$ [d]	$0.25^{+0.02}_{-0.02}$	

Notes. <sup>(a)</sup> Parameterization from Kipping (2013).