TOI-132 b: A short-period planet in the Neptune desert transiting a $V = 11.3$ G-type star

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ABSTRACT

The Neptune desert is a feature seen in the radius-period plane, whereby a notable dearth of short period, Neptune-like planets is found. Here, we report the Transiting Exoplanet Survey Satellite (TESS) discovery of a new short-period planet in the Neptune desert, orbiting the G-type dwarf TYC 8003-1117-1 (TOI-132). TESS photometry shows transit-like dips at the level of $\sim 1400$ ppm occurring every $\sim 2.11$ d. High-precision radial velocity follow-up with High Accuracy Radial Velocity Planet Searcher confirmed the planetary nature of the transit signal and provided a semi-amplitude radial velocity variation of $11.38^{+0.84}_{-0.85}$ ms$^{-1}$, which, when combined with the stellar mass of $0.97^{+0.06}_{-0.06}$ M$_{\odot}$, provides a planetary mass of $22.40^{+1.90}_{-1.92}$ M$_{\oplus}$. Modelling the TESS light curve returns a planet radius of $3.42^{+0.13}_{-0.14}$ R$_{\oplus}$, and therefore the planet bulk density is found to be $3.08^{+0.44}_{-0.46}$ g cm$^{-3}$. Planet structure models suggest that the bulk of the planet mass is in the form of a rocky core, with an atmospheric mass fraction of $4.3^{+1.2}_{-1.3}$ per cent. TOI-132 b is a TESS Level 1 Science Requirement candidate, and therefore priority follow-up will allow the search for additional planets in the system, whilst helping to constrain low-mass planet formation and evolution models, particularly valuable for better understanding of the Neptune desert.

Key words: techniques: photometric – techniques: radial velocities – planets and satellites: fundamental parameters – planetary systems.

1 INTRODUCTION

The Kepler space telescope (Borucki 2010) has allowed us to understand the population of small planets ($R_p < 4 R_\oplus$) in a

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real statistical sense for the first time. *Kepler* revealed that the majority of planets are the so-called super-Earths, with an occurrence rate of ~6 percent of Earth-size planets around Sun-like stars (Petigura et al. 2017; Van Eylen et al. 2018), which could be the result of photoevaporation of the planetary atmosphere due to the intense stellar radiation (Lopez & Fortney 2013; Owen & Wu 2013; Jin et al. 2014; Chen & Rogers 2016). Furthermore, planets in the Neptune regime are also more abundant than the large gas giant planets. It is important to note that the distinction between super-Earths and sub-Neptunes is based on the radius, where the first class is commonly defined as planets with $1 R_\oplus < R_p < 2 R_\oplus$, while the latter comprises planets with $2 R_\oplus < R_p < 4 R_\oplus$. From *Kepler* statistics, 25 percent of Sun-like stars in our Galaxy is found to host at least one small planet ($R_p < 4 R_\oplus$) on a short period orbit ($P < 100$ d; Batalha et al. 2013; Marcy et al. 2014).

Although Neptune-sized planets orbiting Sun-like stars are fairly abundant (e.g. Espinoza et al. 2016; Luque et al. 2019; Mayo et al. 2019; Palle et al. 2019), at short orbital periods they are very rare. A number of early studies indicated a lack of Neptune-sized planets with periods shorter than 2–4 d (Benítez-Llambay, Masset & Beaugé 2011; Szabó & Kiss 2011; Beaugé & Nesvorný 2013; Helled, Lovzovsky & Zucker 2016), and the term ‘Neptune desert’ was coined to explain this paucity. Mazeh, Holczer & Faigler (2016) placed this desert on a statistical footing, whilst providing robust boundaries for the region. Even though the dominant mechanism that produces this desert is currently unknown, models that invoke tidal disruption of a high-eccentricity migration planet, coupled with photoevaporation can explain the triangular shape of the gap described by Mazeh et al. (2016; see also Lundkvist et al. 2016; Owen & Lai 2018).

The Neptune desert may be a region of parameter space with a paucity of such planets, but it is not completely empty. West et al. (2019) discovered the planet NGTS-4b as part of the Next Generation Transit Survey (Wheatley et al. 2018). Although the star is fairly faint ($V = 13.14$), making the constraints on the radius and mass difficult, the planet resides inside the boundaries of the desert, as defined by Mazeh et al. (2016). A more recent example was found using data from the Transiting Exoplanet Survey Satellite (*TESS*; Ricker et al. 2015): a planet orbiting the star HD 21966 residing in the edge of this region (Esposito et al. 2016). The primary goal of *TESS* is to discover 50 planets with radii $4 R_\oplus$ transitting stars brighter than $V \leq 12$, for which precise masses can be measured using high-precision Doppler spectroscopy, better constraining the planetary bulk density. In doing so, the mission is also providing unprecedented targets to follow-up to study the Neptune desert, particularly the discovery of the first ultrahot Neptune, LTT 9779 b ($R_p = 4.59 \pm 0.23 R_\oplus$, $P = 0.79$ d; Jenkins et al. 2020). This planet resides on the edge of the Neptune desert, and since the star is bright ($V = 9.76$), detailed follow-up can be performed to shed light on the processes that sculpt the desert. However, more such examples are necessary in order to uncover the dominant process(es) at play.

Here, we present the discovery of TOI-132 b, a $22.4-M_\oplus$ Neptune-sized planet discovered by *TESS* and confirmed using high-precision Doppler spectroscopy from the High Accuracy Radial velocity Planet Searcher (HARPS; Pepe et al. 2002) and additional ground-based transit detections.

2 PHOTOMETRY

2.1 TESS photometry

TYC 8003-1117-1 (also known as TIC 89020549, TOI-132) was observed by *TESS* in Sector 1 on Camera 2 in short-cadence mode ($\Delta t = 2$ min). The total time baseline of the observations is 27.87 d, spanning from 2018 July 25 to August 22. TOI-132.01 was identified as a potential transiting planet signature by the Science Processing Operations Center (SPOC) in the transit search run on Sector 1 (Jenkins 2002; Jenkins et al. 2010) and promoted to TOI status by the *TESS* Science Office based on the SPOC Data Validation (DV) reports (Twicken et al. 2018; Li et al. 2019).

The target was selected from the *TESS* alerts website, based on the magnitude of the star $(V = 11.2$ mag) and period of the candidate, since it presented a good opportunity to be confirmed relatively quickly with HARPS. In addition, from the DV report for TOI-132.01, we note the planetary signature passed all of the diagnostic tests conducted by DV, including the odd/even depth test, the weak secondary test, the ghost diagnostic test, and the difference image centroid shift test.

We retrieved the photometry provided by the *TESS* SPOC pipeline (Jenkins et al. 2016), and accessed the data from the simple aperture photometry (SAP) and the Presearch Data Conditioning simple aperture photometry (PDCSAP) pipeline (Smith et al. 2012; Stumpe et al. 2014), which contains systematics-corrected data using the algorithms previously used for *Kepler* (Jenkins 2017). The median-normalized SAP photometry is shown in the top panel of Fig. 1. Bottom panel shows the PDCSAP photometry, divided by its median value and after applying a 4σ clipping rejection with the transits masked out. This light curve is used throughout all the analyses in this paper. The gap in the middle of the time series occurred when the observations were stopped to allow for the data down-link. Finally, in order to avoid any bias in our analysis, we excluded the photometric measurements between (BJD - 2457000) 1347.5 and 1349.3 (the grey-shaded area) given that the spacecraft pointing jitter was higher than nominal, as described by Huang et al. (2018) and also noted in recent *TESS* discoveries (see e.g. Espinoza et al. 2019b). A total of 11 transit events were considered for further analysis in this work. Magnitudes and stellar parameters for TOI-132 are shown in Table 1 (see also Section 4).

We also performed a time–frequency analysis (Mathur et al. 2010) and computed the autocorrelation function for the *TESS* light curve to look for signatures of rotation modulation following the methodology described in García et al. (2014), Ceillier et al. (2017) and Santos et al. (2019). However, no significant signal was found. The length of the data is too short to find a periodicity larger than 9 d as we require to observe at least three periods.

2.2 Ground-based time series photometry

We acquired ground-based time series follow-up photometry of TOI-132 as part of the *TESS* Follow-up Observing Program to attempt to rule out nearby eclipsing binaries (NEBs) in all stars that could be blended in the *TESS* aperture as potential sources of the *TESS* detection. Furthermore, we attempt to (i) detect the transit-like event on target to confirm the event depth and thus the *TESS* photometric deblending factor, (ii) refine the *TESS* ephemeris, (iii)

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1. [https://tev.mit.edu/data/](https://tev.mit.edu/data/)
provide additional epochs of transit centre time measurements to supplement the transit timing variation (TTV) analysis, and (iv) place constraints on transit depth differences across filter bands. We used the TESS Transit Finder, which is a customized version of the Tapir software package (Jensen 2013), to schedule our transit observations.

We observed TOI-132 continuously for 443 min on UTC 2018 September 9 in R\textsc{c} band (\( \sigma \approx 1.8 \) mmag) from the Perth Exoplanet Survey Telescope near Perth, Australia. The 0.3-m telescope is equipped with a 1530 \times 1020 pixels SBIG ST-8XME camera with an image scale of 1.2 pixel\(^{-1}\) resulting in a 31 arcmin \times 21 arcmin field of view. A custom pipeline was used to calibrate the images and extract the differential photometry using an aperture with radius 8.2. The images have typical stellar point spread functions (PSFs) with a full width at half-maximum (FWHM) of \( \sim 4 \) arcsec. The data rule out NEBs in stars within 2.5 of the target star that are fainter by as much as 6.4 magnitudes in R\textsc{c} band.

We also observed full predicted transit durations of TOI-132 continuously in z\textsc{}-short band on UTC 2018 November 14, UTC 2019 June 19, and UTC 2019 July 6 from the Las Cumbres Observatory Global Telescope (LCOGT) 1.0 m telescopes (Brown et al. 2013) at Cerro Tololo Inter-American Observatory for 277, 335, and 283 min, respectively. Another full transit was observed continuously for 232 min in B band on UTC 2019 August 2 from an LCOGT 1.0 m telescope at Siding Spring Observatory. The 4096 \times 4096 LCOGT SINISTRO cameras have an image scale of 0.389 pixel\(^{-1}\) resulting in a 26 arcmin \times 26 arcmin field of view. The images were calibrated by the standard LCOGT BANZAI pipeline (McCully et al. 2018) and the photometric data were extracted using the AstroImage\textsc{}J (AIJ) software package (Collins et al. 2017), yielding a mean error of 800 ppm for the z\textsc{}-short band data we include in our analysis.

The November data rule out NEBs in all stars within 2.5 of the target star that are fainter by as much as 8.7 mag in z\textsc{}-short band, which includes all known Gaia DR2 stars that are blended in the TESS aperture. The June observation confirmed a \( \sim 1400 \) ppm deep ingress on target arriving \( \sim 80 \) min late relative to the original TOI ephemeris. The follow-up ephemeris was adjusted to account for the 80 min offset. The July observation confirmed an on-time arrival of a \( \sim 1400 \) ppm deep full transit relative to the adjusted ephemeris, indicating that the transit timing is consistent with a linear ephemeris. The images have stellar PSF FWHMs of \( \sim 2^\prime\prime\), and the transit signal is reliably detected on target using a follow-up aperture with radius as small as 1.5. Therefore, the aperture is negligibly contaminated by the nearest Gaia neighbor 10.5 south. Systematic effects start to dominate the light curve for smaller apertures. The August B\textsc{}-band observation confirmed an on-time arrival of a \( \sim 1400 \) ppm deep full transit, indicating that the transit-like event does not show a filter-dependent depth in B and z\textsc{}-short bands, which photometrically strengthens the case for a transiting exoplanet orbiting around TOI-132.

### 3 HARPS SPECTROSCOPIC FOLLOW-UP

TOI-132 was observed using HARPS (Pepe et al. 2002) spectrograph mounted at the 3.6-m ESO telescope at La Silla observatory, during seven consecutive nights between 2019 April 2 and 9, as part of the observing program 0103.C-0442. The exposure time was set to 1200–1800 s, which allowed us to achieve a mean signal-to-noise (S/N) ratio of \( \sim 35 \) pixel\(^{-1}\) at 5500 Å in the extracted spectra giving rise to a typical error of \( \sim 1 \) m s\(^{-1}\). Upon examination of the radial velocities (RVs) and after performing a one-planet model fit to the TESS period, we found it necessary to acquire more observations to improve the phase coverage. Therefore, 13 additional RVs were
Parallax (mas) 6.08 ± 0.04
Photometry SpT G8V

This work

Table 1. Stellar parameters for TOI-132.

| Parameter       | Value                  | Source   |
|-----------------|------------------------|----------|
| TESS Names      | TIC89020549 (TOI-132.01) | Gaia     |
| RA (hh:mm:ss)   | 22:33:35.8683          | Gaia     |
| Dec. (dd:mm:ss) | -43:26:11.9167         | Gaia     |
| μ RA (mas yr^{-1}) | 35.553 ± 0.043      | Gaia     |
| μ (mas yr^{-1}) | 53.055 ± 0.054         | Gaia     |
| Parallax (mas)  | 6.08 ± 0.04            | Gaia*    |
| Distance (pc)   | 164.47 ± 27.32         | Gaia     |
| SpT             | G8V                    | This work|
| Photometry      |                        |          |
| B_T             | 12.07 ± 0.17           | Tycho-2  |
| V_T             | 11.29 ± 0.07           | Tycho-2  |
| g               | 11.85 ± 0.02           | APASS    |
| r               | 11.24 ± 0.01           | APASS    |
| i               | 11.08 ± 0.02           | APASS    |
| TESS            | 10.80 ± 0.02           | Stassun et al. (2018b) |
| Gaia            | 11.2935 ± 0.0003       | Gaia     |
| J               | 10.14 ± 0.02           | 2MASS    |
| H               | 9.76 ± 0.02            | 2MASS    |
| K_s            | 9.65 ± 0.02            | 2MASS    |
| W_1            | 9.61 ± 0.02            | WISE     |
| W_2            | 9.69 ± 0.02            | WISE     |
| W_3            | 9.60 ± 0.04            | WISE     |
| W_4            | 8.67 ± 0.42            | WISE     |
| Derived parameters |                   |          |
| \tau(H) (K)    | 5397 ± 46              | This work|
| \log g (cm s^{-2}) | 4.48 ± 0.23           | This work|
| [Fe/H] (dex)   | 0.16 ± 0.10            | This work|
| L (L_\odot)    | 0.60 ± 0.05            | This work|
| R (R_\odot)    | 0.90 ± 0.02            | This work|
| M (M_\odot)    | 0.97 ± 0.06            | This work|
| \sin(i) (km s^{-1}) | 3.00 ± 0.30          | This work|
| \sin(i) (km s^{-1}) | 1.74 ± 0.20           | This work|
| \rho* (g cm^{-3}) | 1.89 ± 0.15           | This work|
| log R_Hg (dex) | -5.02 ± 0.13           | This work|
| Age (Gyr)       | 6.34^{+0.44}_{-0.25}  | This work|
| (U,V,W) (km s^{-1}) | 18.4 ± 0.2, -32.6 ± 0.4, | This work|
|                 | 16.5 ± 0.4             |          |

Note. *Correction of +82 μas from Stassun & Torres (2018) applied to the Gaia value.

4 STELLAR PARAMETERS

We first estimated the stellar parameters\(^2\) by combining the HARPS spectra into a high-S/N ratio spectrum and fed that into the spectral classification and stellar parameter estimation software package SPECIES (Soto & Jenkins 2018). For a more detailed explanation and outputs from this code, the reader is referred to Díaz et al. (2018) and Soto & Jenkins (2018).

We also analysed the combined HARPS spectrum using both Spectroscopy Made Easy (version 5.22; Valenti & Piskunov 1996; Piskunov & Valenti 2017), and the empirical package SpecMatch – Emp (Yee, Petigura & von Braun 2017). We followed the same procedures outlined in, e.g. Fridlund et al. (2017), Persson et al. (2018), Persson et al. (2019), and Gandolfi et al. (2019). The two methods provide consistent results within 1σ and 2σ, which are also in agreement with those obtained with SPECIES. In particular, the age of the star was determined by isochrone fitting according to the method described in SPECIES. We note that, while there is no reason to prefer one set of spectroscopic parameter estimates over the others, we adopted the results derived with SPECIES for the subsequent analyses presented in this work.

\(^3\)astropy.timeseries.LombScargle(). https://docs.astropy.org/en/stable/timeseries/lombscargle.html.

\(^4\)Including \sin(i) and \sin(i).
Table 2. HARPS radial velocities and spectral activity indices for TOI-132.

| BJD (−2450000) | RV (m s⁻¹) | σ RV (m s⁻¹) | SMW (dex) | σ SMW (dex) | FWHM (km s⁻¹) | σ FWHM (m s⁻¹) | BIS (m s⁻¹) | σ BIS (m s⁻¹) |
|---------------|-------------|--------------|----------|------------|--------------|----------------|-------------|-------------|
| 8576.90725    | -4.737      | 2.967        | 0.056    | 0.003      | 6.885        | 16.180         | 2.967       | 5.933       |
| 8578.89655    | 0.000       | 2.398        | 0.128    | 0.004      | 6.911        | 16.240         | 2.398       | 4.797       |
| 8579.90764    | 5.631       | 1.765        | 0.140    | 0.003      | 6.908        | 16.234         | 1.765       | 3.531       |
| 8580.90988    | -10.056     | 1.972        | 0.121    | 0.003      | 6.914        | 16.248         | 1.972       | 3.943       |
| 8581.91433    | 8.808       | 1.338        | 0.133    | 0.002      | 6.911        | 16.241         | 1.338       | 2.675       |
| 8582.91045    | -9.005      | 1.402        | 0.135    | 0.002      | 6.911        | 16.241         | 1.402       | 2.803       |
| 8583.90870    | 11.771      | 1.656        | 0.138    | 0.003      | 6.916        | 16.252         | 1.656       | 3.312       |
| 8586.81477    | -5.174      | 2.488        | 0.151    | 0.004      | 6.909        | 16.235         | 2.488       | 4.977       |
| 8586.82174    | 9.069       | 1.800        | 0.143    | 0.003      | 6.898        | 16.211         | 1.800       | 3.599       |
| 8587.91868    | 2.175       | 1.649        | 0.134    | 0.003      | 6.914        | 16.247         | 1.649       | 3.297       |
| 8635.81477    | -10.056     | 1.972        | 0.121    | 0.003      | 6.914        | 16.241         | 1.972       | 3.943       |
| 8636.82174    | 8.808       | 1.338        | 0.133    | 0.002      | 6.911        | 16.241         | 1.338       | 2.675       |
| 8637.91868    | 2.175       | 1.649        | 0.134    | 0.003      | 6.914        | 16.247         | 1.649       | 3.297       |
| 8642.93057    | -10.522     | 1.129        | 0.134    | 0.002      | 6.911        | 16.242         | 1.129       | 2.257       |
| 8643.91730    | 10.526      | 1.331        | 0.139    | 0.002      | 6.917        | 16.256         | 1.331       | 2.662       |
| 8644.84072    | -13.834     | 1.945        | 0.152    | 0.003      | 6.905        | 16.228         | 1.945       | 3.891       |
| 8660.89377    | -14.864     | 1.652        | 0.173    | 0.004      | 6.929        | 16.283         | 1.652       | 3.305       |
| 8666.80357    | -5.826      | 1.542        | 0.165    | 0.003      | 6.923        | 16.270         | 1.542       | 3.084       |
| 8667.76863    | 6.145       | 1.530        | 0.165    | 0.003      | 6.910        | 16.238         | 1.530       | 3.061       |
| 8668.82036    | -3.829      | 1.534        | 0.156    | 0.003      | 6.914        | 16.249         | 1.534       | 3.067       |
| 8669.71698    | -0.505      | 1.294        | 0.156    | 0.003      | 6.916        | 16.252         | 1.294       | 2.588       |
| 8669.91776    | 3.943       | 1.344        | 0.137    | 0.003      | 6.915        | 16.250         | 1.344       | 2.687       |

Figure 2. Left to right: correlations between BIS, cross-correlation function FWHM, S-index, and radial velocities after subtraction of their mean, respectively. The first two are obtained from DRS and the latter is derived from the HARPS spectra using the HARPS–TERRA algorithm. On each plot, the dashed line represents a linear fit between the activity index and radial velocity. All three plots show no strong evidence for correlation, although outliers are seen in the FWHM and SMW.

We performed an analysis of the broad-band spectral energy distribution (SED) of the star together with the Gaia DR2 parallaxes (adjusted by +0.08 mas to account for the systematic offset reported by Stassun & Torres 2018), in order to determine an empirical measurement of the stellar radius, following the procedures described in Stassun & Torres (2016) and Stassun, Collins & Gaudi (2017), and Stassun et al. (2018a). We retrieved the $B_V$, $V$, and $I_C$ magnitudes from Tycho-2, the $B_V$, $V$, $g$, and $r$ magnitudes from APASS, the $H$, $J$, $K$, and $S$ magnitudes from 2MASS, the $W1$, $W2$, $W3$, and $W4$ magnitudes from WISE, and the $G$ magnitude from Gaia. Together, the available photometry spans the full stellar SED over the wavelength range 0.2–22 μm (see Fig. 4).

We performed a fit using Kurucz stellar atmosphere models, with the effective temperature ($T_{\text{eff}}$) and metallicity ([Fe/H]) and surface gravity (log $g$) adopted from the spectroscopic analysis of SPECIES. The only free parameter is the extinction ($A_V$), which we restricted to the maximum line-of-sight value from the dust maps of Schlegel, Finkbeiner & Davis (1998). The resulting fit shown in Fig. 4, gives a reduced $\chi^2$ of 2.4 and best-fitting $A_V = 0.03 \pm 0.01$. Integrating the (unreddened) model SED, it gives the bolometric flux at the Earth, $F_{\text{bol}} = 7.492 \pm 0.087 \times 10^{-10}$ erg s⁻¹ cm⁻². Taking the $F_{\text{bol}}$ and $T_{\text{eff}}$ together with the Gaia DR2 parallax, gives the stellar radius, $R_* = 0.90 \pm 0.02$ R$_\odot$. Finally, we can use the empirical relations of Torres, Andersen & Giménez (2010) and a 6 per cent error from the empirical relation itself to estimate the stellar mass, $M_*= 0.97 \pm 0.06$ M$_\odot$; this, in turn, together with the stellar radius provides an empirical estimate of the mean stellar density $\rho_* = 1.89 \pm 0.15$ g cm⁻³. We note the small errorbars on both stellar mass and radius come directly from propagation of uncertainties in $T_{\text{eff}}$, $F_{\text{bol}}$, and parallax. In this case, the fractional errors are of order
Figure 3. Top panels: Time series showing the radial velocities from the HARPS follow-up observations. Generalized Lomb–Scargle periodogram of the radial velocities. The red power spectrum shows the window function. Bottom panels: Same as top panel but for the activity indices obtained with HARPS: BIS, FWHM, and S-index, respectively. The horizontal lines, from bottom to top on each periodogram, represent the 10, 1, and 0.1 per cent significance levels estimated via 5000 bootstrap samples. The vertical line on each plot marks the position of the 2.11-d planet candidate signal present in the radial velocity.

∼1 per cent, ∼1 per cent, and ∼0.5 per cent, respectively. Then, the uncertainty in stellar radius is dominated by the $T_{\text{eff}}$ error, in this case that implies an error of ∼2 per cent (see Table 1).

5 SPECKLE IMAGING

The relatively large 21-arcsec pixels of TESS can result in contamination from companion stars or nearby sources. The additional light from these can dilute the planetary transit, resulting in an underestimated planet radius. We searched for nearby sources with speckle imaging with HRCam on the 4.1-m Southern Astrophysical Research (SOAR) telescope (Tokovinin et al. 2018) on 2018 September 25 UT. From these observations, a potential companion star was detected at low significance. The purported star was located near the first diffraction ring of the primary star, at 0.079 arcsec (and a projected distance of ∼12 au), a similar position as optical ghosts that can occasionally appear in the speckle imaging during periods of low wind. This triggered a warning as the flux contamination due to the companion ($\Delta m \sim 2.6$ mag) would have not been negligible for the spectroscopic observations given that the diameter of the fibers on HARPS is ∼1 arcsec, meaning that the suspected companion was inside the aperture of the fiber. Upon visual inspection of the CCF and the individual spectra, we could not see evidence for such a contamination. The system was observed again on 2019 May 18 UT in excellent conditions, and the possible companion star was not detected. The 5σ detection sensitivity and autocorrelation function of the later observation are shown in Fig. 5.
periastron as free parameters the best-fitting model RMS goes down to \(\sim 2.5 \text{ m s}^{-1}\) and \(e \sim 0.17\). We then performed further analyses considering two scenarios (circular and eccentric) with juliet. This package has been proven to be an excellent tool for analysing both photometry and RVs using a joint model (see e.g. Brahm et al. 2019; Espinoza et al. 2019b; Kossakowski et al. 2019). In short, the code uses batman (Kreidberg 2015) to model the transit data and radvel (Fulton et al. 2018) to model the RVs, and in order to estimate the Bayesian log-evidence, \(\ln Z\), for model comparison we used the option of the Dynamic Nested Sampling algorithm that the dynesty (Speagle & Barbary 2018; Speagle 2020) package provides. We note that, while juliet has the option to include Gaussian Processes to model the light curve, RVs, or both, we did not set this option as there was no evidence of additional variability in the PDCSAP\_FLUX-corrected light curve (see Fig. 1).

We also used the parametrization described in Espinoza (2018) that allows an efficient way to sample the impact parameter, \(b\), and the planet-to-star radius ratio, \(p\), where only values that are physically plausible in the \((p, b)\) plane are sampled via the \(r_2\) and \(r_3\) coefficients (Espinoza 2018). For the limb-darkening coefficients, we use the parametrization of Kipping (2013) for two-parameter laws. Speckle images obtained for TOI-132 rules out the possibility of significant nearby sources of light. Therefore, we fixed the dilution factor to a value of 1 for the photometric data sets. The priors and boundaries for the parameters used in the joint analysis are listed in Table 3.

We set up two different runs, first by fixing eccentricity to zero, and another treating it (along with \(\omega\)) as free parameter. Comparing the evidences from the circular (\(\ln Z = 89705.63\)) and eccentric model (\(\ln Z = 89706.85\)), we obtain \(\Delta \ln Z = 1.22\) that suggests weak evidence the latter is preferred over the circular model according to the model selections criteria and thresholds described in Espinoza et al. (2019a). The joint model results are shown in Fig. 7 and the best fit, or most probable parameters given the data are listed in Table 4. The quoted values are the median value from the posterior distribution.

As a sanity check, we also performed an independent joint analysis using the Python/\textsc{FORTRAN} software suite pycat (Barragán, Gandolfi & Antoniciello 2019a). Results are consistent with those obtained with juliet well within the nominal error bars.

Using the luminosity of the host star, we could retrieve the incident flux on TOI-132\(b\) using the semimajor axis from our joint model. We estimated that the insolation of TOI-132\(b\) is \(S_\oplus = 860 S_\oplus\).

In order to estimate the average equilibrium temperature of the planet, considering the physical properties of TOI-132\(b\) we assumed a Bond albedo of \(A_\text{B} = 0.31\), which corresponds to the value accepted for Neptune. Then,

\[
T_{\text{eq}} = T_* \sqrt{\frac{R_*}{2a} (1 - A_\text{B})^{\frac{1}{4}}} \quad (1)
\]

yields an equilibrium temperature of \(T_{\text{eq}} = 1395^{+52}_{-37} K\) for the planet.

### 8 TTV ANALYSIS

In order to search for possible TTVs in TOI-132\(b\), we computed the individual transit time of each light curve using the EXOFASTv2 code (Eastman, Gaudi & Agol 2013; Eastman 2017). EXOFASTv2 uses the Differential Evolution Markov chain Monte Carlo method to derive the values and their uncertainties for the stellar, orbital, and physical parameters of the system.

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\(5\text{MAD} = \text{median}(|X_i - \bar{X}|)/0.6745\)

\(6\text{https://docs.astropy.org/en/stable/timeseries/lombscargle.html}\)

\(7\text{https://github.com/nespinoza/juliet}\)
Table 3. Below are the priors used for TOI-132 for the final joint analysis fit using juliet. As a reminder, \( p = R_p/R_\star \) and \( b = (a R_\star) \cos (i_\star) \), where \( R_p \) is the planetary radius, \( R_\star \) the stellar radius, \( a \) the semimajor axis of the orbit, and \( i_\star \) the inclination of the planetary orbit with respect to the plane of the sky. \( e \) and \( \omega \) are the eccentricity and argument of periastron of the orbits. The prior labels of \( N \), \( U \), and \( J \) represent normal, uniform, and Jeffreys distributions. See text for explanations about other parameters.

| Parameter name | Prior | Units | Description |
|----------------|-------|-------|-------------|
| \( P_b \) | \( \mathcal{N}(2.10937, 0.001) \) | d | Period. |
| \( T_c b - 2458000 \) | \( \mathcal{N}(337.451, 10) \) | d | Time of transit centre. |
| \( r_1, b \) | \( U(0, 1) \) | – | Parametrization for \( p \) and \( b^p \). |
| \( r_2, b \) | \( U(0, 1) \) | – | Parametrization for \( p \) and \( b^p \). |
| \( a_b \) | \( U(4.5, 7.0) \) | – | Scaled semimajor axis. |
| \( K_b \) | \( U(1, 100) \) | m s\(^{-1} \) | Radial-velocity semi-amplitude. |
| \( e_b \) | \( U(0, 1) \) | – | Eccentricity. |
| \( \omega_b \) | \( U(0, 359) \) | deg | Argument of periastron. |

Parameters for TESS

| \( D_{\text{Tess}} \) | \( 0.001 \) (Fixed) | – | Dilution factor for TESS. |
| \( M_{\text{Tess}} \) | \( \mathcal{N}(0, 1) \) | ppm | Relative flux offset for TESS. |
| \( \sigma_w_{\text{Tess}} \) | \( J(0.1, 100) \) | ppm | Extra jitter term for TESS light curve. |
| \( \psi_1, \text{Tess} \) | \( U(0, 1) \) | – | Quadratic limb-darkening parametrization. |
| \( \psi_2, \text{Tess} \) | \( U(0, 1) \) | – | Quadratic limb-darkening parametrization. |

Parameters for LCOGT

| \( D_{\text{LCOGT}} \) | \( 0.001 \) (Fixed) | – | Dilution factor for LCOGT. |
| \( M_{\text{LCOGT}} \) | \( \mathcal{N}(0, 1) \) | ppm | Relative flux offset for LCOGT. |
| \( \sigma_w_{\text{LCOGT}} \) | \( J(0.1, 100) \) | ppm | Extra jitter term for LCOGT light curve. |
| \( \psi_1, \text{LCOGT} \) | \( U(0, 1) \) | – | Quadratic limb-darkening parametrization. |
| \( \psi_2, \text{LCOGT} \) | \( U(0, 1) \) | – | Quadratic limb-darkening parametrization. |

Parameters for HARPS

| \( \mu_{\text{HARPS}} \) | \( \mathcal{N}(-0.6, 1) \) | m s\(^{-1} \) | Radial velocity zero-point (offset). |
| \( \sigma_w_{\text{HARPS}} \) | \( J(0.1, 10) \) | m s\(^{-1} \) | Extra jitter term for HARPS radial velocities. |

Note. \( ^* \)We used the transformations outlined in Espinoza (2018) and also set \( p_b = 0.03 \) and \( p_a = 0.05 \) in the juliet call.

So, to obtain the transit time of each light curve, we fixed the stellar and orbital parameters to the values obtained from the global fit performed by juliet, except for the transit time and their baseline flux. If a planet follows strictly a Keplerian orbit, the transit time of a given epoch \( T(E) \) is a linear function of the orbital period \( P \):

\[
T(E) = T_0 + P \times E
\]

where \( T_0 \) is a reference transit time and \( E \) is the number of epochs since \( T_0 \). The best-fitting values for equation (2) from juliet are shown in Table 4 along with the planetary parameters fixed to compute the individual transit time.

Considering the theoretical and the observed transit times of the light curves, we obtained the TTV values for TOI-132 b presented in Fig. 8. Even though the larger variation is about 22 min, we found no evidence of a clear periodic variation in the transit time. This outlier is probably induced by a gap in the light curve of epoch 5. The RMS variation from the linear ephemeris is \( \sigma = 8.03 \) min, however, the reduced chi-squared for this model is \( \chi^2_{\text{red}} = 1.37 \). This is an indicator that the transit times, considering their errors, fit well with the proposed linear ephemeris.

The lack of an additional RV signal, as well as no evidence of a TTV signal for our given time span of our transit data, suggests that there is no other close-in companion of TOI-132 b. These results also rule out additional planets in low-order resonant configurations with TOI-132 b. Nevertheless, further ground-based follow-up will be required to unveil the possible existence of companions in TOI-132.

9 DISCUSSION AND CONCLUSIONS

By combining TESS space-based photometry with HARPS high-precision RV measurements, along with additional high-sensitivity ground-based photometric observations, we were able to confirm a short period, hot Neptune-like planet orbiting the nearby metal-rich G8V star TOI-132. The planet was found to have an orbital period of only 2.1 d, a radius of 3.42 \( \oplus \) and a mass of \( 22.40^{+1.90}_{-1.14} \) \( M_{\oplus} \), implying a density and equilibrium temperature of \( 3.08^{+0.44}_{-0.46} \) \( \text{g cm}^{-3} \) and 1395\( ^{+52}_{-17} \) K, respectively.

In Fig. 9, we can see that TOI-132 b is located in an underpopulated region of the mass–radius diagram. Of the relatively small number of known Neptune-like planets with well-constrained properties, TOI-132 b stands out as bridging the gap between 100 per cent water worlds and more typical Neptunes that have atmospheric mass fractions of \( \sim 10 \) per cent. The planet likely more closely resembles NGTS-4 b (West et al. 2019), which is shown in the figure despite the relatively high uncertainties measured for the planetary parameters, or TOI-824 b (Burt et al., private communication). These three planets appear to have similar masses and radii, giving rise to similar densities and bulk.
Figure 7. Results from the joint fit for the one-planet model. Top panel: HARPS–TERRA radial velocities and best-fitting Keplerian model (the solid curve) the bands around it show 68 per cent, 95 per cent, and 99 per cent posterior credibility bands. Mid panels: TESS photometry (left) and LCOGT $z$-short photometry (right) phase-folded to the 2.109 d period of TOI-132 b along with best-fitting transit model from the joint fit. The red points show the binned photometry in phase bins of 0.005. Bottom panel: phase-folded RVs from HARPS. The black line shows the model. Credibility bands are shown in the same way as in top panel. Best-fitting parameters are the most probable parameters given the data and the quoted values are the median value from the posterior distribution. The error bars of both photometry and RV data include their corresponding jitter.
the proposed linear ephemeris (optimal transit time. The TTV values shown in this plot fit accordingly with TESS first transit observed by EXOFASTv2. The area is the propagation of 1 linear ephemeris. The dashed line corresponds to zero variation and the grey observed minus computed mid-transit times of TOI-132 b. The Figure 8. Planetary properties for TOI-132 b.

| Property                | Value               |
|-------------------------|---------------------|
| Fitted parameters       |                     |
| $P$ (d)                 | 2.1097019$^{+0.000012}_{-0.000011}$ |
| $T_0$ (BJD - 2450000)   | 8333.23095$^{+0.00094}_{-0.00096}$ |
| $a$/$R_*$              | 6.36$^{+0.413}_{-0.627}$ |
| $b$                     | 0.533$^{+0.124}_{-0.137}$ |
| $K$ (m s$^{-1}$)        | 11.38$^{+0.84}_{-1.30}$ |
| $i_p$ (deg)             | 85.03$^{+1.84}_{-1.30}$ |
| $e$                     | 0.059$^{+0.050}_{-0.037}$ |
| $\omega$ (deg)          | 125.88$^{+57.23}_{-30.65}$ |
| Derived parameters      |                     |
| $M_p$ ($M_\oplus$)      | 22.40$^{+1.90}_{-1.92}$ |
| $R_p$ ($R_\oplus$)      | 3.42$^{+0.13}_{-0.14}$ |
| $a$ (AU)                | 0.026$^{+0.003}_{-0.003}$ |
| $\rho_p$ (g cm$^{-3}$)  | 3.08$^{+0.44}_{-0.46}$ |
| $T_\text{eq}$ (K)       | 1395$^{+5.72}_{-5.72}$ |
| Instrumental parameters |                     |
| $M_{\text{TESS}}$ (ppm) | $-0.000069^{+0.000011}_{-0.000012}$ |
| $\sigma_{w,\text{TESS}}$ (ppm) | 10.58$^{+2.71}_{-3.84}$ |
| $q_{1,\text{TESS}}$     | 0.361$^{+0.344}_{-0.242}$ |
| $q_{2,\text{TESS}}$     | 0.331$^{+0.342}_{-0.223}$ |
| $M_{\text{LCOGT}}$ (ppm) | $-0.000057^{+0.000060}_{-0.000057}$ |
| $\sigma_{w,\text{LCOGT}}$ (ppm) | 462.35$^{+72.73}_{-73.70}$ |
| $q_{1,\text{LCOGT}}$    | 0.426$^{+0.309}_{-0.262}$ |
| $q_{2,\text{LCOGT}}$    | 0.282$^{+0.296}_{-0.186}$ |
| $\mu_{\text{HARPS}}$ (m s$^{-1}$) | $-0.18^{+0.51}_{-0.51}$ |
| $\sigma_{w,\text{HARPS}}$ (m s$^{-1}$) | 2.00$^{+0.72}_{-0.64}$ |

Note. *Estimated using a Bond albedo of 0.31 (see text).

Figure 8. Observed minus computed mid-transit times of TOI-132 b. The residuals (TTV) of the transit times are shown considering the proposed linear ephemeris. The dashed line corresponds to zero variation and the grey area is the propagation of 1σ uncertainties, considering the optimal transit time from EXOFASTv2, and the period from juliet. The epoch 0 is the first transit observed by TESS and it is also the corresponding epoch of the optimal transit time. The TTV values shown in this plot fit accordingly with the proposed linear ephemeris ($\chi^{2}_\text{red} = 1.37$).

Figure 9. Top: Period–radius diagram for planets whose radius has been measured with a precision better than 5 per cent. We have included recent TESS discoveries (Burt et al., private communication; Nielsen et al. 2020). The shaded area indicates the Neptune desert where the edges are defined by Mazeh et al. (2016). TOI-132 b is highlighted with a red circle, near the edge of the desert. Bottom: Mass–radius diagram for planets whose mass and radius have been measured with a precision better than 25 per cent (the grey circles) in the range $R_p < 5R_\oplus$ and $M_p < 30M_\oplus$, retrieved from the transiting planets catalog TEPCat (available at https://www.astro.keele.ac.uk/jkt/tepcat/, Southworth 2011). The black points show recent discoveries from TESS. TOI-132 b is shown with a red circle. The solid, coloured lines show models for different compositions from Zeng, Sasselov & Jacobsen (2016) ranging from 100 per cent iron core planet to 100 per cent H$_2$O planet. Also, two-layer models from Zeng et al. (2019) are shown for 2 per cent H$_2$ envelopes at different temperatures (magenta, purple). Extended models (Lopez & Fortney 2014) are shown for 95 per cent and 98 per cent core mass fraction, 6.2 Gyr (orange).

compositions, which might indicate they share similar formation histories.

Moreover, it is interesting to mention the planet K2-100 b from the K2 mission (Mann et al. 2017). Recently characterized by Barragán et al. (2019b), the planet consists of a young, inflated Neptune on a short period around a G-type star. TOI-132 b falls within the evolutionary range of K2-100 b after 5 Gyr. This may indicate in the past TOI-132 b could have shared similar characteristics to that of K2-100 b, and at some point given the strong stellar irradiation on TOI-132 b could have caused atmospheric loss we see in the present. Hence, TOI-132 b is an interesting target for atmospheric transit spectroscopy, to check for evidence of ongoing atmospheric loss through a wind.

While TOI-132 b is not as extreme in some respects as the recently discovered, first ultrahot Neptune LTT 9779 b (Jenkins et al. 2020), it is placed right at the edge of the Neptune desert.
The survival of the planet’s atmosphere can likely be understood based on its large core mass, and also the incompatibility with being composed of either 100 per cent rock or water. This would imply that, at the present time, TOI-132 b could maintain some significant gaseous atmosphere. We employed a 1D thermal evolution model (Lopez & Fortney 2014), and for an Earth-like rocky core we find a best-fitting current day atmospheric mass fraction of $4.3^{+1.2}_{-1.3}$ per cent gas, which can be retained with an initial envelope fraction of $\sim 9$ per cent at 10 Myr. We note here that rocky core likely consists of a combination of rock and iron even if the relative core mass fraction is not clear. Moreover, these results are model dependent rather than being directly constrained by the data.

With the Gaia parameters from Table 1, we calculated the star’s Galactic space motion. We used the TIDL routine ca.l.c.uvw, based upon Johnson & Soderblom (1987) and the local standard of rest which aims to precisely measure the masses for 50 transiting support from the MINECO FPI-SO doctoral research project SEV-

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