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HD 219666 b: a hot-Neptune from TESS Sector 1

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ABSTRACT

We report on the confirmation and mass determination of a transiting planet orbiting the old and inactive G7 dwarf star HD 219666 ($M_\star = 0.92 \pm 0.03 \, M_\odot$, $R_\star = 1.03 \pm 0.03 \, R_\odot$, $\tau_\star = 10 \pm 2$ Gyr). With a mass of $M_\oplus = 16.6 \pm 1.3 \, M_\oplus$, a radius of $R_\oplus = 4.71 \pm 0.17 \, R_\oplus$, and an orbital period of $P_\text{orb} = 6$ days, HD 219666 b is a new member of a rare class of exoplanets: the hot-Neptunes. The Transiting Exoplanet Survey Satellite (TESS) observed HD 219666 (also known as TOI-118) in its Sector 1 and the light curve shows four transit-like events, equally spaced in time. We confirmed the planetary nature of the candidate by gathering precise radial-velocity measurements with the High Accuracy Radial velocity Planet Searcher (HARPS) at ESO 3.6 m. We used the co-added HARPS spectrum to derive the host star fundamental parameters ($T_{\text{eff}} = 5527 \pm 65$ K, log $g = 4.40 \pm 0.11$ (cgs), [Fe/H] = 0.04 \pm 0.04 dex, log $R_H^\prime = -5.07 \pm 0.03$), as well as the abundances of many volatile and refractory elements. The host star brightness ($V = 9.9$) makes it suitable for further characterisation by means of in-transit spectroscopy. The determination of the planet orbital obliquity, along with the atmospheric metal-to-hydrogen content and thermal structure could provide us with important clues on the formation mechanisms of this class of objects.

Key words. planets and satellites: detection – planets and satellites: fundamental parameters – techniques: radial velocities – stars: fundamental parameters – techniques: photometric – planets and satellites: individual: HD 219666 b

1. Introduction

Following the success of the Kepler space mission (Borucki 2016), in April 2018 NASA launched a new satellite, the Transiting Exoplanet Survey Satellite (TESS, Ricker et al. 2015). By performing a full-sky survey, TESS is expected to detect approximately 10 000 transiting exoplanets (TEPs; Barclay et al. 2018; Huang et al. 2018a). Most interestingly, nearly 1000 of them will orbit host stars with magnitudes $V \leq 10$ (as of November 2018 there are 56 known TEPs around stars with $V < 10$, only 13 of which have masses $< 20 \, M_\odot$, according to the NASA exoplanet archive\textsuperscript{1}). Bright host stars are suitable for precise radial-velocity (RV) measurements that can lead to planet mass determinations down to a few Earth masses, and to estimates of the planet bulk density for TEPs. In-transit precise RVs also allow us to measure the planet orbital obliquity through the observation of the Rossiter-McLaughlin effect (see, e.g. Traud 2017). High-signal-to-noise ratio (S/N) number spectra are very much needed for transmission spectroscopy studies aimed at the detection of atomic and molecular species, and the characterisation of the thermal structure of planet atmospheres (Snellen et al. 2010; Bean et al. 2013).

TESS has a field of view of 24° × 96°, and will cover almost the full sky in 26 Sectors, each monitored for about 27 days. Full frame images (FFIs) are registered every 30 min, while for a selected sample of bright targets (~16 000 per Sector) pixel sub-arrays are saved with a two-minute cadence. The first TESS data set of FFIs from Sectors 1 and 2 was released on December 6, 2018, and the TESS Science Office, supported by the Payload Operations Centre at MIT, had already issued TESS data alerts for a number of transiting planet-host star candidates, the so-called TESS objects of interest (TOIs). Preliminary two-minute cadence light curves and target pixel files (Twicken et al. 2018) are made publicly available for download at the MAST web site\textsuperscript{2}.

Several TESS confirmed planets have already been announced: π Mensae c (TOI-144), a super-Earth orbiting a $V = 5.65$ mag G0 V star (Huang et al. 2018b; Gandolfi et al. 2018); HD 1397 b (TOI-120), a warm giant planet around a $V = 7.8$ mag sub-giant star (Brahm et al. 2018; Nielsen et al. 2019); HD 2685 b (TOI-135), a hot-Jupiter hosted by an early G star (Hippke et al. 2018). With a mass of $M_\oplus = 4.40 \pm 0.35 \, M_\oplus$ and a radius of $R_\oplus = 1.61 \pm 0.11 \, R_\oplus$, this planet is currently the most massive transiting planet discovered by TESS, and the second planet confirmed by the TESS sector 1 data release.

\textsuperscript{1} Based on observations made with the 3.6 m-ESO telescope at La Silla observatory under ESO programmes IDs 1102.C-0923 (PI: Gandolfi) and 1102.C-0249 (PI: Armstrong).

\textsuperscript{2} Mikulski Archive for Space Telescopes, https://archive.stsci.edu/prepds/teess-data-alerts/
Table 1. Main identifiers, coordinates, parallax, and optical and infrared magnitudes of HD 219666.

| Parameter | Value | Source |
|-----------|-------|--------|
| HD        | 219666|        |
| TIC ID    | 266980320 | TIC    |
| TOI ID    | 118   | TESS Alerts |
| Gaia DR2 ID | 6492940453524756128 | Gaia DR2 |
| RA (J2000) | 23° 18' 13.630" | Gaia DR2 |
| Dec (J2000) | -56° 54' 14.036" | Gaia DR2 |
| $\mu_R$ (mas yr$^{-1}$) | 313.918 ± 0.039 | Gaia DR2 |
| $\mu_D$ (mas yr$^{-1}$) | -20.177 ± 0.043 | Gaia DR2 |
| $\pi$ (mas) | 10.590 ± 0.028 | Gaia DR2 |
| $V_T$ | 9.897 ± 0.018 | Tycho-2$^b$ |
| $G$ | 9.6496 ± 0.0002 | Gaia DR2 |
| $G_{BP}$ | 10.0349 ± 0.0009 | Gaia DR2 |
| $G_{RP}$ | 9.1331 ± 0.0008 | Gaia DR2 |
| $J$ | 8.557 ± 0.020 | 2MASS$^c$ |
| $H$ | 8.254 ± 0.042 | 2MASS$^c$ |
| $K_s$ | 8.158 ± 0.033 | 2MASS$^c$ |
| W1(3.35 $\mu$m) | 8.080 ± 0.023 | WISE$^d$ |
| W2(4.6 $\mu$m) | 8.138 ± 0.020 | WISE$^d$ |
| W3(11.6 $\mu$m) | 8.100 ± 0.021 | WISE$^d$ |
| W4(22.1 $\mu$m) | 8.250 ± 0.288 | WISE$^d$ |

Notes. $^{(a)}$Gaia Collaborations (2018). $^{(b)}$Høg et al. (2000). $^{(c)}$Cutri et al. (2003). $^{(d)}$Cutri et al. (2013).

F-type star (Jones et al. 2019); and an ultra-short-period Earth-like planet around the M-dwarf star LHS 3844 (TOI-136; Vanderspek et al. 2019). Here we report on the detection and characterisation of a transiting planet TOI-136 around LHS 3844. The planet was confirmed to be Earth-like and orbiting a G-type star with an orbital period of approximately 27.9 days.

Table 2. Fundamental parameters and elemental abundances of HD 219666.

| Parameter | Value | Source |
|-----------|-------|--------|
| Star mass $M_\star$ ($M_\odot$) | 0.92 ± 0.03 |        |
| Star radius $R_\star$ ($R_\odot$) | 1.03 ± 0.03 |        |
| Effective Temperature $T_{\text{eff}}$ (K) | 5527 ± 65 |        |
| Surface gravity log $g_\star$ (cgs) | 4.40 ± 0.11 |        |
| Iron abundance $[\text{Fe/H}]$ (dex) | 0.04 ± 0.04 |        |
| Project. rot. vel. $v \sin i_\star$ (km s$^{-1}$) | 2.2 ± 0.8 |        |
| Micro-turb. vel. $v_{\text{mic}}$ (km s$^{-1}$) | 0.9 ± 0.1 |        |
| Macro-turb. vel. $v_{\text{mac}}$ (km s$^{-1}$) | 2.8 ± 0.9 |        |
| Ca II activity indicator log $R_{\text{HK}}$ | -5.07 ± 0.03 |        |
| Age $\tau_\star$ (Gyr) | 10 ± 2 |        |
| Lithium abundance $A$(Li) | <0.40 |        |

[The rest of the text continues with further details on the detection and characterisation of the planet, its orbit, and implications for exoplanet research.]

2. TESS photometry

HD 219666 was observed by TESS in Sector 1 (CCD #2 of Camera #2) and falls in a region of the sky that will not be further visited by TESS. Sector 1 was monitored continuously for ~27.9 days, from 2018-07-25 (BJD$_\text{TDB}$ = 2458350) to 2018-08-22 (BJD$_\text{TDB}$ = 2458353), with only a 1.14 day gap in the observations. The data were later reanalysed and the light curve was reprocessed to improve the signal-to-noise ratio and to search for additional transiting planets.

2.1. Custom light-curve preparation

To check that the SPOC aperture is indeed an optimal choice, we extracted a series of light curves from the pixel data using contiguous sets of pixels centred on HD 219666. We first computed the 50th–95th percentiles (in 1% steps) of the median image, and then selected pixels with median counts above each percentile value to form each aperture. We then computed the 6.5 h combined differential photometric precision (CDPP; Christiansen et al. 2012) of the light curve resulting from each of these apertures, and we found that the aperture that minimised the CDPP was slightly larger than the SPOC aperture shown in Fig. 1. However, we opted to use the PDCSAP light curve produced from the SPOC aperture, which has lower levels of systematic noise.
as a result of the processing performed by the SPOC pipeline (Ricker & Vanderspek 2018).

The median-normalised light curve that we used in our analysis is shown in Fig. 2.

2.2. Limits on photometric contamination

To investigate the possibility of contaminating flux from nearby stars within the SPOC photometric aperture, we compared the Gaia DR2 (Gaia Collaborations 2018) sources with the aperture and an archival image of HD 219666 from the SERC-J survey 3. To do so, we executed a query centred on the coordinates of HD 219666 from the TESS Input Catalog 4 (TIC; Stassun et al. 2018) using a search radius of 3′. The archival image, taken in 1980, shows HD 219666 to be offset from its current position by ∼4.8″. The proper motion is not sufficient to completely rule out chance alignment with a background source, but such an alignment with a bright source is qualitatively unlikely. We also note the non-detection by Gaia of any other sources within ∼30″ of HD 219666. Figure 1 shows Gaia DR2 source positions overlaid on the archival image, along with the SPOC photometric aperture. Using a 2D Gaussian profile with a FWHM of ∼25″ to approximate the TESS point spread function (PSF), and a negligible difference between the $G_{RP}$ and $T$ bandpasses, we found that the transit depth of HD 219666 should be diluted by no more than 0.1%, even considering partial flux contributions from nearby stars outside the aperture. Furthermore, we found that HD 219666 is the only star in or near the aperture that is bright enough to be the source of the transit signal, given the observed depth and assuming a maximum eclipse depth of 100%.

3. HARPS observations

We acquired 21 high-resolution ($R \approx 115,000$) spectra of HD 219666 with the HARPS spectrograph (Mayor et al. 2003) mounted at the ESO-3.6 m telescope of La Silla observatory (Chile). The observations were performed between 02 October and 05 November 2018 UTC, as part of the large observing programmes 1102.C-0923 (PI: Gandolfi) and 1102.C-0249 (PI: Armstrong). We reduced the data using the dedicated HARPS Data Reduction Software (DRS) and extracted the RVs by cross-correlating the echelle spectra with a G2 numerical mask (Baranne et al. 1996; Pepe et al. 2002; Lovis & Pepe 2007). Table 3 lists the HARPS RVs and their uncertainties, along with the BIS and FWHM of the cross-correlation function (CCF), the Ca H and K Mount-Wilson S-index, and S/N per pixel at 5500 Å.

The generalised Lomb-Scargle (GLS; Zechmeister & Kürster 2009) periodogram of the HARPS RV measurements (Fig. 3, first panel) shows a significant peak at the frequency of the transit signal ($f_1 = 0.166$ d$^{-1}$; vertical dashed red line), with a false alarm probability 5 (FAP) lower than 0.1% (horizontal dashed blue line). The peak has no counterpart in the periodograms of the activity indicators, as shown in the second, third, and fourth panels of Fig. 3. This provides strong evidence that the signal detected in our Doppler data is induced by an orbiting companion and confirms the presence of the transiting planet with a period of about 6 days. The periodogram of the RV measurements shows additional peaks symmetrically distributed to the left and right of the dominant frequency. We interpreted these peaks as aliases of the orbital frequency, as shown by the position of the peaks in the periodogram of the window function (Fig. 3, fifth panel).

4. Stellar fundamental parameters

The determination of the stellar parameters from the spectrum of the host star is crucial in order to derive the planetary parameters from transit and RV data. The three most important planetary parameters are the mass, $M_\star$, the radius $R_\star$, and the age $\tau_\star$, of all of them only derivable with knowledge of the same parameters for the host star, $M_\star$, $R_\star$, and $\tau_\star$. Therefore, we have used two independent methods in order to determine the stellar parameters with the highest degree of confidence available today. To this aim, we used the co-added HARPS spectrum, which has a S/N per pixel of ∼300 at 5500 Å.

In one of the methods, we used version 5.22 of the Spectroscopy made easy (SME) code (Valenti & Piskunov 1996; Valenti & Fischer 2005; Piskunov & Valenti 2017). The SME code calculates synthetic spectra, using a grid of stellar models and a set of initial (assumed) fundamental stellar parameters and fits the result to the observed high-resolution spectrum with a chi-square minimisation procedure. The code contains a large library of different 1D and 3D model grids. In our analysis of the co-added HD 219666 HARPS spectrum, we used the ATLAS12 model atmosphere grid (Kurucz 2013). This is a set of 1D models applicable to solar-like stars. The observed spectral features that we fit are sensitive to the different photospheric parameters, including the effective temperature $T_{\text{eff}}$, metallicity [M/H], surface gravity log $g_\star$, micro- and macro-turbulent velocities $v_{\text{mic}}$ and $v_{\text{mac}}$, and the projected rotational velocity $v\sin i_\star$. In order to minimise the number of free parameters we adopted the calibration equation of Bruntt et al. (2010) to estimate $v_{\text{mac}}$ and we fitted many isolated and blended metal lines to determine $v\sin i_\star$.

We used several different observed spectral features as indicators of each fundamental stellar parameter. The $T_{\text{eff}}$ was

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3 Available at http://archive.stsci.edu/cgi-bin/dss_form
4 Available at https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html
5 Computed following the Monte Carlo bootstrap method described in Kuerster et al. (1997).
Table 3. HARPS RV measurements of HD 219666.

| BJD_{TDB} - 2450000 | RV (km s\(^{-1}\)) | \(\sigma_{RV}\) (km s\(^{-1}\)) | BIS | FWHM (km s\(^{-1}\)) | \(S\)-index | \(\sigma_{S\text{-index}}\) | \(T_{\text{exp}}\) (s) | \(S/N\)* |
|---------------------|---------------------|-------------------------------|-----|--------------------|-------------|----------------|-----------------|--------|
| 8394.521096         | -20.0909            | 0.0008                        | -0.0274 | 6.9061             | 0.154       | 0.001          | 1200            | 87.9   |
| 8394.646180         | -20.0939            | 0.0009                        | -0.0281 | 6.9033             | 0.152       | 0.002          | 1200            | 85.7   |
| 8396.644285         | -20.1024            | 0.0012                        | -0.0242 | 6.9048             | 0.144       | 0.003          | 1200            | 62.5   |
| 8396.756848         | -20.1029            | 0.0011                        | -0.0267 | 6.9081             | 0.147       | 0.003          | 1200            | 72.4   |
| 8397.501496         | -20.1066            | 0.0016                        | -0.0274 | 6.9102             | 0.143       | 0.004          | 1500            | 50.9   |
| 8397.710686         | -20.1027            | 0.0014                        | -0.0253 | 6.9070             | 0.144       | 0.003          | 1200            | 54.2   |
| 8398.571357         | -20.0984            | 0.0011                        | -0.0278 | 6.9130             | 0.148       | 0.002          | 1200            | 67.3   |
| 8398.671630         | -20.0968            | 0.0011                        | -0.0264 | 6.9103             | 0.144       | 0.002          | 1200            | 70.3   |
| 8399.513841         | -20.0951            | 0.0015                        | -0.0316 | 6.9114             | 0.148       | 0.004          | 1200            | 53.4   |
| 8401.643664         | -20.0975            | 0.0016                        | -0.0280 | 6.9094             | 0.161       | 0.006          | 1200            | 51.8   |
| 8404.619501         | -20.1005            | 0.0013                        | -0.0295 | 6.9103             | 0.145       | 0.003          | 1200            | 59.9   |
| 8406.554873         | -20.0890            | 0.0017                        | -0.0282 | 6.9095             | 0.146       | 0.004          | 1200            | 47.3   |
| 8406.657043         | -20.0905            | 0.0014                        | -0.0225 | 6.9092             | 0.140       | 0.003          | 1200            | 58.1   |
| 8407.538610         | -20.1001            | 0.0013                        | -0.0242 | 6.9058             | 0.144       | 0.003          | 1200            | 58.0   |
| 8407.688373         | -20.0963            | 0.0010                        | -0.0274 | 6.9078             | 0.150       | 0.002          | 1200            | 78.3   |
| 8408.519940         | -20.1033            | 0.0014                        | -0.0304 | 6.9129             | 0.153       | 0.003          | 1200            | 55.6   |
| 8408.669882         | -20.1005            | 0.0012                        | -0.0285 | 6.9096             | 0.145       | 0.003          | 1200            | 64.8   |
| 8424.508079         | -20.0910            | 0.0007                        | -0.0263 | 6.9102             | 0.153       | 0.001          | 1200            | 108.7  |
| 8424.760122         | -20.0922            | 0.0010                        | -0.0262 | 6.9148             | 0.144       | 0.003          | 1200            | 84.8   |
| 8426.505548         | -20.1016            | 0.0008                        | -0.0236 | 6.9117             | 0.153       | 0.001          | 1200            | 86.6   |
| 8427.693940         | -20.1020            | 0.0009                        | -0.0267 | 6.9079             | 0.152       | 0.002          | 1200            | 89.2   |

Notes. *Barycentric Julian dates are given in barycentric dynamical time. *\(S/N\) per pixel at 5500 Å.

Fig. 2. TESS light curve of HD 219666. The red arrows point to the four planet-transit occurrences.

Primarily determined by fitting the wings of Balmer lines, which for solar-type stars are almost totally dependent on the temperature and weakly dependent on gravity and metallicity (Fuhrmann et al. 1993). The surface gravity \(g_*\) was determined by fitting the line profiles of the Ca I lines at 6102, 6122, 6162, and 6439 Å, and the profiles of the Mg I triplet at 5160–5185 Å. Results were then checked by fitting also the line wings of the sodium doublet at 5896 and 5890 Å using a sodium abundance determined from a number of fainter lines. In this case all three ions provided the same value for \(g_*\). Using this method we derived an effective temperature \(T_{\text{eff}} = 5450 \pm 70 \text{ K}\), surface gravity \(\log g_* = 4.35 \pm 0.06\) (cgs), iron content of [Fe/H] = +0.06 ± 0.03 dex, calcium content of [Ca/H] = 0.12 ± 0.05 dex, magnesium [Mg/H] = 0.18 ± 0.10 dex, and sodium [Na/H] = 0.15 ± 0.01 dex. The \(v_{\text{mic}}\) used was 0.9 ± 0.1 km s\(^{-1}\), and we found \(v \sin i_* = 2.2 \pm 0.8 \text{ km s}^{-1}\) and \(v_{\text{mac}} = 2.8 \pm 0.9 \text{ km s}^{-1}\).

In an independent analysis, stellar atmospheric parameters \((T_{\text{eff}}, \log g_*, v_{\text{mic}}, \text{ and [Fe/H]}\) and respective error bars were derived using the methodology described in Sousa (2014) and Santos et al. (2013). Briefly, we made use of the equivalent widths (EWs) of 224 Fe I and 35 Fe II lines, as measured in the combined HARPS spectrum of HD 219666 using the
The last version of the ARES code (ARES v2) can be downloaded at [http://www.astro.up.pt/~sousasag/ares](http://www.astro.up.pt/~sousasag/ares). The two sets of spectroscopic parameters obtained using the two independent methods described above are in good agreement. While we have no reason to prefer one method over the other, in the following analyses we adopted the values derived using the EW method. We stress that the quoted uncertainties are internal error bars that do not account for the choice of spectral lines and/or atmospheric models. Following Sousa et al. (2011), we accounted for systematic effects by quadratically adding 60 K, 0.1 (cgs), and 0.04 dex to the nominal uncertainty of the effective temperature, surface gravity, and iron content, respectively. The adopted values of $T_{\text{eff}} = 5527 \pm 25$ K, $\log g_\star = 4.34 \pm 0.04$ (cgs), $v_{\text{mic}} = 0.90 \pm 0.04$ km s$^{-1}$, and [Fe/H] = 0.04 ± 0.02 dex. The surface gravity corrected for the systematic effects discussed in Mortier et al. (2013) has a value of $\log g_\star = 4.40 \pm 0.04$ (cgs).

Stellar abundances of the elements were also derived using the same tools and models as for stellar parameter determination, as well as using the classical curve-of-growth analysis method, assuming local thermodynamic equilibrium (LTE). Although the EWs of the spectral lines were automatically measured with ARES, for the elements with only two or three lines available we performed careful visual inspection of the EWs. For the derivation of chemical abundances of refractory elements we closely followed the methods described in Adibekyan et al. (2012, 2015) and Delgado Mena et al. (2017). Abundances of the volatile elements O and C were derived following the method of Delgado Mena et al. (2010) and Bertran de Lis et al. (2015). Since the two spectral lines of oxygen are usually weak and the 6300 Å line is blended with Ni and CN lines, the EWs of these lines were manually measured with the task sp101 in IRAF. We noticed that for several individual spectra of the star, the 6300 Å region was contaminated by telluric [OI] emission line. We excluded these contaminated spectra when measuring the EW of the stellar oxygen line at 6300.3 Å.

We derived the stellar radius ($R_\star$) combining the Tycho $B_T$, $V_T$ magnitudes, the Gaia $G$, $G_R$, $G_B$ photometry, and 2MASS $J$, $H$, $K_s$ magnitudes (see Table 1) with our spectroscopic parameters ($T_{\text{eff}}$, $\log g_\star$, [Fe/H]; see Table 2) and the Gaia' parallax (10.590 ± 0.028 mas, Gaia Collaborations 2018, see Table 2). We corrected the Gaia $G$ photometry for the magnitude dependent offset using Eq. (3) from Casagrande & VandenBerg (2018), and adopted a minimum uncertainty of 0.01 mag for the Gaia magnitudes to account for additional systematic uncertainties in the Gaia photometry. We added 0.06 mas to the nominal Gaia’s parallax to account for the systematic offset found by Stassun & Torres (2018), Riess et al. (2018), and Zinn et al. (2018). Following the method described in Gandolfi et al. (2008), we performed careful visual inspection of the EWs. For the derivation of chemical abundances of refractory elements we closely followed the methods described in Adibekyan et al. (2012, 2015) and Delgado Mena et al. (2017). Abundances of the volatile elements O and C were derived following the method of Delgado Mena et al. (2010) and Bertran de Lis et al. (2015). Since the two spectral lines of oxygen are usually weak and the 6300 Å line is blended with Ni and CN lines, the EWs of these lines were manually measured with the task sp101 in IRAF. We noticed that for several individual spectra of the star, the 6300 Å region was contaminated by telluric [OI] emission line. We excluded these contaminated spectra when measuring the EW of the stellar oxygen line at 6300.3 Å. Lithium and sulfur abundances were derived by performing spectral synthesis with MOOG (Delgado Mena et al. 2014). The final abundances of the elements are listed in Table 2. It is worth noting that the abundances of Na, Mg, and Ca derived with this EW method are in agreement with the abundances obtained with the spectral fitting method. Perhaps it is also interesting to note that the star seems to be enhanced in several α elements (Mg, Si, Ti) and show under-abundance of some heavy elements (e.g. Ba and Y). Such a chemical composition is typical for the so-called high-α metal-rich stars first discovered by Adibekyan et al. (2011, 2013). The origin of this population is not yet fully clear, but most probably these stars are migrants from the inner Galaxy (Adibekyan et al. 2011; Anders et al. 2018).

We derived the stellar radius ($R_\star$) combining the Tycho $B_T$, $V_T$ magnitudes, the Gaia $G$, $G_R$, $G_B$ photometry, and 2MASS $J$, $H$, $K_s$ magnitudes (see Table 1) with our spectroscopic parameters ($T_{\text{eff}}$, $\log g_\star$, [Fe/H]; see Table 2) and the Gaia’ parallax (10.590 ± 0.028 mas, Gaia Collaborations 2018, see Table 2). We corrected the Gaia $G$ photometry for the magnitude dependent offset using Eq. (3) from Casagrande & VandenBerg (2018), and adopted a minimum uncertainty of 0.01 mag for the Gaia magnitudes to account for additional systematic uncertainties in the Gaia photometry. We added 0.06 mas to the nominal Gaia’s parallax to account for the systematic offset found by Stassun & Torres (2018), Riess et al. (2018), and Zinn et al. (2018). Following the method described in Gandolfi et al. (2008), we...
Table 4. HD 219666 system parameters.

| Parameter | Prior$^{a}$ | Derived value |
|-----------|-------------|---------------|
| **Model parameters of HD 219666 b** | | |
| Orbital period $P_{\text{orb},b}$ (days) | $\mathcal{U}[6.00, 6.08]$ | 6.03607$^{+0.00064}_{-0.00063}$ |
| Transit epoch $T_{0b}$ (BJD$_{\text{TDB}}$ - 2450000) | $\mathcal{U}[8329.10, 8329.30]$ | 8329.1966$^{+0.0012}_{-0.0012}$ |
| Scaled semi-major axis $a_b/R_*$ | $\mathcal{N}[14.39, 0.30]$ | 13.27$^{+0.39}_{-0.39}$ |
| Planet-to-star radius ratio $R_b/R_*$ | $\mathcal{U}[0, 0.1]$ | 0.04192$^{+0.00083}_{-0.00083}$ |
| Impact parameter $b_0$ | $\mathcal{U}[0, 1]$ | 0.0$^{+0.0}_{-0.0}$ |
| $\sqrt{e} \sin \omega_*$ | $\mathcal{F}[0]$ | 0 |
| $\sqrt{e} \cos \omega_*$ | $\mathcal{F}[0]$ | 0 |
| Radial velocity semi-amplitude variation $K_*$ (m s$^{-1}$) | $\mathcal{U}[0, 10]$ | 6.17$^{+0.46}_{-0.46}$ |

| Additional model parameters | | |
| Parameterized limb-darkening coefficient $q_1$ | $\mathcal{N}[0.34, 0.1]$ | 0.33$^{+0.10}_{-0.10}$ |
| Parameterized limb-darkening coefficient $q_2$ | $\mathcal{N}[0.23, 0.1]$ | 0.20$^{+0.10}_{-0.10}$ |
| Systemic velocity $\gamma_{\text{HARPS}}$ (km s$^{-1}$) | $\mathcal{U}[-20.30, -19.9]$ | $-20.0976^{+0.0004}_{-0.0004}$ |
| RV jitter term $\sigma_{\text{HARPS}}$ (m s$^{-1}$) | $\mathcal{U}[0, 100]$ | 1.04$^{+0.48}_{-0.47}$ |

| Derived parameters of HD 219666 b | | |
| Planet mass $M_b$ ($M_\odot$) | ... | 16.6$^{+1.3}_{-1.3}$ |
| Planet radius $R_b$ ($R_\odot$) | ... | 4.71$^{+0.17}_{-0.17}$ |
| Planet mean density $\rho_b$ (g cm$^{-3}$) | ... | 0.87$^{+0.12}_{-0.11}$ |
| Semi-major axis of the planetary orbit $a_b$ (AU) | ... | 0.06356$^{+0.00265}_{-0.00265}$ |
| Orbit eccentricity $e_b$ | ... | 0 (fixed) |
| Orbit inclination $i_b$ (deg) | ... | 86.38$^{+0.15}_{-0.15}$ |
| Equilibrium temperature $T_{eq,b}$ (K) | ... | 1073$^{+20}_{-20}$ |
| Transit duration $\tau_{14,b}$ (h) | ... | 2.158$^{+0.034}_{-0.034}$ |

Notes. ($^a$) $\mathcal{U}(a, b)$ refers to uniform priors between $a$ and $b$, and $\mathcal{F}[a]$ to a fixed $a$ value. ($^b$) Assuming zero albedo and uniform redistribution of heat.

5. Joint analysis of the transit and Doppler data

We performed a joint fit to the TESS light curve (Sect. 2) and the 21 HARPS measurements (Sect. 3) using the code pynesi (Barragán et al. 2019). The code uses a Bayesian approach for the model parameter estimations, and samples the posteriors via Markov chain Monte Carlo (MCMC) methods.

We selected 10 h of photometric data-points centred around each of the four transits observed by TESS and flattened the four segments using a second-order polynomial fitted to the out-of-transit data. We fitted the transit light curves using the limb-darkened quadratic model of Mandel & Agol (2002). We set Gaussian priors on the limb-darkening coefficients adopting the theoretical values predicted by Claret (2017) along with a conservative error bar of 0.1 for both the linear and the quadratic limb-darkening term. The transit light curve poorly constrains the scaled semi-major axis ($a/R_*$). We therefore set a Gaussian prior on $a/R_*$ using the orbital period and the derived stellar parameters (Sect. 4) via Kepler’s third law.

The RV model consists of a Keplerian equation. Following Anderson et al. (2011), we fitted for $\sqrt{e} \sin \omega_*$ and $\sqrt{e} \cos \omega_*$, where $e$ is the eccentricity and $\omega_*$ is the argument of periastron. We also fitted for an RV jitter term to account for instrumental noise not included in the nominal uncertainties, and/or for RV variations induced by stellar activity. We imposed uniform priors for the remaining fitted parameters. Details of the fitted parameters and prior ranges are given in Table 4.

We used 500 independent Markov chains initialized randomly inside the prior ranges. Once all chains converged, we used the last 5000 iterations and saved the chain states every ten iterations. This approach generates a posterior distribution of 250000 points for each fitted parameter. Table 4 lists the inferred planetary parameters. They are defined as the median and 68% region of the credible interval of the posterior distributions for each fitted parameter. The transit and RV curves are shown in Figs. 4 and 5, respectively.

An initial fit for an eccentric orbit yielded $e = 0.07^{+0.06}_{-0.05}$, which is consistent with zero within less than 2$\sigma$. We determined found that the reddening along the line of sight to the star is consistent with zero and did not correct the apparent magnitudes. The bolometric correction for each band-pass was computed using the routine from Casagrande & VandenBerg (2018). We determined a stellar radius of $R_\star = 1.03 \pm 0.03 R_\odot$.

We used the Bayesian STellar Algorithm (BASTA, Silva Aguirre et al. 2015) to determine a stellar mass of $M_\star = 0.92 \pm 0.03 M_\odot$ and an age of $\tau_\star = 10 \pm 2$ Gyr by fitting the stellar radius $R_\star$, effective temperature $T_\text{eff}$ and iron abundance [Fe/H] to a large, finely-sampled grid of GARSTEC stellar models (Weiss & Schlattl 2008).

From the Ca II H and K S-index values provided by the HARPS DRS, we calculated $\log R'_{\text{HK}} = -5.07 \pm 0.03$ (Lovis et al. 2011). Using the activity-rotation empirical relationships reported in Noyes et al. (1984) and Mamajek & Hillenbrand (2008), we derived a stellar rotation period of $P_{\text{rot}} = 34 \pm 6$ and $37 \pm 4$ days respectively, which are in good mutual agreement. An upper limit to $P_{\text{rot}}$ of $22^{+13}_{-7}$ days can be inferred from the stellar radius and $\nu \sin i_\star$, which is compatible with good alignment between the stellar rotation axis and the planetary orbital axis. We note that the 27.9 day duration of the TESS observations is not long enough to attempt a reliable estimation of the photometric stellar rotational period.
the probability that the best-fitting eccentric solution could have arisen by chance if the orbit were actually circular using Monte Carlo simulations. Briefly, we created $10^3$ sets of synthetic RVs that sample the best-fitting circular solution at the epochs of our observations. We added Gaussian noise at the level of our measurements and fitted the simulated data allowing for an eccentric solution. We found that, given our measurements, there is a 35% probability that an eccentric solution with $e \geq 0.07$ could have arisen by chance if the orbit were actually circular. As this is above the 5% significance level suggested by Lucy & Sweeney (1971), we decided to conservatively assume a circular model. We note that the eccentric solution provides a planetary mass that is consistent within less than 1-$\sigma$ of the result from the circular model.

6. Discussion and conclusion

HD 219666 b has almost the same mass as Neptune ($M_p = 16.6 \pm 1.3 \, M_\oplus$) but a larger radius ($R_p = 4.71 \pm 0.17 \, R_\oplus$). With an orbital period of $P_{orb} = 6$ days and an equilibrium temperature of $T_{eq} = 1073$ K, it is a new member of a relatively rare class of exoplanets: the hot-Neptunes. Figure 6 shows that HD 219666 b lies in a region of the mass–radius diagram that is scarcely populated. The comparison with rocky planets composition models (Zeng et al. 2016) suggests that HD 219666 b holds a conspicuous gas envelope.

The existence of a hot-Neptunes “desert” has already been pointed out (see, e.g. Szabó & Kiss 2011; Mazeh et al. 2016; Owen & Lai 2018), and HD 219666 b falls close to the lower edge of the desert in the mass–period diagram (see Fig. 1 in Mazeh et al. 2016), and well inside the desert in the radius–period diagram (see Fig. 7). The relative paucity of hot-Neptunes (as compared to hot super-Earths and hot-Jupiters) could be interpreted as a consequence of two different formation mechanisms for short-period planets: in situ formation for terrestrial planets (Ogihara et al. 2018; Matsumoto & Kokubo 2017), and formation at larger separations followed by inward migration for giant planets (Nelson et al. 2017). Intermediate-mass planets like HD 219666 b would then be either the upper tail of terrestrial planets or the lower tail of giant-planet distributions. Alternatively, giant and small close-in planets could have a common origin but a dramatically different atmospheric escape history (Lundkvist et al. 2016; Ionov et al. 2018; Owen & Lai 2018). Other mechanisms have been proposed to explain the observed hot-Neptune desert. Mataksos & Königl (2016) advanced an explanation based on high-eccentricity migration followed by tidal circularization. They interpreted the two distinct segments of the desert boundary as a consequence of the different slopes of the empirical mass-radius relation for small and large planets. Batygin et al. (2016) advocated the in situ formation of close-in super-Earths and hot-Jupiters alike. In the rare cases when a core mass of $M_{core} \geq 15 \, M_\oplus$ was reached, rapid gas accretion would lead to the formation of a gaseous giant planet. In this way the relative occurrence of Earth-like, Neptune- and Jupiter-like close-in planets can be explained.

To determine whether or not in-situ formation of a planet so close to its star is even possible, we calculate the isolation mass of a planet orbiting with a period of 6 days around a 0.9 $M_\odot$ star. This is the mass of the planet that can form assuming that it grows by consuming all the planetesimals that are within its
is a good assumption because the host star has a mass close to solar and appears to be rather inactive and old. We obtained a hydrogen mass-loss rate of about \( \approx 1 \times 10^{-9} \text{ g s}^{-1} \), which is comparable to what is obtained employing the energy-limited formula \((5.2 \times 10^{6} \text{ g s}^{-1}) \) \cite{Erkaev2007}. This indicates that, for this planet, atmospheric expansion and mass loss are driven mostly by atmospheric heating due to absorption of the stellar XUV flux, with an additional component due to the intrinsic thermal energy of the atmosphere and low planetary gravity \cite{Fossati2017}. The obtained mass-loss rate corresponds to 0.06 \( M_{\odot} \text{Gyr}^{-1} \), suggesting that mass loss does not play a major role in the current evolution of the planetary atmosphere. However, this does not account for the fact that the star was probably more active in the past, particularly during the first few hundred million years, up to about 1 Gyr \cite{Jackson2012, Tu2015}, when the XUV fluxes could have been up to 500 times larger than the current estimate. This would lead to mass-loss rates about 500 times higher. It is therefore likely that atmospheric escape played a significant role in shaping the early planetary atmospheric evolution.

HD 219666 b is an interesting target for further atmospheric characterisation, given its equilibrium temperature of \( \approx 1070 \text{ K} \), since the range of expected temperatures at the terminator (depending on the planet’s albedo and energy transport) straddles the modelled transmission spectrum of the planet using the Python Radiative Transfer in a Bayesian framework (\cite{Cubillos2017}, in prep.), which is based on the Bayesian Atmospheric Radiative Transfer package \cite{Blecic2016, Cubillos2016}, and simulated James Webb Space Telescope (JWST) observations with Pandexo \cite{Batalha2017}. These models consider opacities from the main spectroscopically active species expected for exoplanets at these wavelengths: \( \text{H}_{2} \text{O} \) and \( \text{CO} \) from \cite{Rothenflug2010}, \( \text{CH}_{4} \), \( \text{NH}_{3} \), and \( \text{HCN} \) from \cite{Yurchenko2014}; \( \text{CO} \) from \cite{Li2015}, Na and K from \cite{Burrows2000}; Rayleigh opacities from H, He, and \( \text{H}_{2} \) \cite{Kurucz1970, Leavelier2014}; and \( \text{H}^{+} \text{He}^{2+} \) \cite{Borysow1988, Borysow1989, Borysow1991}. We compressed the HITEMP and ExoMol databases with the open-source repack package \cite{Cubillos2017} to extract only the strong, dominating line transitions.

Figure 8 shows estimated transmission spectra of HD 219666 b assuming a cloud-free atmosphere, in thermochemical equilibrium \cite{Blecic2016} for solar elemental composition, at two illustrative atmospheric temperatures that lead to different transmission spectra. By combining NIRISS SOSS and NIRSpec G395H observations, one could potentially constrain the atmospheric chemistry and temperature of the planet with a single-transit observation with each instrument. The transmission spectrum at wavelengths shorter than 2 \( \mu \text{m} \) constrain the \( \text{H}_{2} \text{O} \) abundance for both models, setting the baseline to constrain the abundances of other species. At longer wavelengths, either \( \text{CH}_{4} \) (\( T = 600 \text{ K} \) model) or \( \text{CO}/\text{CO}_{2} \) (\( T = 1000 \text{ K} \) model) dominate the carbon chemistry at the probed altitudes (Fig. 8, bottom panels), producing widely different features in the transmission spectrum (Fig. 8, top panel).

An important clue to the formation mechanism of HD 219666 b could come from the knowledge of its orbital inclivity with respect to the stellar equatorial plane, which can be estimated through the observation of the Rossiter–McLaughlin
Fig. 8. Model transmission spectra of HD 219666 b (top panel). The dots and error bars denote simulated single-transit JWST transmission observations with NIRISS SOSS and NIRSpec G395H (wavelength coverage at bottom) for two underlying models (solid curves) at temperatures of 600 and 1000 K (see legend). CH$_4$ shows strong absorption bands at 1.7, 2.3, and 3.3 µm in the 600 K model; whereas CO and CO$_2$ show their strongest absorption features at wavelengths beyond 4 µm in the 1000 K model. Bottom panels: composition of the main species that shape the transmission spectrum. Depending on the atmospheric temperature, carbon favours either higher CH$_4$ (temperatures lower than ~900 K) or CO/CO$_2$ abundances (otherwise).

(RM) effect. We calculated that the RV amplitude of the RM effect is of ~3 m s$^{-1}$, meaning that it would probably be detectable with HARPS, and certainly with ESPRESSO (Pepe et al. 2010). Remarkably, there are only two hot-Neptunes with a reported measure of the orbital obliquity, GJ 436 b (Bourrier et al. 2018) and HAT-P-11 b (Winn et al. 2010), and both have a misaligned orbit.

Given the precise RV measurements from HARPS and the mid-transit time from the TESS mission, we can also constrain the presence of co-orbital planets (or trojans) to HD 219666 b, by putting upper limits to their mass $M_t$ (assuming there are no other planets in the system or they are far enough to not perturb the RVs in the time span of our observations). We followed the technique described in Leleu et al. (2017), and subsequently applied in Lillo-Box et al. (2018a,b), to model the RV data by including the so-called $\alpha$ parameter, which accounts for the possible mass imbalance between the L4 and L5 regions in the co-orbital region of the planet. The parameter $\alpha$ is defined as $M_t/M_0 \sin \theta + O(e^2)$, where $\theta$ is the resonant angle representing the difference between the mean longitudes of the trojan and the planet. We set Gaussian priors on the time of transit and period of the planet, and left the rest of the parameters (i.e. $e \cos \omega$, $e \sin \omega$, $\alpha$, $\gamma$, and $K_p$) with uniform broad priors. We also included a slope term and a jitter term to account for white noise. The result of this analysis provides parameters compatible with the prior joint analysis and allows us to set constraints on co-orbital planets in the system. In particular, we find $\alpha = -0.14 \pm 0.22$, which assuming the estimated planet mass provides an upper limit (95% confidence level) of $M_t = 4.6 M_{\oplus}$ at L5 and no constraint (i.e. up to the mass of the planet) at L4.

In conclusion, we report the discovery of a hot-Neptune transiting the bright ($V = 9.9$) G7 V star HD 219666. The collaboration between the RESPRINT and NCORES consortia has made possible a rapid spectroscopic follow-up with HARPS, leading to the confirmation and characterisation of the planet candidate detected by TESS. HD 219666 b adds to a list of only five Neptune-like planets ($0.5 < M_p < 2 M_{\text{Nep}}$ with $1 M_{\text{Nep}} = 17.2 M_{\oplus}$) transiting a V $< 10$ star. We carried out detailed analyses to derive the fundamental parameters and the elemental abundances of the host star. We discuss the possibility of further characterisation of the planet, in particular by examining the potential of JWST in-transit observations to detect the presence of molecular features in transmission spectra.

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