An ultra-short-period transiting super-Earth orbiting the M3 dwarf TOI-1685

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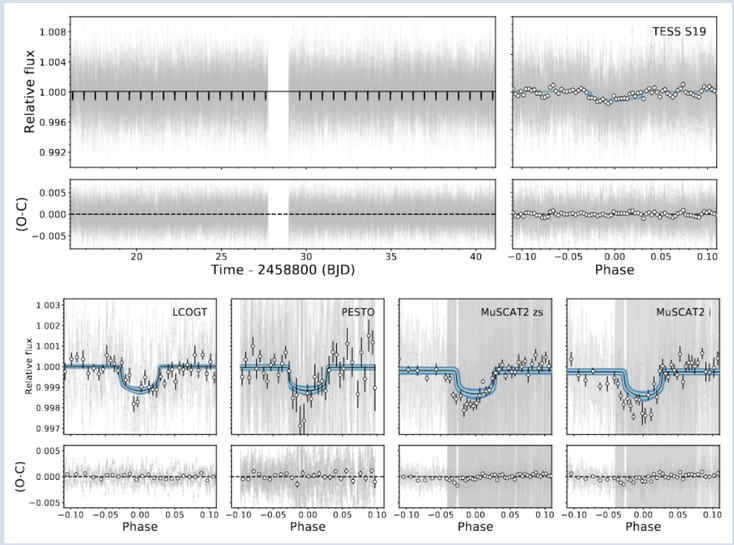
ABSTRACT

Dynamical histories of planetary systems, as well as the atmospheric evolution of highly irradiated planets, can be studied by characterizing the ultra-short-period planet population, which the TESS mission is particularly well suited to discover. Here, we report on the follow-up of a transit signal detected in the TESS sector 19 photometric time series of the M3.0 V star TOI-1685. We confirm the planetary nature of the transit signal, which has a period of **P_b = 0.6691403+0.0000023−0.0000021 d**, using precise radial velocity measurements taken with the CARMENES spectrograph. From the joint photometry and radial velocity analysis, we estimate the following parameters for TOI-1685 b: A mass of **M_b = 3.78±0.63 $M_\oplus$**, a radius of **R_b = 1.70±0.07 $R_\oplus$**, which together result in a bulk density of **ρ_b = 4.21+0.95−0.82 gcm^{-3}**, and an equilibrium temperature of **Teq = 1069±16 K**. TOI-1685 b is the least dense ultra-short-period planet around an M dwarf known to date. TOI-1685 b is also one of the hottest transiting super-Earth planets with accurate dynamical mass measurements, which makes it a particularly attractive target for thermal emission spectroscopy. Additionally, we report with moderate evidence an additional non-transiting planet candidate in the system, TOI-1685 [c], which has an orbitalperiod of P_c = 9.02+0.10−0.12 d

Data

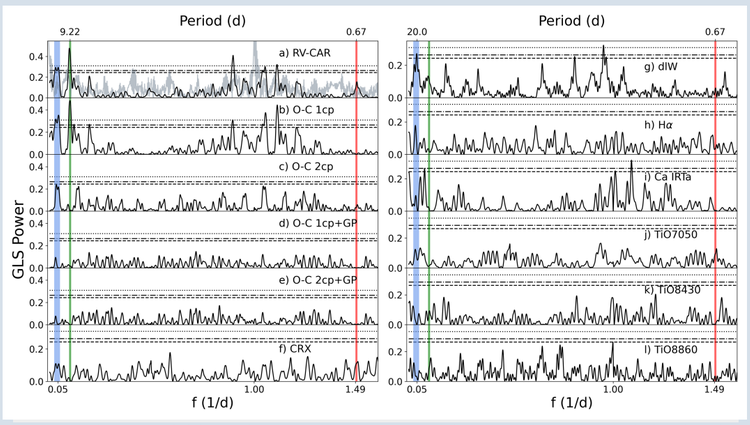
TOI-1685 (TIC 28900646) was observed by **TESS** in 2 min short-cadence integrations during cycle 2 in sector 19. Additionally, we used ground-based photometry from **MuSCAT2**, **LCOGT**, and **PESTO** cameras, and we collected radial velocities using the **CARMENES** high-resolution spectrograph.



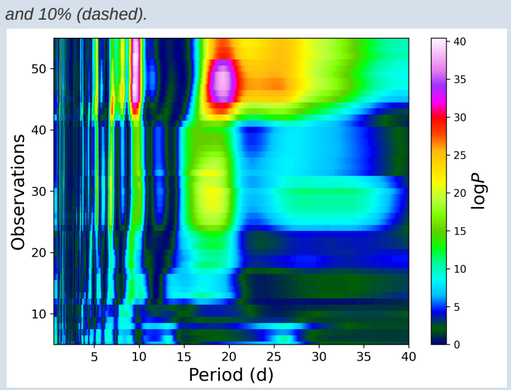
Upper panels: PDCSAP light curve TESS of TOI-1685 and the corresponding phase-folded light curve. Lower panels: phase-folded light curves of LCOGT, PESTO, and MuSCAT2 in filter i and z_s of TOI-1685. For all phase-folded light curves the residuals are shown for the USP found in the system. White circles are binned data (shown only for reference; data used to fit the model were the unbinned points). Black curves are the best-fit models, and light and dark blue areas are the 68% and 95% credibility bands. The different sizes of the MuSCAT2 error bars correspond to the two observing night.

Signals in spectroscopic data

We explored the generalized Lomb-Scargle (GLS) periodograms of the RVs and the activity indices of TOI-1685. The periodogram and window function are shown in panel **(a)**. The strongest signal was found at ∼ 9 d, with a nominal false alarm probability (FAP) 1% and its aliases around periods of one day (due to the sampling of the data). A double peak is visible in the period range of ∼ 19-26 d with FAP ≤ 5%, while a small, isolated peak is discernible at the orbital frequency of TOI-1685 b. The formal FAP for this feature is ≥ 10%.



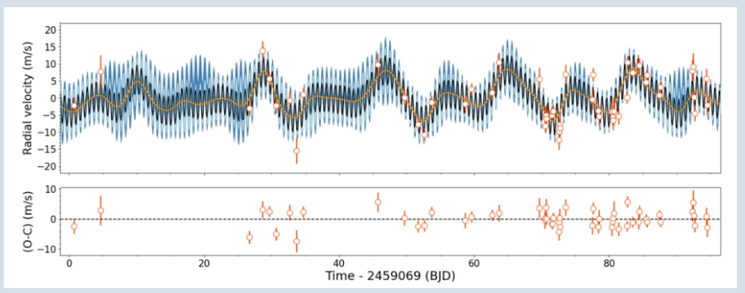
*GLS periodograms of: **(a)** RVs from CARMENES VIS and the respective spectral window function (gray), **(b)** RV residuals after subtracting the 1-planet signal, **(c)** RV residuals after subtracting the 2-planet signal, **(d)** RV residuals after subtracting the 1-planet signal plus GP, **(e)** RV residuals after subtracting the 2-planet signal plus GP. The "cp" in the residual models corresponds to circular orbits. **(f)** - **(l)** CRX, dLW, Hα, CaIRTa, TiO7050, TiO8430, and TiO8860 activity index from CARMENES VIS data. In all panels the vertical lines indicate the periods of 0.67 d (red, USP), and, ∼9 d (green, second planet candidate). The rotational period of the star (blue line) falls in the region between ∼19-26 d. The horizontal lines mark the theoretical FAP levels of 1% (dotted), 5% (dash-dotted), and 10% (dashed).*



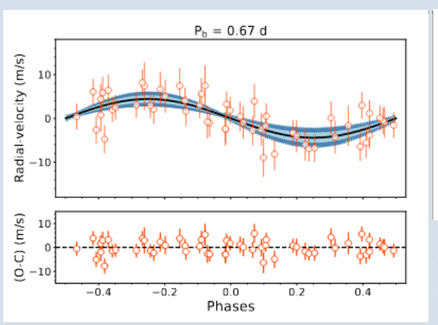
sBGLS: We used the stacked Bayesian generalized Lomb-Scargle periodogram to verify whether the 20.6 d signal was coherent over the whole observational time baseline of CARMENES VIS. We display s-BGLS periodograms of the raw RV data around 0.5 d and 40 d, after subtracting the USP signal. The planet candidate is at∼9 d and the activity signal related to the rotational period is visible around 19 d. This signal related to the activity showed a first probability maximum after around 44 observations and thereafter decreased for some time. This incoherence is characteristic of a nonplanetary origin of the signal. On the other hand, the∼9 d signal showed a monotonically increasing probability, as expected for a Keplerian signal.

Modeling results

In order to obtain precise parameters of the TOI-1685 system, we performed a joint analysis with **juliet** (Espinoza et al. 2019). For the joint fit we used TESS, LCOGT, PESTO, MuSCAT2, and CARMENES VIS data. We performed a simultaneous fit to a one-planet circular model together with a GP (1cp+GP). We selected our GP around the suspected stellar rotational period centered at ∼19 d. As we discuss, the ∼9 d signal does not seem to be related to the ∼19 d rotational period of TOI-1685, could be due to a second (non-transiting) planet in the system. We explore the possibility of include the ∼9 d signal with a 2cp+GP model. The residuals of these two fits are shown in panel **(d)** and **(e)** of the GLS periodogram.



RV Model:: Radial velocity data from CARMENES (red). The gray curve is the median best-fit Keplerian juliet model, the light and dark blue areas are its 68% and 95% credibility bands, and the orange curve is the quasi-periodic kernel (QP-GP).

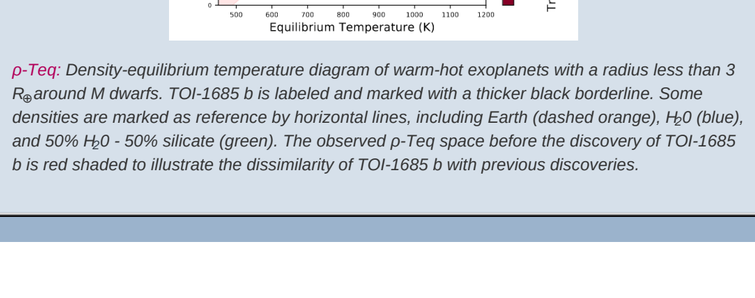


Derived physical parameters	
M_b ($M_\oplus$)	$3.78^{+0.63}_{-0.63}$
R_b ($R_\oplus$)	$1.70^{+0.07}_{-0.07}$
ρ_b (g cm^{-3})	$4.21^{+0.95}_{-0.82}$
g_b (m s^{-2})	$12.79^{+2.49}_{-2.28}$
$T_{eq,b}$ (K)$^{(b)}$	1069^{+16}_{-16}
S_b ($S_\oplus$)	217^{+13}_{-13}

Phase-folded RV curve and their residuals of the USP. Black curve is the best-fit model and blue areas are the 68% and 95% credibility bands.

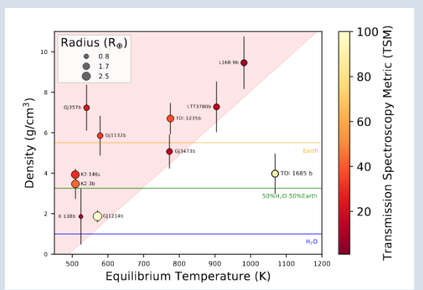
6-Discussion and Conclusions

We present the discovery of the ultra-short-period planet TOI-1685 b, which orbits its host star with a period of 0.669 d. To confirm the planetary nature of the TESS transiting candidate we obtained high resolution spectra using the CARMENES spectrograph.
A comparison of the physical properties of TOI-1685 b with compositional models from Zeng et al. (2016, 2019) is consistent with a bulk composition of 50% H_20 - 50% silicate. In terms of separation from its host star (a ∼ 0.012 AU), TOI-1685 b is one of the closest known planets with a mass determination. An insolation flux of S = 217±13 $S_\oplus$ makes TOI-1685 b one of the hottest transiting super-Earth discovered to date. TOI-1685 b is the third known USP to be found orbiting an M star, and the least dense of the three.



Left: Mass-radius diagram in Earth units. Open circles are transiting planets around M-dwarf stars from the TEPCat database planets (Southworth 2011) and (Martínes-Rodríguez et al. 2019), blue-filled circles are USPs, and the filled star symbol is TOI-1685 b. Right: Density-radius diagram for all known exoplanets with planet bulk density ρ ≤ 15 gcm^{-3} and radius R ≤ 4 $R_\oplus$(gray) from the NASA exoplanet archive. USPs are drawn in black including the error bars of the measurements. Blue-filled circles mark USPs around M dwarfs, and the filled star symbol is TOI-1685 b.

The measured values for the transmission spectroscopy metric (TSM) and the emission spectroscopy metric (ESM) metrics qualify this planet for atmospheric characterization through emission and transmission spectroscopy, as well as make it an interesting planet for studying atmospheric evolution and escape processes.



ρ-Teq: Density-equilibrium temperature diagram of warm-hot exoplanets with a radius less than 3 $R_\oplus$around M dwarfs. TOI-1685 b is labeled and marked with a thicker black borderline. Some densities are marked as reference by horizontal lines, including Earth (dashed orange), H_20 (blue), and 50% H_20 - 50% silicate (green). The observed ρ-Teq space before the discovery of TOI-1685 b is red shaded to illustrate the dissimilarity of TOI-1685 b with previous discoveries.