Lava worlds are cool: two new ultra-short-period planets discovered by TESS

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What are ultra-short-period planets?

Ultra-short-period (USP) planets are defined by the community as planetary-mass objects with orbital periods shorter than one day [1]. Of the current full sample of approximately 5500 confirmed exoplanets, only 130 are USP planets and around 40 have mass and radius measurements. Owing to their short planet-to-star distance, they experience levels of irradiation on the order of hundreds or thousands of times stronger than Earth's, and are thus subject to extreme temperatures. These planets typically have small sizes, with planetary radii up to $R_p < 2\ R_\oplus$ [2], and appear to have mostly Earth-like compositions [3]. The formation pathway of USP planets is still unknown. Because of the high irradiation levels they experience, USP planets typically lie within the region where dust is sublimated, which means that they probably had to form farther away from their current orbit. Proposed formation mechanisms include photo-evaporation of sub-Neptune planets and migration of rocky planets.

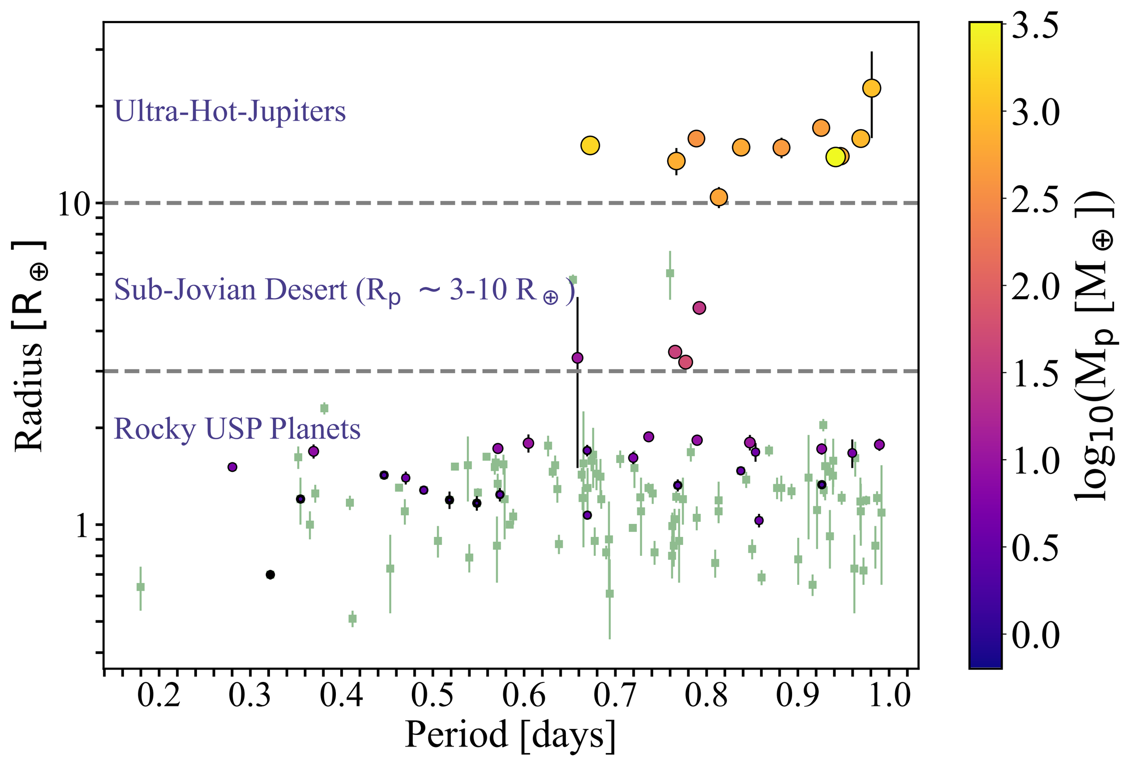

Figure 1. Orbital period versus radius diagram for USP planets. Confirmed planets with only radius measurements are shown with green squares, and planets with mass and radius values are shown with circles. The color and size of the circles represent the mass of the planet. Data taken from NASA Exoplanet Archive.

Highly irradiated rocky USP planets may offer a unique opportunity to study the surface and internal composition of exoplanets with current instrumentation. Planets with surface temperatures above ~1100 K will probably have large molten regions since this temperature range marks the melting point of rocks for Earth-like compositions [4]. Although USP rocky planets probably lose their primordial atmospheres in the early stages of their formation owing to the effects of the stellar activity and winds of their host star, some volatile elements associated with the magma oceans located in the planet's dayside may be detected in emission [5, 6].

Why study USP planets?

The formation history of small, rocky USP planets is not well understood. To further improve our understanding of the formation and evolution of USP planets, it is important to increase the sample of this type of object with accurately measured radii and masses. By studying USP planets, we can learn about:

- **Planetary systems architecture and migration** Rocky USP planets tend to be found in multi-planet systems. Many theories of USP formation require the presence of additional planets to allow for migration. USP planets can provide a laboratory for testing planetary migration theories.
- **Detection of secondary atmospheres** Small USP planets are expected to have lost their primary atmospheres. However, they could produce a secondary atmosphere through their lava oceans and volcanism; these atmospheres may be detectable in emission. The study of these atmospheres can give us insight into the internal composition of exoplanets and allow comparative studies with the rocky planets of our Solar System.

At the IAC we have started a program to measure the masses of the USP transiting planet candidates found by NASA's TESS mission. We are using the high resolution spectrographs HARPS-N (on the 3.6 m TNG) and CARMENES (on the 3.5 m CAHA) to obtain high precision radial velocity time series of the planet candidates.

Check the papers!

You can scan the QR codes to read the papers on the mass measurements of two new ultra-short-period planets discovered by TESS.

(a) HD 20329b (b) Wolf 327b

HD 20329b: a rocky USP planet around G-type star

HD 20329 (TIC 333657795, TOI 4524) is a G5 star with $M_\star = 0.90 \pm 0.05$ $M_\odot$, $R_\star = 1.13 \pm 0.02$ $R_\odot$, and $T_{eff} = 5596 \pm 50$ K. We analyzed data from TESS sectors 42 and 43 for the star HD 20329. The planet candidate has a period of $P = 0.926$ days and a transit depth of 210 ± 0.60 ppm. Between 29 November 2021 (UT) and 30 January 2022 (UT), we collected 120 spectra with HARPS-N; the exposure time was set to 259–1800 seconds.

To obtain the planetary mass and radius, we fit the light curves and radial velocity measurements simultaneously.

Planet parameters and composition

We determined that HD 20329b has a radius of $R_p = 1.72 \pm 0.07$ $R_\oplus$, a mass of $M_p = 7.42 \pm 1.09$ $M_\oplus$, and a bulk density of $\rho_p = 8.06 \pm 1.53$ g cm^{-3}. Assuming a Bond albedo of 0.3, we find that this planet has an equilibrium temperature of $T_{eq} = 1958 \pm 25$ K.

Parameter	Value
R_p/R_*	$0.0139^{+0.0005}_{-0.0005}$
P [days]	$0.926118^{+0.000050}_{-0.000043}$
T_c [BJD]	$2459472.14321^{+0.00082}_{-0.00075}$
K [m/s]	$5.07^{+0.41}_{-0.42}$
R_p [$R_\oplus$]	1.72 ± 0.07
M_p [$M_\oplus$]	7.42 ± 1.09
ρ_p [g cm^{-3}]	8.06 ± 1.53
g_p [m s^{-2}]	24.7 ± 4.1
a [au]	0.0180 ± 0.0003
T_{eq} ($A_B = 0.3$) [K]	1958 ± 25
S_p [$S_\oplus$]	3474 ± 124

Table 1. HD 20329b fitted and derived parameters.

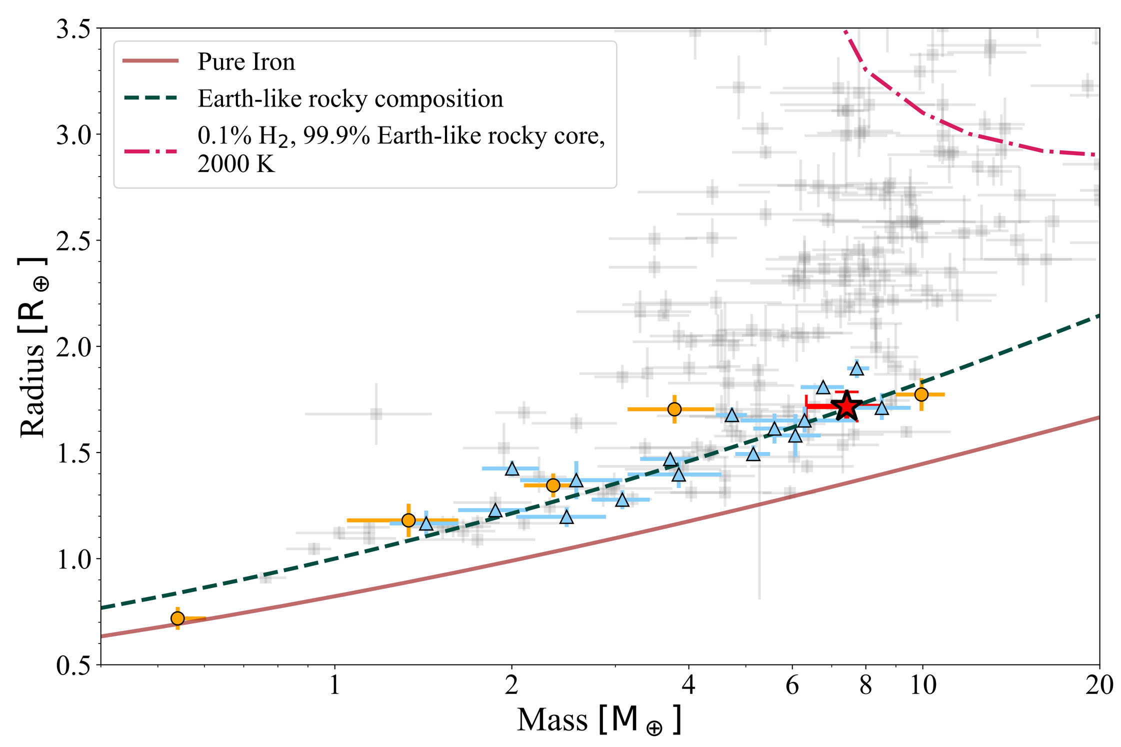

Figure 2. Mass-radius diagram for transiting planets with mass determinations with a precision better than 30% (parameters taken from the TEPcat database [7]). The position of HD 20329b is shown by the red star, USP planets orbiting M-type stars ($T_{eff} \leq 4000$ K) are marked with the orange circles, USP planets around stars with $T_{eff} > 4000$ K are represented by blue triangles, and non-USP planets around other types of stars are marked by gray squares.

Figure 2 shows the mass – radius distribution for known transiting planets. We show the rocky planet models of [8, 9] with an equilibrium temperature of 2000 K. The composition models shown in Fig. 2 are planets with pure iron cores, Earth-like rocky compositions, and Earth-like composition planet cores with H_2 gaseous envelopes. The position of HD 20329b in the mass-radius diagram agrees with other known USP planets with radii smaller than 2.0 $R_\oplus$, and it most likely indicates a rocky composition with little to no atmosphere.

Prospects for atmospheric characterization

We find a transmission spectroscopy metric (TSM) value of 45.7 and an emission spectroscopy metric ESM = 10.2 [10]. We used a simple phase-curve model including reflected light and thermal emission to search for the secondary transit and phase variations in *TESS* light curves. Our results support the existence of a significant, although not conclusive, eclipse signal in the *TESS* data, with a dayside flux ratio of 11% and a relatively strong planetary emission signal. Our modeling indicates a brightness temperature of ~3500 K for low geometric albedo values ($A_g < 0.25$) and an upper limit on the brightness temperature of ~4000 K over the range $A_g \in [0, 1]$.

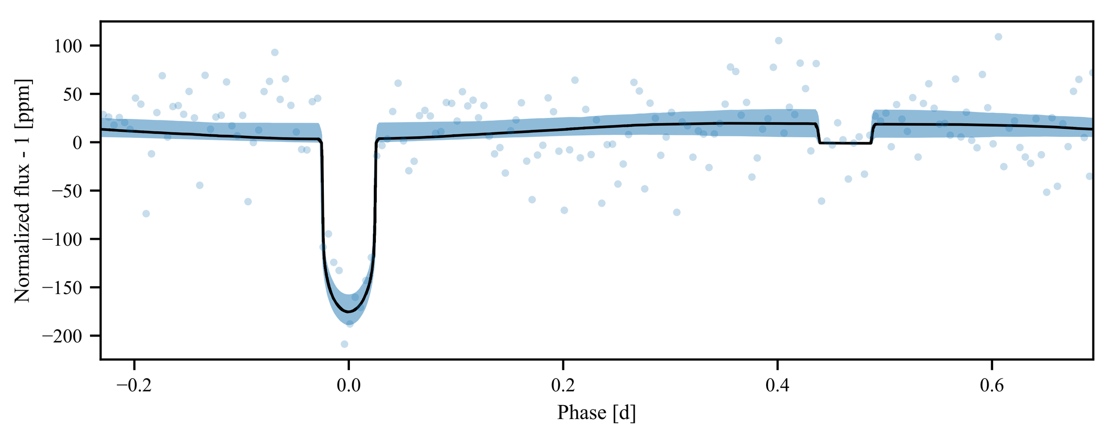

Figure 3. TESS binned observations from sectors 42 and 43 folded over the orbital phase (in days) with the median posterior phase-curve model (black line) and its 1σ uncertainty levels (blue shading).The eclipse is modeled assuming a uniform stellar disk with a depth scaled from 0 (eclipse) to 1 (out of eclipse).

Wolf 327b: a USP super-Earth around an M dwarf

Wolf 327 (TIC 4918918, TOI 5747) is an M2.5 V dwarf with an effective temperature of $T_{eff} = 3542 \pm 70$ K, and a stellar mass and radius of $M_\star = 0.405 \pm 0.019$ $M_\odot$ and $R_\star = 0.406 \pm 0.015$ $R_\odot$, respectively. We have analyzed TESS PDCSAP photometry of Wolf 327 from sectors 21 and 48, both taken with a 2-minute cadence, and ground-based observations taken with the LCOGT 1m and MuSCAT3 2m telescopes. We collected a total of 22 CARMENES spectra from 6 January 2023 to 6 February 2023, covering a time baseline of 31 d. The exposure time used to acquire the spectra was 1800 s. All the data were fitted together.

Planet parameters and composition

We find that Wolf 327b has a radius of $R_p = 1.24 \pm 0.06$ $R_\oplus$ and a mass of $M_p = 2.53 \pm 0.46$ $M_\oplus$. This planet orbits its host star with a period of $P = 0.57347$ d (13.76 h) and has an equilibrium temperature of $T_{eq} = 996 \pm 22$ K.

Parameter	Value
R_p/R_*	0.0280 ± 0.0007
P [days]	0.5734745 ± 0.0000003
T_c [BJD]	2459252.9811 ± 0.0003
K [m/s]	$3.54^{+0.61}_{-0.62}$
R_p [$R_\oplus$]	1.24 ± 0.06
M_p [$M_\oplus$]	2.53 ± 0.46
ρ_p [g cm^{-3}]	7.24 ± 1.66
g_p [m s^{-2}]	16.0 ± 3.3
a [au]	0.0100 ± 0.0004
T_{eq} ($A_B = 0.3$) [K]	996 ± 22
S_p [$S_\oplus$]	233.9 ± 18.3

Table 2. Wolf 327b fitted and derived parameters.

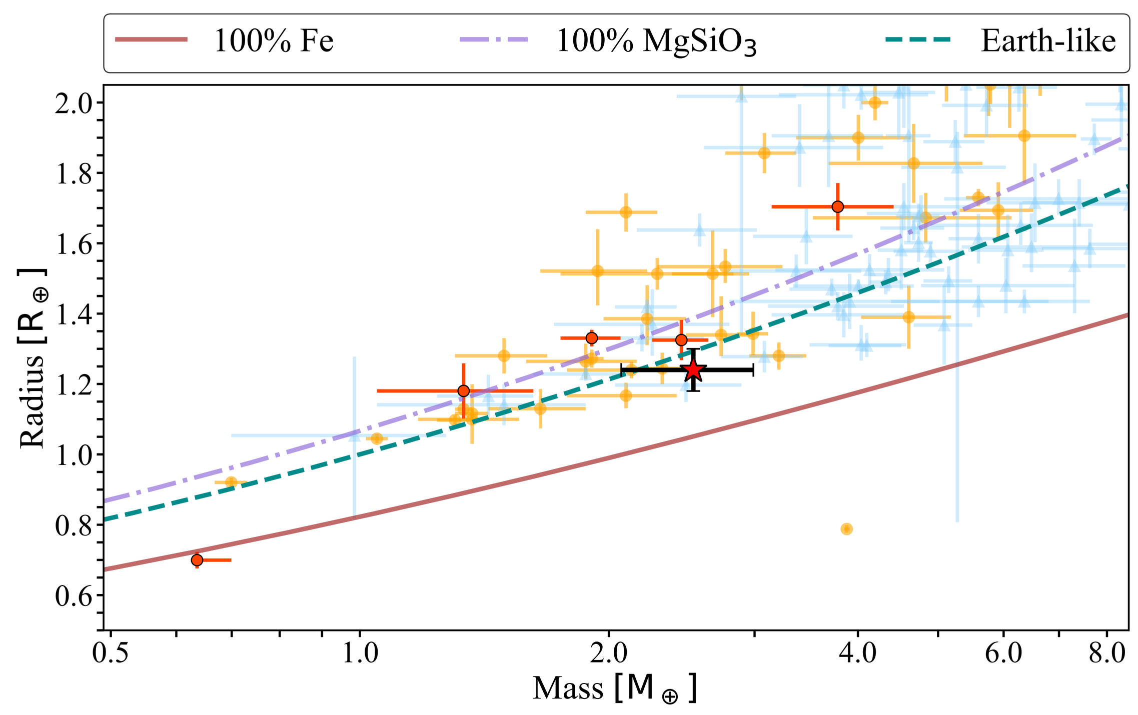

Figure 4. Mass–radius diagram for Wolf 327b (red star) and known transiting planets with mass determinations with a precision better than 30% (parameters taken from the TEPcat database). Planets orbiting M-type stars ($T_{eff} \leq 4000$ K) are marked with circles, orange indicate planets with periods $P > 1$ d, and red circles indicate USP planets ($P \leq 1$ d) around M dwarfs. The lines in the mass–radius diagram represent the composition models of [8, 9] for planets with pure iron cores (100% Fe, solid brown line), Earth-like rocky compositions (32.5% Fe plus 67.5% $MgSiO_3$, dashed green line) and pure rock (100% $MgSiO_3$, dash-dotted purple line).

Planet interior and prospects for atmospheric characterization

We utilized `ExoMDN` [11] to model the interior of Wolf 327b. The interior model predicts that the planet is dominated in terms of layer size and mass fraction by a large planetary iron core; Wolf 327b's core could take up as much as 78% of the planet's size and 93% of its mass. For the other layers the model predicts a relatively small mantle, and a negligible fraction of water and gas layers.

For Wolf 327b we find a TSM of 13, which marks this planet as a potential candidate for future transmission spectroscopy studies. As for the possibility of eclipse detection, we find an ESM of 12.5; the recommended ESM threshold for rocky planets is of 7.5 which indicates that this planet is also a good candidate for eclipse spectroscopy with JWST.

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