Note: the illustration of the TOI-431 system is, well, illustrative! The distances are approximately to scale, and the planets are to approximately to scale relative to each other, but not to the star or the distance scale.

TOI-431: A SUPER-EARTH AND SUB-NEPTUNE TRANSITING A BRIGHT, EARLY K DWARF, WITH AN ADDITIONAL RV PLANET CANDIDATE

TOI-431b:
the ultra-short period super-Earth

TOI-431d:
the gaseous sub-Neptune

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TOI-431c:
the additional RV planet

Abstract

- ★ We present the bright multi-planet system TOI-431, characterized with photometry from TESS, LCOGT, Spitzer telescopes, and NGTS, and HARPS, iSHELL, FEROS and MINERVA-Australis radial velocities.
  - ★ **TOI-431b:** a super-Earth with P = 0.49 d, R = 1.28 R_E, M = 2.96 M_E, and a density = 7.70 gcm^{-3}.
  - ★ **TOI-431c:** discovered in the HARPS RVs and not seen to transit, with P = 4.85 d and Msini = 2.90 M_E.
  - ★ **TOI-431d:** a sub-Neptune with P = 12.46 d, R = 3.29 R_E, M = 8.82 M_E, and a density = 1.36 gcm^{-3}.
- ★ TOI-431d likely has an extended atmosphere and is one of the best-known TESS discoveries for atmospheric characterization, while TOI-431b may be a stripped core.
- ★ These two planets straddle the radius gap, presenting an interesting case-study for atmospheric evolution, TOI-431b is a prime TESS discovery for the study of rocky planet phase curves.
- ★ TOI-431b and d both contribute to the TESS Level-1 mission goal to measure the masses and radii of at least 50 planets with radii smaller than 4 R_E.
- ★ We'll be submitting the discovery paper for this system soon, so keep an eye out!

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1. Intro

- The Kepler Space Telescope allowed us to do statistical studies on the exoplanet population for the first time.
- This includes the identification of the "photoevaporation valley," a bi-modality in the radius distribution of small planets, explained by photoevaporation of close-in planetary atmospheres **(Fig. 6)**.
- The Transiting Exoplanet Survey Satellite (TESS) is building on Kepler's legacy: now at the end of its primary two-year mission, there have been over 2000 TESS Objects of Interest (TOIs) released.
- We present here the discovery of TOI-431b, c, and d; planets b and d were discovered by TESS and confirmed via extensive follow-up. Planet c was found in RV data from HARPS.

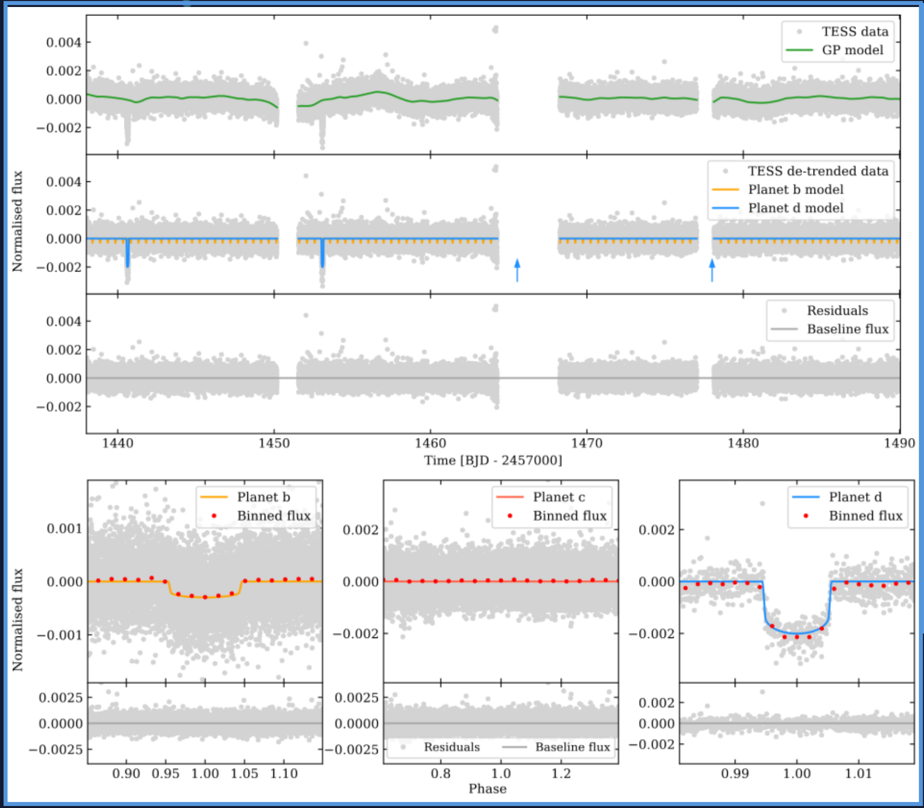
2. Observations

Photometry

- **TESS:** the TOI-431 system was observed in TESS Sectors 5 (15 Nov to 11 Dec 2018) and 6 (Dec 15 2018 to Jan 6 2019) on Camera 2 in short-cadence mode (t_{exp} = 2 min), see **Fig. 1.**
- **Spitzer:** a full double-transit event of TOI-431b and TOI-431d was observed from UT times 23 May 2019 21:13 to 24 May 2019 04:42 **(Fig. 2)**.
- **LCOGT:** two partial transits were obtained on UT 9 Dec 2019, which covered the ingress and egress events of TOI-431d with CTIO and SSO respectively **(Fig. 3, next page)**.
- **NGTS:** a transit ingress of TOI-431d was observed using 5 NGTS telescopes on 20 Feb 2020; 5922 images were taken across the 5 telescopes, with t_{exp} = 10 sec **(Fig. 3)**.

High-resolution imaging

- High angular resolution imaging is needed to search for nearby sources that can contaminate the TESS photometry, resulting in an underestimated planetary radius, or that can be the source of astrophysical false positives, such as background eclipsing binaries.
- We have HR imaging from SOAR HRCam, Gemini NIRI, Gemini Zorro, and Keck NIRC2, and perform a Blended Source Confidence (BSC) analysis that shows a very low probability of an undetected source capable of mimicking the transit signal.



<- Fig 1: *TESS data for TOI-431 in S5/6.*
Top plot: *detrending the TESS light curves and fitting planets b and c.*
Top panel: *the full TESS light curve, with no detrending for stellar activity. Each sector has 2 segments of continuous viewing, and the gaps in the data correspond to the spacecraft down-linking the data to Earth after a TESS orbit of 13.7 days. Overlaid is the GP model that detrends the stellar activity.*
Middle panel: *the flux detrended with the GP model, with the transit models for planet b and d.*
Bottom panel: *residuals when the best fit models and GP have been subtracted from the TESS flux.*
Bottom plot: *phase folds of the TESS data for planet b (left), c (middle, with no transit evident), and d (right), with residuals underneath.*

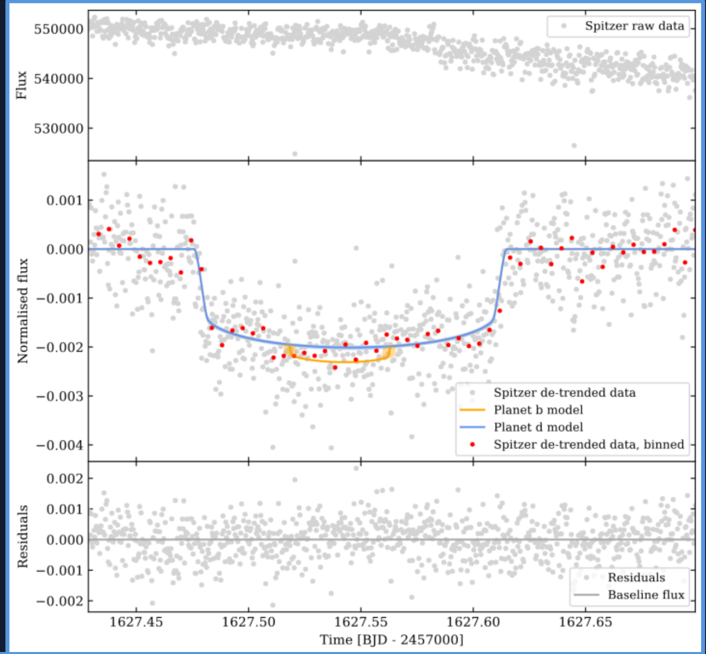


Fig 2: *The Spitzer double-transit.*
Top panel: *the raw Spitzer data, without any pixel-level decorrelation (PLD) applied.*
Middle panel: *the Spitzer light curve detrended with PLD in grey and binned as red circles, with the best fit models of planet b (orange) and d (blue) overlaid.*
Bottom panel: *the residuals when the best fit model has been subtracted from the detrended flux.*

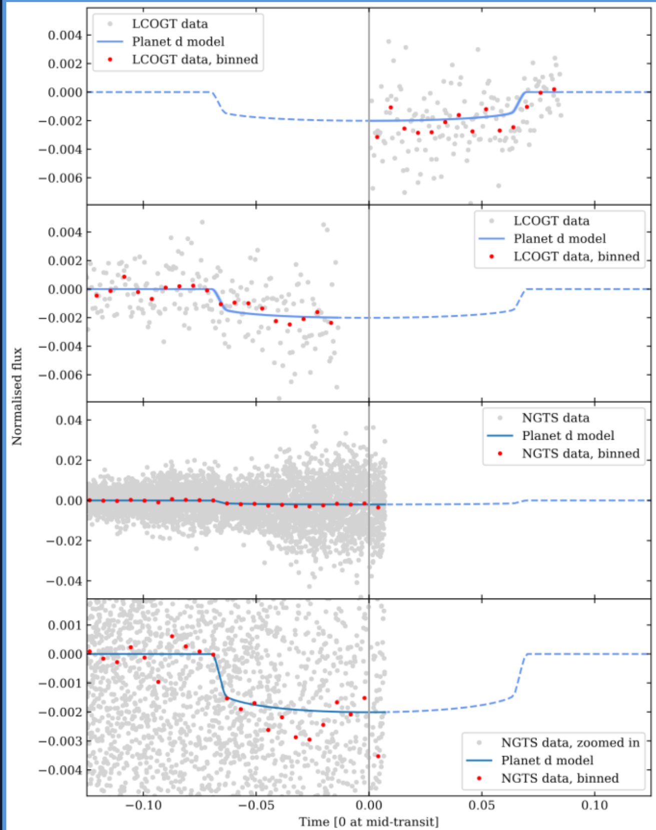


Fig 3: *best fit models of planet d to the LCOGT egress* **(top panel)**, *ingress* **(upper middle)** *and NGTS light curves* **(lower middle and bottom, where bottom is zoomed in)**. *In all plots, the observed flux is shown as light grey circles, the binned flux as red circles, and the planet d model is given as the blue line.*

Spectroscopy

- **HARPS:** TOI-431 was observed between February 2 and October 21 2019; under the NCORES large programme (ID 1102.C-0249, PI: Armstrong), a total of 113 spectra were obtained **(Fig. 5)**.
- **iSHELL:** we obtained 108 spectra during 11 nights for TOI 431 spanning 108 days from Sep-Dec 2019.
- **FEROS:** 10 spectra were obtained.
- **MINERVA-Australis:** 16 spectra were obtained between February 11 and April 17 2019.

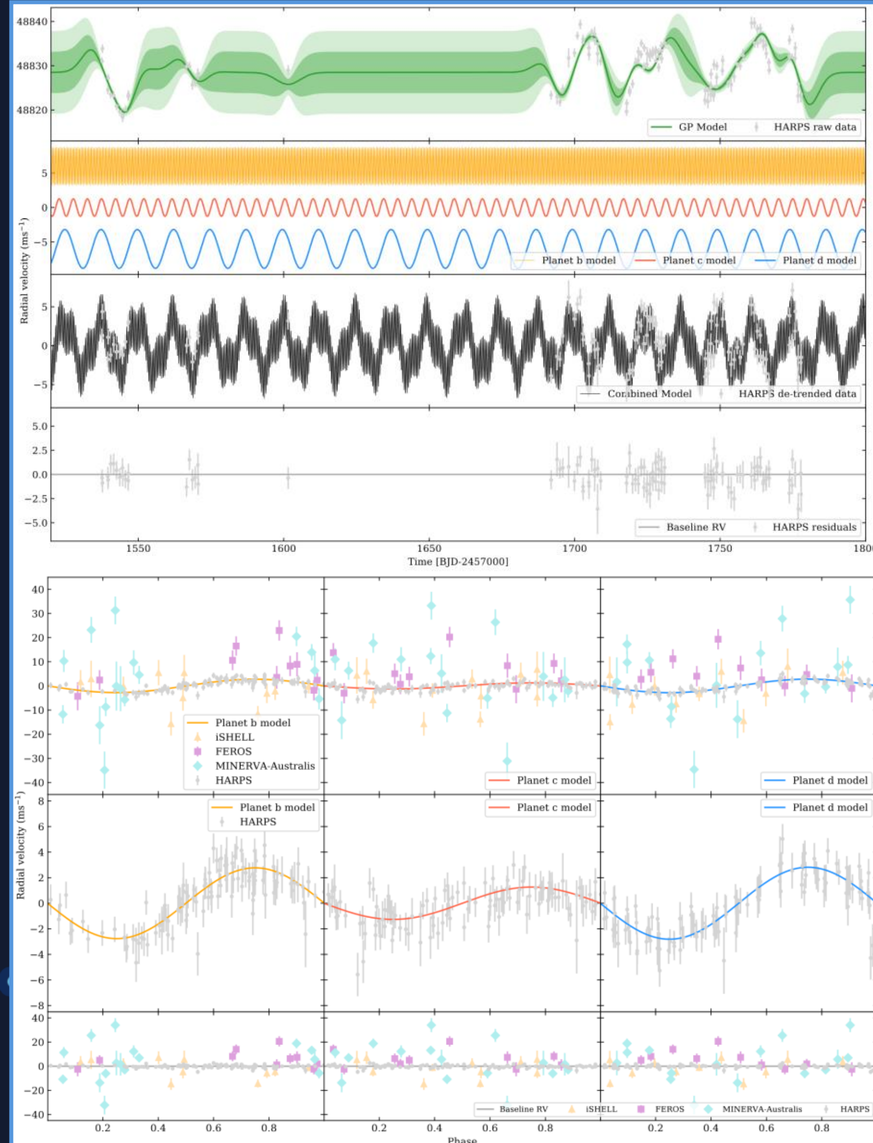


Fig 4: *RV data plots.* **Top plot:** *the HARPS RVs, the GP, and planet models that have been fit.* **Top panel:** *the GP used to detrend the stellar activity is shown. The green shaded areas represent the 1 and 2 standard deviations of the GP fit.* **Upper middle panel:** *the models for each planet, b (offset by +6 ms^{-1}), c, and d (offset by -6 ms^{-1}).* **Lower middle panel:** *the total model (the addition of the models for all planets).* **Bottom panel:** *the residuals after the total model, GP and offset has been subtracted from the RV data.* **Bottom plot:** *phase folds for each planet, with all the data in the top panels, just HARPS the middle panels, and the residuals in the bottom panels.*

Stellar Analysis

- We use 2 independent methods to derive the stellar atmospheric parameters.
- We also perform SED fitting to derive further stellar parameters: bolometric flux, mass, radius, and rotation period.
- WASP-South observed this system for 180 days in 2012, 175 days in 2013 and 130 days in 2014, allowing us to determine a rotation period for the star of 30.5 ± 0.7 d.
- The rotation period is further corroborated by monitoring with NGTS between Oct 11 2019 and 20 January 2020.

3. The Joint Fit Model

- We use the `exoplanet` package (Foreman-Mackey et al. 2019) to fit the photometry from TESS, LCOGT, NGTS and Spitzer simultaneously with the HARPS RVs.
- All the figures you see up to this point are generated from this joint fit, as are the system parameters on the next page.
- `exoplanet` uses the light curve modelling package `starry` (Luger et al. 2019), `PyMC3` (Salvatier et al. 2016), and `celerite` (Foreman-Mackey et al. 2017) for gaussian processes (GPs).
- We detrend the stellar activity in the TESS data using a GP kernel included in `exoplanet`, and construct our own quasi-periodic GP kernel using `celerite` for the HARPS data.

4. Results

Tables below: *parameters for the system (references given), the star (methodology given), and the parameters for the planets TOI-431b, c, and d, calculated from our joint fit model.*

System and stellar parameters

Property	Value	Reference
System parameters		
Identifier	TIC ID: 31374837, 2MASS ID: 05330459-2643286, Gaia ID: 29086645570912007	TICv8, 2MASS, GAIA DR2
RA, Dec	05:33:04.62, -26:43:25.93	GAIA DR2
Magnitudes (mag)	TESS: 8.1705, B: 10.104, V: 9.12, G: 8.79171, J: 7.305, H: 6.846, K: 6.723	TICv8
Stellar parameters		
Stellar radius R_* (R_{Sun})	0.729 ± 0.022	SED fitting
Stellar mass M_* (M_{Sun})	0.77 ± 0.07	SED fitting
Rotation period (days)	30.5 ± 0.7	WASP-South

Planetary fit parameters

Parameter	TOI-431b	TOI-431c	TOI-431d
Period P (days)	0.490054 ± 0.000008	4.84941 ± 0.00009	12.46103 ± 0.00001
Ephemeris t_0 (BJD - 2457000)	1627.541 ± 0.002	-1502.01 ± 0.08	1627.5453 ± 0.0003
Radius R_P (R_E)	1.28 ± 0.04	-	$3.29 \pm^{0.09}_{0.08}$
Eccentricity e	0 (fixed)	0 (fixed)	0 (fixed)
Argument of periastron ω	0 (fixed)	0 (fixed)	0 (fixed)
Radial velocity semi-amplitude K (ms^{-1})	2.77 ± 0.31	$1.26 \pm^{0.17}_{0.15}$	$2.82 \pm^{0.71}_{0.73}$
Mass M_P (M_E)	$2.96 \pm^{0.37}_{0.36}$	$2.90 \pm^{0.41}_{0.36}$	$8.82 \pm^{2.28}_{2.32}$
Bulk density ρ (g cm^{-3})	$7.70 \pm^{1.08}_{1.03}$	-	1.36 ± 0.36

Thank you for reading!

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5. Discussion

- TOI-431 is an unusual system in that its middle planet is not transiting, while those on either side of it are. This has been seen before in the Kepler-20 system but is rare.
- The TOI-431 system is a good target system for studying planetary evolution. TOI-431b and d reside either side of the radius-period valley **(Fig. 5)**, providing a test-bed for the mechanisms behind it. By examining the X-ray and EUV-driven photoevaporation of the system leads us to believe that TOI-431b could have easily lost its envelope, while TOI-431d likely retains a substantial envelope.
- We can also examine the compositions of TOI-431b and d – see **Fig 6**. TOI-431b follows the Earth-like composition line and likely has a negligible H-He envelope, while TOI-431d sits above the pure-water curve and probably has significant volatile layer of H-He and/or water of about 4 or 34 per cent of its total mass, respectively.

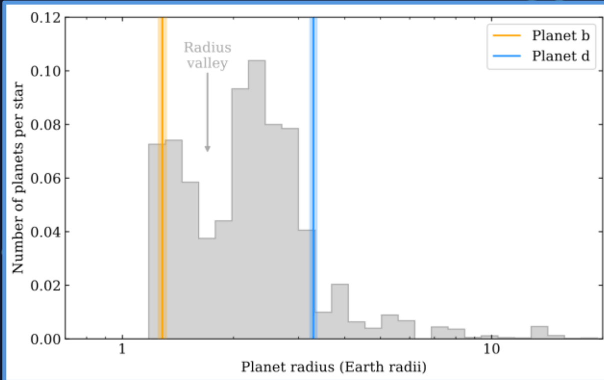

Fig 5: *a histogram of the number of planets (with orbital periods less than 100 days) per star, as given in Fulton et al. 2018. The radius valley can be seen at ~1.7 R_E: below the gap are rocky super-Earths, above the gap are gaseous sub-Neptunes. TOI-431b (orange, with 1 sigma confidence intervals shaded) is the former, while TOI-431d (blue) is the latter.*

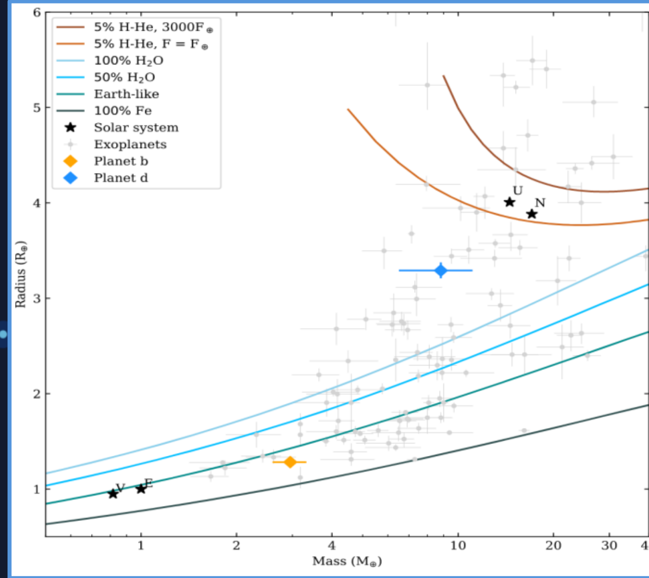

Fig. 6: *A mass-radius plot displaying known exoplanets from the NASA exoplanet archive with mass determinations better than 4 sigma. TOI-431b is shown in orange, and TOI-431d in blue. Composition tracks are shown. U, N, V and E are the solar system planets Uranus, Neptune, Venus, and Earth.*

Conclusion

- We have presented here the discovery of three new planets from the TESS mission in the TOI-431 system.
- **TOI-431b** is a super-Earth characterised by both photometry and RVs, with a period of 0.49 days. It likely has a negligible envelope due to substantial atmosphere evolution via photoevaporation, and an Earth-like composition.
- **TOI-431c** is found in the HARPS RV data and is not seen to transit. It has a period of 4.84 days and a minimum mass similar to the mass of TOI-431b
- **TOI-431d** is a sub-Neptune with a period of 12.46 days, characterised by both photometry and RVs. It has likely retained a substantial H-He envelope of about 4% of its total mass.
- This system is a candidate for further study of planetary evolution, with TOI-431b and d either side of the radius valley. The system is bright, making it amenable to follow-up observations. TOI-431b would potentially be an interesting target for phase-curve observations with JWST.