TOI-1778 b: Confronting compositional confusion through the characterisation of a sub-Neptune

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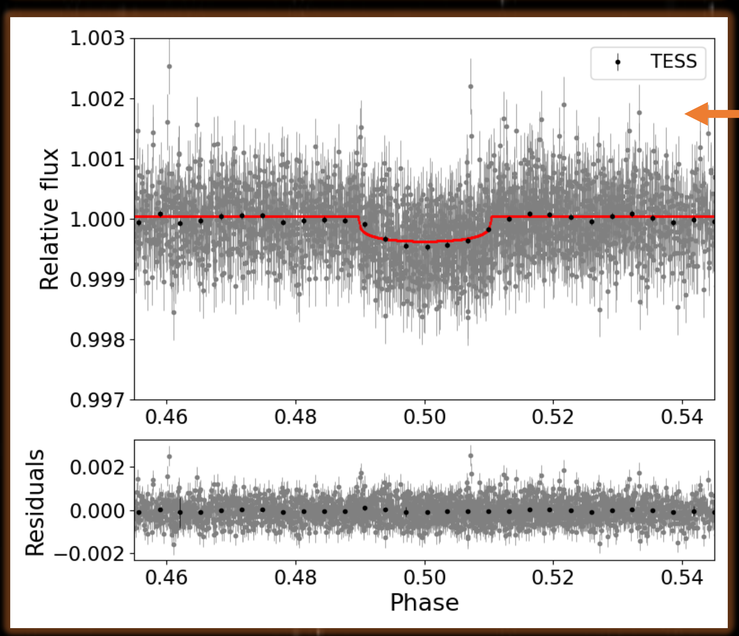
Motivation

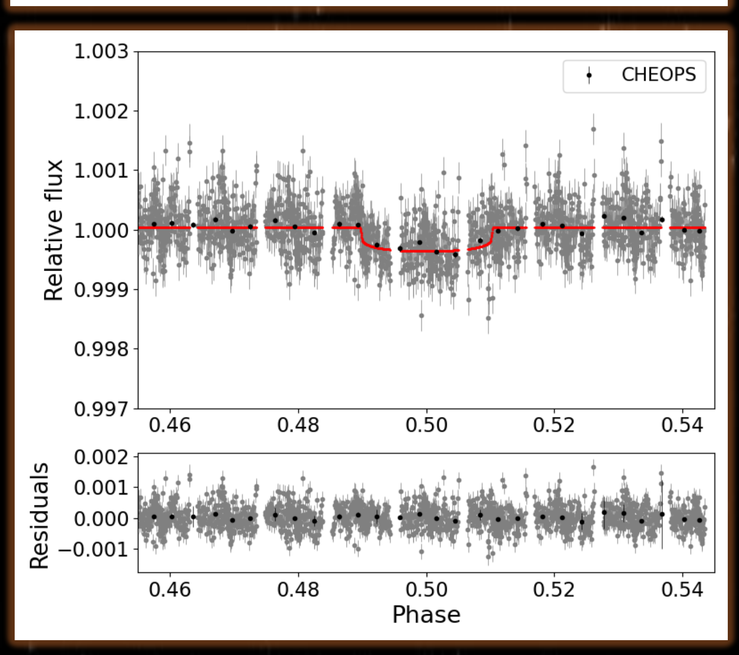
The exoplanet, TOI-1778 b, exists in a region of parameter space where there is currently compositional degeneracy between water-worlds and silicate/iron hydrogen models. Precise mass and radii measurements of exoplanets are crucial for breaking this degeneracy, and the characterisation of TOI-1778 b, adding to the small sample of well characterised sub-Neptunes, is an important step forwards on our journey to refute or confirm the existence of water-worlds, and thus constrain planet formation and evolution pathways, helping us to better understand our own place in the Universe.

Observations

- NASA'S Transiting Exoplanet Survey Satellite (*TESS*) first observed TOI-1778 during sector 21 (year 2) of its cycle and again in sector 47 (year 4), observing a total of 7 transits of TOI-1778 b.
- 2 further transits were observed with ESA's Characterising Exoplanet Satellite (*CHEOPS*) in January & December 2021.
- We carried out a total of 102 follow-up radial velocity (RV) observations between December 2020 and January 2023 with HARPS-N on the ground-based Telescopio Nazionale Galileo (TNG) in La Palma, Canary Islands.

Figure 1 (below): *Transit fit to the data from TESS* ***(top)*** *and CHEOPS* ***(bottom)****. The short cadence fluxes are plotted in grey, 30min binned fluxes are plotted in black, and the fitted transit is shown by the red solid line.*





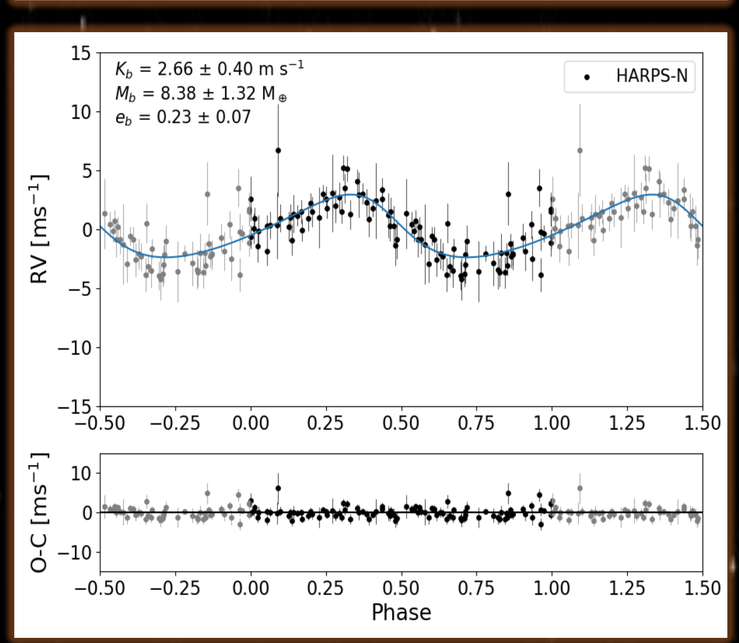


Figure 2 (above): *RV fit to the data from HARPS-N. Black points show phase-folded RVs, grey points show the same values in subsequent phases, and the blue line shows the best fit Keplerian model.*

Further in-depth results are presented in Palethorpe et al. (2024).
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Modelling

- We estimated the stellar rotation period using the activity indicators and analysis of the stellar parameters.
- We found TOI-1778 to be an F5 star with V mag = 9.0, Teff = 6154K (~380K hotter than the Sun), and an approximate 13.6-day stellar rotation period.
- It was deemed necessary to include a Gaussian Process (GP) (with a quasi-periodic kernel) in our fit to account for the stellar activity and rotation. Not accounting for this can lead to severe miscalculations of a planet's mass.
- A combined transit, RV, and GP fit was obtained using nested sampling with the software package `PyORBIT`.

Results

- We find TOI-1778 to host one small (**M = 8.38 $M_\oplus$, R = 2.71 $R_\oplus$, P = 6.53 day**) transiting sub-Neptune.
- Whilst we modelled a 1% H/He atmosphere, the concept of water-world remains ambiguous due to the high equilibrium temperature of the planet.
- TOI-1778 b has a transmission spectroscopic metric (TSM) of 56.81, and whilst there are currently no sub-Neptunes orbiting hot stars that pass the recommended threshold of 90, Fig. 4 shows that TOI-1778 b is in the **top 5 candidates of small planets around hot stars** (>6000K) for follow-up atmospheric observations with NASA's James Webb Space Telescope (*JWST*).
- This result contributes to the highlighted degeneracy between water-worlds and sub-Neptune models, and TOI-1778 b is a prime target to gain a better understanding of planetary composition and evolution.
- The precision of our results places it in the **top 10 mass and radius measurements** for confirmed small F star planets.
- Combining datasets from both space- and ground-based telescopes presents a promising approach to planetary precision.

Composition

- Interior structure modelling of the planet indicates a gaseous H/He atmosphere less than 1% of its total mass, but 1/3 of its radius.
- Compared to Earth, this would indicate an iron core that is smaller but a mantle that is bigger.
- Plotting it on a M-R diagram, however, indicates the planet could have a H/He or steam atmosphere.
- The planet has an **equilibrium temperature** of **~1248K** (about 4x Earth's temperature).
- At this temperature water is in a supercritical state meaning that the concept of a water-world cannot be entirely discounted.

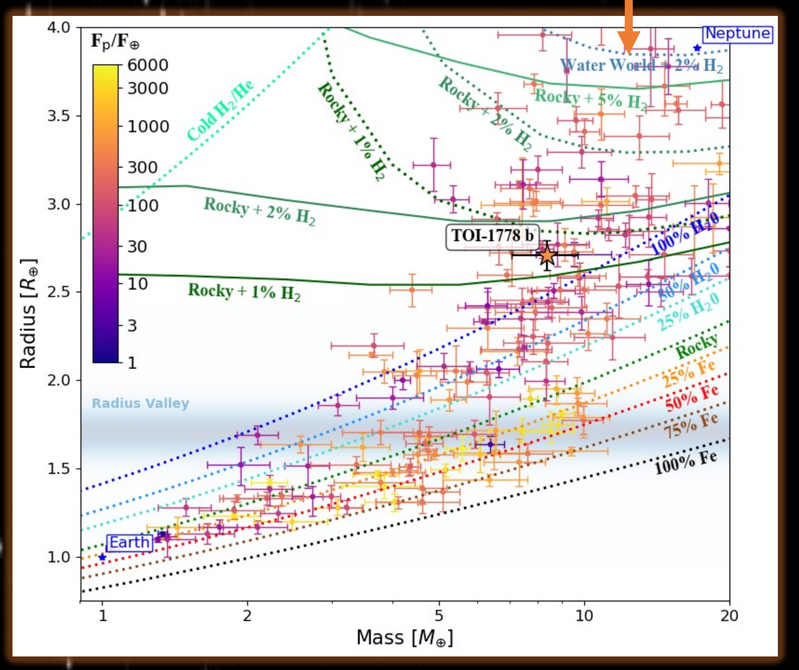

Figure 3 (above): *M-R diagram. TOI-1778 b is indicated by the star and confirmed planets with masses and radii with precision better than 20% and 10% respectively are also shown, colour-coded by their incident flux. The dotted and solid lines show different composition models.*

Figure 4 (above): *R_P vs TSM plot for small planets with host stars with an effective temperature > 6000K. Planets are colour-coded by incident flux. Additionally plotted is the recommended TSM=90 threshold from Kempton et al. (2018).*

Key Points

- **We modelled a 2.71 $R_\oplus$ and 8.38 $M_\oplus$ sub-Neptune with a 6.53 d period orbiting a hot bright star.**
- **We estimate TOI-1778 b has a ~1% H/He atmosphere and is one of the hottest planets in this region of the M-R plot.**
- **Further atmospheric observations of TOI-1778 b with NASA's *JWST* would help confirm its composition.**
- **Confirming or refuting the existence of water-worlds could have strong implications for the understanding of our own solar system.**