Vaporized "Rock Rain": Direct Detection of SiO in the Atmosphere of Ultra-hot Jupiter WASP-178b

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Why SiO Matters in UHJ Atmospheres

- **Ultra-Hot Jupiters** (UHJs, T_{eq} > 2200 K) are **unique labs for refractory chemistry**, as species that would normally condense (e.g. silicates) remain in the gas phase.
- **Silicon monoxide (SiO)** is predicted to **dominate near-UV opacity under high temperatures**, absorbing stellar UV photons and depositing heat high in the atmosphere. This can drive strong thermal inversions, where temperature increases with altitude.
- **A direct SiO detection** can validate UHJ chemical / radiative-transfer models and inform **how high-altitude UV heating drives thermal inversions**.

WASP-178b: Excess near-UV Absorption

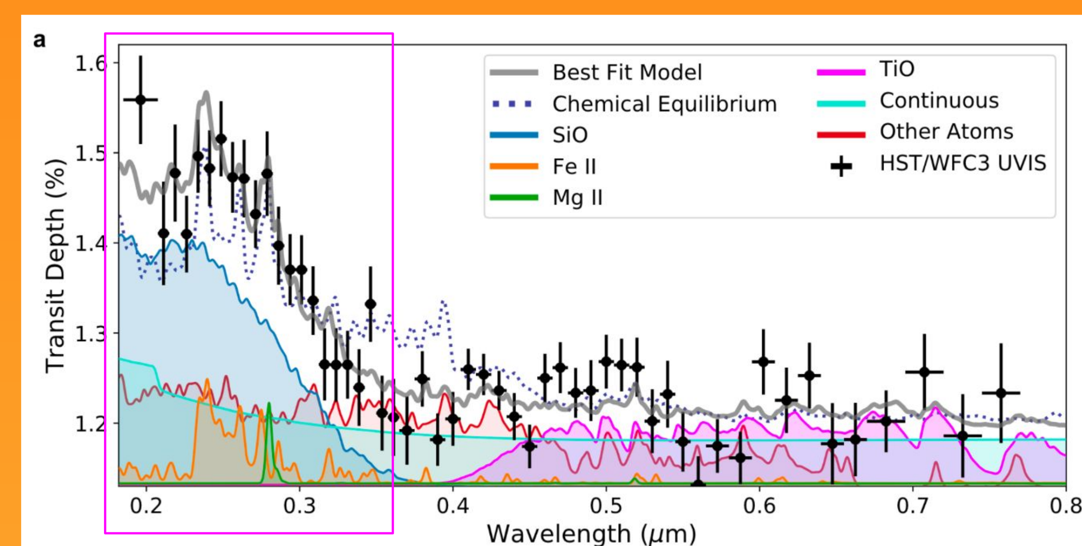


Figure 1, Lothringer et al., 2022

Figure: Lothringer et al. (2022) reported a broad 0.20-0.28 μm NUV strong absorption feature using HST/WFC3/UVIS. Bayesian retrievals show that SiO is expected to dominate the contribution at short wavelengths.

WASP-178b (T_{eq} = 2470 K) orbits an A1 IV-V star with T_{eff} = 9360 K, making its host the second hottest known planet hosting star after KELT-9.

Research Question

Can we directly detect and confirm the presence of gaseous SiO in UHJ WASP-178b's atmosphere, using archival HST/STIS E230M high-resolution NUV data?

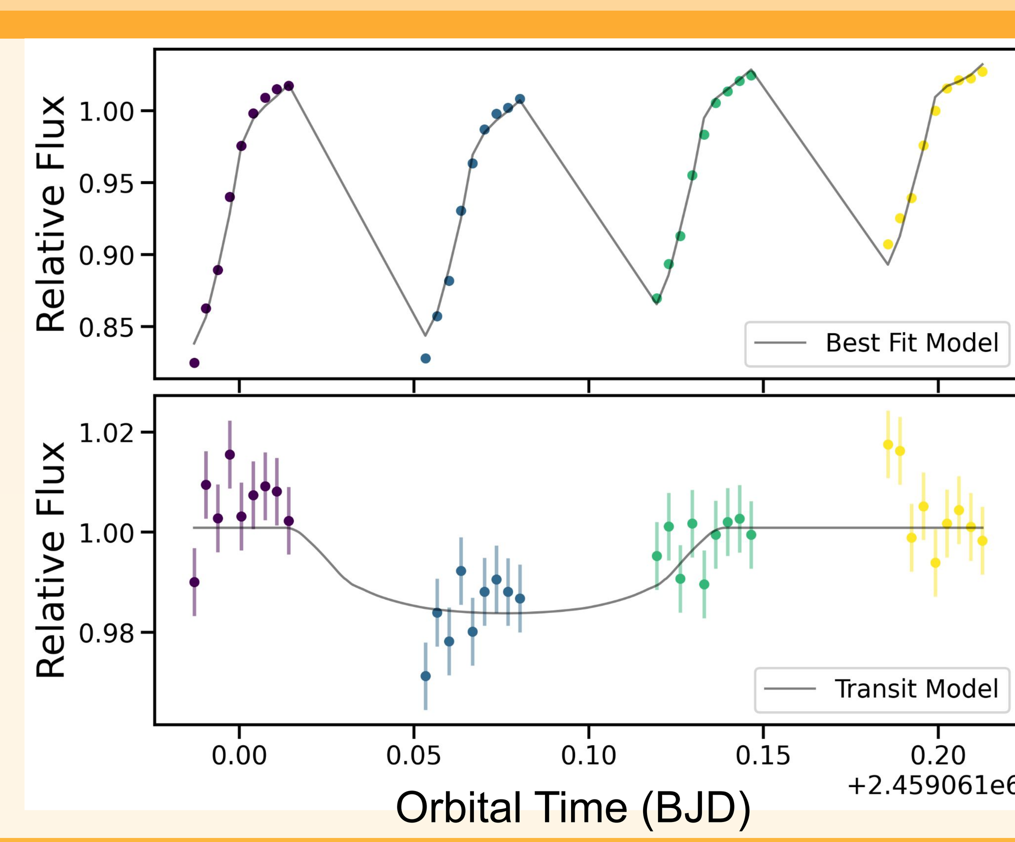
HST/STIS Systematics Correction with Jitter Data

- "Ramping effect": HST/STIS light curves are highly affected by instrument-related systematics
- Following Sing et al. (2019), we use jitter parameters from the EDPS in the systematic correction model S(x)
- Flux over time is modeled as:

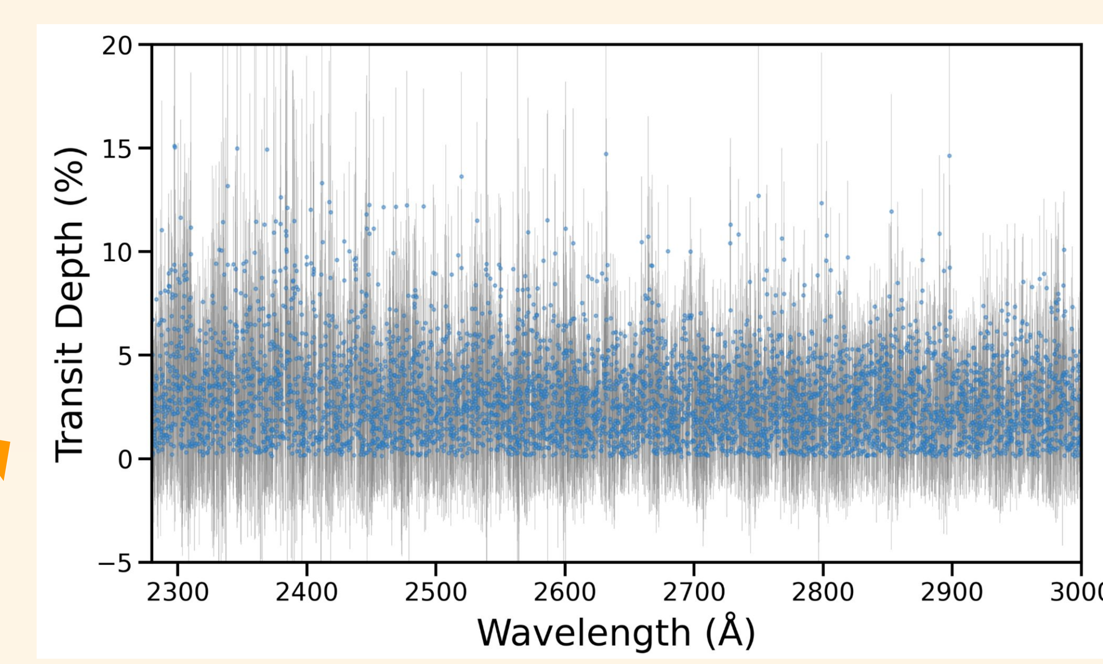
f (t) = Theoretical Transit model * baseline flux * Systematics model
= T (t, θ) × F0 × S (X)

Raw White Light

Corrected flux



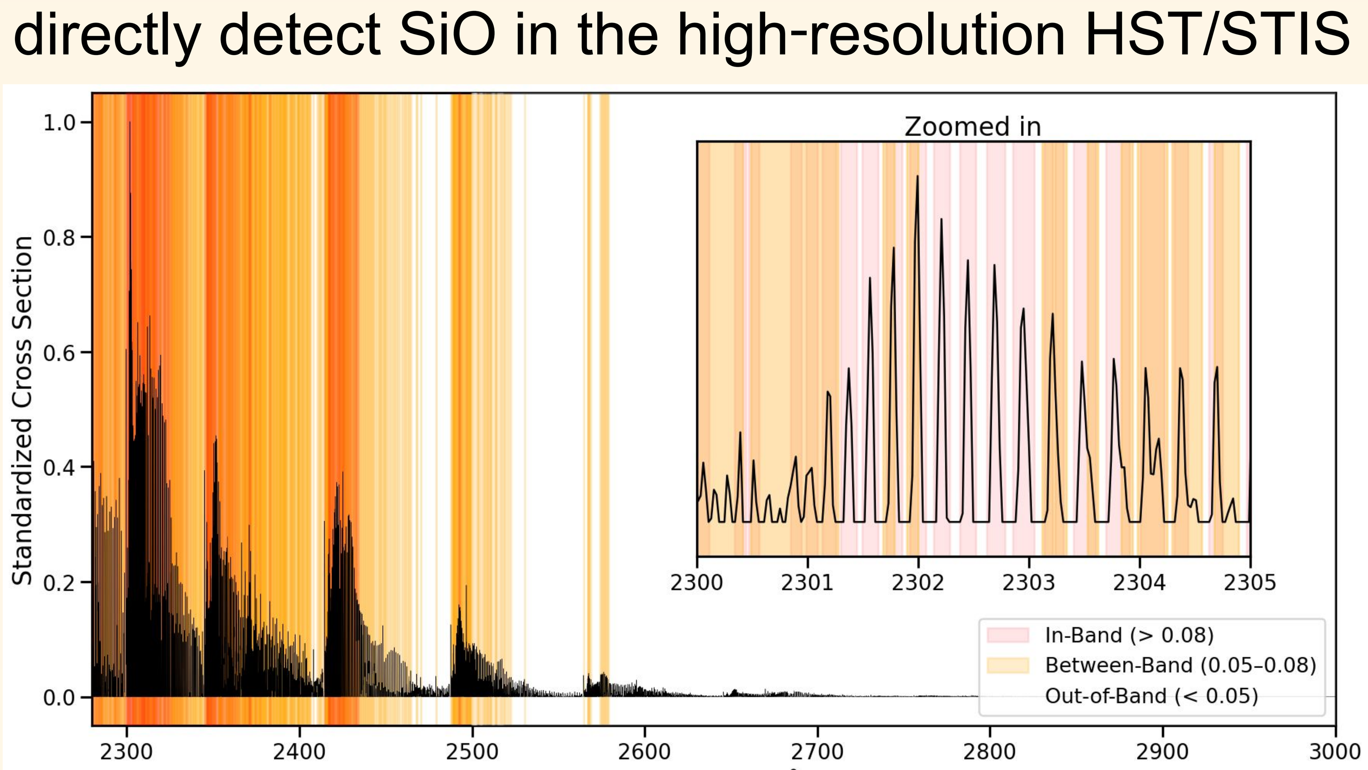
Spectral light curve fitting



WASP-178b high resolution (R~30,000) NUV transmission spectrum

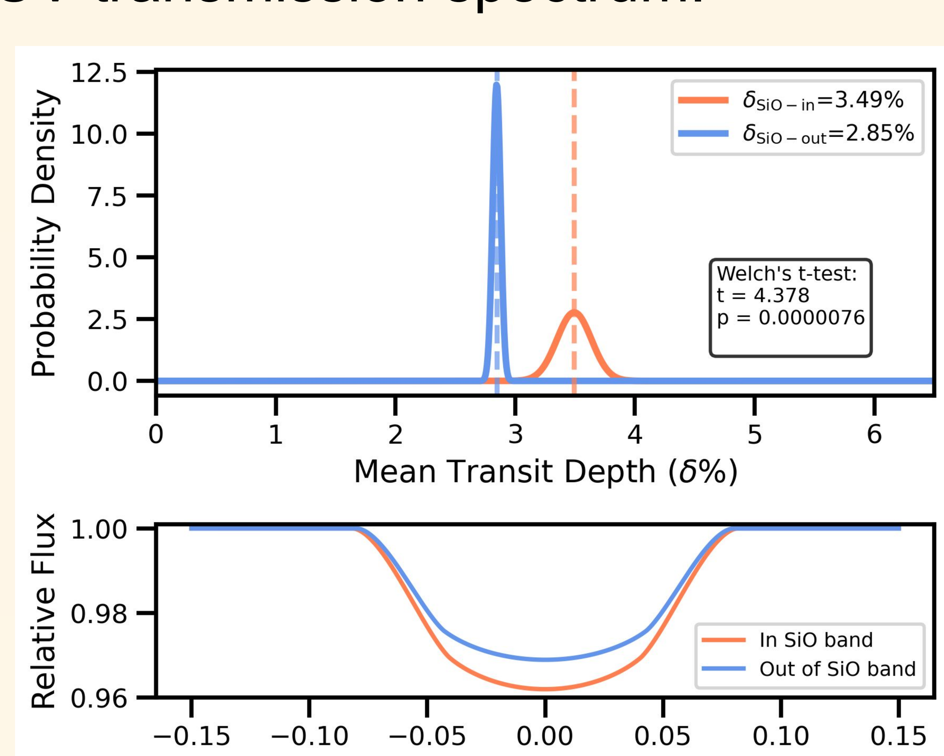
In-Band vs. Out-of-Band Analysis for SiO Detection

We adapt an in-band/out-of-band technique from Grant et al. (2023) that was used to detect CO's 4.6 μm band with JWST/NIRSpec to directly detect SiO in the high-resolution HST/STIS NUV transmission spectrum.



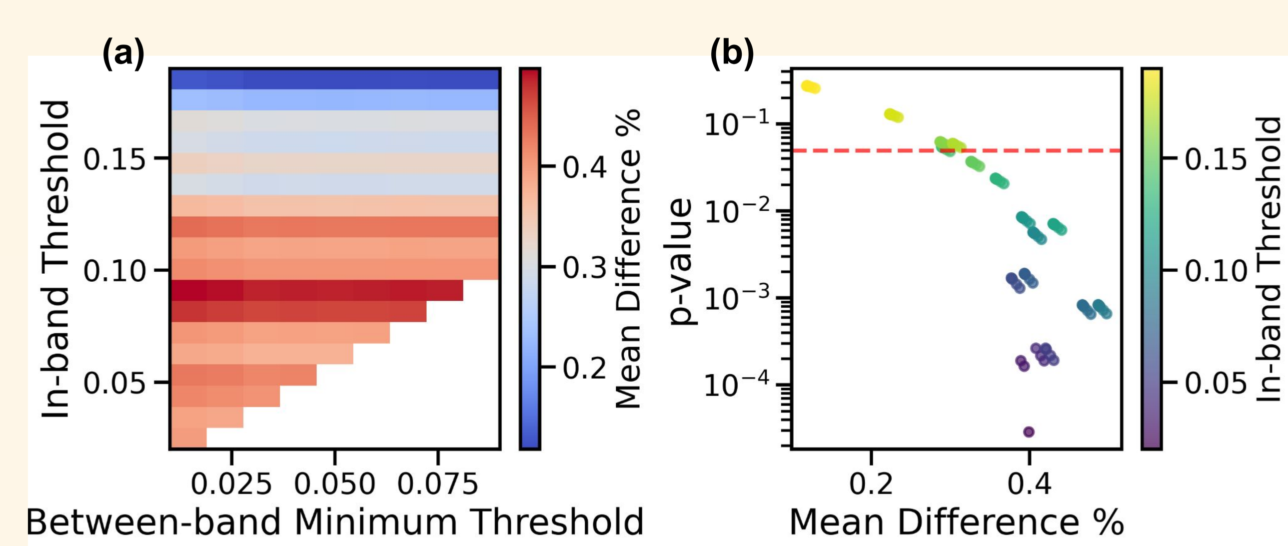
Theoretical SiO Template & Band Threshold

- We first compute SiO cross-sections at T = 2470 K using the 2021 ExoMol SiO line list.
- The in-band and out-of-band limits are chosen to balance statistical power against potential blending of minor absorptions.



Statistical Detection

We measure mean transit depths for each bandpass and perform a Welch's t-test on the $\delta_{in} - \delta_{out}$ distribution to quantify detection significance.



Sensitivity Test

- We vary threshold values over a grid of in-band minima and between-band maxima and map resulting Δδ% and associated p-values to verify detection stability.
- Figure: **(a)** heatmap of the mean in-band and out-of-band transit depth difference (Δδ%) across threshold combinations, where redder regions indicate stronger SiO signals. **(b)** scatter of Δδ% versus p-value, with the dashed p = 0.05 line marking 2σ significance.

Conclusion and Takeaways

- We detect **a transit depth difference of 0.647 ± 0.148% from SiO at > 4.3σ significance** ($p = 7.6 \times 10^{-6}$) in WASP-178b's atmosphere using an in-band/out-of-band technique of archival HST/STIS NUV data.
- This direct detection confirms that **silicon remains in the gas phase** at the extreme temperature of Ultra-hot Jupiter WASP-178b, consistent with expectations that SiO is the dominant silicon species at ~2500 K.
- **Our technique can be applied to archival and future HST/STIS high-resolution NUV observations of other hot and ultra-hot Jupiters.**

References

1. Lothringer, J. D., Sing, D. K., Rustamkulov, Z., et al. 2021, doi: 10.21203/rs.3.rs-923439/v1
2. Sing, D. K., Lavvas, P., Ballester, G. E., et al. 2019, AJ, 158, 91
3. Grant, D., Lothringer, J. D., Wakeford, H. R., et al. 2023, AJL, 950, L9