Atmospheric Characterization of TOI-1685b using *JWST NIRISS SOSS*

Hanna Adamski[1], Björn Benneke[1] & Hilke Schlichting[1]

[1] Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles

Email: hadamski@g.ucla.edu

MOTIVATION & OBSERVATIONS

It remains an outstanding mystery whether rocky planets orbiting M-dwarfs can retain their own atmospheres. Transmission spectroscopy provides us with an unprecedented opportunity to characterize the atmospheres of the most promising 'water-world' candidates and place constraints on the MMW of their potential upper atmospheres. **TOI-1685b** has been proposed as an intriguing candidate due to its low bulk-density ($\rho \sim 5.3$ g/cm^3) and high surface temperature ($T_{eq} \sim 1065$K). Here we present the analysis of GO #4098 observation of the hot super-Earth — one of three JWST Cycle 2 programs probing the atmosphere of the candidate[1,2].

- **Two Transits** of TOI-1685b were observed using Single Object Slit-less Spectroscopy Mode **(SOSS) on NIRISS**.
- **Each TSO lasted 2.9 hours** and is composed of **320 integrations**, each consisting of **5 groups**
- Order 1 (**0.85 to 2.85 µm**; R ~ 700) and Order 2 (**0.6 to 1.0 µm**; R ~ 1400) — Spectral Resolution

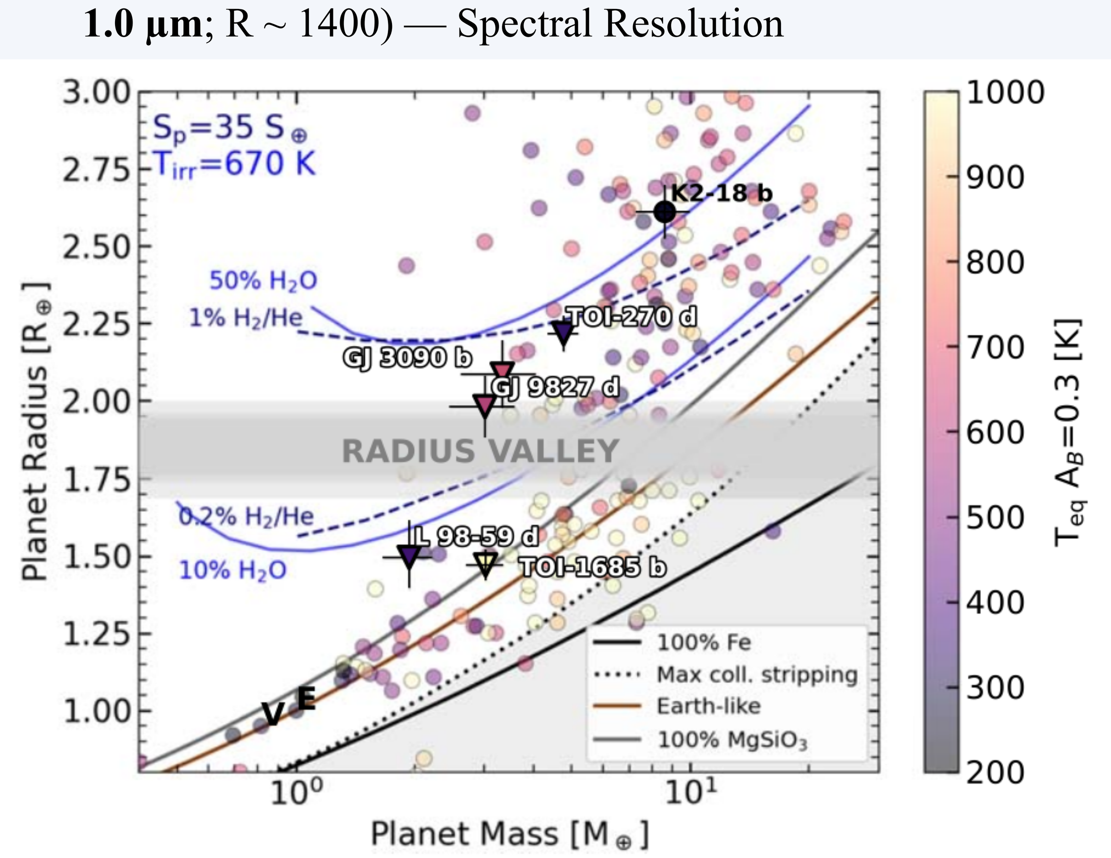

Figure 1 from Piaulet-Ghorayeb et al. 2024: Mass-radius diagram visualizing planets observed in JWST Cycle 2 Program (GO 4098; PI: Benneke, co-PI: Evans-Soma) — Exploring the Existence & Diversity of Volatile-Rich Water Worlds.

This work aims to address the following questions:

What formation mechanism is responsible for the planet's low bulk density?	What does this imply for the planet's atmospheric & interior structure?

REFERENCES & ACKNOWLEDGEMENTS

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INDEPENDENT DATA REDUCTION PIPELINES

Each SOSS TSO was reduced using the exoTEDRF[3] pipeline. We began with detector-level calibrations across 4-D *jwst .uncal* data cube (i.e. integrations, groups, spatial pixels, spectral pixels) — which included non-linearity corrections, a custom 1/f noise correction & piecewise background correction. Spectroscopic calibrations were performed across 3-D data (i.e. after ramp-fitting transition to integration-level) — these calibrations included flat-fielding, bad pixel correction & final background subtraction.

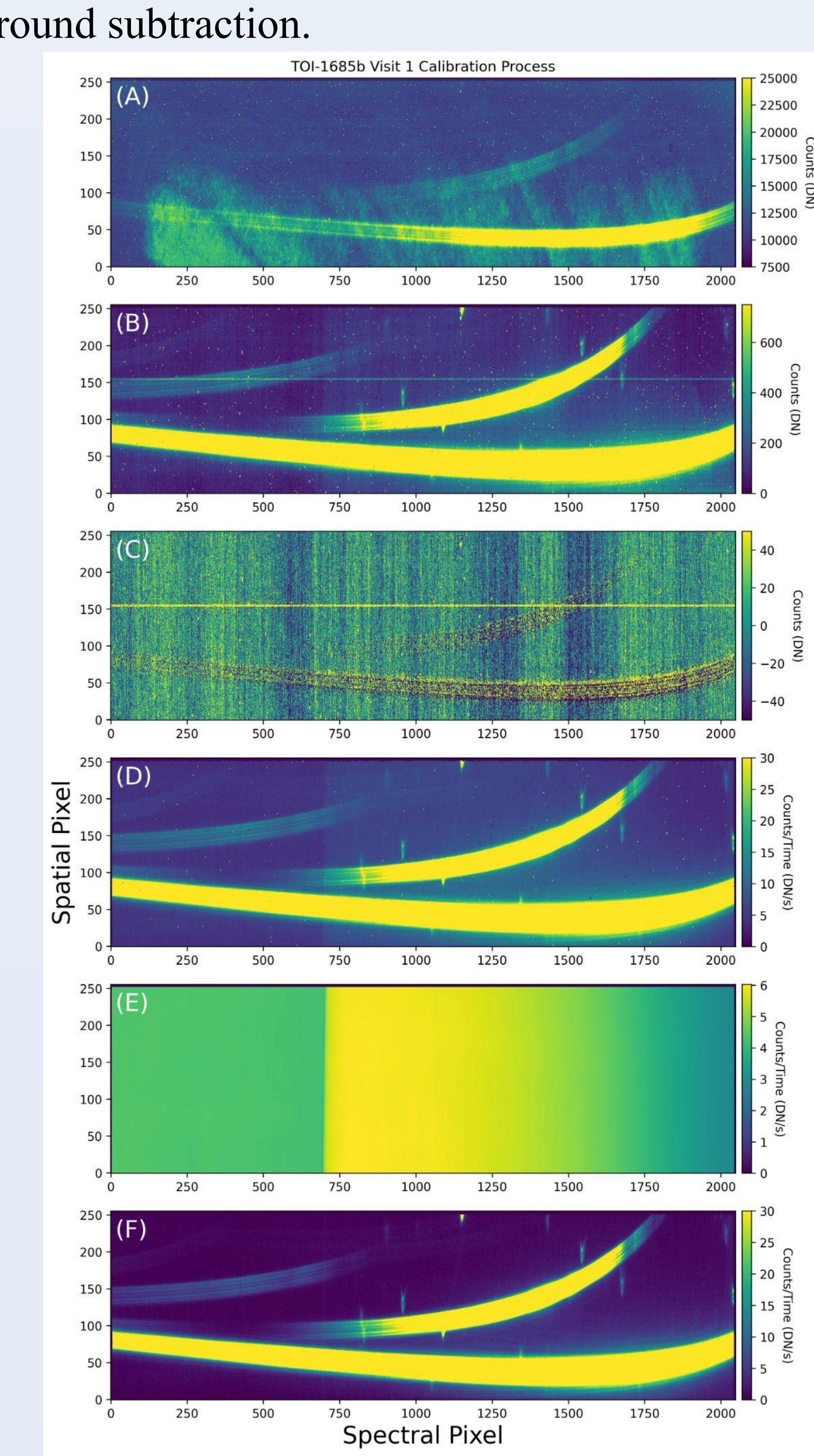

Figure 2: Spectral Calibration Process. A) Raw, uncalibrated image (100th integration, 5th group). B) Frame after superbias & reference pixel correction. C) 2D image (B) after first background subtraction & subtraction of scaled median of all integrations to reveal 1/f noise. D) Frame after ramp-fitting & flat-fielding. E) STScI model background scaled to the flux level of (D) with custom extraction box. F) Final calibrated 2D image produced from the 100th integration, after completing all detector-level and spectroscopic calibrations.

After spectral extraction across both orders, we produce broadband white light curves for each visit. Using EXOTEP[4] we independently fit our white light curves for R_p/R_s, mid-transit time T_0, and a/R_s. For the spectroscopic fits, we fix T_0 and a/R_s and fit for R_p/R_s, and the free parameters in systematics model.

- **Fit sequence of systematics models to data & determine optimal (via negative log-likelihood) model includes correction for:**
  - **Linear Trend with time & residual correlated noise (Matern 3/2 GP Kernel — characteristic timescale adopted from WLC + correlation strength fit to each spectroscopic bin)**

TOI-1685b TRANSMISSION SPECTRUM

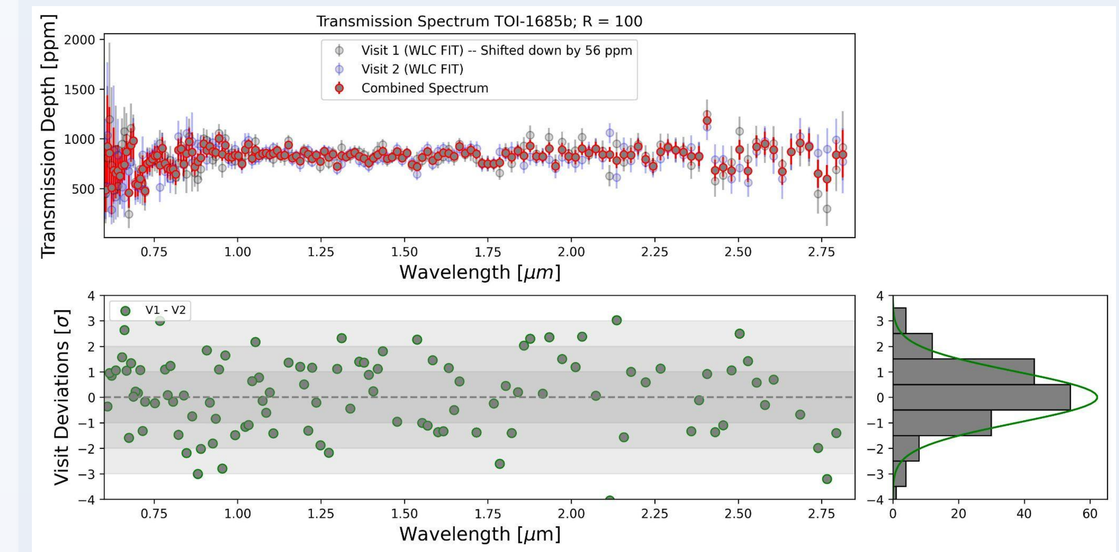

Figure 3: Error-Propagated Transmission Spectrum across Visits 1 & 2 for both Orders 1 & 2 binned to R ~ 100. The difference in transmission depth between both visits per wavelength bin was found to follow a normal, gaussian-like distribution in accordance with the overlaid green line of **μ = 0 & σ = 1**.

ATMOSPHERIC RETRIEVALS

We perform free chemistry & chemically consistent retrievals over the error-propagated mean spectrum of TOI-1685b using the SCARLET retrieval framework[4,5,6].

- Atmosphere divided into 60 Layers of pressures: 10^{-5} to 10^{9} [Pa]
- Free retrievals with well-mixed abundances of fitted species — H_2, He, H_2O, CH_4, CO_2, CO, NH_3, & SO_2 — wide log-uniform prior on volume mixing ratios (lower bound at 10^{-9})
- Chemical equilibrium retrievals assume estimated molecular abundances in thermochemical equilibrium for given, fitted isothermal temperature, atmospheric metallicity & C/O ratio

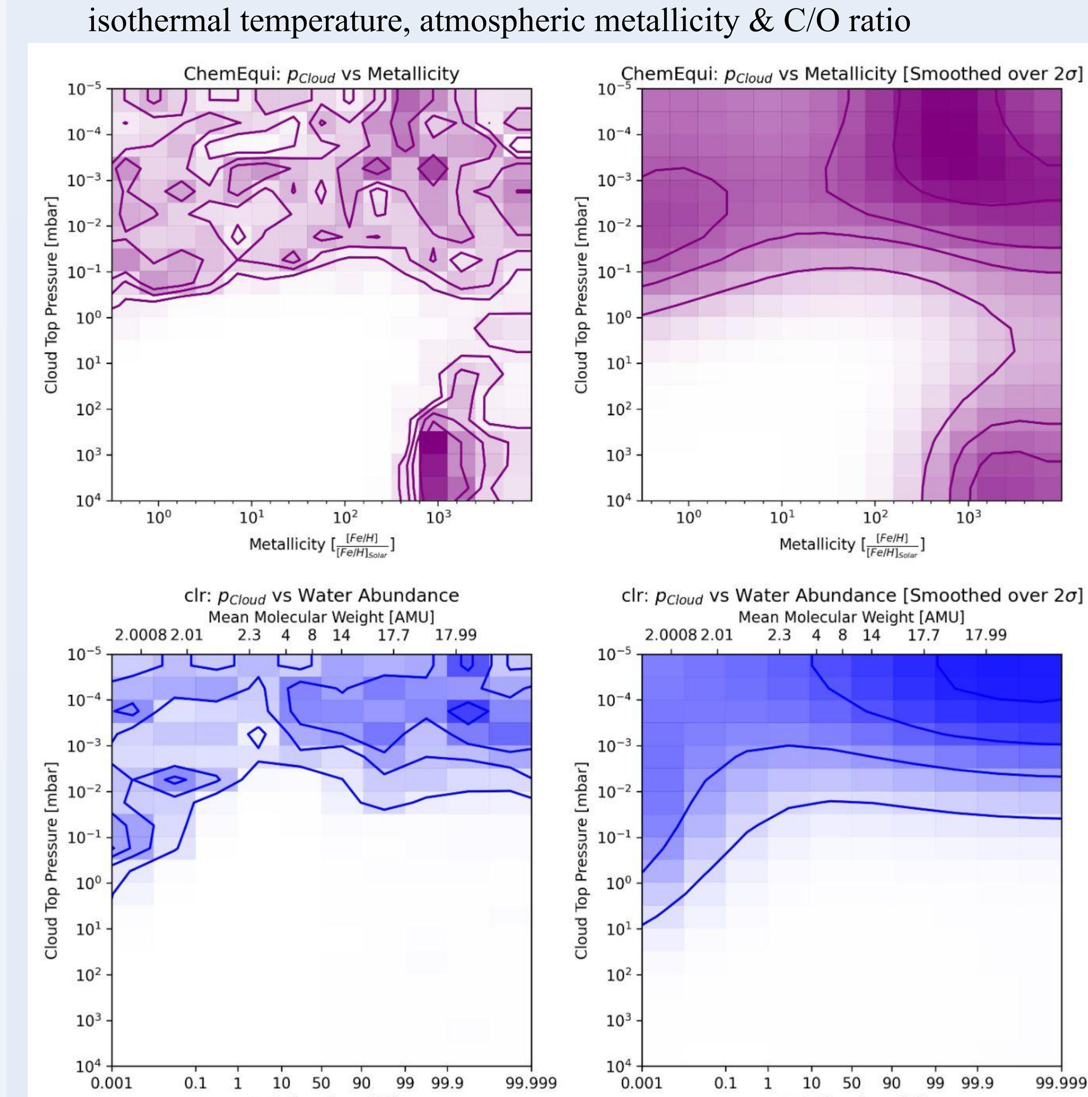

Figure 4: *(Top Row)* 2-D Correlation between atmospheric metallicity and cloud-top pressure in retrieved posterior distribution. *(Bottom Row)* 2-D Correlation between H_2O abundance and cloud-top pressure.

- Contours favor **high metallicity/low altitude cloud-top pressure** or **high altitude aerosol coverage w/ varying metallicity**

How do 1σ & 2σ contours of posterior distribution explain relatively FEATURELESS SPECTRUM?

- 1) **Low-metallicities** — low column-density of constituent molecules
- 2) **Intermediate metallicities** — Feature amplitudes are dampened by clouds
- 3) **High metallicities** — reduced atmospheric scale height attenuates molecular absorption features without needing to invoke clouds/hazes

DISCUSSION: BARE ROCK CASE SCENARIO & CLOUDS/HAZES

We begin to explore the implications of two scenarios: 1) Bare Rock (i.e. high metallicity) with reduced bulk density and 2) High-Altitude Clouds/Hazes to explain transmission spectrum's features. We suggest that lower bulk densities can be attained by Earth-like core mass fractions (~ 32.5%) if cores have undergone significant sequestration of H & O — leading to overall core density deficits[7]. A 20 to 40% deficit is easily justifiable by planets which have lost their primordial gas envelopes (of few% H) to core-powered mass loss or photoevaporative stripping.

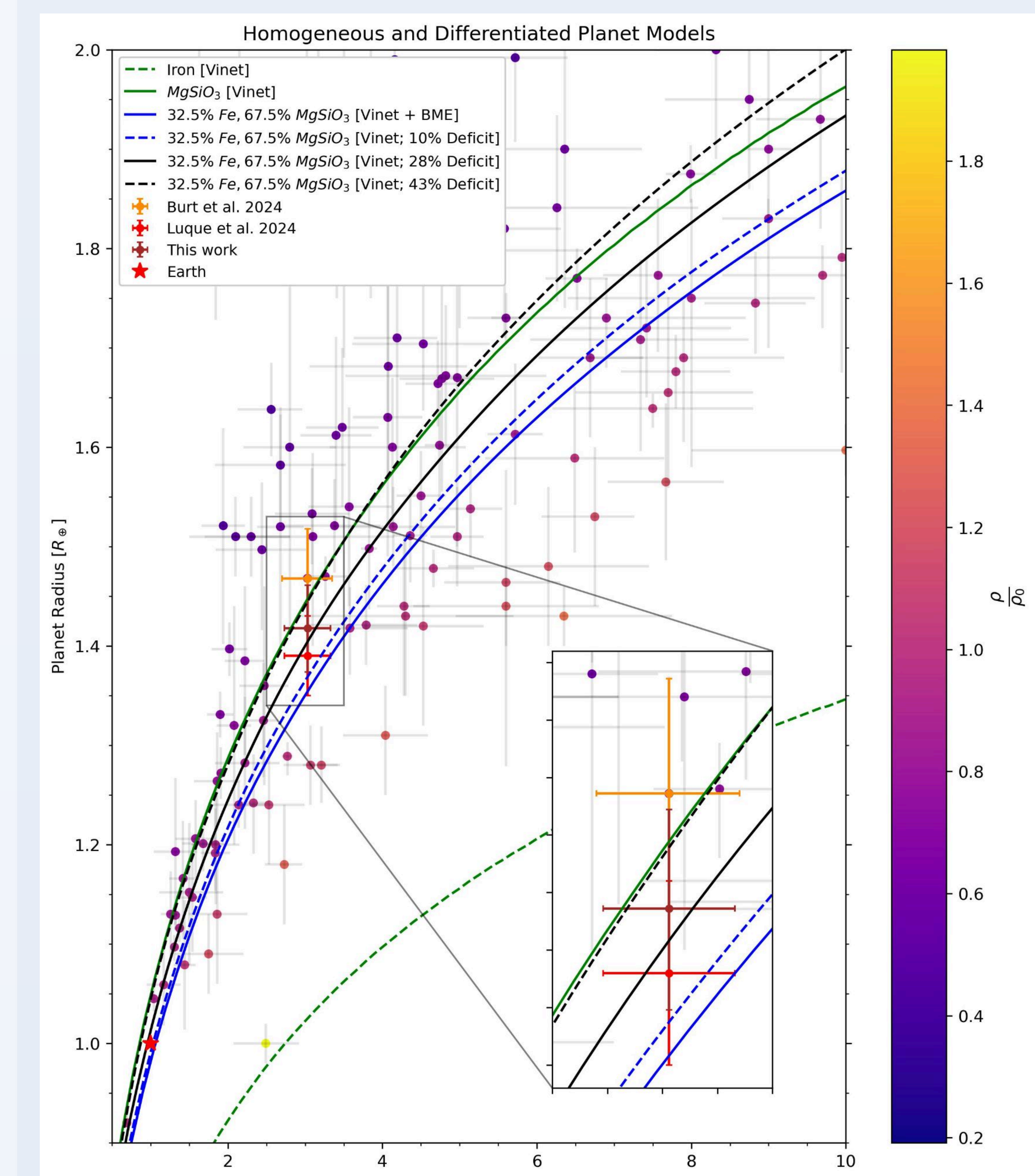

Figure 5: Mass-radius diagram given range of central pressures. The inset captures three independent measurements of TOI-1685b's radius — each with characteristic uncertainty range. The brown point is the result of this work, while the remaining two correspond to the results of Luque et al. 2024 & Burt et al. 2024 utilizing NIRSPEC G395H and TESS measurements, respectively.

FURTHER RESEARCH GOALS

- Discuss implications of the presence of high-altitude aerosols in the context of condensation curves & temperature-pressure profile of TOI-1685b
- Use combined transmission spectrum of TOI-1685b using our NIRISS/SOSS data & **NIRSPEC G395H data** to constrain atmospheric properties[2]
- Perform **well-mixed retrievals** to place constraints on statistical significance of certain species — CH_4 (~ 3.3 µm) — by calculating respective Bayesian Evidence