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A Scale-Height Estimate of the Mean Molecular Weight of K2-18 b from JWST NIRISS SOSS and NIRSpec G395H Transmission Spectra

Muhammad Ibraheem

iamphaser@gmail.com

not affiliated

Short Report

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A Scale-Height Estimate of the Mean Molecular Weight of K2-18 b from JWST NIRISS SOSS and NIRSpec G395H Transmission Spectra

Muhammad Ibraheem

1. Abstract

I estimate the mean molecular weight (μ) of the sub-Neptune K2-18 b from published JWST NIRISS SOSS and NIRSpec G395H transmission spectra. I measure the excess depth of six CH_4 and CO_2 bands against neighbouring continuum, convert it to a scale height, and invert for μ. The mean amplitude is $\Delta D = 56.1 \pm 9.1$ ppm. The resulting μ ranges from 2.0 to 5.3 depending on the assumed temperature (120–255 K) and number of scale heights (N = 4–5), with a statistical error of about 16% at each choice. For 120–160 K, the range of values retrieved at 10 mbar, $\mu = 2.0 – 3.3$. The data are consistent with both light and enriched atmospheres, and the answer is dominated by T and N rather than by measurement noise.

2. Introduction and Data

K2-18 b is a ~2.6 $R_\oplus$, ~8.6 $M_\oplus$ planet in the habitable zone of an M dwarf (Montet et al. 2015; Cloutier et al. 2019). HST/WFC3 spectra showed a water-vapour feature (Tsiaras et al. 2019; Benneke et al. 2019), and interior models allow a water-rich "Hycean" world beneath an H_2-rich envelope (Madhusudhan et al. 2020, 2021). JWST then revealed CH_4 and CO_2 (Madhusudhan et al. 2023). Alternatives include a gas-rich mini-Neptune (Wogan et al. 2024) and a magma-ocean world (Shorttle et al. 2024).

The interpretation remains contested. A reanalysis of the NIRISS SOSS and NIRSpec G395H spectra confirms CH_4 at about 4σ but finds no statistically significant or reliable evidence for CO_2 or DMS (Schmidt et al. 2025). A joint 0.6–12 μm analysis likewise finds insufficient evidence for DMS or DMDS (Piaulet-Ghorayeb et al. 2025). The CO_2 band in my data is the weakest feature, and excluding it leaves the result essentially unchanged (Section 4).

Feature amplitudes constrain μ only through the scale height. A hydrogen-dominated gas has $\mu \approx 2.3$, whereas a heavy secondary atmosphere has $\mu \gtrsim 4$ (Miller-Ricci et al. 2009). So μ can test whether a heavy secondary atmosphere is required. It cannot separate a mini-Neptune from a hydrogen-rich Hycean world, since both are H_2-dominated.

Data: I used the spectra released with Madhusudhan et al. (2023) on OSF (DOI 10.17605/OSF.IO/36DJH), derived from JWST observations archived at MAST. I used the low-resolution products (30 SOSS and 34 NIRSpec bins). The native files (1,010 and 3,401 points, ~250–400 ppm each) were read for QC only.

3. Methodology

Data handling: Each file lists wavelength, bin half-width, depth and uncertainty. All files loaded without NaNs, non-positive errors or ordering problems. I converted to ppm and applied no outlier rejection and no inter-instrument offset. NIRSpec has a gap at 3.70–3.84 μm.

No retrieval: I ran no forward-model retrieval. This is a back-of-envelope estimate that cannot constrain abundances, clouds or temperature structure.

Band amplitudes: Band and baseline windows (Figure 1) are fixed from nominal band positions and the bin grid before any amplitude was computed. Window means are inverse-variance weighted. The six amplitudes are combined by inverse-variance weighting. Because the SOSS baselines share points, the analytic combined error (8.4 ppm) is too small. I adopt $\sigma_{\Delta D} = 9.1$ ppm, the standard deviation of the combined ΔD over 10,000 flat-spectrum Monte Carlo realisations using the observed errors.

Scale height and μ: With ΔD in fractional units,

$$\Delta D \approx \frac{2 \cdot R_p \cdot (N \cdot H)}{R_*^2}$$

$$H = \frac{k_B \cdot T}{\mu \cdot m_H \cdot g}$$

with R* = 308,900 km, Rp = 16,620 km, g = 12.3 m s^{-2}, and N = 4 or 5. I have $\sigma_{\mu/\mu} = \sigma_{\Delta D/\Delta D}$, and I also quote the asymmetric range from $\Delta D \pm \sigma_{\Delta D}$. I evaluate T = 255 K (equilibrium) and T = 120–160 K. Since $\mu \propto T$, T = 140 K scales μ by 0.549.

Rejected alternative: Taking the maximum minus the minimum depth in each instrument gives ΔD = 156 ± 49 and 177 ± 45 ppm, hence μ = 1.35–1.92, below the physical limit. A flat-spectrum Monte Carlo gives median ranges of 170 and 178 ppm, so this estimator measures noise and I discarded it.

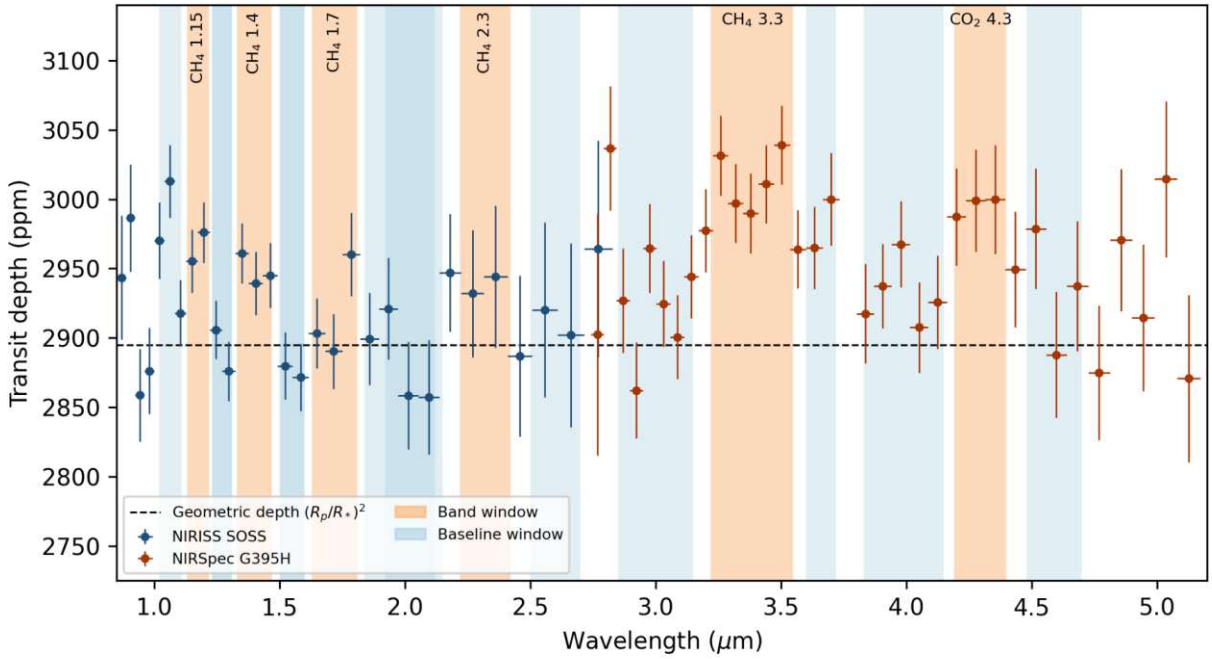


Figure 1. Low-resolution spectra with band (orange) and baseline (blue) windows shaded. The dashed line is the geometric depth $(Rp/R*)^2$ = 2,894.9 ppm.

4. Results and Discussion

Amplitudes: All six bands show a positive excess (individually 1.3–4.5σ) and are mutually consistent (χ^2 = 3.87 for 5 degrees of freedom, p = 0.57). The combined ΔD = 56.1 ± 9.1 ppm is a 6.1σ excess. Excluding CO_2 gives 55.5 ± 8.9 ppm (formal errors), so the result does not depend on the contested CO_2 detection. Single-feature fractional errors range from 22% to 79%.

Scale height and μ: The combined amplitude gives H = 40.3 ± 6.6 km (N = 4) and 32.2 ± 5.2 km (N = 5). At T = 255 K and N = 4, μ is just above 4.0 but its 1σ range extends below it, and it is 2.8σ from the light-envelope value of 2.3. Over 120–160 K and N = 4–5, μ = 2.0–3.3, which

lies in the light-to-gap range. Because the features form where retrievals give 120–160 K, not at the equilibrium temperature, I do not claim a lean toward enrichment. The data are consistent with both a light envelope and enriched atmospheres, neither favoured, and a heavy secondary atmosphere is not required.

Comparison with published values: The adopted radii give a geometric depth of 2,894.9 ppm. The observed mean depths are 2,922.1 ppm (SOSS) and 2,955.2 ppm (NIRSpec), i.e. 27 and 60 ppm above geometric, as expected from atmospheric absorption. The 33 ppm difference between instruments is comparable to the stellar-spot-related offset discussed by Madhusudhan et al. (2023). My positive CH_4 excesses agree qualitatively with the CH_4 detection that reanalyses confirm. I did not compare against retrieved abundances.

Caveats: (i) $\mu \propto N$ and N is unmeasured. (ii) T is uncertain by a factor of ~2. (iii) Band averaging dilutes peaks and the "continuum" contains other absorbers, biasing μ high. (iv) One N is applied to all features. (v) Clouds, hazes and the instrument offset are unmodelled. (vi) A low μ cannot separate a mini-Neptune from an H_2-rich Hycean world, and transmission spectra cannot distinguish liquid from magma oceans. Robust CO_2, CH_4 and DMS detections, more transits and interior modelling are required.

5. Acknowledgments and AI Disclosure

The author thanks Kiranjot Kaur Ma'am for reading a draft of this note, and Amity International School Pushp Vihar for helping with the research. Claude (Anthropic) was used to understand the concepts easily, go through the massive amount of data and perform the lengthy calculations. The author reviewed the results and is responsible for the content.

6. Code and Data Availability

Spectra: OSF DOI 10.17605/OSF.IO/36DJH. Scripts and processed arrays: https://github.com/iamphaser/Research-Paper

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