# ASTR 405
# Planetary Systems
# Transmission Spectroscopy

Fall 2025

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Supplementary Readings: **atmosphere.pdf** on Canvas

*Exoplanet Atmospheres by Sara Seager and Drake Deming*

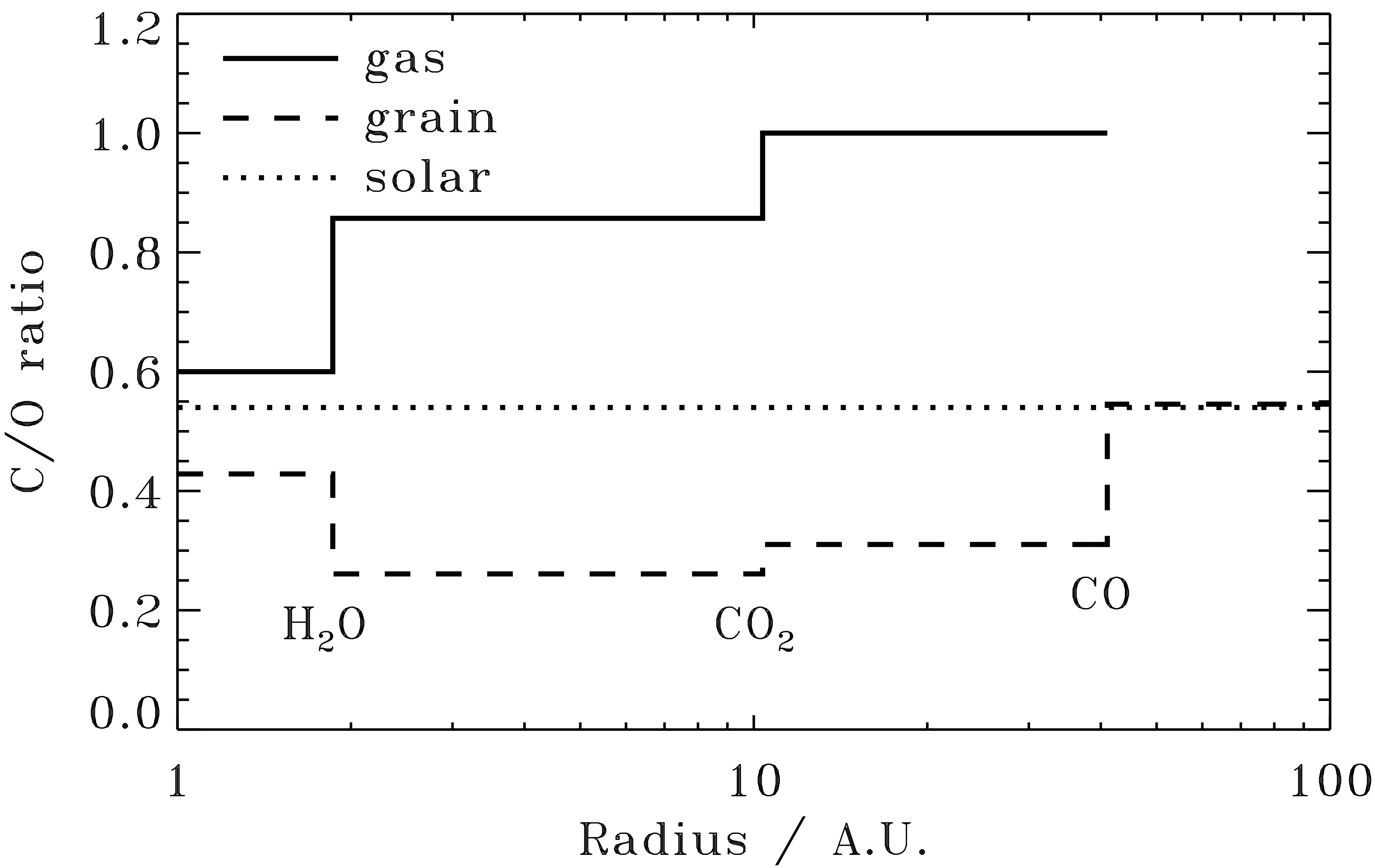
# Modules

- Part I: Exoplanet Detection Methods
  - Explore the techniques astronomers use to discover planets beyond our solar system
- Part II: Exoplanet Demographics and Planet Formation
  - Investigate the statistical properties of exoplanets and theories of how planetary systems form
- **Part III: Exoplanet Atmospheres, Interiors, and Characterization**
  - **Examine methods for studying the physical properties and compositions of distant worlds**

# Atmospheric Composition ↔ Planet Formation

The C/O ratio of a planet's atmosphere reflects where it formed relative to major ice lines in the protoplanetary disk.

Oberg+11



# Module III: Exoplanet Atmospheres, Interiors, and Characterization

- **Exoplanet Characterization**
  - Transmission, emission & phase curves → atmospheric composition, P-T profile
  - Rossiter–McLaughlin effect → spin–orbit angles
- **Atmospheric Physics**
  - Hydrostatic structure and P-T profiles
  - Thermodynamics: convection, lapse rate, and radiative balance
  - Composition and clouds: metallicity, C/O ratio, disequilibrium chemistry
  - Atmospheric loss and the cosmic shoreline
- **Planetary Interiors**
  - Giant planets: phase diagram of hydrogen, central pressure, Hot Jupiter radius inflation
  - Terrestrial planets: heat transport, cooling, and mass–radius relation

# Atmosphere Scale Height

Recall the hydrostatics balance of protoplanetary disks, the exoplanet atmosphere in hydrostatic equilibrium can be expressed as

$$\frac{dp}{dz} = -\rho g \ .$$

From ideal gas law, $p = \rho RT$, and assume an isothermal atmosphere, we get

$$p = p_0 e^{-z/H} \ ,$$

where the scale height is $\boxed{H = \frac{RT}{g}}$.

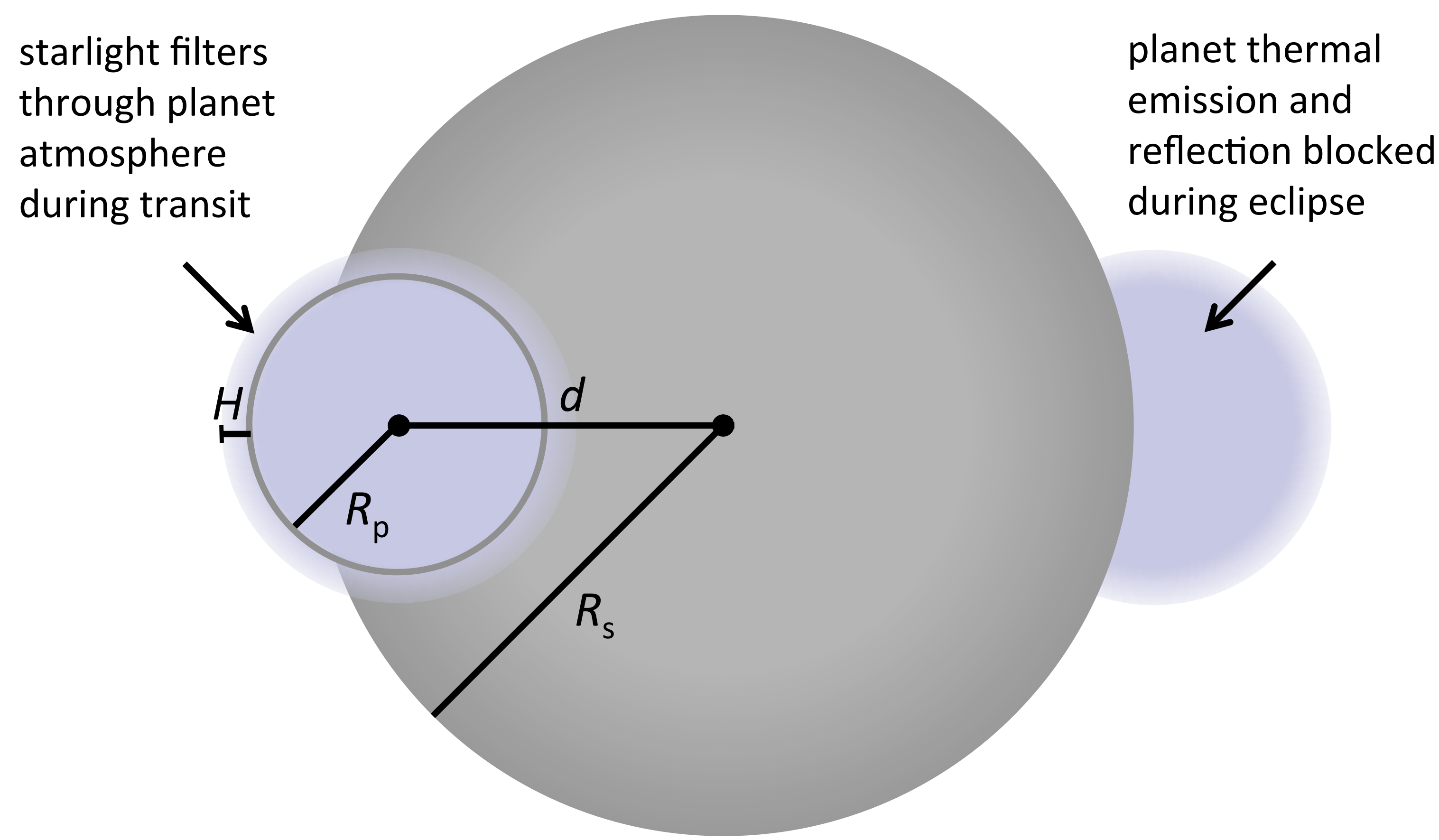
$R = \frac{R_u}{\mu}$ is the **specific gas constant**, which depends on the gas composition. $R_u = 8.3145\ \mathrm{J\,mol^{-1}\,K^{-1}}$ is the universal gas constant and $\mu$ is the mean molecular weight (in $\mathrm{g\,mol^{-1}}$).

**In-Class Activity**

Atmospheric Scale Height of Planets

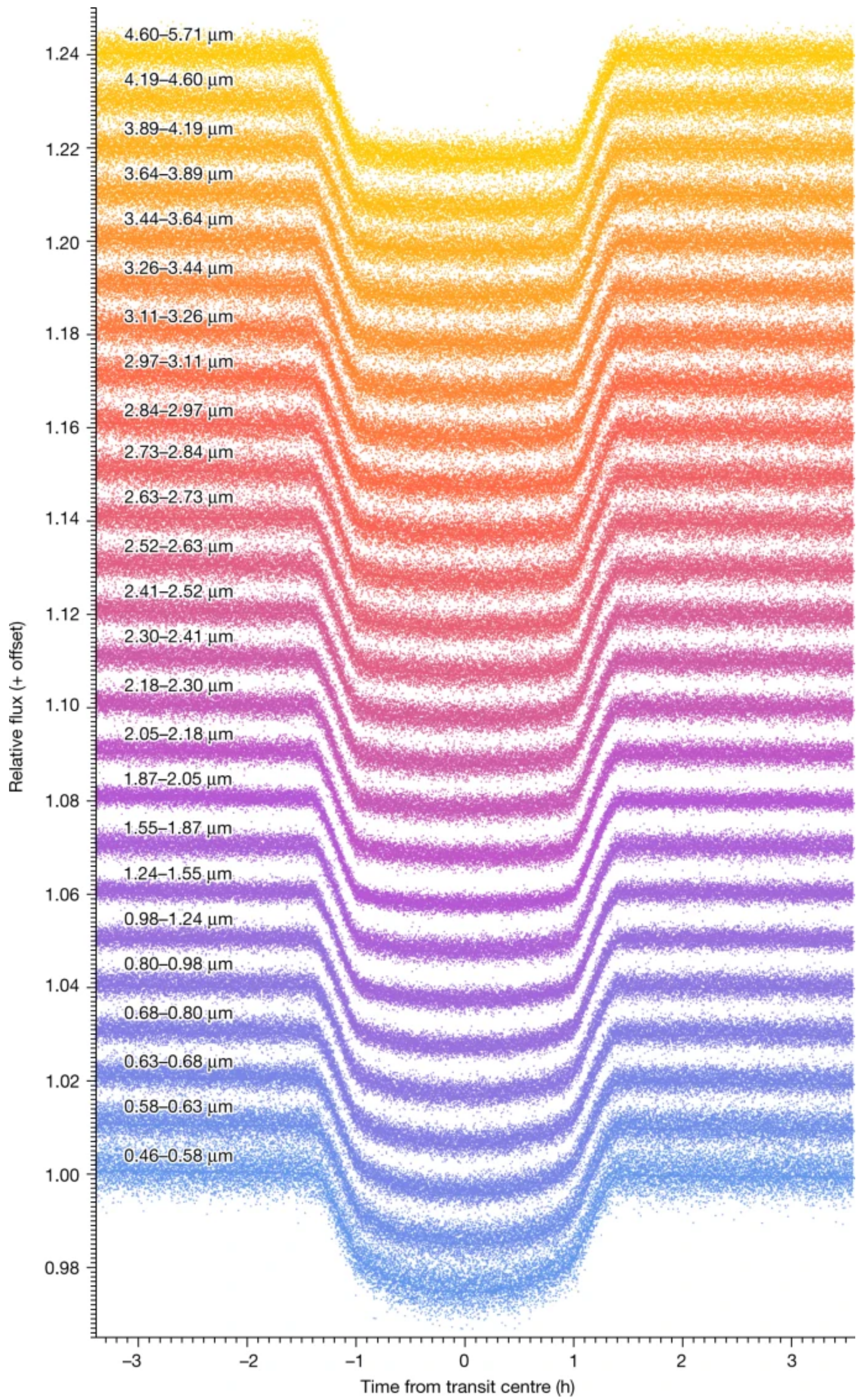
# Transmission Spectroscopy

Transmission spectroscopy probes the atmospheres of exoplanets by studying the transmission (or filtering) of light from the host star through the limb of an exoplanet that appears to occult the host star.

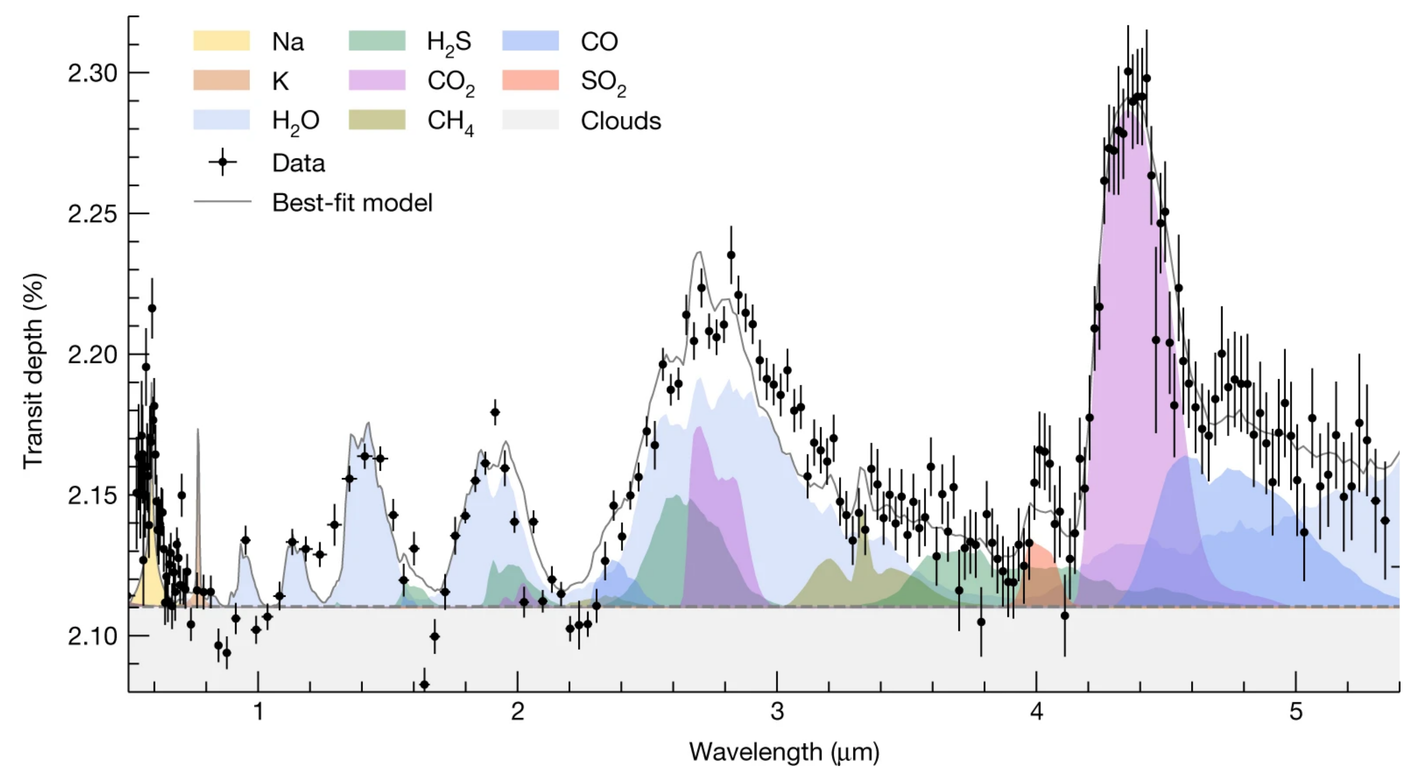



The geometry of a transit event, along with the geometry of the secondary eclipse that is used to derive planetary emission spectra (Kreidberg 17).

# Transmission Spectrum of the hot Jupiters WASP-39b by JWST



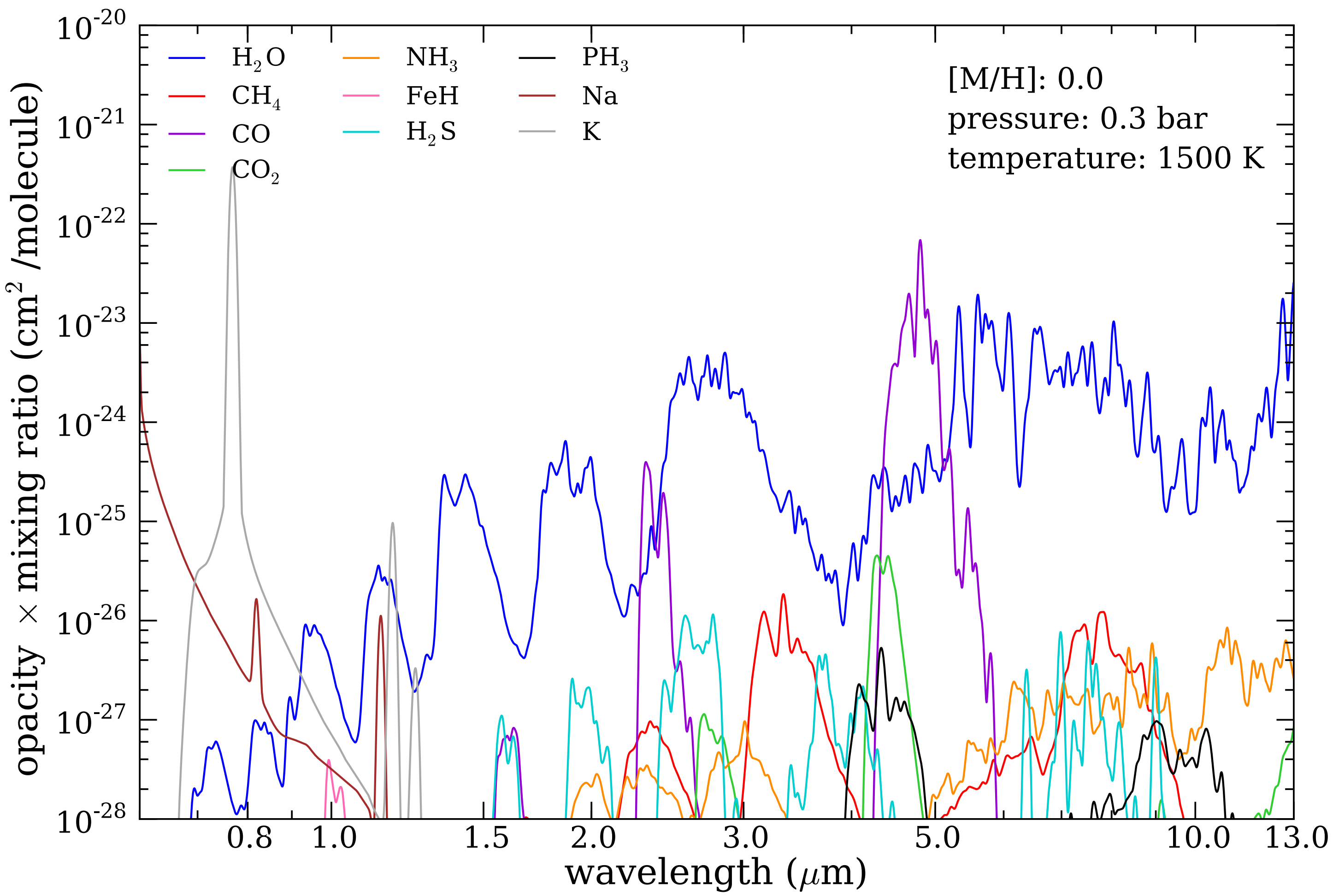

Rustamkulov+23



# Transmission Spectral Features

Transmission spectral features reveal which molecules absorb starlight at specific wavelengths.

- Each molecule has a unique set of absorption bands.
- By matching observed features to these predicted opacities, we can determine which species are present in the atmosphere.




In hot Jupiter atmospheres,

- The strong feature near 1.4 μm arises from water vapor ($H_2O$).
- Carbon monoxide (CO) and carbon dioxide ($CO_2$) dominate at longer infrared wavelengths
- Sodium (Na) and potassium (K) produce broad visible absorption features.

# Transmission Flux Ratio

Transit depth (solid planet): $\delta = \left(\dfrac{R_p}{R_\star}\right)^2$

Including atmosphere: $\delta_\lambda = \dfrac{(R_p + A_{H,\lambda})^2}{R_\star^2}$ , where $A_{H,\lambda} = nH = n\dfrac{RT}{g}$ is the apparent atmospheric height.

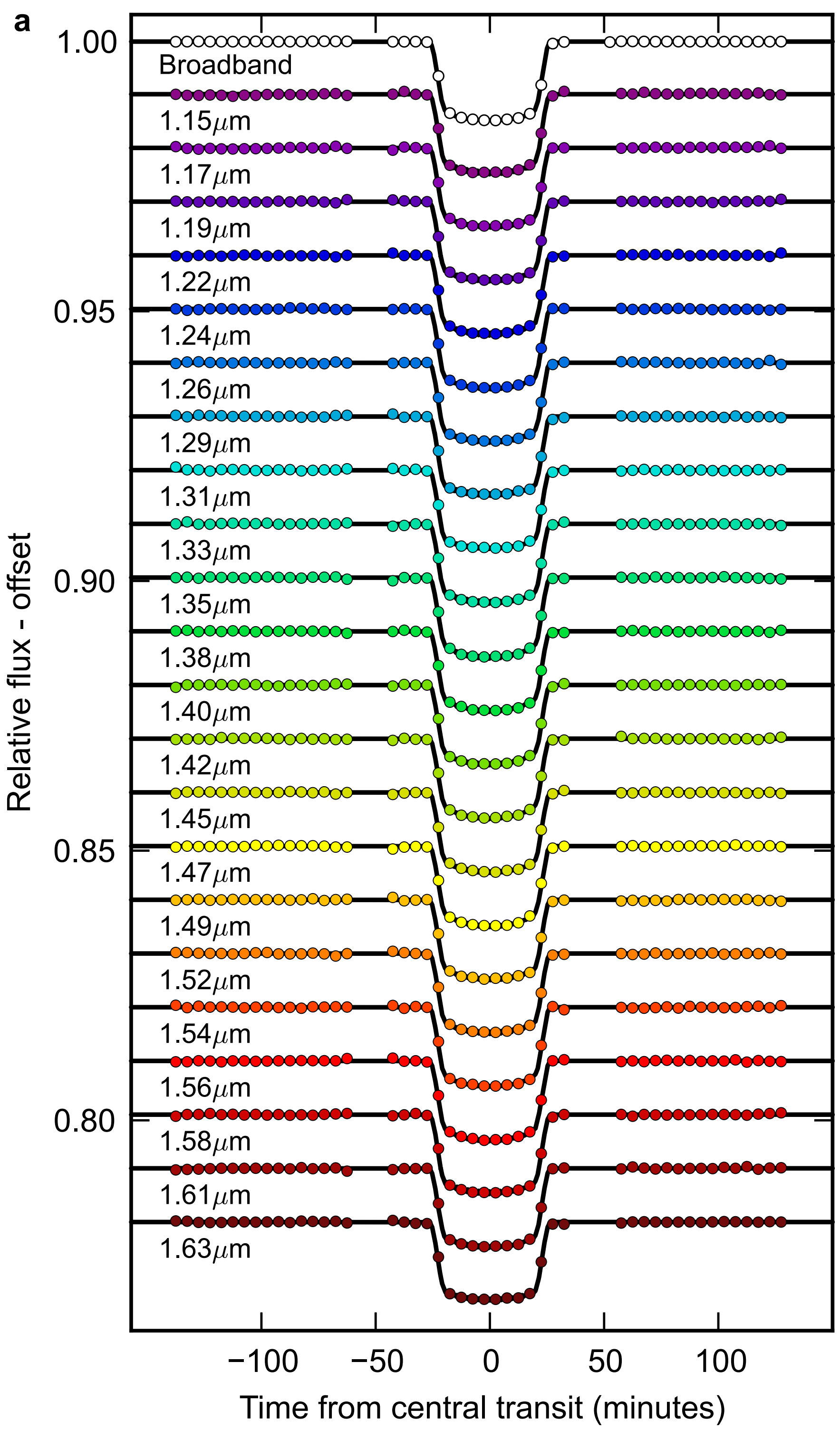
Amplitude of atmospheric feature:

$$\boxed{\delta_{\lambda,atm} = \frac{(R_p + nH)^2}{R_\star^2} - \frac{R_p^2}{R_\star^2} \approx \frac{2R_p nH}{R_\star^2} \approx \frac{2R_p nRT}{gR_\star^2}}$$

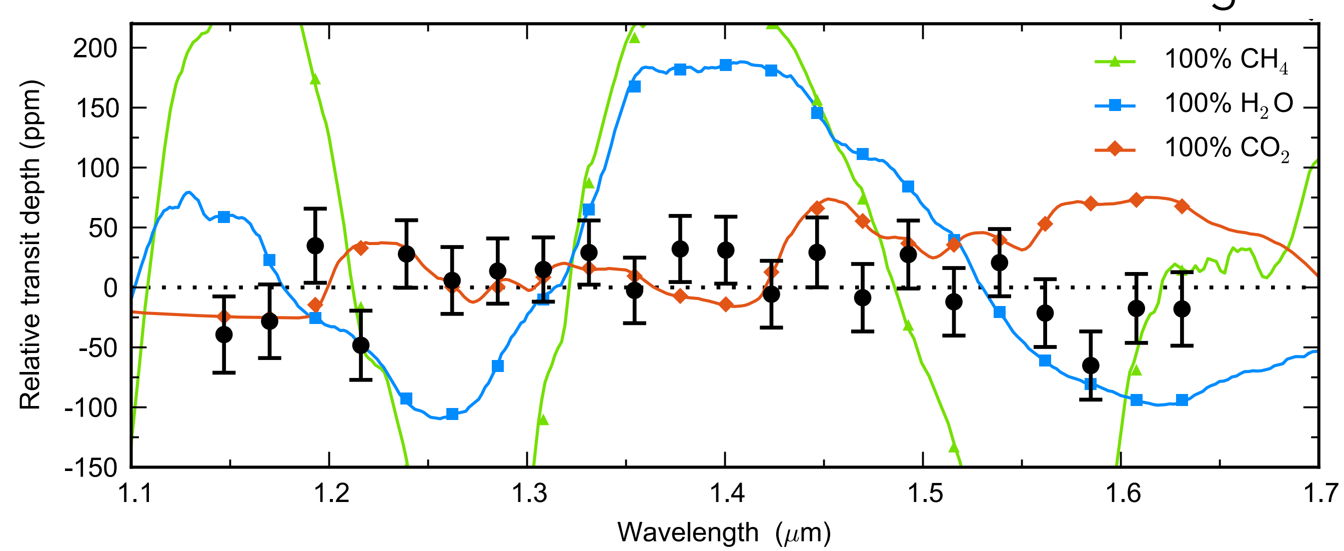
Typical value $n \approx 2$ for low-resolution, cloud-free spectra (Kreidberg 2017).

Feature amplitude increases for hotter, lower-gravity, and low–mean-molecular-weight atmospheres.

# **Featureless** Transmission Spectrum of the sub-Neptune GJ 1214b by HST




Kreidberg 14



# The sub-Neptune GJ 1214b by JWST

*A reflective, metal-rich atmosphere for GJ 1214b from its JWST phase curve* by Eliza Kempton+23

**Eliza is giving a colloquium on 11/18!**