The effect of metallicity on the CH_4 and CO quenched abundance in H-dominated atmospheres

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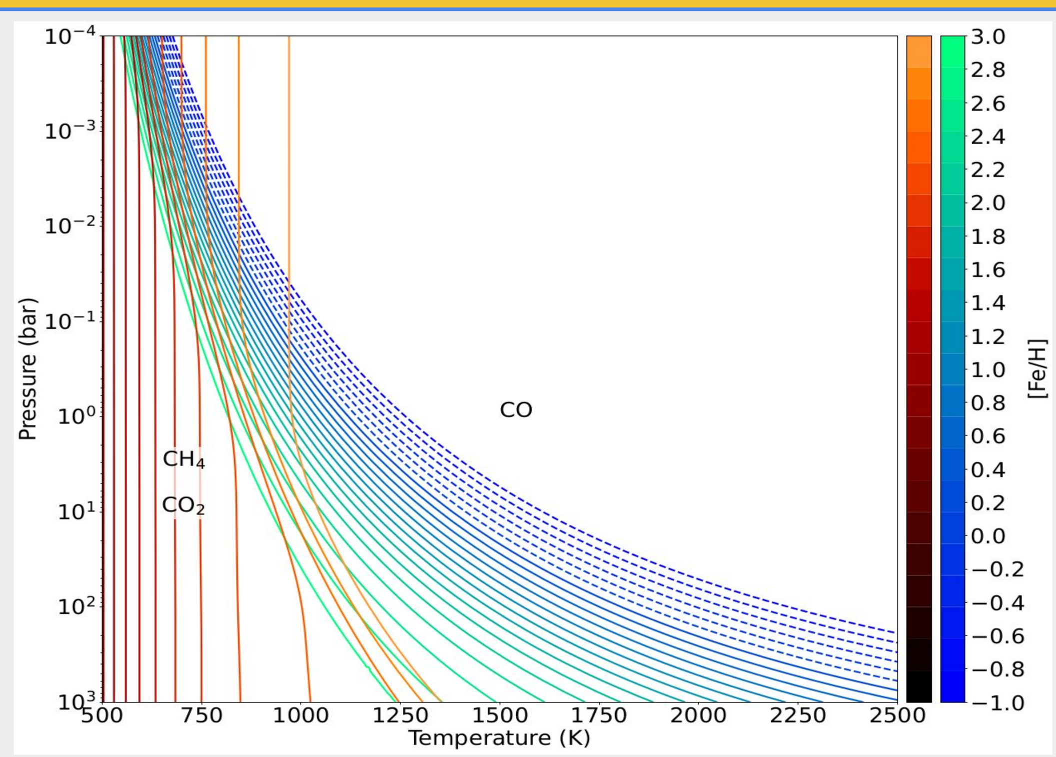
Introduction

- The atmospheric metallicity greatly influences the composition of exoplanet atmospheres.
- We calculate the chemical equilibrium abundance, chemical time scale and vertical mixing time scale to find the quenched curve in our parameter space (temperature: 500-2500 K, pressure: 10^{-4}-10^{3} bar, metallicity: 0.1-1000 × solar metallicity).
- We find the quenched curve for various transport-strength in our parameter range by comparing the chemical and vertical mixing timescales.
- To benchmark our quenched curve, we compare the result of quenching approximation with the 1D photochemistry-transport model.
- We also found that the quenching approximation is a powerful tool to constrain atmospheric parameters.

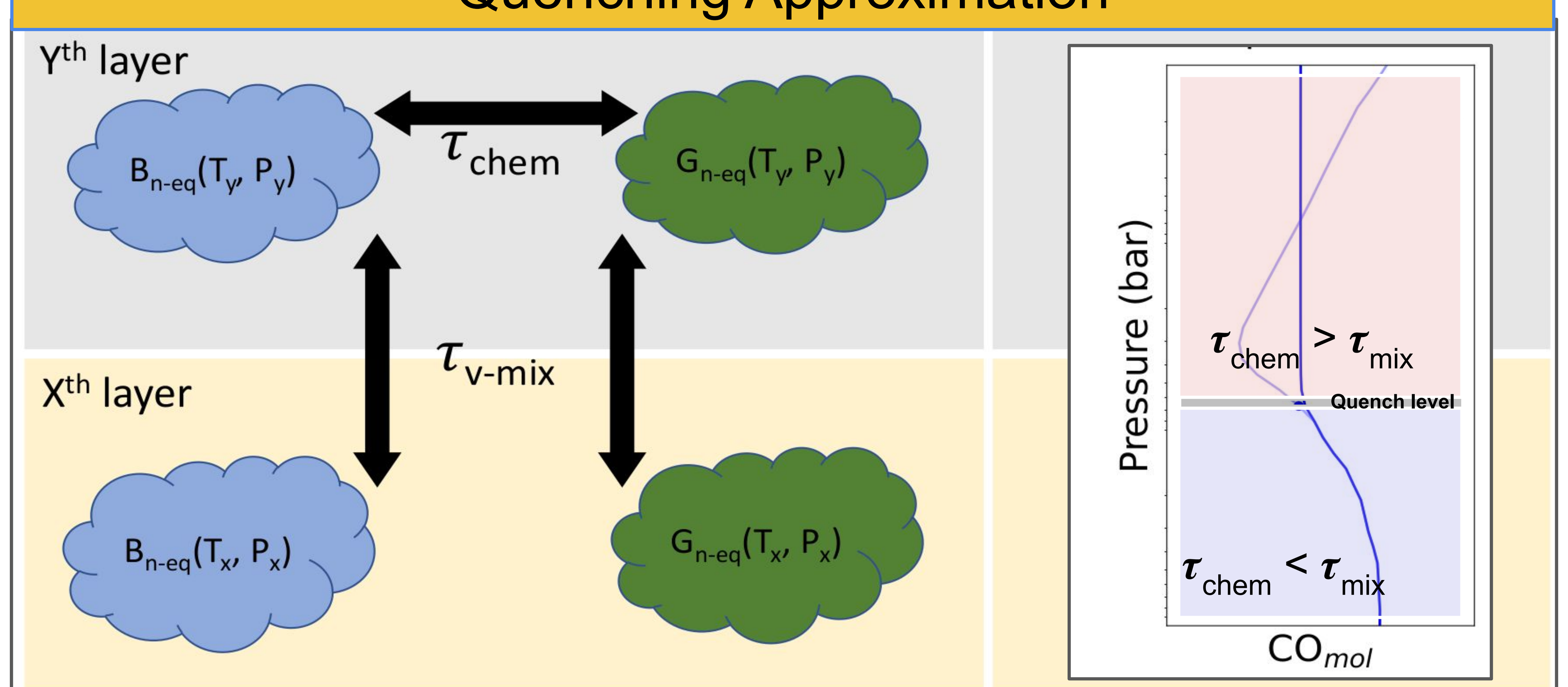
Equilibrium calculation, and mixing processes



Contours of CH_4/CO = 1 and CO_2/CO = 1 for assorted metallicity values are shown. The cyan to blue lines delimitate the region where CH_4 (left) or CO (right) is the dominant species, and the orange to black lines delimitate the region where CO_2 (left) or CO (right) is the dominant species.

- The CO, H_2O, and CO_2 abundances increase with metallicity; however, the CH_4 abundance increases only in the CH_4 dominant region.
- The equal-abundance curve of CH_4 and CO divides the temperature-pressure space of CH_4, CO, CO_2, H_2O into two regions.
- In the CO dominant region, CH_4, CO and CO_2 vary as ≈ $[Fe/H]^0$, ≈ $[Fe/H]^1$, ≈ $[Fe/H]^2$ respectively.
- In the CH_4 dominant region, the increment in CH_4 is proportional to the metallicity, while CO and CO_2 increase more rapidly with metallicity than in the first region.

Quenching Approximation

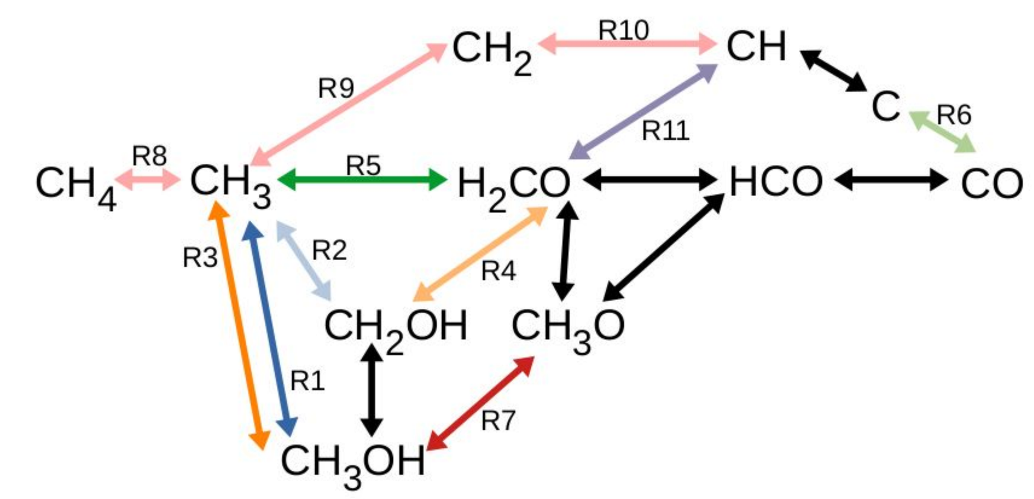


Quenching Approximation (contd.)

Chemical time scale (τ_{chem})

$$\tau_{CO} = \frac{[CO]}{\text{Reaction rate of RLS}} + \tau_{H_2} \times \frac{3[CO]}{H_2}, \quad \tau_{CH_4} = \frac{[CH_4]}{\text{Reaction rate of RLS}} + \tau_{H_2} \times \frac{3[CO]}{H_2}$$

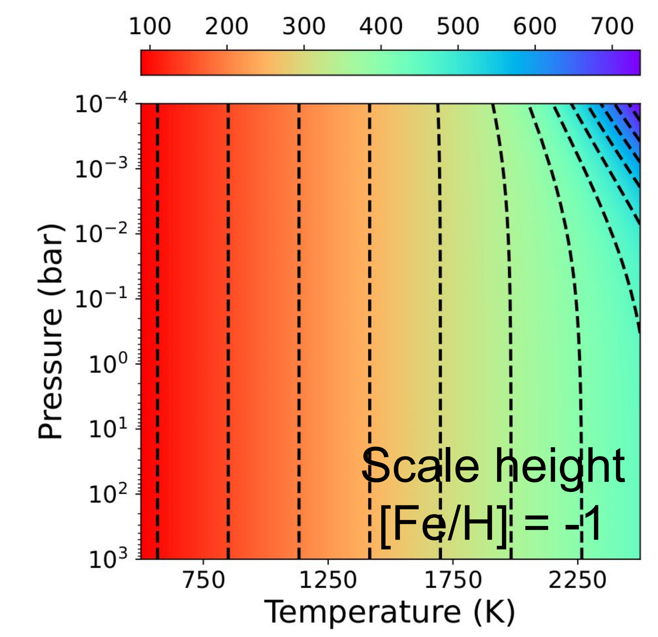
RLS is the rate limiting step, which is the slowest reaction in the fastest conversion scheme. We find the RLS in each of our grid points for the conversion of CH_4-CO-H_2O-CO_2 using an in house developed network analysis tool.



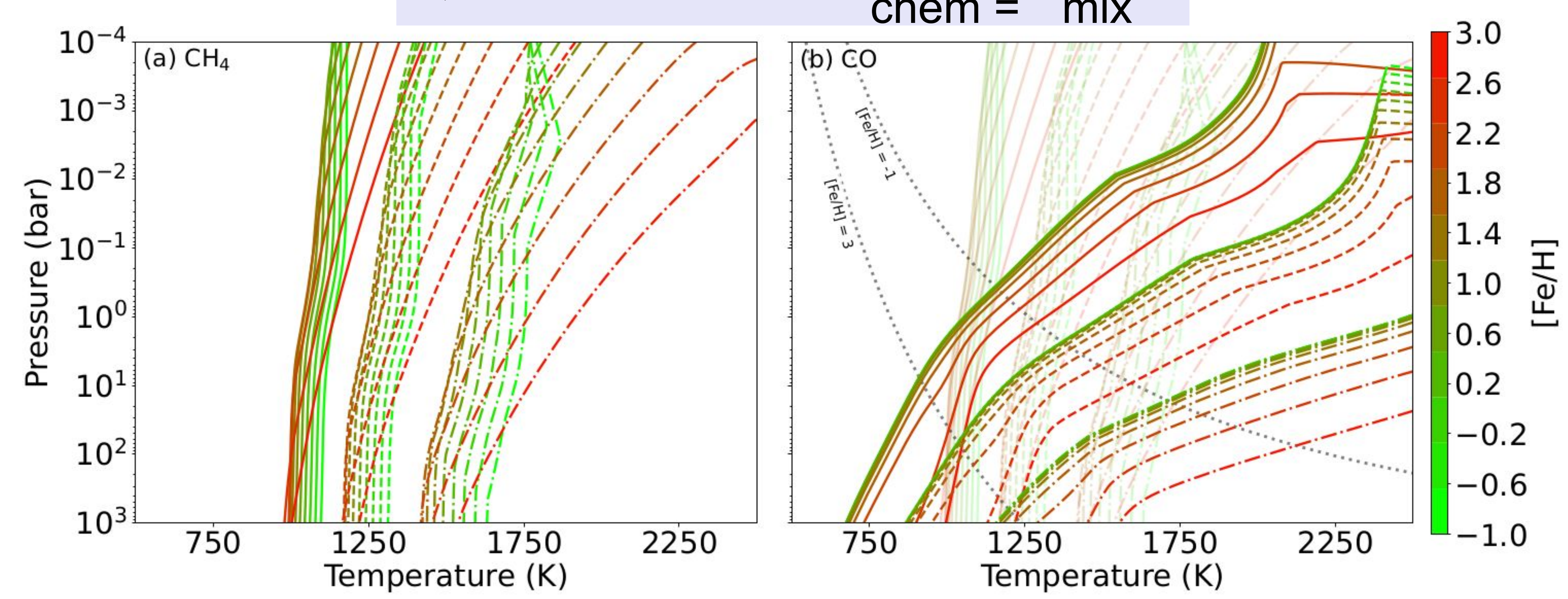
Mixing time scale (τ_{mix})

$$\tau_{mix} = L^2/K_{zz}, \quad H = \frac{K_b T}{\mu g}$$

$$\tau_{mix} = (\eta H)^2/K_{zz}, \text{ where } \eta \in [0.1, 1]$$

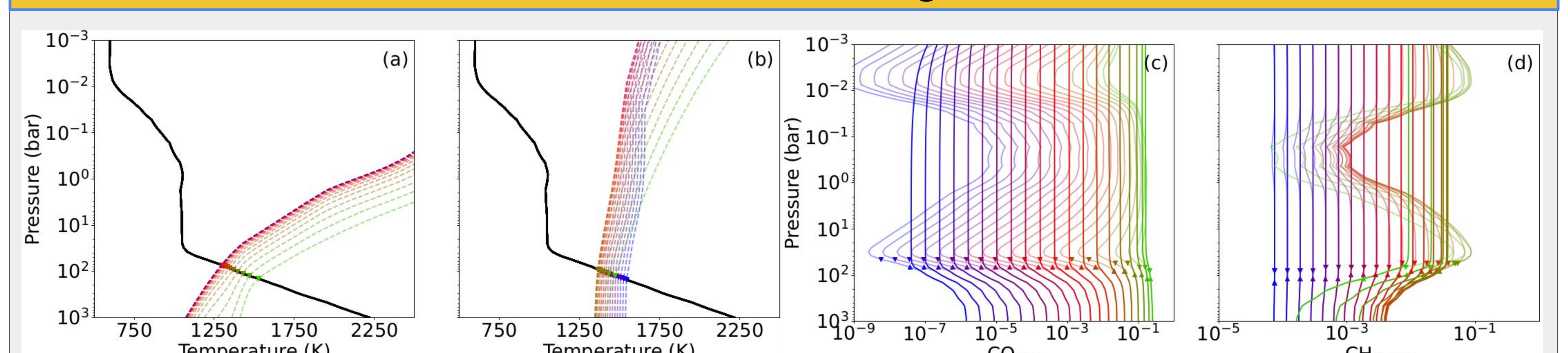


Quenched Curve $\tau_{chem} = \tau_{mix}$



Contour lines on which the vertical mixing and chemical conversion timescales are equal for CH_4 and CO, respectively. The three sets of lines are for different values of K_{zz} coefficients (solid: 10^4 cm^2 s^{-1} , dotted: 10^8 cm^2 s^{-1} , and dashed-dotted: 10^{12} cm^2 s^{-1}). Each set of lines runs from green to red (shown in the color bar), representing eleven different metallicity values.

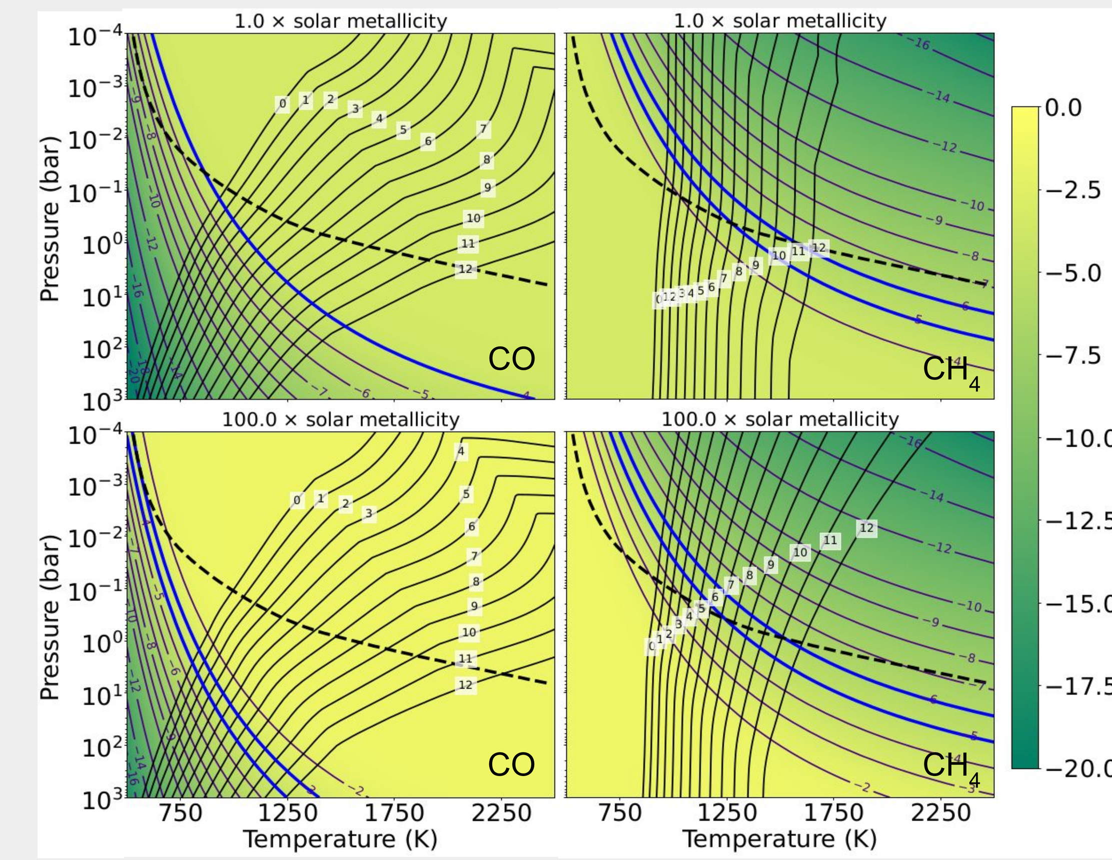
Benchmarking



In (a) and (b) we overplot the thermal profile with the quenched curve of CO and CH4. In (c) and (d) the solid colored lines are the output of the in house developed 1D photochemistry-transport model and the corresponding faded colored lines are the equilibrium abundances. The upper and lower triangles are the quench levels calculated using 0.1H and 1H as the mixing length.

Constraining the parameters

The observed abundance of molecules and the thermal profiles of the exoplanets are overplotted with the color-mesh plot of the equilibrium mixing ratio and quenched curve of the molecules.



Simultaneous constraints on the observed CH_4 and CO abundance conclude that the solar metallicity can explain the abundance along with K_{zz} = 10^7 to 10^{10} cm^2 s^{-1} . The same conclusion has been made by Moses et al. (2016) with a kinetic/transport model. They use K_{zz} = 4 × 10^7 cm^2 s^{-1} , the solar metallicity, and C/O = 0.66 to best fit the observed abundance.

Conclusion

- In the CO dominant region, CH_4, CO and CO_2 vary as ≈ $[Fe/H]^0$, ≈ $[Fe/H]^1$, ≈ $[Fe/H]^2$ respectively, and in the CH_4 dominant region CH_4 varies as ≈ $[Fe/H]^1$
- For a fixed K_{zz} value, the CO quenched curve shifts towards the lower atmosphere with increasing metallicity, and CH_4 quenched curve shows complex behaviour.
- The quenching approximation is a powerful tool that can constrain the metallicity and transport strength without solving the transport model.

References

1. Quenching approximation
   Smith, M. D. 1998, Icarus, 132, 176
2. Chemical timescale
   Tsai, S.-M., Kitzmann, D., Lyons, J. R., et al. 2018, ApJ, 862, 31
3. Vertical mixing timescale
   Moses, J. I., Visscher, C., Fortney, J. J., et al. 2011, ApJ, 737, 1
4. Constraining the parameters
   Moses, J. I., Marley, M. S., Zahnle, K., et al. 2016, ApJ, 829, 66

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