Differentiating Mini-Neptune and Terrestrial Atmospheres for HWO

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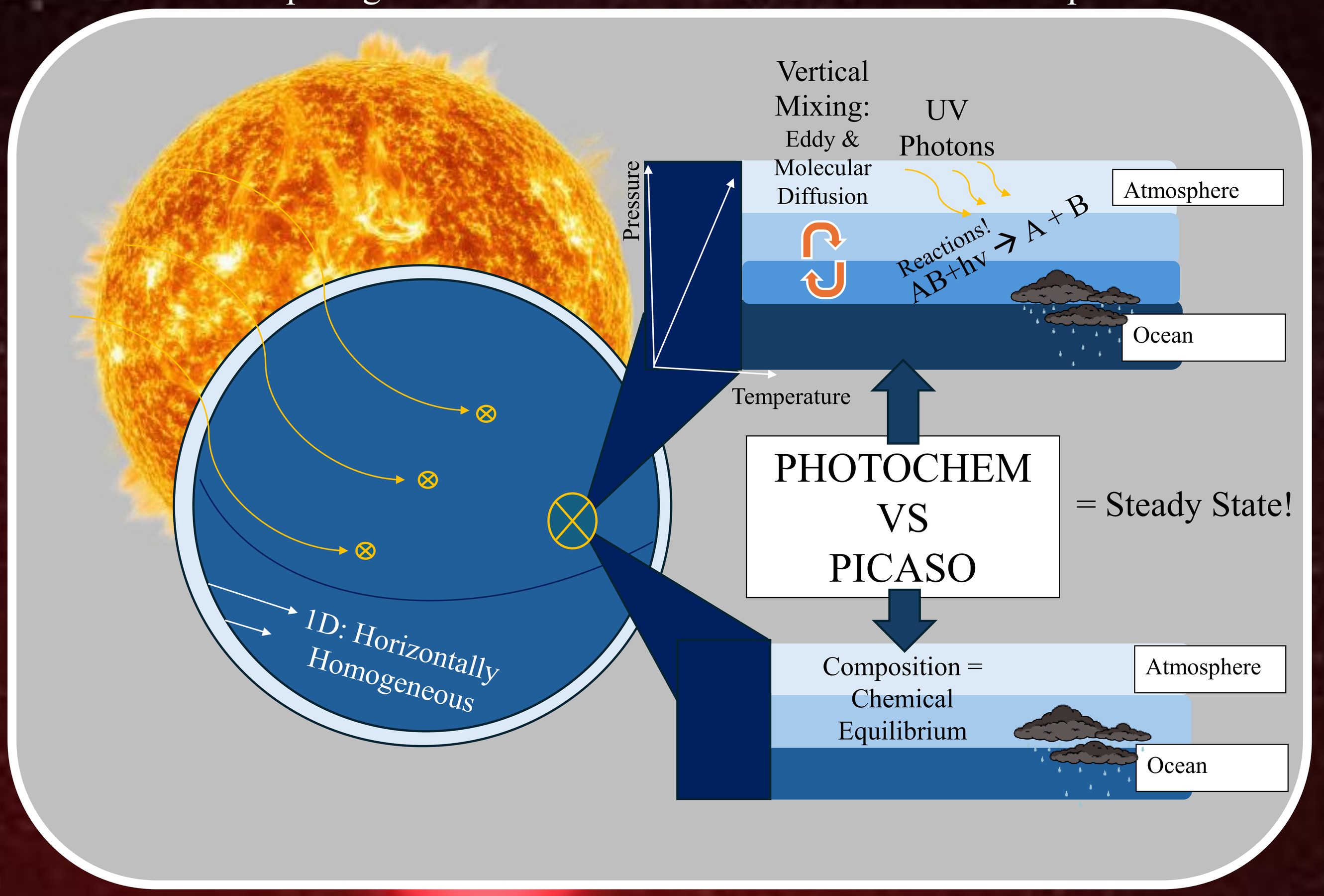
Introduction:

The Habitable Worlds Observatory (HWO), one of NASA's next flagship missions, aims to detect and characterize Earth-like planets around Sun-like stars in search for biosignatures and potentially habitable conditions. One means of characterization is through examining the spectra of reflected light; however, without implementing a secondary detection method like radial velocity, the mass, radius, and bulk density are poorly constrained.

Previous research, such as Wogan et. al. 2024, has applied Photochem and PICASO that are 1D photochemical and climate models for planets like K2-18b, whose CH_4 and CO_2 levels could be explained by being hycean (global surface ocean with atmosphere) with a methane-producing biosphere, or by being an abiotic gas-rich mini-Neptune.

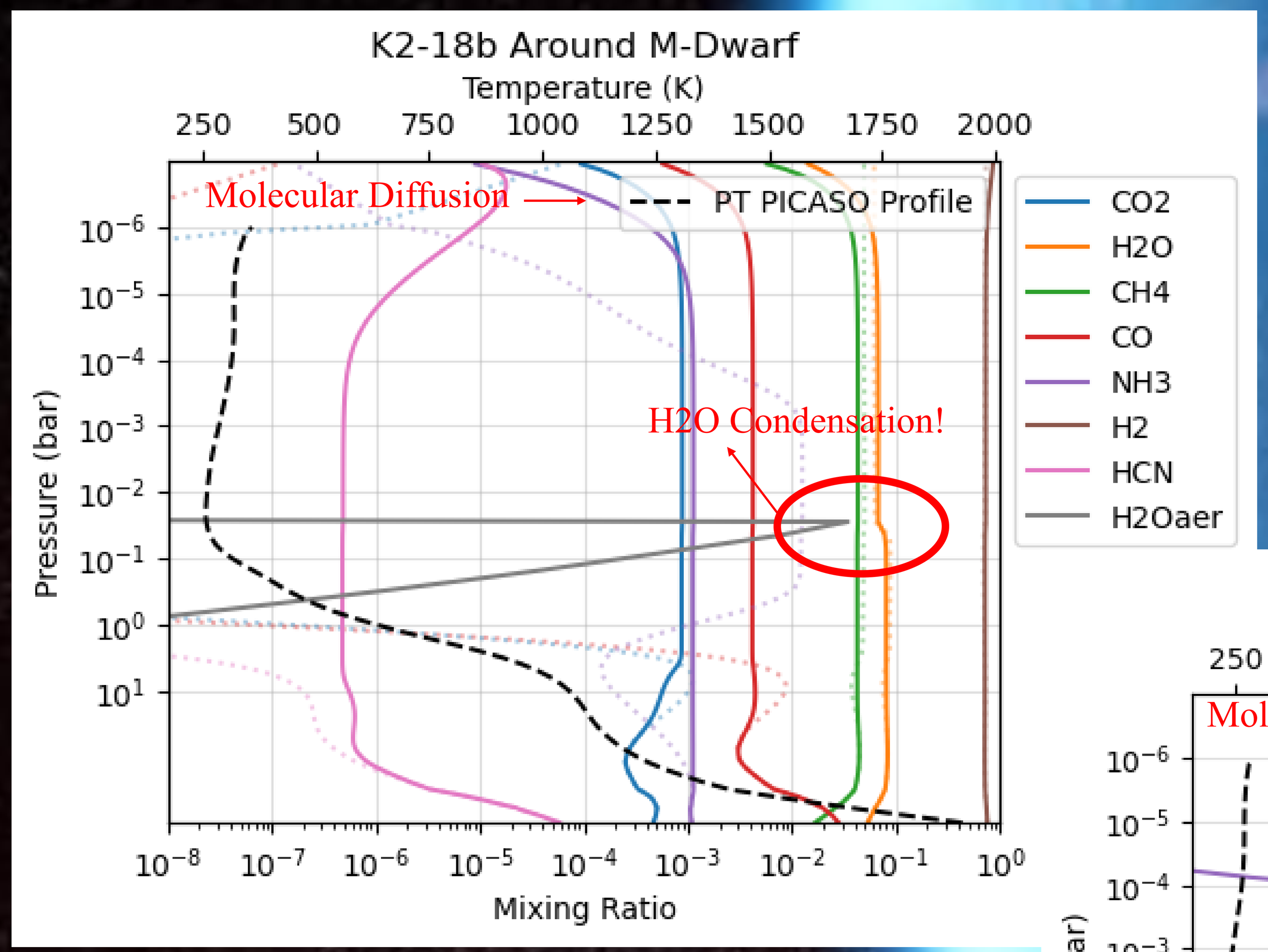
1D Photochemical Model:
Comparing PICASO & Photochem Limitations & Assumptions



We will extend the application of these models to the following questions; How can we differentiate the reflected spectra of uninhabitable mini-Neptunes that differ by host star and planet properties to an inhabited terrestrial planet like Earth? And how does this affect required wavelength binning (resolution) and precision necessary for HWO?

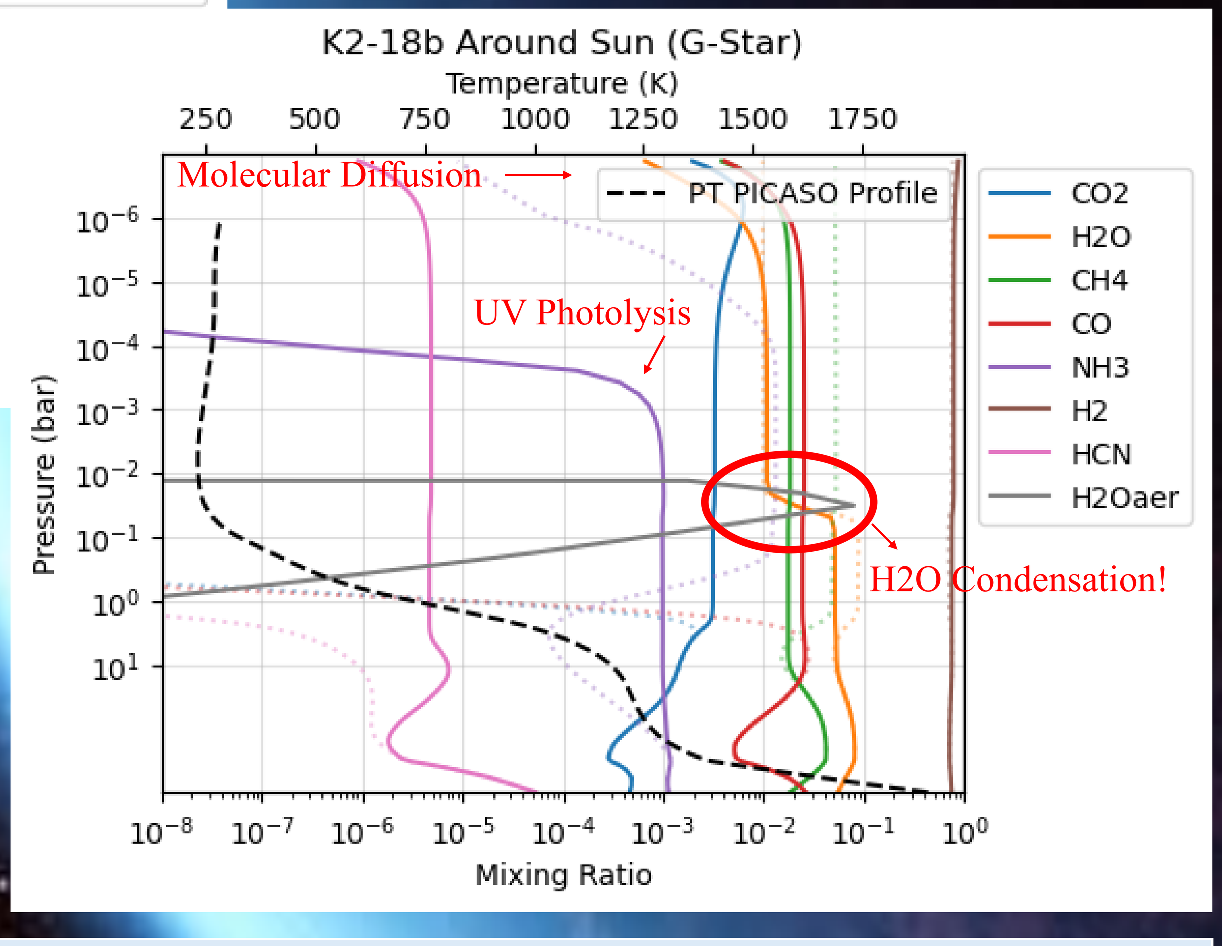
Preliminary Results:

Major assumptions include that K2-18b has 100x solar metallicity, solar C/O ratio, a Kzz (eddy diffusion) coefficient of 10^7 cm^2/s, and an equilibrium temperature of 278 K, around its M-dwarf with stellar flux determined by a proxy (GJ 176) like Wogan et. al. 2024, and around the Sun (G-star). The solid lines represent abundances of gas molecules (aer is liquid) in the atmosphere at a steady state, while dashed colored lines were at chemical equilibrium. The black dashed line is the PT profile PICASO solved for.



K2-18b for the G-star generally had higher abundances of CO & CO_2 higher in the atmosphere. It also had a sharper drop-off in abundance at around 0.0001 bar for NH_3 likely due to stronger UV Photolysis and more extensive condensation of H_2O.

K2-18b around an M-dwarf and G-star have similar abundances of CH_4, NH_3 (lower atmosphere), while the condensation of H_2O occurs at around 0.01-0.1 bar of pressure.



Methodology

Step 1: Apply PICASO model to solve for temperature as a function of pressure for 1D climate modeling.

Known Inputs:

Planet effective temperature and gravity.

Star opacity, temperature, gravity, metallicity, radius, semi major axis

Initial Guesses to iterate over for the Planet:

Mainly initial temperature for a number of pressure levels with defined bottom/top boundaries.

Also, equilibrium temperature, number of convective zones, top and bottom of convective zone(s), how much external radiation on the planet in %.

Relates TP profile, chemical structure, and energy transport in the atmosphere, assuming chemical equilibrium & energy conservation. For more specifics see Mukherjee et. al. 2022.

Outputs: PT profile

Step 2: Take the PT profile from PICASO and solve for photochemistry of the atmosphere using Photochem.

Known Inputs:

Allowable photochemical reactions and elements, mass, radius, thermodynamics for the planet.

The flux and molecular abundance composition of the host star.

Guesses initial atmospheric composition in molecules/cm^3/s from the PICASO PT profile, eddy diffusion coefficient (free parameter), metallicity, and C/O ratio of the planet in chemical equilibrium.

Iterates over the atmospheric composition until reaching a steady state (no more reactions) accounting for UV radiation and vertical mixing with a temperature gradient (more than just chemical equilibrium); assumes mass conservation.

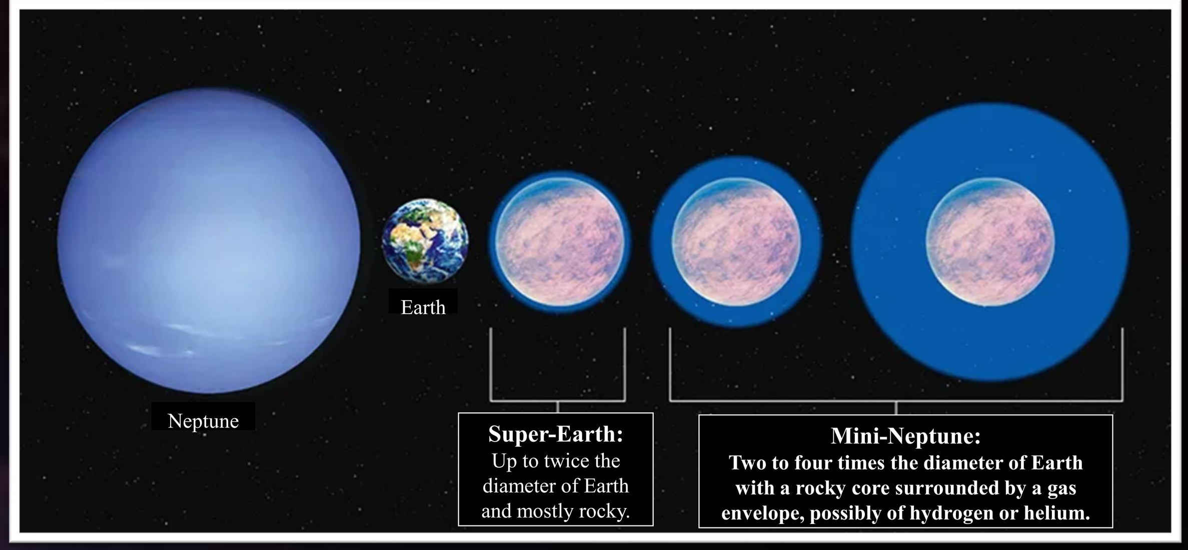
Outputs: Composition in molecules/cm^3 over time.

Step 3: Loop over steps 1-2 changing known inputs for a range of mini-Neptunes & Earth.

Future Work:

We are actively working on exploring…

1. A parameter space of spectra for mini-Neptunes that vary in planet metallicity, vertical mixing, internal heat flux, pressure, radius, and mass, as well as type of host star and binning wavelength.
2. The differences between these mini-Neptunes, and the spectra of Archean, Proterozoic, and Modern Earth conditions.
3. How we can apply these differences between mini-Neptunes and terrestrial planets to requirements for observed wavelengths, SNRs, and spectral resolution for HWO.



Comparison of the size of terrestrial planets (Earth and Super Earth) to gas-giants like Neptune and mini-Neptunes (NASA/ESA/CSA and STScI).

References

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Mukherjee, et al. "PICASO 3.0: A One-Dimensional Climate Model for Giant Planets and Brown Dwarfs." The Astrophysical Journal (2022): 157.

Wogan N. F., Batalha N. E., Zahnle K. J. et al. 2024 ApJL ***963*** *L7* **DOI** 10.3847/2041-8213/ad2616