

Comparing the Transmission and Emission Spectra of Hypothetical ExoEarths and ExoVenuses. C. M. Ostberg¹, S. R. Kane¹, P. A. Dalba¹, and A. Lincowski² ¹University of California, Riverside, ²University of Washington, Seattle

Introduction: Venus' popularity has grown immensely in the past few years and is best illustrated by recently announced missions like VERITAS [1], DAVINCI [2], and EnVision [3]. These missions will obtain information that will be vital for understanding Venus' evolutionary history. Studying Venus' past is vital as it is possible it had an extended temperate period [4], but it has evolved to become drastically different from Earth. An improved understanding of what caused the demise of Venus is necessary for learning what it takes to make a planet uninhabitable/habitable.

Studying the atmospheres of potential exoVenuses offers a complementary route of investigating Venus' past. Atmospheric observations of a planet similar to Venus could support hypotheses of past Venus' climate states. Additionally, surveying large samples of potential exoVenus atmospheres could give insight into whether Venus' current state is common among terrestrial planets in similar circumstances.

There is currently a surplus of confirmed terrestrial exoplanets which are in the Venus Zone (VZ) [5]. The VZ is defined as the area around a star where we can expect planets to be too hot to sustain liquid surface water, while still maintaining an atmosphere. Assuming that a planet with radius less than 2.0x the radius of Earth qualifies as terrestrial, then the NASA Exoplanet Archive [6] yields 312 terrestrial planets in the VZ. This number will be increasing continuously over the coming years as the 5,000+ planet candidates discovered by the Transiting Exoplanet Survey Satellite (TESS) are confirmed. TESS planets differ from that of Kepler/K2 as their host stars are in our galactic neighborhood, making the planets well-suited for follow-up observations with the James Webb Space Telescope (JWST) or other future facilities. Ostberg & Kane (2019) [7] used the Transmission Spectroscopy Metric (TSM) [8] to demonstrate that TESS planets in the VZ have a high S/N ceiling if observed by JWST with transmission spectroscopy.

The presence of Venus-like clouds and haze on a VZ planet would significantly impact the ability of JWST to identify absorption features in transmission spectra [9], but it is still unclear the types of atmospheres VZ planets may yield. Another problem that may be encountered when observing VZ planets is deriving surface conditions from their transit spectra. This arises from similarities in absorption features in the transit spectra of Venus-like and Earth-like planets that cause retrieval models to mistake Venus-like planets as having Earth-like surface conditions [10]. In this work we compare the transmission and emission spectra of 6 hypothetical

Earth-like and Venus-like planets to determine if any absorption/emission features may reliably differentiate the two types of planets.

Modeling ExoEarths and ExoVenuses: We used a single hypothetical Earth-sized planet on the runaway greenhouse boundary [11] of the TRAPPIST-1 system for both planet types. For the exoVenuses, we first assumed a 96% CO₂ Venus-like atmosphere with a surface pressure of 10 bars instead of 92 bars. We then created 5 other exoVenuses with 10 bar surface pressure but with varying atmospheric CO₂ less than 96%. The abundance of N₂ was increased in the atmospheres when decreasing CO₂ to keep the 10-bar surface pressure constant. No clouds or hazes were included in any of the six exoVenus atmospheres. The default exoEarth atmosphere we used is that of present-day Earth including its pressure-temperature profile and atmospheric abundances. We created 5 additional exoEarth atmospheres that vary from 0.4 ppm to 4% CO₂.

The 6 exoEarth and exoVenus atmospheres were used as initial conditions for a Virtual Planet Laboratory climate model that is derived from the SMART radiative transfer model [12]. The model has been used for modelling both Venus-like and Earth-like exoplanets [13]. We ran the model for all 12 planets until the planets reached thermal and hydrostatic equilibrium.

Producing Transmission and Emission Spectra: The resulting atmospheres produced from the climate models along with the physical, orbital, and stellar parameters of our hypothetical planets were used as inputs for the Planetary Spectrum Generator (PSG) [14]. PSG is an online radiative transfer code with the ability to simulate transmission and emission spectra of exoplanets and solar system bodies. The transit spectra we produced with PSG (Figure 1) used the wavelength range of the James Webb Space Telescope (JWST) NIRSpec PRISM instrument (0.6 – 5.0 μm), while the emission spectra (Figure 2) are in the wavelength range of JWST MIRI LRS (5.0 – 12.0 μm). We assumed no noise sources for all PSG spectra.

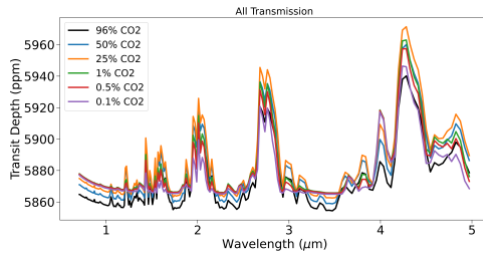


Figure 1: Transmission spectra of the 6 exoVenuses created with PSG

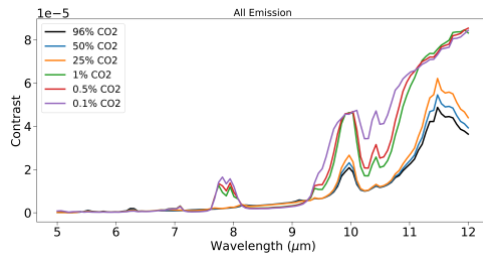


Figure 1: Emission spectra of the 6 exoVenuses created with PSG

Comparing Spectra and Modelling JWST Observations: The transmission spectra of Earth and Venus analogs have been shown to be hard to differentiate despite their drastic differences in atmospheres and climates. We further investigate this issue by analyzing the absorption features in the transmission spectra of both the exoEarths and exoVenuses. Since the similarity in CO₂ features between the two planets is primarily responsible for the ambiguities when comparing the two, we test to see whether CO₂ variants of the two planets are also similar. We also check to see whether other absorption features in either planets' transmission spectra may be used to differentiate one from another. Additionally, we compare the emission spectra of the two sets of planets to determine whether emission spectra may be a better method of telling the two planet types apart.

JWST transit and secondary eclipse observations are simulated for both planet types using PandExo (Batalha et al. 2018). These simulations will be used to confirm whether the differences seen in the noise-less, modelled spectra will be detectable by JWST. This analysis will clarify if there are certain features to prioritize capturing in observations when confronted with a planet that may be Earth-like or Venus-like, as well as the amount of observations that would be required to resolve the features.

References: [1] Garvin, James B., et al. "Revealing the Mysteries of Venus: The DAVINCI Mission." *The Planetary Science Journal* 3.5 (2022): 117. [2] Cascioli, Gael, et al. "The

determination of the rotational state and interior structure of Venus with VERITAS." *The Planetary Science Journal* 2.6 (2021): 220. [3] Widemann, Thomas, et al. "EnVision: Europe's proposed mission to Venus." *Agu fall meeting abstracts*. Vol. 2020. 2020. [4] Way, Michael J., and Anthony D. Del Genio. "Venusian habitable climate scenarios: Modeling Venus through time and applications to slowly rotating Venus-like exoplanets." *Journal of Geophysical Research: Planets* 125.5 (2020): e2019JE006276. [5] Kane, Stephen R., Ravi Kumar Kopparapu, and Shawn D. Domagal-Goldman. "On the frequency of potential Venus analogs from Kepler data." *The Astrophysical Journal Letters* 794.1 (2014): L5. [6] Akeson, R. L., et al. "The NASA exoplanet archive: data and tools for exoplanet research." *Publications of the Astronomical Society of the Pacific* 125.930 (2013): 989. [7] Ostberg, Colby, and Stephen R. Kane. "Predicting the yield of potential venus analogs from TESS and their potential for atmospheric characterization." *The Astronomical Journal* 158.5 (2019): 195. [8] Kempton, Eliza M-R., et al. "A framework for prioritizing the TESS planetary candidates most amenable to atmospheric characterization." *Publications of the Astronomical Society of the Pacific* 130.993 (2018): 114401. [9] Lustig-Yaeger, Jacob, Victoria S. Meadows, and Andrew P. Lincowski. "The detectability and characterization of the TRAPPIST-1 exoplanet atmospheres with JWST." *The Astronomical Journal* 158.1 (2019): 27. [10] Barstow, Joanna K., et al. "Telling twins apart: exo-Earths and Venuses with transit spectroscopy." *Monthly Notices of the Royal Astronomical Society* 458.3 (2016): 2657-2666. [11] Kopparapu, Ravi Kumar, et al. "Habitable zones around main-sequence stars: new estimates." *The Astrophysical Journal* 765.2 (2013): 131. [12] Robinson, Tyler D., and David Crisp. "Linearized Flux Evolution (LiFE): A technique for rapidly adapting fluxes from full-physics radiative transfer models." *Journal of Quantitative Spectroscopy and Radiative Transfer* 211 (2018): 78-95. [13] Lincowski, Andrew P., et al. "Evolved climates and observational discriminants for the TRAPPIST-1 planetary system." *The Astrophysical Journal* 867.1 (2018): 76. [14] Villanueva, Geronimo L., et al. "Planetary Spectrum Generator: An accurate online radiative transfer suite for atmospheres, comets, small bodies and exoplanets." *Journal of Quantitative Spectroscopy and Radiative Transfer* 217 (2018): 86-104. [15] Batalha, Natasha E., et al. "PandExo: a community tool for transiting exoplanet science with JWST & HST." *Publications of the Astronomical Society of the Pacific* 129.976 (2017): 064501.