A Catalog of ExoVenus Candidates and Their Potential for Follow-up Observations

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Introduction: Venus' popularity has grown immensely in the past few years, which is best illustrated through the approval of the NASA discovery missions VERITAS and DAVINCI, and the ESA EnVision mission. These missions will obtain information that will be vital for understanding Venus' evolutionary history, which may have included an extended period of temperate surface temperatures (Way et al. 2020). Studying the atmospheres of potential exo-Venuses 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 exo-Venus atmospheres could give insight into whether Venus' current state is common among terrestrial planets in similar circumstances.

There are currently a surplus of confirmed terrestrial exoplanets which are in the Venus Zone (VZ; Kane et al. 2014). 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 Rp < 2.5 Rearth qualifies as terrestrial, then the NASA Exoplanet Archive yields 445 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; Ricker et al. 2015) 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) used the Transmission Spectroscopy Metric (TSM; Kempton et al. 2018) to demonstrate that TESS planets in the VZ have a high S/N ceiling if observed by JWST with transmission spectroscopy. The TSM assumes terrestrial planets have cloudless, steam-dominated atmospheres, however still provides a useful 1st-order estimate of the S/N obtainable with JWST observations.

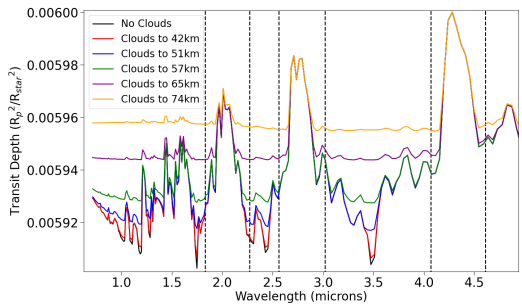
The presence of Venus-like clouds and haze on a VZ planet would significantly impact the ability of JWST to identify absorption features in transmission spectra. Furthermore, it has been shown that it may be difficult to distinguish the transit spectra of a Venus-like planet from that of an Earth-like planet (Barstow et al. 2016). It is unknown whether JWST will observe planets that resemble Venus or Earth however, which makes it vital to consider other possible planets that may be encountered.

Here we introduce the catalog of VZ planets that is currently being developed. The catalog will provide all confirmed terrestrial planets in the VZ along with all of the associated planetary and stellar parameters that are available. We will then discuss work that has been performed to investigate transmission spectroscopy observations of a variety of potential exo-Earths and exo-Venuses with atmospheric CO2 abundances and cloud decks that differ from present-day Earth and Venus. This includes 'ideal' modeled transit spectra using the Planetary Spectrum Generator (PSG; Villanueva et al. 2018), and simulated JWST transit spectra with Pandexo (Batalha et al. 2018).

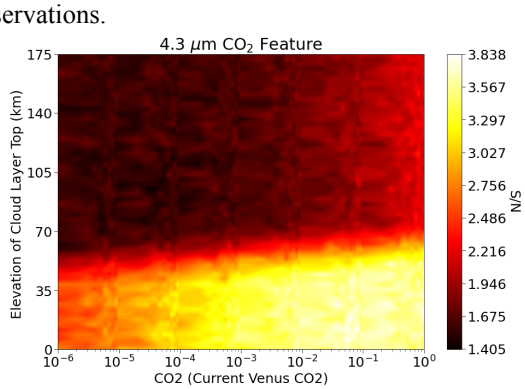
Catalog of Exo-Venuses: The recent launch of JWST marks the beginning of a new era of exoplanetary research. JWST will provide the first opportunity to investigate the atmospheres of terrestrial exoplanets with the potential of discerning their chemical compositions. The exo-Venus catalog is designed to be utilized as a resource for planning follow-up observations of discovered exoplanets in the VZ. The catalog obtains information for each planet from the publicly available NASA Exoplanet Archive, and will include the TSM values for each planet. As mentioned previously, although the assumptions made to develop the TSM are not analogous with a Venus-analog, it is used here as a reference to demonstrate which planets offer the best opportunity for successful follow-up observations. The catalog will be included in a paper of ours in the near future.

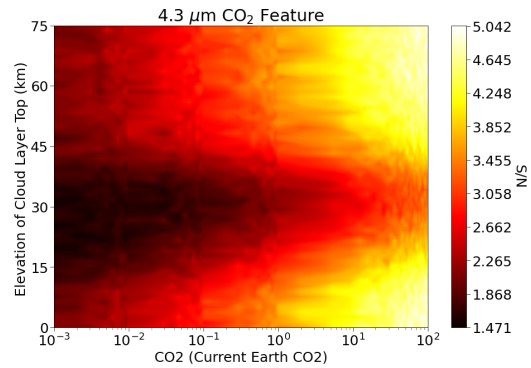
Developing exo-Earth and exo-Venus Transmission Spectra: This work utilized PSG to produce transmission spectra for potential exo-Earths and exo-Venuses. PSG is an open-source, publically available radiative transfer code with the capability of producing transmission and emission spectra for solar system bodies and exoplanets. PSG provides atmospheric data for Earth and Venus, which were used to create the baseline Earth- and Venus-analog transit spectra. Variants exo-Earths and exo-Venuses were developed by adjusting the atmospheric CO2 abundance and cloud deck heights for the respective planets. The Earth and Venus atmospheres were overlaid onto TRAPPIST-1c to be able to model the transit spectra of an exoplanet. From this we accumulated a total of 3600 transit spectra for both the

exo-Venuses and exo-Earths. A wavelength range of 0.6-5.3 µm was used for each spectra, so that it coincides with the wavelength range of JWST NIRSpec PRISM. Encompassed in this range is 3 major CO2 features at 2.0, 2.7, and 4.3 µm. The figure below illustrates 6 different exo-Venus transit spectra with varying cloud-top elevations and constant CO2 abundance. The dotted lines denote the 3 major CO2 features present in the spectra. Given the large difference in CO2 abundance between Earth and Venus, and the size of the 3 CO2 features, we investigated whether CO2 features could be a method of distinguishing an exo-Earth and exo-Venus.



Simulating JWST Transmission Spectra: The array of exo-Venus and exo-Earth transit spectra were used as inputs for Pandexo. As was done with PSG, Trappist-1c was used as the planet template, and the observations were assumed to be done using NIRSpec PRISM. We calculated the S/N of the 3 major CO2 features for all planet variants, as well as a function of the number of transit observations. Shown below are two figures that illustrate the S/N of the 4.3 µm feature as a function of atmospheric CO2 abundance, and cloud-top elevation, for the exo-Venuses (top) and exo-Earths (bottom). Both figures assume 15 transit observations.





Both figures exhibit the effects of clouds on the S/N of the feature. The exo-Venus is the more severely affected of the two, with any clouds above 50 km causing a stark decrease in S/N. The exo-Earth can reach a higher maximum S/N than that of the exo-Venus, however it needs at least 10x the CO2 abundance of present-day Earth to accomplish that. We conducted additional analysis not shown here that includes the S/N as a function of transits for all 3 CO2 features. Such work will be included in our paper that will be submitted in the near future.

Future Work: We plan on applying the methods described here to all current and future VZ catalog planets in order to evaluate potential follow-up observations for all planets in the catalog. Furthermore, we will be examining how the data from future Venus missions may help improve the ability to derive surface conditions from exo-Venus spectra, and how it will affect current models of Venus' atmosphere.

References:

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