Differentiating Exo-Venus and Exo-Earth Using Transmission Spectroscopy

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Abstract: The Transiting Exoplanet Survey Satellite (TESS) is expected to discover a multitude of multi-planetary systems. Of particular interest for comparative planetology are systems with a terrestrial planet in both the Venus Zone and the Habitable Zone. Studying the atmospheres of these planets through transmission spectroscopy will offer a unique opportunity to directly compare the evolutionary differences of two terrestrial planets in the same system. The transmission spectra of Earth and Venus have been shown to be remarkably similar however, which can cause ambiguities when inferring the differences between exo-Earth and exo-Venus climates. In this work, we present a new method of comparing Earth and Venus transmission spectra by conducting a feature-by-feature comparison of four major CO2 absorption bands between 1 and 5 microns. In comparing the transmission spectra, we find that the CO2 feature at 4.3 microns is comparable in absorption size for both exo-Venus and exo-Earth transit spectra, while the smaller CO2 features at 1.7 and 2.0 microns are the best indicators of a CO2-rich atmosphere. We conclude that the CO2 feature at 2.7 microns should be used as a basis for comparison of the amounts of CO2 in exo-Venus and exo-Earth atmospheres, since it most consistently portrays exo-Venus with the more CO2-rich atmosphere.

Introduction: The discovery of multiplanetary systems with planets in both the Venus Zone (VZ; Kane et al. 2014) and the Habitable Zone (HZ; Kopparapu et al. 2013) will allow for the opportunity to directly compare the evolutionary differences of Earth and Venus to another system. This will not be a straightforward endeavor however since identifying whether a planet is Earth-like or Venus-like from its transmission spectrum can be quite ambiguous. Barstow et al. (2016) conducted an extensive study which illustrated how retrieval methods can struggle to determine whether a Venus spectrum was best fit by an Earth or Venus model. A major result from their work showed that their retrieval method found that an Earth model was the best fit for a cloudy Venus transmission spectrum when using a reduced cloud prior. This illustrates that the lack of unique features in Venus' transmission spectrum will make it very difficult to clearly identify that a planet is Venus-like. Although the Earth spectrum can be distinguished from a Venus spectrum by its H2O and O3 absorption features, it would require significantly high S/N, which would take over 20 transit observations to achieve (Morley et al. 2017). Additionally, the presence of clouds will vastly increase the amount of time needed to detect an Earth-like atmosphere, and the H2O features could be completely removed (Komacek et al. 2020). Therefore, we choose to focus on CO2 bands when comparing the spectra of Earth and Venus, as they are the largest absorption features and would require far less time to detect in comparison to H2O and O3 (Lustig-yaeger et al. 2019, Morley et al. 2017). Specifically, we are analyzing the features located between 1 and 5 microns, as there are several CO2 features present, and JWST can most efficiently detect absorption features in that wavelength range (Lustig-Yaeger et al. 2019).

To conduct the comparison, we first created spectra for Earth and Venus using Exo-Transmit (Kempton et al. 2017). We first produced spectra for a baseline Earth and Venus with cloud decks that extend to their present-day elevations, and then created additional spectra which have cloud decks that are at elevations both higher and lower than present-day Earth and Venus. Creating this matrix of spectra allows the comparison to be applicable to exo-Earths and exo-Venuses that have a variety of different cloud scenarios. To quantify the differences of a feature's absorption depth in each planet's transit spectra, we calculated the integrated absorption depth of the same feature for both planets and compared their values. This allows us to determine which planet has the larger absorption feature, and by what amount. The goal of this comparison is to determine which of the 4 features can best be used as a proxy for determining whether a planet has a CO2 dense atmosphere like Venus.

Results: We compared the CO2 absorption features located at 1.7, 2.0, 2.7, and 4.3 microns for a Venus and Earth transit spectrum. To determine which feature would best be suited for future comparison of Earth and Venus transit spectra, we considered the

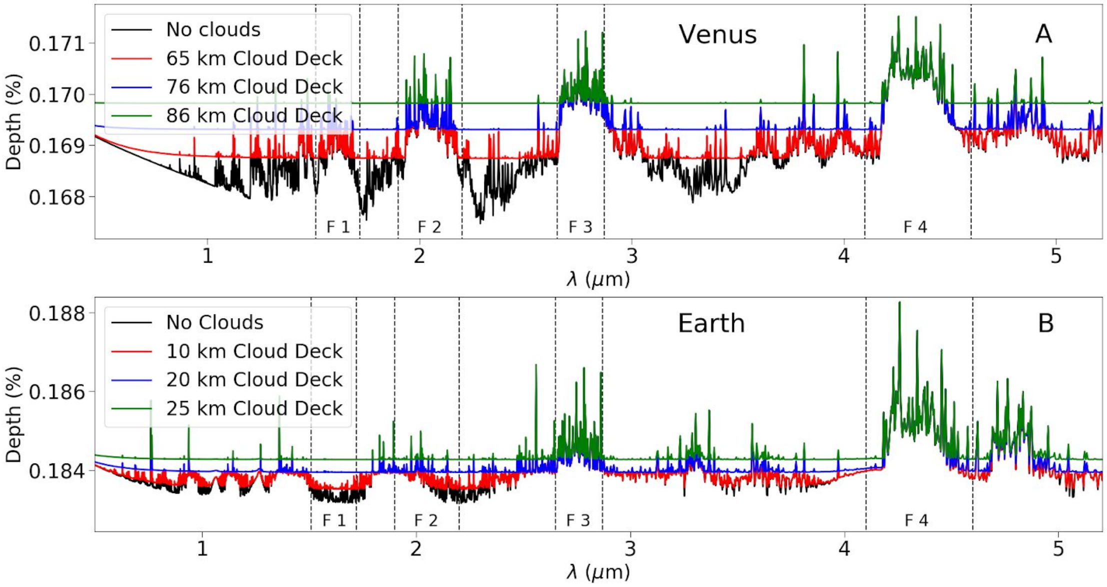

Figure 1: Transmission spectra for Earth and Venus with 4 different cloud scenarios generated using Exo-Transmit. The four CO2 features are labeled with dotted lines as 'F1-F4'.

size of the feature, the amount of scenarios where the feature is larger on Venus than on Earth, and how the size of the feature is affected by clouds. Our results show that the largest feature at 4.3 microns would be the best feature used to identify CO2 in the atmosphere of either planet. However this feature is frequently larger in the Earth spectrum than the Venus spectrum, and by a large margin. Both the features at 1.7 and 2.0 microns are excellent for identifying a CO2 dense planet, however they also are much smaller than the features at 2.7, and 4.3, which would result in the need for far more observation time with JWST. Additionally, there are H2O features in the Earth transit spectra which overlap with these CO2 features, which could make it difficult to determine whether the feature was created by CO2 or H2O in JWST observations. The feature at 2.7 microns is consistently larger in the Venus transit spectrum, and would be the second easiest feature to detect with transmission spectroscopy given its size.

Conclusions: We have determined that the smaller CO2 features at 1.7 and 2.0 microns are the best indicators of a CO2 dense atmosphere, since their absorption cross sections require large amounts of CO2 for the feature to be significant in a transit spectrum. However those features are also quite small, and unless large amounts of JWST time was allotted, they would be very difficult to resolve. We conclude that when comparing the transmission spectrum of an exo-Earth and exo-Venus, the CO2 feature at 2.7 microns would give the best opportunity of identifying which planet truly has the larger amount of CO2, and therefore is more likely to be Venus-like

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