Lessons Learned from Radiative Transfer Simulations of the Venus Atmosphere. G. Arney[1,2], V. S. Meadows[2,3], A. Lincowski[2,3] [1]NASA Goddard Space Flight Center, [2]NASA Astrobiology Institute Virtual Planetary Laboratory, [3]University of Washington (giada.n.arney@nasa.gov)

Introduction: The Venus atmosphere is extremely complex, and because of this the spectrum of Earth's sister planet is likewise intricate and a challenge to model accurately. However, accurate modeling of Venus' spectrum opens up multiple opportunities to better understand the planet next door, and even for understanding Venus-like planets beyond our solar system.

Near-infrared (1-2.5 um, NIR) spectral windows observable on the Venus nigthside present the opportunity to probe beneath the Venusian cloud deck and measure thermal emission from the surface and lower atmosphere remotely from Earth or from orbit. These nigthside spectral windows were discovered by Allen and Crawford (1984) [1] and have since been used measure trace gas abundances in the Venus lower atmosphere (< 45 km), map surface emissivity varisions, and measure properties of the lower cloud deck [e.g. 2,3,4]. These windows sample radiation from below the cloud base at roughly 45 km, and pressures in this region range from roughly Earthlike (~1 bar) up to 90 bars at the surface. Temperatures in this region are high: they range from about 400 K at the base of the cloud deck up to about 740 K at the surface. This high temperature and pressure presents several challenges to modelers attempting radiative transfer simulations of this region of the atmosphere, which we will review.

Venus is also important to spectrally model to predict the remote observables of Venus-like exoplanets in anticipation of data from future observatories. Venus-like planets are likely one of the most common types of terrestrial planets [5] and so simulations of them are valuable for planning observatory and detector properties of future telescopes being designed, as well as predicting the types of observations required to characterize them.

Methods: We have modeled the spectrum of Venus using the Spectral Mapping Atmospheric Radiative Transfer Model (SMART), a 1-D line-by-line fully multiple scattering radiative transfer model to characterize its lower atmosphere based on observations and to predict the spectral remote observables of exo-Venus planets.

Challlenges of Modeling the Venus Lower Atmosphere: Due to high temperature and pressure, unusual lineshapes are required to model CO_2 and H_2O in the sub-cloud atmosphere: the far wings of H_2O lines are modeled with super-Lorentzian profiles, while the CO_2 band far winds are modeled as sub-Lorentzian. In order to fit the shapes of the spectral windows near 1.73 μm and 2.3 μm, it is necessary to include an additional CO_2 continuum absorption (α) providing extra opacity in these regions. From nightside spectra of Venus, we have measured $\alpha = (2.5 \pm 0.5)10^{-8}$ cm^{-1} amagat^{-2} for the 2.3 μm window, and $\alpha = (6.0 \pm 0.9)10^{-9}$ cm^{-1} amagat^{-2} for the 1.74 μm window, both of which are broadly consistent with previous constraints. It is not possible to adequately model the lower atmosphere spectrum without these extra continuum opacities.

Limitations of existing CO_2 linelists present additional challenges for modeling Venus' spectrum. The HITEMP 2010 linelist fits the spectral region between 2.2 and 2.3 μm poorly even when the additional CO_2 continuum opacity is included. HITEMP 2010 also significantly under-estimates the CO_2 opacity between the 1.1 μm and 1.18 μm spectral windows. These windows sense radiation from < 16 km, and this spectral region is important to model accurately because the short-wavelength side of the 1.18 μm spectral window is used to retrieve water vapor abundance in the lowest atmospheric scale height. Fortunately, newer CO_2 linelists such as that of Huang et al. (2014) [6] include temperature-dependent pressure broadening parameters (unlike HITEMP that includes broadening parameters at only one temperature), and we will show how this newer linelist addresses these issues in the Venus spectrum.

The Venus cloud deck presents additional challenges for spectral modeling. Because the optical properties of the Venus clouds vary with wavelength, it is vital to model the cloud deck carefully in order to remove its wavelength-dependent spectral effects from trace gas retrievals. Otherwise, spurious corrlations between the cloud deck opacity and trace gas abundances can be inferred, a phenomenon we call "cloud ghosting" because the cloud patterns can produce "ghostly" illusionary imprints of themselves on trace gas maps. Cloud ghosting has the greatest potential to be problematic in the 2.29-2.45 μm spectral region where the cloud particles have the largest extinction coefficient. To remove cloud effects, it is most critical to account for variations in cloud optical depth, but second order variability caused by differences in the refractive indices of the cloud particles from variable H_2SO_4/H_2O fractions are more difficult to account for. Unfortunately, laboratory measurements of H_2SO_4/H_2O solution refractive indices only exist at 75%, 84.5%, and 95.6% H_2SO_4 at Venus-like temperatures [7], and therefore more finely graded measurements of the lower cloud acid percentage are very difficult to perform. New measurements at additional H_2SO_4/H_2O concentrations are therefore needed for these types of studies.

The Spectrum of Exo-Venuses: A different, yet equally important application of radiative transfer modeling of Venus concerns what we may be able to learn about exo-Venus analogs. JWST may be able to observe exo-Venus analogs transiting their host stars. Venuslike exoplanets orbit their stars at closer orbital distances than Earthlike exoplanets, making them more detectable targets owing to their more frequent transits and higher transit probability. We have modeled the transit transmission spectrum of Venus and found that sulfuric acid produces spectral features in the near-infrared at 2.7, 6, 8.5, 9.7, and 11.5 μm that may be detectable on an exo-Venus planet. Such features may allow remote characterization of exo-Venus cloud decks. CO_2 features are also present, with strongest features near 4.5 and 15 μm.

The planets orbiting TRAPPIST-1 [8] are among the best known targets for JWST to observe because the large ratio of the planet sizes relative to the small star makes for deeper transit features. TRAPPIST-1 is an M8V dwarf, and M dwarfs experience a long super-luminous pre-main sequence phase (pre-MS) while the young star is contracting [9]. Even the planets currently in the TRAPPPIST-1 habitable zone would have experienced enough stellar irradiation over a period of 10s or 100s of millions of years during the pre-MS to drive them into a desiccated, post-runaway greenhouse state if they did not experience post-pre main sequence water delivery or late migration into the habitable zone. Therefore, Venus represents a plausible analog for many of the TRAPPIST-1 planets, and Venuslike spectra re interesting to consider for what the remote observables of these worlds may be like. We have modeled the spectrum of Venus-like TRAPPIST-1 planets and anticipate that spectral features with strengths of 10s of ppm are possible.

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