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Coordinated Hubble Space Telescope and Venus Express Observations of Venus' upper cloud deck

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ABSTRACT

Hubble Space Telescope Imaging Spectrograph (HST/STIS) UV observations of Venus' upper cloud tops were obtained between 20N and 40S latitude on December 28, 2010; January 22, 2011 and January 27, 2011 in coordination with the Venus Express (VEx) mission. The high spectral (0.27 nm) and spatial (40–60 km/pixel) resolution HST/STIS data provide the first direct and simultaneous record of the latitude and local time distribution of Venus' 70–80 km SO and SO_2 (SO_x) gas density on Venus' morning quadrant. These data were obtained simultaneously with (a) VEx/SOIR occultation and/or ground-based James Clerk Maxwell Telescope sub-mm observations that record respectively, Venus' near-terminator SO_2 and dayside SO_x vertical profiles between ∼75 and 100 km; and (b) 0.36 μm VEx/VMC images of Venus' cloud-tops. Updating the (Marcq, E. et al. [2011]. Icarus 211, 58–69) radiative transfer model SO_2 gas column densities of ∼2–10 μm-atm and ∼0.4–1.8 μm-atm are retrieved from the December 2010 and January 2011 HST observations, respectively on Venus' dayside (i.e., at solar zenith angles (SZA) < 60°); SO gas column densities of 0.1–0.11 μm-atm, 0.03–0.31 μm-atm and 0.01–0.13 μm-atm are also retrieved from the respective December 28, 2010, January 22, 2011 and January 27, 2011 HST observations. A decline in the observed low-latitude 0.24 and 0.36 μm cloud top brightness paralleled the declining SO_x gas densities. On December 28, 2010 SO_2 VMR values ∼280–290 ppb are retrieved between 74 and 81 km from the HST and SOIR data obtained near Venus' morning terminator (at SZAs equal to 70° and 90°, respectively); these values are 10× higher than the HST-retrieved January 2011 near terminator values. Thus, the cloud top SO_2 gas abundance declined at all local times between the three HST observing dates. On all dates the average dayside SO_2/SO ratio inferred from HST between 70 and 80 km is higher than that inferred from the sub-mm the JCMT data above 84 km confirming that SO_x photolysis is more efficient at higher altitudes. The direct correlation of the SO_x gases provides the first clear evidence that SO_x photolysis is not the only source for Venus' 70–80 km sulfur reservoir. The cloud top SO_2 gas density is dependent in part on the vertical transport of the gas from the lower atmosphere; and the 0.24 μm cloud top brightness levels are linked to the density of the sub-micron haze. Thus, the new results may suggest a correlation between Venus' cloud-top sub-micron haze density and the vertical transport rate. These new results must be considered in models designed to simulate and explore the relationship between Venus' sulfur chemistry cycle, H_2SO_4 cloud formation rate and climate evolution. Additionally, we present the first photochemical model that uniquely tracks the transition of the SO_2 atmosphere from steady to non-steady state with increasing SZA, as function of altitude within Venus'

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mesosphere, showing the photochemical and dynamical basis for the factor of ~2 enhancements in the SO_x gas densities observed by HST near the terminator above that observed at smaller SZA. These results must also be considered when modeling the long-term evolution of Venus' atmospheric chemistry and dynamics.

1. Introduction and overview

Venus' atmosphere is known to be composed predominantly of carbon dioxide and nitrogen gas, where the ~0.14 total volume mixing ratio of the latter is a distant second to the 0.965 CO_2 volume mixing ratio. Although sulfur oxide gases and aerosols are only trace components of Venus' atmosphere, chemical reactions in Venus' atmosphere that involve these species such as SO_2, SO, OCS, and H_2SO_4, are important because they are closely linked to the global-scale H_2SO_4 cloud and haze layers located at altitudes between 30 and 100 km (Fig. 1). Additionally, though volcanic activity has yet to be directly observed on Venus, detailed thermochemical modeling of Venus' near surface chemical make-up indicates that volcanic outgassing is the most probable source atmospheric sulfur in Venus' lower atmosphere (i.e. below 60 km) (Johnson and Fegley, 2002).

Notably, Venus' 60–100 km altitude region was extensively observed during the time period extending from the late 1970s to early 1990s and during the Venus Express (VEx) mission (2006–2014). Likewise, extensive modeling of the dynamics and chemistry of Venus' atmosphere (e.g., Krasnopolsky and Pollack, 1994; Krasnopolsky, 2006) has been on-going. Yet, the mechanism(s) that control the exchange of SO_2 between the lower atmosphere and the mesosphere are not fully understood. Some recent modeling efforts have considered whether the vertical transport of the gas to the mesosphere occurs in conjunction with Hadley cell circulation (Yung et al., 2009; Marcq et al., 2013); while previous observers have suggested that direct volcanic ejection (Esposito et al., 1988) may be a key mechanism for the exchange of the gas from the troposphere ($z < 60$ km) to the mesosphere (~60–90 km, see Clancy et al., 2003; Bertaux et al., 2007). The biggest challenge to understanding how the exchange occurs is the fact that portions of the lower atmospheric region are statically stable. Suppression of this stability due to changes in the vertical temperature profile may help promote the vertical transport of sulfur, and other processes such as small scale eddies, and or adsorption/desorption on cloud particles (just to name a few) may also contribute to the vertical transport of sulfur in Venus' atmosphere. Because the exact mechanism for the vertical transport of sulfur is unknown sulfur oxide observations are highly prized since they provide the data needed to properly assess the ongoing chemical evolution of Venus' atmosphere, atmospheric dynamics, and could even provide insight into the nature and frequency of volcanism on Venus.

Consequently, a vast suite of SO_2 and SO observations were obtained in conjunction with the VEx mission (e.g., Sandor et al., 2010; Belyaev et al., 2012; Marcq et al., 2011) in order to probe the 60–100 km altitude region of Venus' atmosphere using both Earth-based telescopes and VEx instrumentation. These observations have revealed unexpected spatial patterns and spatial/temporal variability that have not been satisfactorily explained by

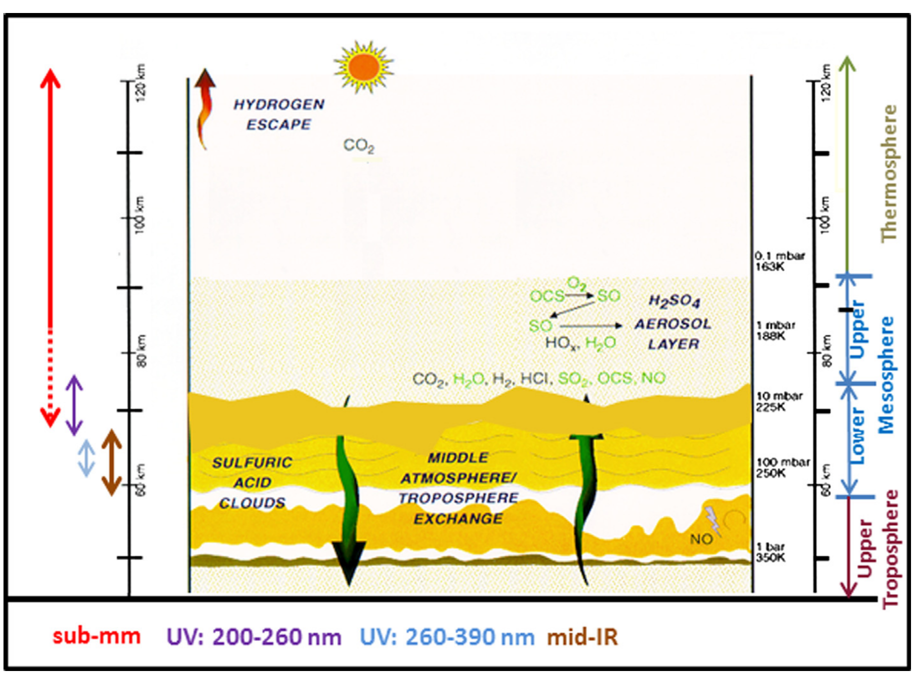

Fig. 1. Adaption of a schematic presented in Mills et al. (2009) showing Venus' atmospheric structure between 44 and 120 km. On the right axis, we highlight the altitude extent of Venus' lower troposphere, mesosphere and lower thermosphere; these demarcations reflect recent observations which have defined Venus' mesopause altitude to be ~90 km (see Bertaux et al., 2007; Clancy et al., 2003). On the left axis we highlight the altitude range probed by observations made from nadir viewing at sub-mm (red), UV, and mid-IR (brown) wavelengths. While the sub-mm observations are known to be sensitive to the 70–100 km region (see Clancy et al., 2012), all known sub-mm observations of Venus are best fit by a 2-layer model where-in the exact magnitude of the abundance of the SO_x species is only defined above ~85 ± 3 km; thus the region between 70 and 85 km is represented as a dashed line (see Section 6.2 for details). UV observations made between 200–260 nm (indigo) and 260–390 nm (blue) are sensitive to the 68–78 km and 63–68 km altitude regions, respectively. In the mid-IR (7–19 μm) the altitude sensitivity extends from 60 to 70 km.