

**OBSERVING THE VENUS ATMOSPHERE WITH NASA'S SOFIA AIRBORNE TELESCOPE: MEASUREMENTS OF CLOUD-TOP H<sub>2</sub>O, HDO AND SO<sub>2</sub>.** C.C.C. Tsang<sup>1</sup>, T. Encrenaz<sup>2</sup>, M. Richter<sup>3</sup>, P.G.J. Irwin<sup>4</sup>, C. DeWitt<sup>5</sup> and M.A. Bullock<sup>1</sup>, <sup>1</sup>Southwest Research Institute, Department of Space Studies, 1050 Walnut Street, Suite 300, Boulder, Colorado, 80302, USA ([con@boulder.swri.edu](mailto:con@boulder.swri.edu)), <sup>2</sup>Observatoire de Paris, Paris, France, <sup>3</sup>University of California at Davis, CA, USA, <sup>4</sup>University of Oxford, Department of Physics, 1 Park Road, Oxford, Oxon, UK, <sup>5</sup>NASA Ames Research Center, California, USA.

**Introduction:** A pressing goal of astronomy and planetary science today is to understand how the planets formed and evolved, not only in our Solar System, but also around other stars. An important aspect of this is to understand how planetary atmospheres evolve, especially on Earth-like extra-solar planets, which Venus is a key archetype. This is clearly illustrated by the divergent evolutionary paths that Venus and Earth have taken. Venus was thought to once have a substantial amount of liquid water on its surface that eventually evaporated and escaped into space. A critical measurement for this deduction is the D/H ratio, which can be made by measuring H<sub>2</sub>O and HDO in the Venus atmosphere. This can only truly be done in space or in the air.

We present initial spectra and spatial maps taken by NASA's Stratospheric Observatory For Infrared Astronomy (SOFIA) in January 2017, at altitudes of between 39K and 41K ft, over two nights, using the EXES high resolution, mid-infrared spectrograph, of H<sub>2</sub>O, HDO and SO<sub>2</sub> at 7.4 μm. These data will help us understand the loss rates of D/H, as well as the evolution of H<sub>2</sub>O which is a critical component of the H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O cloud system on Venus.

**Background:** The idea that Venus once had a wetter climate comes from cosmogonical arguments - Venus should have accreted similar amounts of water as the Earth during the end of oligarchic growth of the planetary embryos [1,2]. The fractionation of atmospheric hydrogen (H) and deuterium (D) is critical to this hypothesis, since the D/H ratio in the Venus atmosphere is between 100 and 200 times greater than that on the Earth, suggesting the H reservoir was greatly depleted in the past [3,4]. It is estimated as much as an Earth's ocean worth of water was lost from Venus in the first 500 million years [5], which is approximately in line with the loss rate and observed D/H ratio. The question we face now is what temporal (diurnal and long-term) and spatial (latitude and longitude) variations are there across Venus's cloud tops that contribute to this loss process. Cloud-top H<sub>2</sub>O on Venus is important not only because we can deduce the D/H ratio, but also because 1) H<sub>2</sub>O is key to making H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O clouds that globally blanket Venus at ~65 km, and 2) H<sub>2</sub>O is also an important infrared absorber, influencing the radiative balance of the entire atmos-

phere. For all these reasons, measurement of Venus's tenuous H<sub>2</sub>O and its variability is critical for atmospheric evolution and dynamics. However, there are conflicting measurements on the spatial variability of cloud-top H<sub>2</sub>O from NASA's Pioneer Venus Orbiter and the Soviet's Venera-15 spacecraft during the 1980's era.

*Venus Express:* The arrival of ESA's Venus Express spacecraft around Venus, which ended its mission in 2015, significantly increased our knowledge of the atmosphere. Vertical profiling of HDO and H<sub>2</sub>O was conducted. The SPICAV-SOIR spectrometer (R~20,000) with a limb pointing geometry allowed [6] to measure three vertical profiles of both H<sub>2</sub>O (3832 cm<sup>-1</sup>) and HDO (2722 cm<sup>-1</sup>) from 70 – 100 km in the initial year of the VEX mission. They found the D/H ratio were enriched by 150 compared to telluric value, and a significant depletion region of H<sub>2</sub>O at 80 – 90km. Subsequent work [7] using the same technique but with more data showed the D/H ratio was 240 ± 25 times the terrestrial ocean value, 1.5 times higher than previous values. These are spatially inhomogeneous vertical profiles, however.

*Infrared Telescope Facility (IRTF):* The difficulty in determining the D/H ratio from the ground is the need to assume the H<sub>2</sub>O abundance due to telluric (Earth) absorption. Alternatively, an estimate of the D/H ratio is implied when retrieving the H<sub>2</sub>O mixing ratio at the cloud tops, depending on the ultimate goal of the research. More recently, the Texas Echelon-Cross-Echelle Spectrograph (TEXES) spectrometer on the IRTF was used to measure CO<sub>2</sub>, HDO and SO<sub>2</sub> around 7.35 μm in January 2012 and both the 7.35 and 19 μm bands in October 2012 [8,9]. The spectral resolving power of TEXES at these wavelengths was 80,000 and 53,000 respectively. In all, these mid-IR observations occurred over five nights, when Venus's angular size was between 13" and 15" (arc-seconds). These observations showed little day-night HDO variation, but did show a slight enhancement at the limb, indicating a possible increase of D/H ratio with increasing altitude. They assumed a D/H ratio of 200 to yield estimates of the H<sub>2</sub>O mixing ratio. Ultimately, a much clearer understand can only be gained by observing both cloudtop H<sub>2</sub>O and HDO simultaneously rather than assuming a constant number for either H<sub>2</sub>O or

D/H ratio, especially given indications of H<sub>2</sub>O spatial variability and D/H vertical variability already described. This proposal aims to address this major deficiency.



Figure 1: NASA's SOFIA airborne observatory (left).

**SOFIA/EXES 2017 Observations:** This work aims to spatially map H<sub>2</sub>O and HDO mixing ratios at the Venus cloud-tops simultaneously using SOFIA's EXES mid-infrared spectrometer between 1400 and 1420 cm<sup>-1</sup> (7.25 μm) at resolving powers of 100,000, across Venus's entire disk. Venus' angular diameter on January 25, 2017 was 28 arcseconds (″), at 43% phase, making for a set of dusk observations from Palmdale, CA. Because the SOFIA image equality FWHM is 3.3″ at 1400 cm<sup>-1</sup>, we obtain an effective spatial resolution of ~1400 km/pixel. We took takeoff before sunset, get to altitude and setup EXES. Immediately after sunset, we observed Venus for ~1.5 hr before Venus sets below 18° elevation visibility limit of SOFIA. The airmass range during this observing period (between when the Sun sets and when Venus sets) is 1.6 – 2.1.

SOFIA data is essential to the investigation because H<sub>2</sub>O cannot be observed from the ground. The typical telluric transmission in this spectral region is <0.2 at 13,800 ft. on the summit of Mauna Kea, compared to 0.9 with SOFIA flying at 41,000 ft. The last time observations of Venus's H<sub>2</sub>O and HDO were conducted on Earth was with SOFIA's predecessor, the Kuiper Airborne Observatory in 1992 [10] estimating a D/H ratio of 157 ± 15 from H<sub>2</sub>O and HDO in the near-IR. Given the large variability in the D/H measurements over the past two decades (100–240 D/H enhancement over terrestrial levels), it is essential we measure both H<sub>2</sub>O and HDO simultaneously in order to obtain the best possible estimates of the D/H ratio. H<sub>2</sub>O may also show spatially variability that could be correlated to the spatial variations of SO<sub>2</sub> discovered by IRTF-TEXES [8, 9].

The SOFIA measured spatial distribution of D/H as a function of local time will help quantify where the escaping H and D atoms are taking place, and D can be further correlated with mass 2 ion escape with the Venus Express/ASPERA data [11], providing an upper limit on D<sup>+</sup> ion escape (due to degeneracy of H<sup>2+</sup> ions. Measuring H<sub>2</sub>O, and modeling the exospheric escape of H as a diffusion process will also constrain the loss

rate of H more accurately. Our SOFIA measurement of D/H will constrain D and H escape rates. Coupled to the then better understanding of D<sup>+</sup> escape variability, we can update a climate evolution model (which takes all these measurements as inputs) such as one developed by Co-I Bullock [12] to move backwards in time to see the effect of the most recent improvements in measurement capability of SOFIA and Venus Express. This will provide a much needed up-to-date improvement in estimating water loss on Venus.

**Summary:** We will present initial data and results from the first ever observations of Venus from NASA's SOFIA aircraft on January 23 and 25, 2017. Our measurements of H<sub>2</sub>O, HDO and SO<sub>2</sub> will improve our understanding of the spatial and temporal variability of the D/H loss rates across the entire disk of Venus by constraining the variability at the cloud tops, which cannot be done on the ground. By leveraging the unique capabilities SOFIA, namely access to wavelengths and absorption bands that previously could not be measured from the ground, this data will open a new window to constraining the escape rate and cloud chemistry of the Venus's atmosphere.

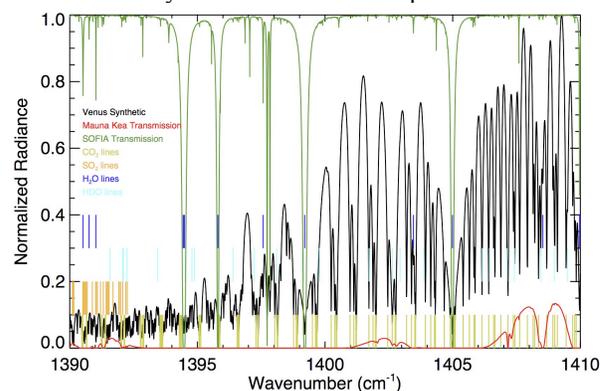


Figure 2: Synthetic Venus spectra at 1390–1410 cm<sup>-1</sup> (black), telluric transmission spectra from Mauna Kea (red) and SOFIA (green).

#### References:

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