Spatially-Resolved High-Resolution Spectroscopy of Venus : Variations of CO_2, CO, HF, HCl, HDO, OCS, and SO_2 at the Cloud Tops, OH and O_2 Nightglow

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Venus night and day sides were observed in a few sessions at NASA IRTF using a high-resolution ($\nu/\delta\nu = 4\times10^4$) long-slit spectrograph CSHELL. Variations of the O_2 airglow at 1.27 μm and its rotational temperature are extracted from the observed spectra. The mean O_2 nightglow is 0.57 MR at 21:30 at 35ºS to 35ºN with $T \approx 180$ K. We found a narrow window that covers the OH (1-0) P1(4.5) and (2-1) Q1(1.5) airglow lines. The detected line intensities are converted into the (1-0) and (2-1) band intensities of 7.2 ± 1.8 kR and <1.4 kR at 21:30 and 15.5 ± 2 kR and 4.7 ± 1 kR at 4:00.

Dayside observations of the CO_2 lines at 2.25 μm revealed variations of the cloud aerosol density (~25%) and scale height near 65 km. The measured reflectivity of Venus at low latitudes is 0.7 at 2.25 μm and 0.028 at 3.66 μm, and the effective CO_2 column density is smaller at 3.66 μm than those at 2.25 μm by a factor of 4. This agrees with the almost conservative multiple scattering at 2.25 μm and single scattering in the almost black aerosol at 3.66 μm. The expected difference is just a factor of $(1 - g)^{-1} = 4$, where $g = 0.75$ is the scattering asymmetry factor for Venus' clouds.

The observed CO mixing ratio is 52 ± 4 ppm near 08:00 and 40 ± 4 ppm near 16:30 at 68 km, and the higher ratio in the morning may be caused by extension of the CO morningside bulge to the cloud tops. The observed weak limb brightening in CO indicates an increase of the CO mixing ratio with altitude. HF is constant at 3.5 ± 0.2 ppb at 68 km in both morningside and afternoon observations and in the latitude range ±60º. Therefore the observations do not favor a bulge of HF, though HF is lighter than CO.

The recent measurements of HCl near 70 km are controversial (0.1 and 0.74 ppm) and require either a strong sink or a strong source of HCl in the clouds. The HCl (2-0) lines are blended by the solar and telluric lines, and we observed the P8 lines of the (1-0) band at 3.44 μm. These lines are spectrally clean and result in the HCl mixing ratio of 0.40 ± 0.03 ppm at 74 km. HCl does not vary with latitude within ±60º. Our observations support a uniformly mixed HCl throughout the Venus atmosphere.

Lines of HDO, OCS, and SO_2 are either very weak or blended by the telluric lines and have not been observed previously by ground-based infrared spectroscopy at the Venus cloud tops. Converted to H_2O with D/H ≈ 200, our observations at 2722 cm^{-1} in the Venus afternoon show the H_2O mixing ratio of ~1.2 ppm at latitudes between ±40º increasing to ±60º by a factor of 2. The observations in the early morning reveal the mean H_2O mixing ratio of ~2.9 ppm at 74 km within latitudes of ±75º.

OCS was detected at the cloud tops using its P-branch at 4094 cm^{-1}, and four latitudinal distributions have been retrieved. The observed OCS mixing ratio varies from ~0.3 to 9 ppb with the mean value of ~3 ppb at 65 km. The OCS scale height is retrieved from the observed limb darkening and varies from 1 to 4 km with a mean value of half the atmospheric scale height. in the latitude range ±60º.

SO_2 at the cloud tops has been detected for the first time by means of ground-based infrared spectroscopy. The SO_2 lines look irregular in the observed spectra at 2476 cm^{-1}. The retrieved mean SO_2 mixing ratio of 380 ± 50 ppb at 72 km favors a significant increase in SO_2 above the clouds since the period of 1978-1995 and agrees with the VEX/SOIR observations. Scale heights of OCS and SO_2 may be similar, and the SO_2/OCS ratio is ~500 and may be rather stable at 65-70 km.