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Spatially-resolved high-resolution spectroscopy of Venus 1. Variations of CO_2, CO, HF, and HCl at the cloud tops

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ABSTRACT

Variations of the upper cloud boundary and the CO, HF, and HCl mixing ratios were observed using the CSHELL spectrograph at NASA IRTF. The observations were made in three sessions (October 2007, January 2009, and June 2009) at early morning and late afternoon on Venus in the latitude range of ±60°. CO_2 lines at 2.25 μm reveal 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 ±60°. Therefore the observations do not favor a bulge of HF, though HF is lighter than CO. Probably a source in the upper atmosphere facilitates the bulge formation. 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 lines of the (2-0) band are blended by the solar and telluric lines. Therefore 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 ±60°. Our observations support a uniformly mixed HCl throughout the Venus atmosphere.

1. Introduction

High-resolution infrared spectroscopy is a powerful tool to study chemical composition of the planetary atmospheres. High-resolution spectra of Venus, Mars, Jupiter, and Saturn were observed for the first time in the pioneering work by Connes et al. (1969) using their Fourier transform spectrometer (FTS). The spectra of Venus were measured with the unprecedented resolving power $v/\delta v \approx 10^5$ and resulted in the first detections of HCl, HF, and CO (Connes et al., 1967, 1968).

Kuiper et al. (1969) and Fink et al. (1972) made the first reliable observations of H_2O on Venus using an FTS at an airborne observatory. (Column density of H_2O above Venus' clouds is ~1 precipitable μm, lower than that on Mars by an order of magnitude, and poorly accessible to the ground-based infrared astronomy.)

High-resolution spectra of the nightside thermal emissions at 1.74 and 2.3 μm were observed by Bezard et al. (1990) and resulted in the first reliable detection of OCS that refers to the lower atmosphere near 33 km. Absorption lines of CO_2, CO, SO_2, H_2O, HDO, HCl, and HF were detected as well. That was the first spectroscopic determination of the D/H ratio (de Bergh et al., 1991); previous measurements of D/H on Venus were based on the Pioneer Venus mass spectrometers (Donahue et al., 1982; Hartle and Taylor, 1983). The observed spectra along with some medium resolution observations were analyzed by Pollack et al. (1993), Taylor et al. (1997) and Bezard and de Bergh (2007) to retrieve abundances of the above species in the lower atmosphere of Venus and their variations with altitude.

Venus was observed at 2.6 μm using an FTS at the Kuiper Airborne Observatory (Bjoraker et al., 1992). Absorption lines of H_2O, HDO, HF, and CO_2 were measured; $H_2{}^{18}O$ was detected for the first time on Venus.

The most sensitive search for O_2 on Venus was made by Trauger and Lunine (1983) who established an upper limit of 10^{18} cm^{-2}

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above the clouds (see Krasnopolsky, 2006b). They used a triple pressure-scanning Fabry–Perot interferometer with resolving power of 2.4×10^5. Photons were collected from the full Venus disk by that instrument, and the signal-to-noise ratio was very high. This important result has not been improved for the last quarter of century.

Due to a progress in the multielement detector arrays, high-resolution long-slit echelle spectrographs have been built and replaced the FTS's at astronomical observatories. These spectrographs have lower resolving power than the FTS's but make feasible spatially resolved and mapping observations. Spectra of all points along the slit are measured, and species abundances may be extracted at all those points.

NO was detected for the first time at the Venus cloud tops (Krasnopolsky, 2006a) using the TEXES spectrograph (Lacy et al., 2002). That was a convincing proof of lightning on Venus. Recently OCS at the cloud tops was detected (Krasnopolsky, 2008, hereafter Paper I) using the CSHELL spectrograph (Greene et al., 1993). Both detections were made at the NASA Infrared Telescope Facility (IRTF) on Hawaii.

High-resolution spectroscopy significantly contributed to study of the Venus night airglow. The O_2 nightglow at 1.27 μm was detected by Connes et al. (1979) using FTS. Slanger et al. (2001) detected the oxygen green line at 558 nm in Venus nightglow using the HIRES spectrograph at the Keck Observatory. Recently the OH nightglow, which was detected by Venus Express (Piccioni et al., 2008), was observed using CSHELL (Krasnopolsky, 2010).

High-resolution spectrographs are complicated and heavy, and this hindered them at spacecraft missions to the planets. The SOIR at Venus Express is probably the first and only exception here. SOIR is observing vertical profiles of CO, HCl, HF, H_2O, HDO, and SO_2 above 70 km in the solar occultation mode (Bertaux et al., 2007; Fedorova et al., 2008; Vandaele et al., 2008; Belyaev et al., 2008).

The SOIR observations are restricted by the Venus Express orbit geometry, and almost all published data refer to the north polar regions above 60°N. Only two SO_2 observations were made at low latitudes, 23 and 30°N. Therefore spatially-resolved high-resolution ground-based observations may complement the Venus Express data. Our goal is to study variations of minor constituents of the Venus atmosphere with latitude, local time, and from place to place. Some data from the first session have been published in Paper I, and the current paper is a continuation of that work.

2. Observations

We have observed Venus at three sessions using CSHELL at NASA IRTF. CSHELL is a high-resolution long-slit echelle spectrograph for the near infrared range of 1–5.5 μm. A spectral interval within this range may be chosen by varying angles of the diffraction grating and the circular variable filter. It is rather narrow and equal to $0.0023\nu_0$, where ν_0 is the central wavenumber. Therefore ν_0 should be carefully chosen. The instrument has an InSb detector array of 256 spectral to 150 spatial elements. Each pixel is $9 \times 10^{-6}\nu_0$ in the spectral direction and 0.2 arcsec in the spatial direction. The array is cooled to 30 K. Some parts of the instruments are also cooled. The instrument resolving power is $\nu/\delta\nu = 4 \times 10^4$ with a slit of 0.5 arcsec, that is, a resolution element is 2.8 pixels FWHM (full width at half maximum). Spatial resolution of the telescope–spectrograph combination is typically 1 arcsec.

NASA IRTF has a telescope with diameter of 3 m that is sufficient for many Solar System studies. The observatory is on the summit of Mauna Kea, Hawaii, with elevation of 4.2 km, pressure 0.6 bar, and typical overhead water of 2 pr. mm. These values are probably the best for the ground-based astronomy and facilitate detection of weak absorptions in planetary spectra.

We have had three sessions to observe Venus on October 18, 2007, January 13, 2009, and June 20, 2009. Venus was near its maximal solar elongation of ~45° in all our observations. Phase (Sun–planet-observer) angle is ~90° at this position, and this geometry is convenient for observations of both day and nightsides. Doppler shifts from geocentric velocity of Venus are maximal at ±13 km s^{-1} as well, improving the detection conditions relative to the telluric lines. The Venus size of 20–25 arcsec at these positions is also optimum for observations with the CSHELL slit of 30 arcsec. Usually we place the instrument slit parallel to the central meridian and at the middle of the illuminated part of the disk in our dayside observations. Then the observations cover a latitude range of ±60° and refer to local time of either 08:00 or 16:00, making therefore possible studying of variations with latitude and local time. Actually local time varies along the slit in our geometry, and local times mentioned here and below refer to the low latitudes. We also observed the instrument dark current, flat fields, the sky foreground, and standard infrared stars for calibration. Our observations and analysis of the Venus night airglow (Krasnopolsky, 2010) will not be considered here.

3. CO_2 lines and the upper cloud layer

Light scattering in absorption lines is rather complicated in the Venus clouds, and the best way to get a mixing ratio of an absorbing species is to measure CO_2 lines in the nearby spectral range. Many uncertainties in the retrieved column densities of the species and CO_2 cancel out in their ratio, especially if equivalent widths of the lines are similar. Therefore the chosen CO_2 lines should be rather weak. For example, if a CO line strength is $\sim 10^{-22}$ cm and the expected CO mixing ratio is ~40 ppm, then a desirable CO_2 line strength is $\sim 4 \times 10^{-27}$ cm.

Venus dayside is bright, exposures are short in our observations, and a typical interval between the observations of a species and CO_2 is ~30 min. Using the four-day rotation of Venus, this time is converted to the meridional shift of 2°, that is, 0.35 arcsec for the Venus diameter 20–25 arcsec. This shift is smaller than the spatial resolution of 1 arcsec, and the observations of a species and CO_2 may be considered as almost simultaneous.

3.1. CO_2 lines at 2.25 μm and variations of the upper clouds

We observed the CO_2 lines near 4444 cm^{-1} (Fig. 1, lower panel) for comparison with CO, HF, OCS, and the (2-0) band of HCl. High-resolution solar spectra observed by the ATMOS (Farmer and Norton, 1989) spacecraft cover this region and help to avoid contamination by the solar lines. We use a version of the ATMOS spectrum suggested by Kurucz (2009). Of six CO_2 lines in the spectrum two lines, R32 and R34, are rather clean at the negative Doppler shift. The R30 and R36 lines are better at the positive Doppler shift, and a minor contamination of R36 by a CH_4 telluric line is corrected using the nearby CH_4 lines in the spectrum.

Similar to the other spectroscopic studies cited in Section 1, we apply a simple reflection model. Multiple scattering in the clouds is substituted in this model by reflection at an effective level in the atmosphere. To find this effective level for each point along the chord on the Venus disk, we measure equivalent widths of the CO_2 lines in the spectrum. Then we calculate the equivalent width of the CO_2 line as a function of height by integration from 90 down to 60 km. We use the temperature and pressure profiles from the Venus International Reference Atmosphere (VIRA; Seiff et al., 1985) at latitude 45°. According to VIRA, latitudinal variations of temperature are ~3 K near 65–75 km, where the lines form, and weakly affect our results. The CO_2 line strengths and collisional self-broadened line widths for various temperatures are taken from the HITRAN 2008 spectroscopic database (Rothman et al.,