



WATER IN THE DEEP ATMOSPHERE OF VENUS FROM HIGH-RESOLUTION SPECTRA OF THE NIGHT SIDE

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ABSTRACT

High-resolution, near-infrared (1.09 to 2.5 μm) spectra of the night side of Venus have been obtained in 1990 and 1991 using the Fourier Transform Spectrometer at the 3.6-m Canada-France-Hawaii telescope. Absorptions due to H₂O were detected in spectral windows near 2.3, 1.74, and 1.18 μm . Our analysis of these absorptions constrains the abundance of water vapor in three different altitude ranges located between the clouds and the surface: 30-40 km, 15-25 km and 0-15 km. A constant water vapor mixing ratio of 30 ± 15 ppm below the clouds can fit the observations. These values are consistent with recent near-infrared studies of the night side of Venus at lower spectral resolution. The atmosphere of Venus appears to be dryer than originally suggested by the in-situ measurements made by the Pioneer Venus and Venera mass-spectrometers and gas-chromatographs.

INTRODUCTION

Improved estimates of the abundance and vertical distribution of water in the deep atmosphere of Venus are crucial for studies of cloud formation, atmospheric thermochemistry, and surface-atmosphere interactions. This information is also essential for studies of the long-term evolution of the surface and atmosphere of Venus.

Until recently, the only existing estimates of the water abundance below the clouds had been derived from in-situ measurements. They provided a broad range of values - between 5200 and 20 ppm -, with values differing by as much as a factor of 35 at a given altitude. These large differences could not be attributed entirely to spatial or temporal variations in the water abundance, because some of the largest discrepancies were detected by different instruments on the same entry probe.

The spectrophotometric measurements made by the Venera 11 and 12 entry probes provided some indication that the water vapor mixing ratios decreased dramatically between the cloud base (altitude about 50 km) and the surface. The Pioneer Venus mass spectrometer observations also showed this trend, but such a behavior is difficult to explain with current thermochemical equilibrium models. There was thus a strong need for additional measurements.

A few years ago, Allen and Crawford /1/ discovered that the night side of Venus emits thermal radiation at wavelengths less than 3 μm that can be detected by remote-sensing observations. This radiation originates from deep atmospheric layers /1,2,3/. Since that time, several observers have studied this emission to probe the deep atmosphere of the planet. We will report here on results from high spectral resolution ground-based studies that provide unique information on the water vertical profile, as well as on the abundances of many other constituents.

Studies at high spectral resolution are essential to unambiguously separate the different sources of opacity in the spectra of Venus. High resolution can allow us to differentiate between the absorption features due to the various gases, the continuum opacity due to clouds and that due to CO₂. Because of the very intricate nature of the spectra, high resolution studies are particularly

important for a proper modelling of the night-side emission, and can then be used for investigations at lower resolution. High spectral resolution can also allow us to precisely eliminate opacity by telluric water if the resolution is higher than the Doppler shift due to the motion of Venus relative to Earth. In addition, as individual absorption lines can be observed at high resolution, the abundance determinations can be very accurate.

PREVIOUS H₂O MEASUREMENTS

Water vapor measurements by the Pioneer Venus and Venera probes prior to 1982 have been reviewed by Von Zahn *et al.* /4/ and Donahue and Hodges /5/. Values higher than 1000 ppm were measured by the Pioneer Venus large probe gas chromatograph and the Venera 14 gas chromatograph at altitudes near 40 km. A first analysis of the Pioneer Venus mass spectrometer measurements indicated values of the order of 100 ppm between 25 and 10 km, and a decrease by a factor of about 5 between 10 km and the surface /6/. A more recent re-analysis of these measurements /5/ shows lower values closer to 70 ppm, in the 25 to 10 km altitude range, with decreasing values below 10 km altitude. However, a more drastic revision of these results is currently being made, following a re-assessment of the D/H ratio, and suggests a constant water vapor mixing ratio of about 30 ppm from 25 km to the surface /7/. The in-situ spectrophotometric measurements by the Venera 11 and 12 probes also indicated a decrease of the amount of water below the clouds, from about 150 ppm at 42 km to 20 ppm at the surface. However, a re-analysis of these data /8/ shows that they could also be interpreted by a constant mixing ratio of 20 to 30 ppm in the deep atmosphere of the planet (see /4/) if only the band at 1.13 μm is considered (which implies that the extra absorption observed in the 0.94 μm region is not due to H₂O).

The recent discovery of intense near-infrared thermal emission from the Venus night side has provided new opportunities to study the lower atmosphere of this planet by near-infrared spectroscopy of the night side. The clouds are relatively transparent at wavelengths less than 3 μm , allowing thermal radiation from the hot lower atmosphere to escape in a few "spectral windows" where the absorption by gaseous CO₂ and H₂O is weak. It is interesting to note that if the CO₂ line profiles were Lorentzian instead of sub-Lorentzian there would be no measurable thermal flux coming out, as continuum absorption due to the far wings of strong neighboring CO₂ bands and the very far wings of stronger CO₂ bands with centers at longer wavelengths would block all the near-infrared radiation from hot deep atmospheric levels.

There have been several sets of near-infrared observations of the night side of Venus. Most of them have constrained the water abundance just below the clouds. Few have provided measurements below 25 km altitude. After a preliminary analysis of low-resolution ($R \sim 100$) 2.3 μm spectra of the night side by Kamp *et al.* /3/ that indicated a value of about 100 ppm for the water below the clouds, Bézard *et al.* /9/ published the first analysis of high-resolution (R : up to 20000) spectra of the night side of Venus recorded near 2.3 and 1.74 μm with the Fourier Transform Spectrometer at the Canada-France-Hawaii telescope. A much more complete spectroscopic data set was used for CO₂, compared to the one used by Kamp *et al.* /3/ - and later on by Kamp and Taylor /10/-, and produced a much more satisfactory agreement between observed and calculated spectra. This analysis also produced the first detection of several weakly absorbing species like OCS, SO₂ (suspected at that time, and confirmed later), HCl and HF. It also clearly showed the need for the inclusion of CO₂ continuum opacity in models of Venus's atmosphere, and provided a measurement of the D/H ratio /11/. Water vapor absorptions near 2.4 μm were best fitted with a uniform water mixing ratio of about 40 ppm below 55 km altitude. This result was in strong contradiction with some of the in-situ measurements.

This work was followed by an analysis of spectra recorded with the NASA Infrared Telescope Facility (IRTF) at resolutions of 1200 to 1500, also in the 2.3 μm region /12/. Two small areas were observed on the planet: a bright region, and a darker one corresponding to enhanced cloudiness. They provided different values for the H₂O mixing ratio: about 40 ppm below 55 km in the case of the dark region spectrum, and 200 ppm below 40 km for the bright region spectrum. Bell *et al.* /12/ concluded that large horizontal variations in the water vapor concentration could exist below the cloud tops, probably linked to local evaporation/condensation of H₂SO₄ particles.

Data were also obtained at the 3.9-m Anglo-Australian Telescope (AAT) at resolutions up to 2100

between 1 and 2.5 μm . A first analysis of these data by Crisp et al. /13/ that was limited to the 2.3 and 1.27 μm windows provided water vapor mixing ratios of 40 ± 20 ppm, with no indication for significant spatial variations. A much more complete analysis of these AAT spectra has since been made by Pollack et al. /14/ and the results will be reported elsewhere.

Near-infrared (0.7 to 5.2 μm) spectra of the night side of Venus were also recorded with the Near Infrared Mapping Spectrometer (NIMS) on the Galileo spacecraft at a resolution of 90 /15/. A preliminary analysis of these data suggested an increase of the water mixing ratio from 25 ppm above 30 km to about 50 ppm at 20-28 km altitude, based on spectra in the 2.3 and 1.7 μm windows. However, this analysis is currently being revised.

RESULTS OF STUDIES AT HIGH SPECTRAL RESOLUTION

Spectra of Venus have been recorded at high spectral resolution (up to 40000) in 1989 and 1991 with the Fourier Transform Spectrometer at the Canada-France-Hawaii telescope. Several windows have now been covered : at 2.3, 1.74, 1.31, 1.27, 1.18 and 1.1 μm . The first study at high resolution (0.28 cm^{-1}) by Bézard et al. /9/ included only the 2.3 and 1.74 μm windows, and the lack of a good calibration spectrum for the 1.74 μm region precluded an analysis of the H_2O absorption features present in this window. In 1991, additional spectra were obtained in these two windows at twice the previous resolution (0.14 cm^{-1}) and with all the required calibration spectra. In addition, the 1.31, 1.27, 1.18, and 1.10 μm windows were explored for the first time at high resolution. Absorptions due to H_2O are detected in the three windows centered at 2.3, 1.74 and 1.18 μm . Water also absorbs strongly on the short wavenumber side of the 1.1 μm window, but the signal-to-noise ratio is not sufficient for a definitive study of the detected absorption features.

Contamination by reflected sunlight from the day side of the planet was carefully eliminated by using day-side spectra recorded simultaneously. The night-side spectra were divided by the day-side spectra to eliminate telluric absorptions and the response of the filter. Absolute flux calibration was performed by recording spectra of standard stars.

Synthetic spectra have been calculated as explained in Bézard et al /9/, using a line-by-line radiative transfer program that includes scattering. The temperature profile selected is taken from /16/, the cloud model adapted from /17/. The CO_2 and H_2O opacities are from the "high-temperature" data bank generated by R. Wattson (see /14/). The CO_2 continuum opacity was adjusted in each spectral range by fitting spectral regions dominated by absorption from allowed CO_2 transitions. This opacity is assumed to be proportional to the square of the CO_2 density ρ (k (absorption coefficient) = $\alpha \times \rho^2$, where ρ is expressed in amagat and α in $\text{cm}^{-1}\text{am}^{-2}$). As explained in /9/ this additional opacity is probably due in part to the very far wings of strong bands of CO_2 , and in part to pressure-induced bands of CO_2 .

The 2.3- μm window

This window was studied by Bézard et al. /9/. Since this first analysis, the intensity of the CO_2 band at 4416 cm^{-1} has been revised /18/, which reduces the amount of additional continuum opacity needed, and therefore slightly shifts downwards the range of altitudes probed. This continuum opacity is very difficult to measure in the laboratory; the measurements that have been obtained so far in the 2.3 μm region do not all agree (see /14/), and are limited to room-temperature. This is why we chose to estimate this opacity by comparing the shape of the observed spectrum with synthetic spectra computed for different values of the α coefficient, and selecting the value of α that provided the best fit. This is illustrated in Figure 1. The value we retrieve here ($4 \times 10^{-8} \text{cm}^{-1}\text{am}^{-2}$) was assumed to be valid over the whole spectral window.

The cloud optical depth is fixed by matching the observed flux near 4350 cm^{-1} (the region of weakest molecular opacity). Changes in cloud opacity do not however affect the abundance measurements. Lines of the ν_1 and ν_3 bands of H_2O are present in the 4100-4130 cm^{-1} region (along with lines of the $\nu_1 + \nu_2$ and $3\nu_2$ bands of HDO). Absorptions by CO_2 , CO, OCS, SO_2 and HF are also detected /9,19/ and opacity by all these molecules has been included in the spectral modelling. The average value of the H_2O mixing ratio below the clouds that provides the best agreement with our spectra (Figure 2) is about $30 \pm_{-10}^{+15}$ ppm, and pertains to the 30-40 km altitude range. The H_2O mixing ratio derived from our 1991 data set is about the same as that from our 1990 spectrum. In 1991,

we obtained spectra for three different regions on the planet, around 5 degrees North, 25 degrees North and 15 degrees South latitude, and the same longitude. These spectra were recorded with a 5 arc-second circular aperture. They all provide comparable values for the H₂O mixing ratio. High-spectral resolution measurements in the 2.3 μm window also provide some information about the variation of the H₂O mixing ratio above 48 km, within the clouds, but this analysis is still at a preliminary stage.

The 1.74- μm window

Measurements at this wavelength allow us to probe deeper into the atmosphere than with the 2.3- μm data. This region had not been well studied by Bézard *et al.* /9/ because of a lack of a comparison spectrum, as mentioned above, and also because of an obvious lack of data on weak bands of CO₂ that contribute very significantly to the opacity. Both difficulties have now been overcome with the new data recorded in 1991 and the much more complete data bank on CO₂ that has just become available /14/. The new spectrum of the night side recorded in 1991 corresponds to the same region on the planet (centered at 15 degrees South latitude) as the one that provided the 2.3 μm spectrum of Figure 1, and it was obtained on the same day. The absorptions present in that range are due to CO₂, H₂O and HCl. We find that, in order to fit the shape of the window it is necessary to add some continuum CO₂ absorption, as for the 2.3 μm region. This continuum opacity was assumed constant over the whole window, and the value of α that yielded the best reproduction of the observed spectrum is : $\alpha = 5 \times 10^{-9} \text{ cm}^{-1}\text{am}^{-2}$. At the resolution of our spectrum (0.14 cm^{-1}), we see a large number of isolated water vapor features (belonging to the $\nu_2 + \nu_3$ band of H₂O) and the calculated spectrum is extremely sensitive to the H₂O abundance (Figure 3). Our best fit is obtained for 30 ± 10 ppm and corresponds to the 15-25 km altitude range.

The 1.1-1.3 μm region

The new data recorded on 1 July 1991 UT with a standard J-filter cover the entire spectral range from 1.1 to 1.3 μm simultaneously. The spectrum has been recorded near 15 degrees South latitude, at the same location on the planet as for the 1.74 and 2.3 μm spectra, but two days later. O₂ airglow originating in the upper atmosphere of Venus is clearly detected in the 1.27 μm window. No H₂O absorption features are present there. In the 1.18 μm region, all the absorptions lines detected are actually due to H₂O. It is worth noting that many of the H₂O lines present in this window have high energy levels, so that we do not see their telluric counterparts formed at lower temperatures. This is a very favorable situation for Earth-based observations.

The low-frequency edge of the window is limited by the wing of a nearby band of CO₂. Our poor knowledge of far-wing line profiles of CO₂ does not allow us to model it reliably, but fortunately, this uncertainty does not affect our retrieval of the water vapor abundance. The high-frequency side is dominated by the $\nu_1 + \nu_2 + \nu_3$ band of H₂O. Contrary to the 2.3 and 1.74 μm windows, the presence of an additional continuum opacity cannot be assessed at 1.18 μm . This is due to the lack of strong allowed CO₂ bands in this spectral range which could be used to infer the level of line formation. In the absence of any continuum opacity ($\alpha = 0$), most of the observed emission would originate from the surface. In this case, the spectrum is best fitted with a water vapor mixing ratio of ~ 20 ppm. On the other hand, an upper limit of $3.5 \times 10^{-9} \text{ cm}^{-1}\text{am}^{-2}$ can be set on the value of the continuum absorption coefficient α , from flux considerations. Indeed, we have computed that if α was higher than this value, the corresponding outgoing flux would be lower than observed, even if the cloud opacity was set to zero. A higher H₂O concentration, reaching about 40 ppm, is then required to reproduce the observed H₂O absorptions. This determination would pertain to the region around 12 km altitude. Figure 4 shows a synthetic spectrum for an intermediate case ($\alpha = 1.5 \times 10^{-9} \text{ cm}^{-1}\text{am}^{-2}$) in which a mole fraction of 30 ppm allows us to best reproduce the observed spectrum. At this stage of the analysis, we can only conclude conservatively that the H₂O mixing ratio is 30 ± 15 ppm in the probed region, which is located in the lowest 15 kilometers of the Venus atmosphere.

We also note that there is still a lot of uncertainty on the CO₂-broadened linewidths of H₂O transitions, as well as on positions and intensities of high-energy lines. A precise knowledge of these spectroscopic parameters is important in the modelling of high-resolution spectra. The present data also suffer from a too low signal-to-noise ratio, a limitation that should be overcome in the near

future.

DISCUSSION AND CONCLUSION

A comparison with other recent spectra of the lower atmosphere recorded in the near-infrared indicates very consistent results between the different sets of measurements. In particular, the recent analysis by Pollack et al. /14/ that makes use of the complete set of moderate and low resolution spectra recorded at the Anglo-Australian Observatory in 1990 is in good agreement with the analysis presented here. Pollack et al. /14/ also find 30 ppm from about 47 km to 10 km altitude (from an analysis of the 2.3, 1.74, and 1.1- μm windows). They were unable to tell, however, whether the water vapor mixing ratio derived from an analysis of the 1.1 and 1.18- μm windows remained constant or decreased from 10 km to the surface. Besides, as clearly stated by Pollack et al. /14/, it is not yet possible to find a model that fits all windows between 1 and 1.3 μm , and the results at low altitudes (below about 15 km) are only tentative.

Average values near 30 ppm from below the clouds down to altitudes close to the surface fit all the most recent analyses, and therefore those that have benefited from the most accurate and most complete spectroscopic data sets. The higher value observed by Bell et al. /12/ below the clouds seems to correspond to very local and unusual conditions. This conclusion is supported by ground-based narrowband imaging observations of the Venus night side taken at the Palomar 5-meter telescope and spectral imaging data collected at the 3.9-m Anglo-Australian telescope during February 7-15 1990 /13,20/. A preliminary study of spatial variations of the H_2O abundance from the Galileo data at 1.18 μm tends to indicate very weak variations at lower altitudes /21/. The available NIMS-Galileo data set is restricted however to a relatively small fraction of the night side. High spatial resolution on the planet combined with high spectral resolution in all the windows where H_2O can be detected would be extremely useful. This is possible for instance by coupling a Fourier Transform Spectrometer with a near-infrared camera. Successful tests of such a coupling have been made recently at the Canada-France-Hawaii telescope /22/, and we are planning to extensively use this new instrumental configuration to further investigate the deep atmosphere of Venus.

Venus therefore appears to be on the average much dryer than initially suggested by many of the in-situ measurements. Concerning possible vertical variations of the water vapor mixing ratio, there is still some possibility that this ratio may decrease close to the surface of the planet. However, none of the measurements made so far can allow us to be sure of that, and any firm conclusion must await better data at high spectral resolution near 1.18 and 1.1 μm as well as a more reliable spectroscopic data set for CO_2 at wavelengths less than 1.3 μm .

High-resolution spectroscopy of the night side of Venus has also provided extremely interesting information on the abundances of a number of other constituents such as CO, HCl, HF, SO_2 , OCS below the clouds of the planet, as well as on the D/H ratio (see /9,11,19/). Studies of the vertical distributions of some of these species from high-resolution data are only at an early stage. However, the analysis of average resolution data by Pollack et al. /14/ which provides evidence for important vertical variations in the concentrations of both OCS and CO indicates that further work at high-spectral resolution should be extremely rewarding in this respect. One can therefore expect to learn much more about the deep atmosphere of Venus in the near future from ground-based investigations as better near-infrared observations of the night side and better spectroscopic data become available.

The Canada-France-Hawaii Telescope is operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France and the University of Hawaii.

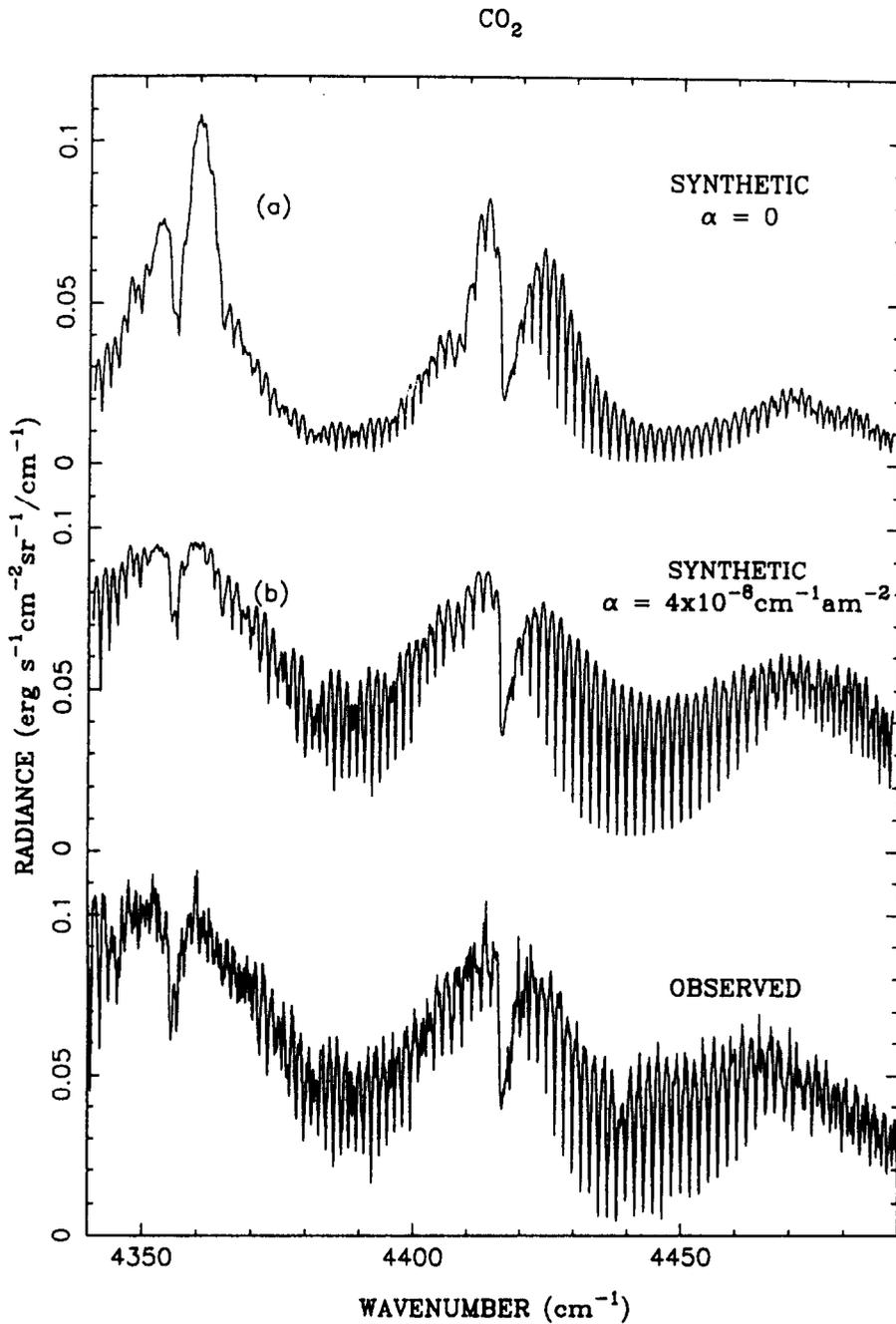


Fig. 1. Lower curve : segment of a 2.3- μm spectrum of the Venus night side recorded on 30 June 1991 UT with the Fourier Transform Spectrometer at the Canada-France-Hawaii telescope. The apodized resolution is 0.14 cm^{-1} . This spectrum was obtained with a 5 arc-second circular aperture centered at 15 degrees South latitude. Upper curve : synthetic spectrum of Venus computed with no extra CO₂ continuum opacity added ($\alpha = 0$). Middle curve : synthetic spectrum of Venus computed with an additional continuum opacity due to CO₂ modelled with a binary absorption coefficient α (see text) equal to $4 \times 10^{-8} \text{ cm}^{-1} \text{ am}^{-2}$. Most of the absorptions detected here correspond to allowed transitions of CO₂.

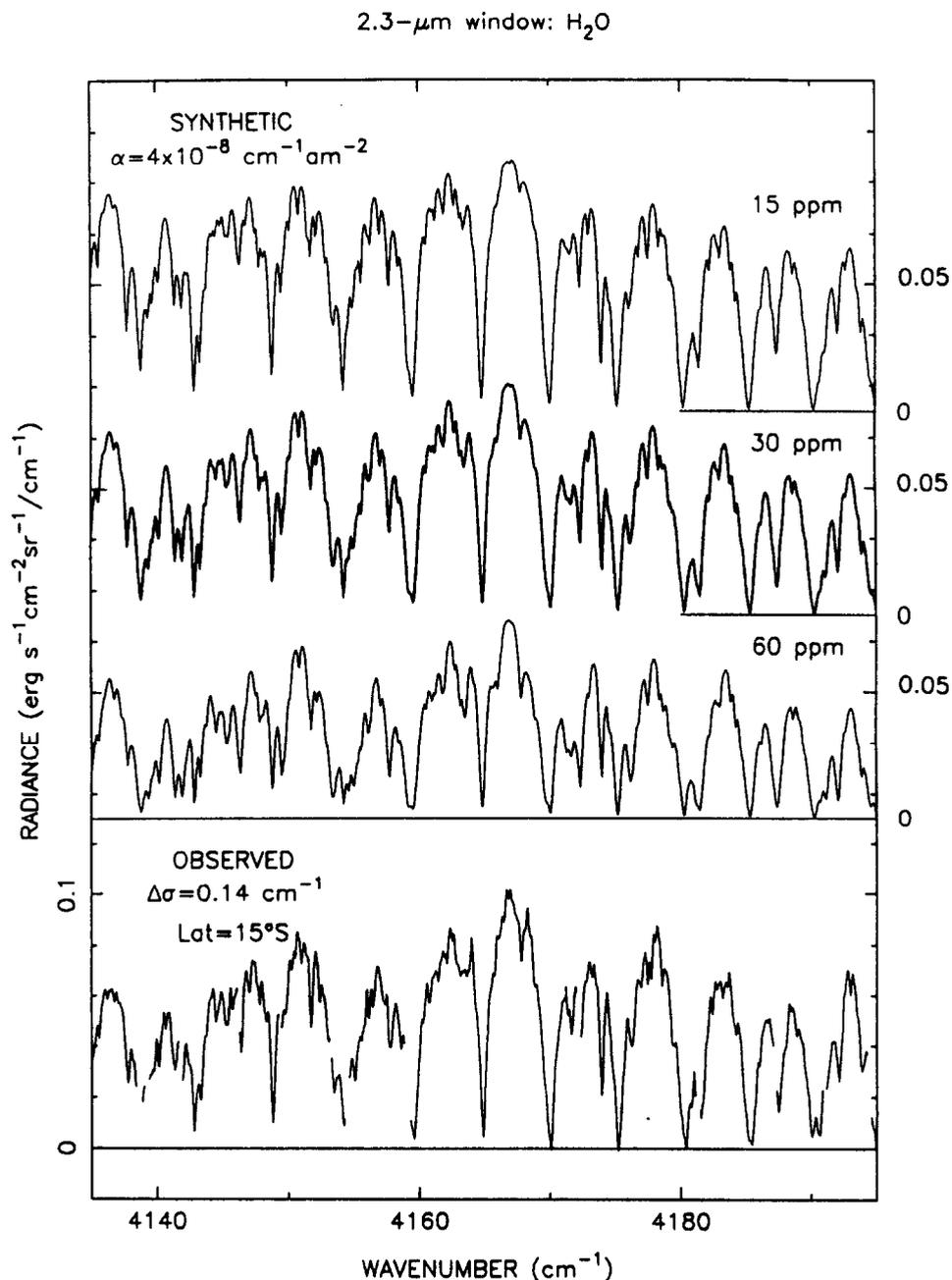


Fig. 2. Lower curve : portion of the same spectrum of the night side of Venus as on Figure 1. The three **upper curves** correspond to synthetic spectra of Venus computed for three different values of the water vapor mixing ratio below the clouds (15, 30 and 60 ppm). The strongest absorptions in this range are due to lines from the 2-0 band of CO. An HF line is also present at 4174 cm^{-1} . The best agreement with the observed spectrum corresponds to a water vapor mixing ratio of 30 ppm. At these wavelengths, emission mostly originates from the 30- to 40-km altitude range.

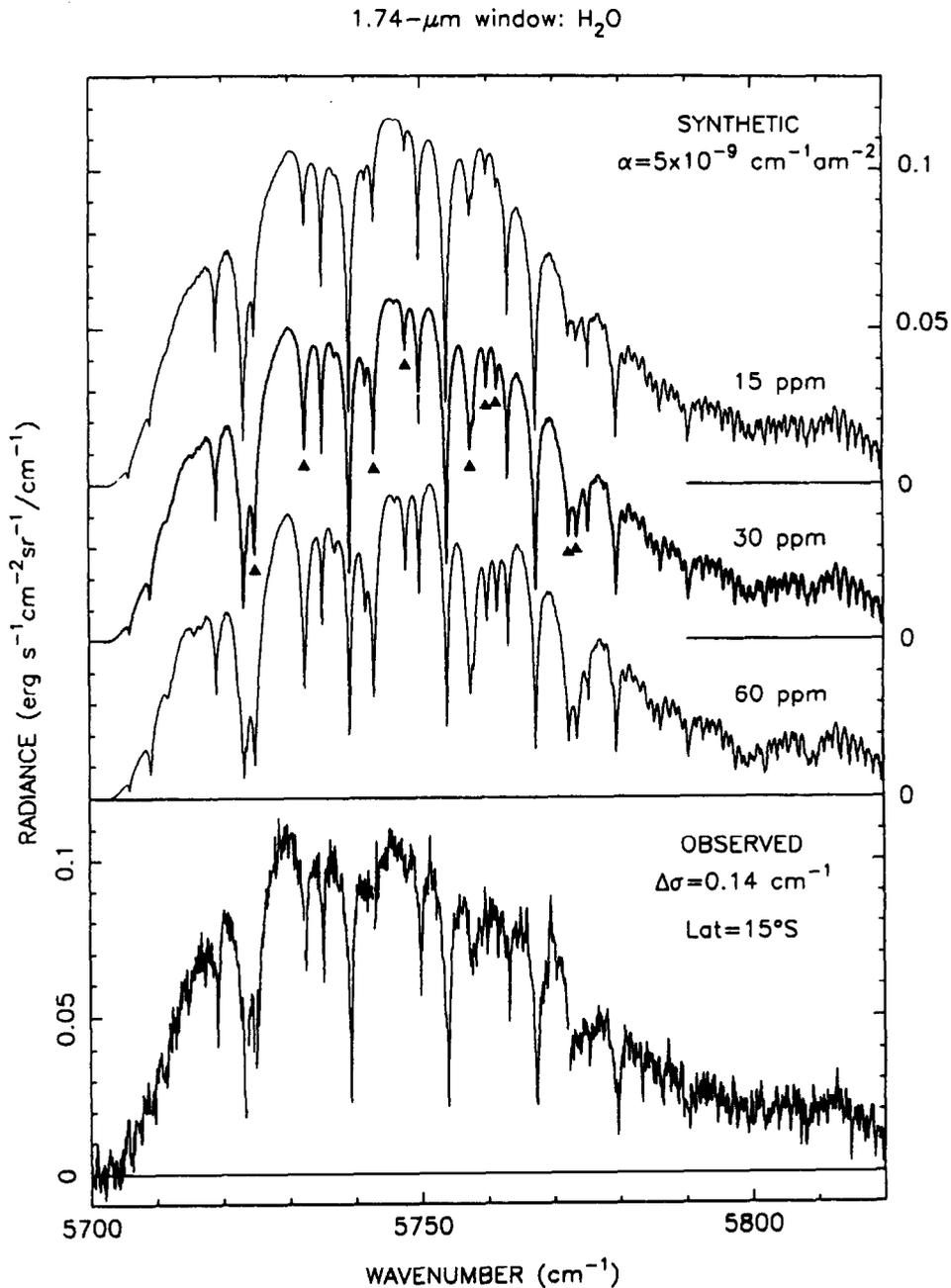


Fig. 3. Lower curve : portion of a 1.74- μm spectrum of the night side of Venus recorded on 30 June 1991 UT with the Fourier Transform Spectrometer at the Canada-France-Hawaii telescope. The apodized resolution is 0.14 cm^{-1} . This spectrum was obtained with a 5 arc-second circular aperture centered at 15 degrees South latitude. The three upper curves correspond to synthetic spectra of Venus computed for three different values of the water vapor mixing ratio below the clouds (15, 30 and 60 ppm), and for a value of the CO₂ binary absorption α equal to $5 \times 10^{-9} \text{ cm}^{-1} \text{ am}^{-2}$. The strongest H₂O lines are identified with arrows. The other strong lines present in this spectral range are due to HCl. The best agreement is obtained for a water vapor mixing ratio of 30 ppm. In this window, we probe the 15- to 25-km altitude range.

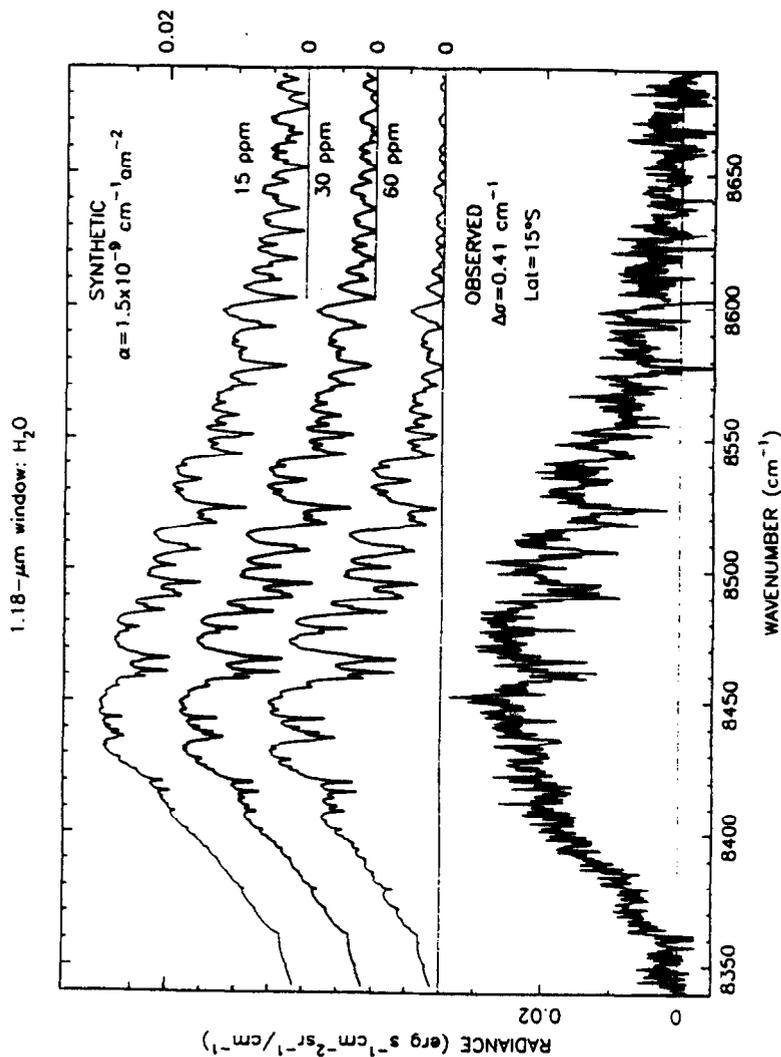


Fig. 4. Lower curve : portion of a spectrum of the night side of Venus recorded on 1 July 1991 UT with the Fourier Transform Spectrometer at the Canada-France-Hawaii telescope using a standard J filter. The apodized resolution is 0.41 cm^{-1} and the signal-to-noise ratio about 10. This spectrum was obtained with a 5 arc-second circular aperture centered at 15 degrees South latitude. The three upper curves correspond to synthetic spectra of Venus computed for three different values of the water vapor mixing ratio below the clouds (15, 30 and 60 ppm) and for a value of the binary absorption coefficient (α) equal to $1.5 \times 10^{-9} \text{ cm}^{-1} \text{ am}^{-2}$. The best agreement is then obtained for a water vapor mixing ratio of 30 ppm. The atmospheric region probed in this window is centered somewhere between 0 to 12 km above the surface, depending on the actual magnitude of the CO_2 continuum opacity.

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