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Infrared imaging of Venus from IRTF/ProtoCAM observations in 1991

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Abstract. Infrared observations of Venus' night-side between 3 and 5 μm provide a valuable means to study the upper cloud structure (at approximately 68 km) and the thermal structure above the clouds. New observations between 3.67 and 5.08 μm, concerning spectral images of Venus obtained in October 1991 with the ProtoCAM/IRTF and a Circular Variable Filter, are presented. A cloud particle scale height for the upper clouds of 3.9 ± 1 km is retrieved from limb darkening measurements, which is in good agreement with measurements from both space probes and Earth-based observatories. The observations show an increase in temperature from the centre towards the poles when sounding altitudes above 72 km. This, along with temperatures at cloud top levels, implies isothermal profiles between 68 and 74 km at high latitudes. Copyright © 1996 Elsevier Science Ltd

1. Introduction

The night-side emission of the cloud deck of Venus has been studied in the infrared by various authors. Diner (1978) recorded spectra from the night-side at wavelengths between 8 and 20 μm. He made use of limb darkening measurements and a simplified radiative transfer model in order to deduce a cloud particle scale height of the upper clouds. The same type of analysis has been performed by Taylor *et al.* (1980) with Pioneer-Venus data. During the Galileo/Venus encounter in February 1990, the Near Infrared Mapping Spectrometer (spectral range 0.7–5.2 μm) provided new information on the composition of Venus' atmosphere and the cloud structure (Carlson *et al.*, 1991). The data allowed limb darkening measurements in the 3–5 μm range (Roos *et al.*, 1993) and the retrieval of the thermal profile above the clouds (Roos-Serote *et al.*, 1995).

Infrared observations of the upper clouds have provided a very stable picture with time. In this context, the results presented in this paper contribute to the confirmation of this constant behaviour.

In the next section we will discuss the observations and the absolute calibration. Section 3 will be devoted to the presentation and the discussion of the results. The conclusions are presented in the last section.

2. Observations and data reduction

The data were obtained at the InfraRed Telescope Facility (IRTF) at Mauna Kea, Hawaii, with the ProtoCAM instrument and a Circular Variable Filter. ProtoCAM is an infrared camera with a CCD of 58×60 pixels. Spectral images were recorded at 29 wavelengths, between 3.673 and 4.156 μm on 12 October 1991 and between 4.654 and 5.084 μm on 16 October 1991. The spectral resolving power is of the order of 60 and the spatial resolution is 0.35 arcsec pix^{-1} corresponding to 140 km pix^{-1} or about 1° pix^{-1} Venus coordinates at the sub-Earth point. Venus had a phase of about 0.38 at the time of the observations (phase angle about 100°), so that a large part of the night-side of the planet was observable. The images of 12 October mainly show the northern hemisphere. The images of 16 October consist of two sequences, one showing the northern hemisphere and the other the southern hemisphere. Figure 1 displays two images at two different wavelengths for 12 October. We followed a standard reduction procedure, i.e. subtraction of the sky from the raw data and division by flat fields.

An absolute flux calibration of the Venus images has been performed. Star images at the same dates and wavelengths as the Venus images were available (HR3826 and HR3547 for 12 and 16 October 1991, respectively). After calibration of the Venus images with the stars, spectra were extracted and compared to Galileo/NIMS spectra at the same latitudes and with the same emission angle (2-01, 2-04 and 2-07 in Table 1, Drossart *et al.* (1993)).

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Table 1. Limb darkening measurements

Authors	T_1 (K)	C (K)	H_{cloud} (km)
Diner (1978)	—	13.5	4.5
Roos *et al.* (1993)	236 ± 1.8	11.7 ± 1	4.1 ± 0.6
This work	233 ± 1.4	11.3 ± 1.8	3.9 ± 1.0

This comparison showed that the shape of the calibrated ProtoCAM spectra corresponds very well to the NIMS spectra, but that the radiances are systematically too high. The difference, averaged over wavelength and latitude, is a factor of 2.45 ± 0.3 for 12 October and 2.41 ± 0.3 for 16 October. Because these two factors are the same for the two different series of images, with two different reference stars, a systematic error is implied. Possible causes might lie in the comparison of a point source to an extended source and/or in differences in air mass between the images of Venus and those of the reference stars. However, this last hypothesis has been verified to reduce the factors by about 25% only.

It was decided to scale the star-calibrated ProtoCAM radiances to the NIMS radiances, using the factors found by the comparison of three ProtoCAM spectra to three similar NIMS spectra, as discussed above. The reason that we prefer the absolute calibration of the Galileo/NIMS spectra, dating 20 months earlier, over the reference stars, is that a comparison of the Galileo/NIMS data (Roos *et al.*, 1993) with the Pioneer-Venus data (Taylor *et al.*, 1980) shows very similar brightness temperatures, indicating that larger scale temporal variations of the absolute flux are unlikely.

Combining all the uncertainties (S/N, absolute infrared flux calibration for the stars, the rescaling to the Galileo/NIMS spectra) it is estimated that the error on the intensity is on the order of 17%. When the intensity is converted to blackbody temperatures, this error implies an uncertainty of 3 K on these temperatures.

Figure 2 shows two spectra at different latitudes, extracted from the images, compared to Galileo/NIMS spectra. The continuum is formed by emission from the upper clouds with a unit cloud optical depth at about 68 km altitude, and superimposed are two CO_2 bands at 4.3 μm (ν_3) and at 4.8 μm ($\nu_1 + \nu_2$). No data were obtained in the centre of the 4.3 μm CO_2 ν_3 band, because of the strong absorption by terrestrial CO_2.

3. Results and discussion

3.1. *Limb darkening*

From the calibrated and Galileo/NIMS-corrected images, limb darkening measuments have been performed at three different continuum wavelengths (3.698, 3.989 and 4.950 μm) in the equatorial region ($-25°$, $+25°$), in order to derive a value for the cloud particle scale height. An approximative radiative transfer model without scattering has been used to derive the following equation (Diner, 1978; Roos *et al.*, 1993):

$$T(\mu) = T_1 + C \times \ln(\mu) \qquad (1)$$

where $C = -(\mathrm{d}T/\mathrm{d}z) \times H_{\text{cloud}}$, T is the brightness temperature, μ the cosine of the emission angle, $\mathrm{d}T/\mathrm{d}z$ the thermal gradient and H_{cloud} the cloud particle scale height. This model has been used by Diner (1978) for limb darkening measurements of Venus' night-side (8–20 μm) and by Roos *et al.* (1993) for measurements in the same spectral region as in this work, covering the same latitudes, using Galileo/NIMS data. Figure 3 shows two typical examples of limb darkening curves. The linear dependence on $\ln(\mu)$ is obvious from this figure. In total, 13 limb darkening curves have been measured, and the mean value for the parametres C and T_1 are found to be 11.3 ± 1.8 K and 233 ± 1.4 K, respectively. The error bars correspond to the 1σ variation about the mean value. It has been checked that the effect of scaling the images to NIMS radiances, as explained in the previous section, is only about 10% on the value of C. This is about two-thirds of the variation around the mean value and it means that the determination of the value of C can be considered independent of the calibration problem. The effect for T_1 is about 6%, or about 14 K.

Assuming the same thermal gradient at 68 km altitude as used by Roos *et al.* (1993), i.e. -2.9 ± 0.4 K km^{-1} (Venus International Reference Atmosphere model (Seiff *et al.*, 1985)), a value for H_{cloud} of 3.9 ± 1 km is derived (the gas scale height at 68 km altitude is about 5 km (Schubert, 1983)). It has been shown by Roos *et al.* (1993) that the accuracy of this simplified model is satisfactory for the determination of the cloud particle scale height. Full scattering calculations (Grinspoon *et al.*, 1993; Roos *et al.*, 1993) result in an augmentation of the value of the cloud particle scale height by about 1 km, which is within the range of the uncertainty. Table 1 summarizes the results and confirms that they correspond well to values found earlier.

As has been discussed by Roos *et al.* (1993), the parameter T_1 gives an indication of the cloud temperature. In view of the absolute calibration problem encountered with the ProtoCAM data, the obtained values of T_1 are not reliable enough to allow a detailed analysis.

3.2. *The high latitude regions*

We will now discuss the variations in thermal structure as a function of latitude that can be observed above the cloud tops in the infrared. Figure 1 shows two images, one at 3.673 μm, the cloud top continuum, and another at 4.217 μm, in the blue wing of the 4.3 μm CO_2 ν_3 band. As can be seen in the second image, the intensity increases relative to the intensity at the equator, with increasing latitude. This effect is essentially due to a change in thermal structure to a (quasi-) isothermal atmosphere above the cloud tops in the northern and southern hemisphere (around $-55°$ and $+60°$). This has been observed before; Taylor *et al.* (1980) and Seiff (1983) found from Pioneer-Venus data isothermal profiles between 60 and 80 km altitude at latitudes $+65°$ and $-52°$ (Seiff, 1983, Fig. 17), with a temperature of about 230 K. Furthermore, Dubois *et al.* (1990) observed inversion structures and quasi-iso-

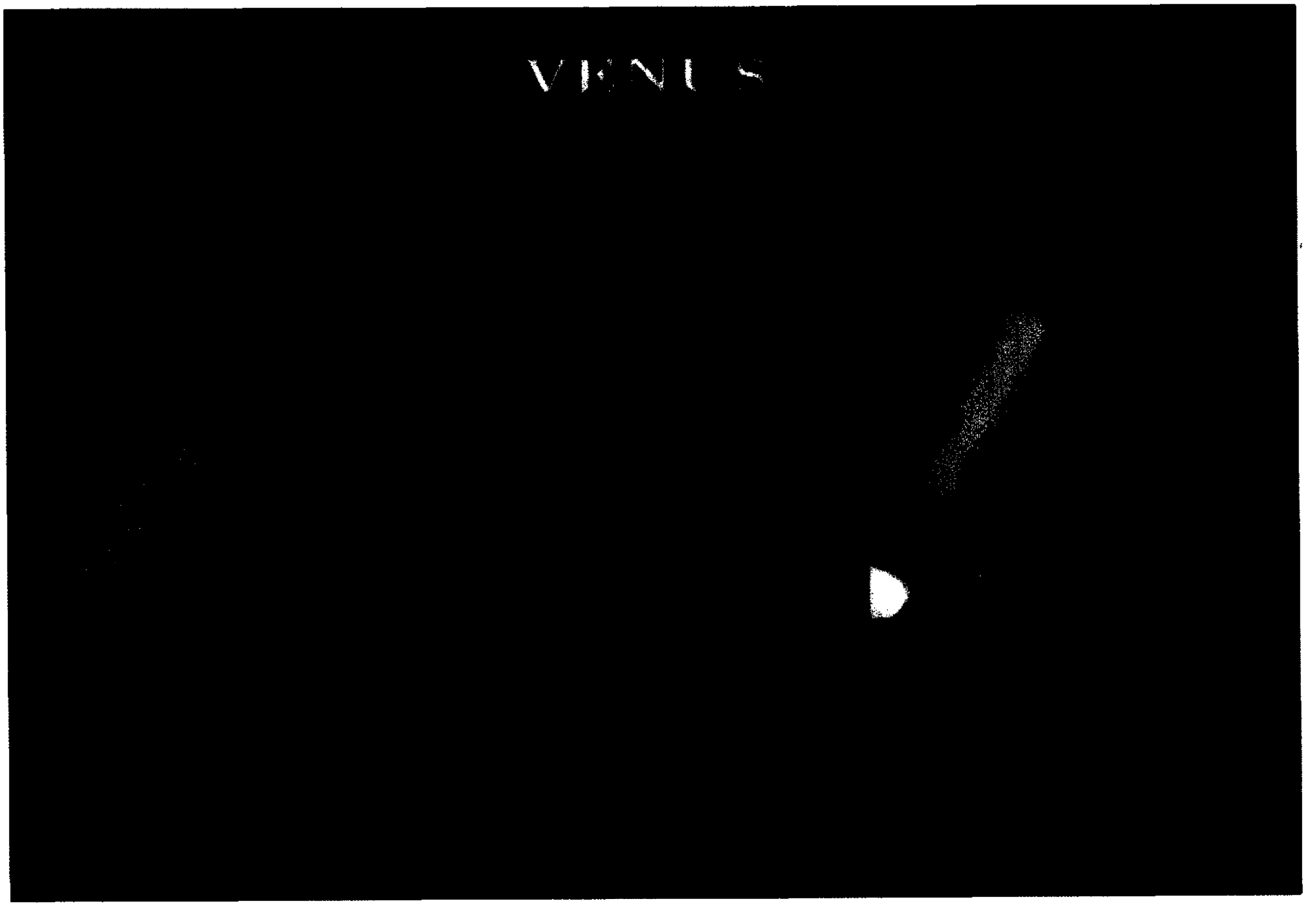


Fig. 1. Two images of 12 October 1991. Spatial resolution is 140 km pix^{-1} at the centre of the disk (emission angle zero). The left image shows the cloud top continuum at 68 km altitude (3.673 μm). The right one is at 4.217 μm, in the blue wing of the 4.3 μm CO_2 ν_3 band, and sounds some 6 km higher. A warmer high latitude region is clearly present. Indicated north and east refer to Venus

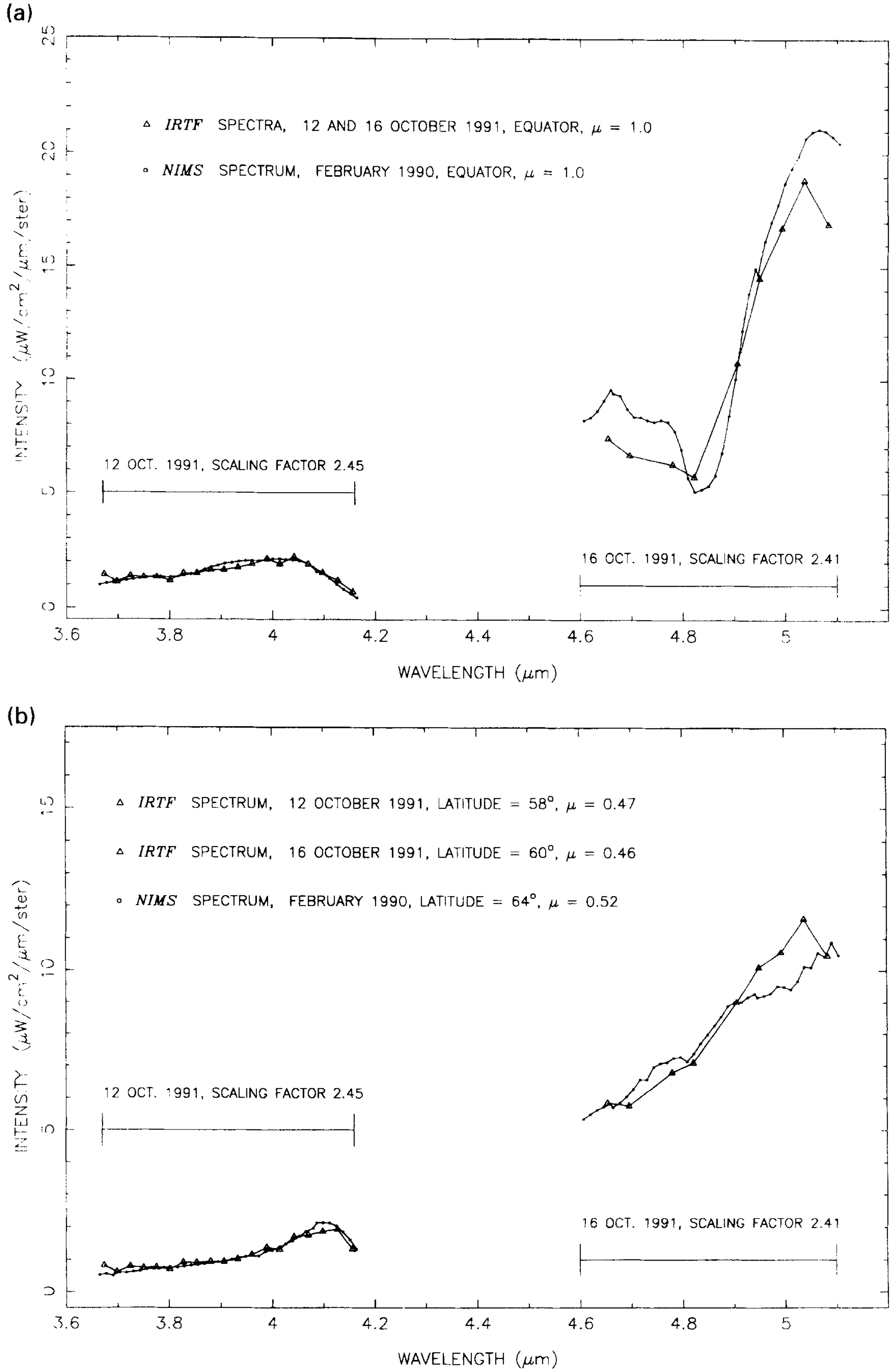


Fig. 2. (a) A spectrum at the equator (emission angle 0°), combining two observation runs of two different nights, in order to cover the different wavelength regions. The spectra are scaled relative to the corresponding Galileo/NIMS spectrum (Table 1, 2-07, Drossart *et al.*, 1993), as explained in the text. (b) A spectrum at high latitude (emission angle 62°), same as (a) (Galileo/NIMS spectrum, Table 1, 2-01, Drossart *et al.*, 1993). As can be seen, both CO_2 absorption features (ν_3 and $\nu_1 + \nu_2$) have drastically changed, indicating an isothermal atmosphere around 70 km

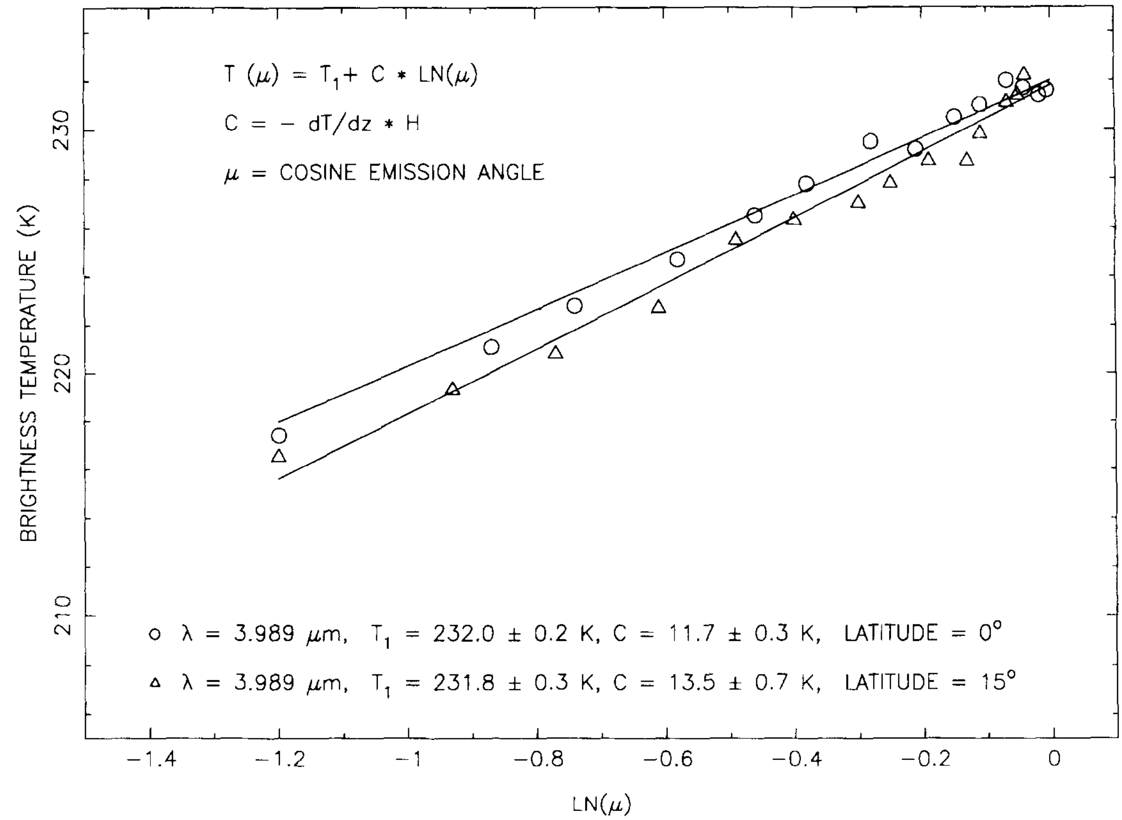


Fig. 3. Two limb darkening measurements from the image at 3.989 μm (12 October 1991), at the equator and at 15° latitude. The line shows the fit as obtained by the model (equation (1), see text). The derived model parameters T_1 and C are shown in the figure. Note the clear linear dependence of the data with $\ln \mu$, where μ is the cosine of the emission angle. Brightness temperature corresponds to a blackbody temperature at 3.989 μm and the intensity as measured from the image

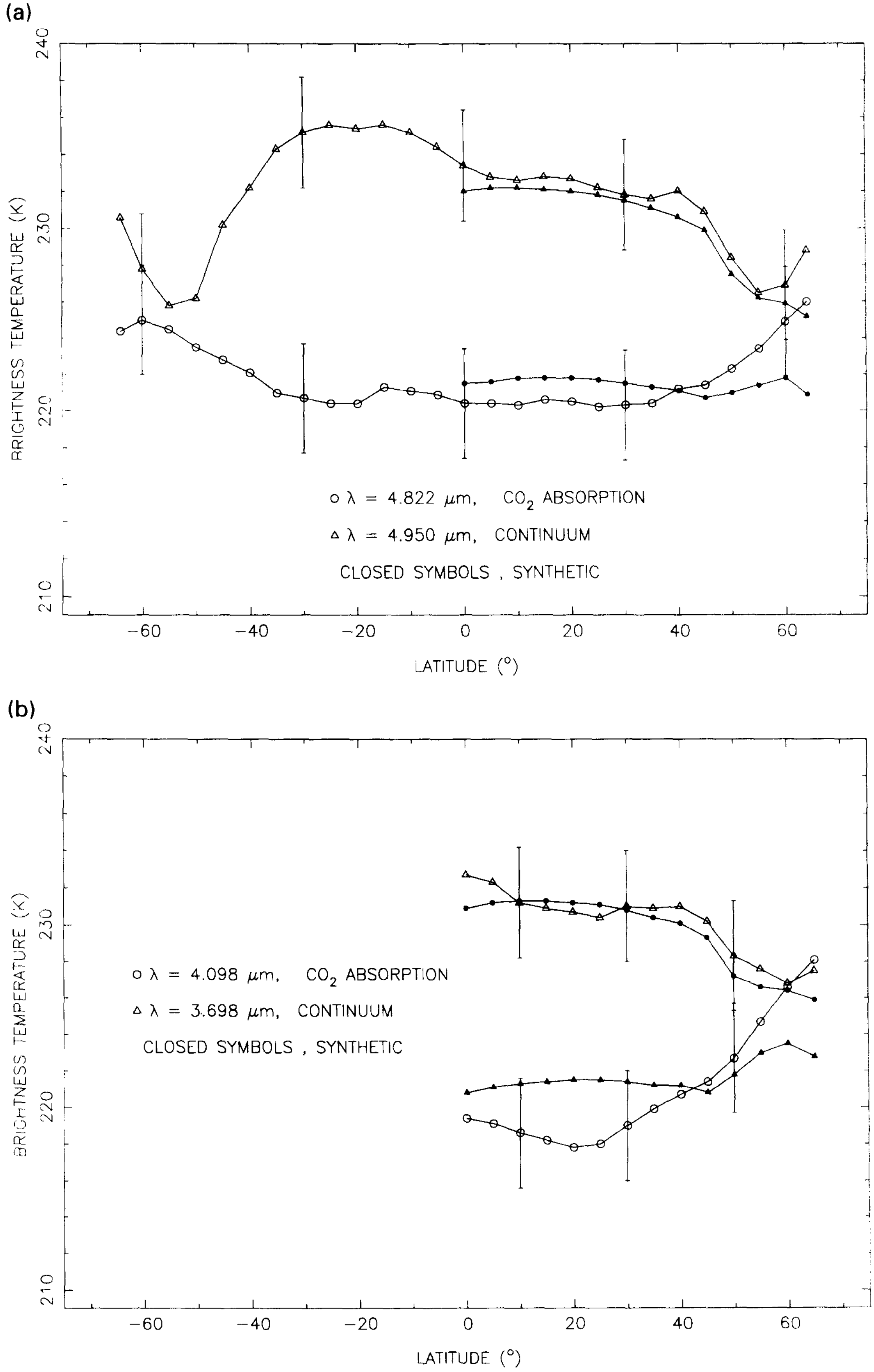
thermal profiles between about 64 and 75 km altitude at +60° ±5° latitude in Venera-15 data, also at a temperature around 230 K.

In previous papers the spectrum of Venus in the 3–5 μm region has been modelled, using a non-scattering band model (Roos *et al.*, 1993; Roos-Serote *et al.*, 1995). This model was used here in order to calculate the intensity and the effective altitude (defined as the altitude where the weighting function in the radiative transfer equation peaks) at a given wavelength, assuming that the thermal structure in the northern hemisphere is described by the Venus International Reference Atmosphere model (Seiff *et al.*, 1985) at the appropriate latitudes.

Going from the continuum to the centre of the 4.3 μm CO_2 ν_3 absorption band, altitudes from 68 up to 90 km are sounded. Since the absorption is very strong in the centre of the band, this part of the spectrum is unobservable from the Earth, because of absorption by terrestrial CO_2. However, observations were done on the blue wing of this band and in the 4.8 μm CO_2 $\nu_1+\nu_2$ band, which is a weak absorption structure.

Two wavelengths were selected, one in the blue wing of the CO_2 ν_3 band at 4.098 μm for 12 October and another in the centre of the CO_2 $\nu_1+\nu_2$ band at 4.822 μm for 16 October. At both these wavelengths altitudes of about 72 km at the equator are sounded, i.e. about 4 km above the cloud top level. They both show evidence for a warmer atmosphere relative to the equator at high latitudes

Fig. 4. (a) A cut at constant longitude showing the difference in brightness temperature as measured at 4.950 (continuum) and 4.822 μm (CO_2 $\nu_1+\nu_2$) for 16 October 1991 (error bars indicate the $1-\sigma$, error of 3 K on the temperatures). The sounded altitudes range from 68 km at the equator to 71 km at ±65° latitude at 4.950 μm and from 72 to 74 km respectively at 4.822 μm. For comparison, the results of a synthetic calculation using the Venus International Reference Atmosphere model as thermal structure for the northern hemisphere are shown and found to reproduce well the general trend of the curves (see text for more details). (b) A cut at constant longitude for 12 October 1991 (northern hemisphere only). At the continuum wavelength (3.698 μm) the sounded altitudes range from 68 km at the equator to 71 km at +65° and in the blue wing of the 4.3 μm CO_2 ν_3 band (4.098 μm) these values are 72 and 74 km, respectively (error bars indicate the $1-\sigma$, error of 3 K on the temperatures). For comparison, the results of a synthetic calculation using the Venus International Reference Atmosphere model as thermal structure for the northern hemisphere are shown and found to reproduce well the general trend of the curves (see text for more details)


(a)
BRIGHTNESS TEMPERATURE (K)
240
230
220
210
-60
-40
-20
0
20
40
60
LATITUDE (°)
○ λ = 4.822 μm, CO2 ABSORPTION
△ λ = 4.950 μm, CONTINUUM
CLOSED SYMBOLS , SYNTHETIC
(b)
BRIGHTNESS TEMPERATURE (K)
240
230
220
210
-60
-40
-20
0
20
40
60
LATITUDE (°)
○ λ = 4.098 μm, CO2 ABSORPTION
△ λ = 3.698 μm, CONTINUUM
CLOSED SYMBOLS , SYNTHETIC

(northern hemisphere for 12 October, and both hemispheres for 16 October). Note that at high latitudes emission angles are large, so that still higher effective levels of up to 74 km are sounded at the wavelengths in the CO_2 bands and up to about 71 km at continuum wavelengths.

When comparing brightness temperatures at the CO_2 band wavelengths to brightness temperatures measured at continuum wavelengths, the general trend is that both temperatures approach each other at latitudes around ±60°. This implies a change in thermal gradient towards an isothermal atmosphere. It can also be clearly seen in the spectrum of the northern region (Fig. 2b). The 4.8 μm CO_2 $\nu_1+\nu_2$ absorption feature has disappeared and the region of the spectrum around 4.1 μm (the beginning of the 4.3 μm CO_2 ν_3 band) has risen, indicating an isothermal atmosphere in the 71–74 km altitude region (emission angle is 62° for this spectrum).

Due to the absolute calibration problem it is impossible to assess absolute values for the temperatures from the ProtoCAM data. However, the relative variation of the brightness temperatures with latitude is well determined. In Figs 4a and b two cuts at constant longitude (relative to the central meridian) are shown and compared to synthetic calculations with the band model and the VIRA thermal structure mentioned above. Figure 4a shows the brightness temperature at 4.950 (continuum) and 4.822 μm (CO_2 $\nu_1+\nu_2$) for 16 October. The sounded altitudes range from about 68 km at the equator to about 71 km at ±65° latitude for the continuum wavelength. In the CO_2 band these numbers are 72 and 74 km. The effect of a decreasing thermal gradient towards high latitude regions is clear in both hemispheres, with a minimum occurring near +60° in the northern hemisphere and at −55° in the southern hemisphere. Figure 4b shows the brightness temperatures at 3.698 μm (continuum, effective altitude ranges from 68 km at the equator to 71 km at +65° latitude) and 4.098 μm (CO_2 ν_3, effective altitude ranges from 72 to 74 km) for 12 October. The synthetic calculations compare fairly well with the observations in that the general form of the brightness temperature versus latitude curves is reproduced. We have interpolated between the three available VIRA models at 0°, 45° and 60° latitude to obtain the thermal structure at any given latitude and we have fitted the continuum level by adjusting the altitude of unit cloud optical depth. The cloud had a scale height of 3.9 km, as determined from the limb darkening measurements presented in the previous section.

The most important difference is that the calculations do not reproduce the increase in brightness temperature observed at continuum wavelengths for latitudes higher than about +55° and lower than −55°. This can be very well due to changes in the thermal structure relative to VIRA, which are known to exist for altitudes between 70 and 90 km (Roos-Serote *et al.*, 1995).

4. Conclusions

Earth-based observations in the near infrared of the nightside of Venus, as have been presented here, do provide a valuable means to study the cloud structure and the thermal structure above the clouds. In the present work the data were acquired by the ProtoCAM instrument at the IRTF facility (Hawaii). They are of good quality and permit a spatial and spectral study at the same time. Limb darkening measurements in the equatorial region are in good agreement with measurements from both space probes and Earth-based observatories and confirm the temporal stability of the cloud structure at infrared wavelengths. A cloud particle scale height of 3.9 ± 1 km is derived for the upper clouds from limb darkening measurements, assuming VIRA temperature profile.

Further, warm high latitude regions show up in the images at wavelengths where one sounds above the cloud tops. This observation indicates temporal stability for the thermal structure, which consists of an approximate isothermal profile above the clouds at 68 km up to at least 74 km.

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