LIMB DARKENING OBSERVATIONS OF VENUS FROM 5 μ TO 18 μ

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Abstract. Limb darkening measurements of the thermal radiation from Venus at 5, 9, 11, 13 and 18 μ are presented. This data, produced by deconvolving the observations with a measured instrumental response function, indicates a complex atmospheric structure which will require careful atmospheric modeling to fully interpret.

1. Introduction

In recent years several models for the atmosphere of Venus above the cloud layer have been proposed (see Samuelson, 1968, for a review). The direct, in situ, measurement of the temperature, pressure, and chemistry by the Venera probes (Avduevsky *et al.*, 1968, Vinogradov *et al.*, 1970) and the temperature-pressure measurements made by Mariner 5 (Kliore *et al.*, 1967) have greatly increased the knowledge of this part of the atmosphere of Venus. Unfortunately the only data bearing on the variation of opacity in the upper atmosphere comes from limb darkening measurements which with one exception have been made from the earth.

Previous limb darkening measurements have been made by Sinton and Strong (1960), Murray *et al.* (1963), Chase *et al.* (1963), Westphal *et al.* (1965), and Westphal (1966). All of these measurements were made in the region from 8–14 μ. Only those of Westphal (1966) were corrected for instrumental and atmospheric effects near the limb and extend to local zenith angles larger than about 60°.

Atmospheric models utilizing the Venera and Mariner data along with the broad band infrared (8–14 μ) measurements have shown the need for both higher spectral resolution, wider wavelength coverage, and more dependable data near the limb (see for example, Samuelson, 1968).

2. Observations

On 24 April 1969, a series of scans of Venus were made with the 200-inch Hale telescope to determine limb darkening profiles at several wavelengths. These measurements were designed to yield the best possible determination of the profiles very near the limb.

Previous experience with this type of measurement (Westphal, 1966) indicated that a very high signal to noise ratio was desirable and that careful attention to the determination of the instrumental profile was essential. Improvements in detectors and photometers during the four years since the previous measurements allowed the necessary

Sagan et al. (eds.), Planetary Atmospheres, 48–54.

signal to noise ratio to be obtained in narrow wavelength regions (≈ 1 μ wide) centered at 5, 9, 11, 13, and 18 μ.

Several changes were made in procedure as well as in the equipment used for the 1964 measurements. Instead of a small round measuring aperture, a very narrow (0.75 arc sec) slit, 7.5 arc sec long was used. This slit was oriented accurately normal to a scan diameter so that the instrumental response function due to the slit alone was less than one arc second halfwidth. The added flux through this slit along with an improved doped germanium detector allow the measurements to be made in approximately one micron wide band passes. Table I lists the details of the filters. The errors

TABLE I

Filter μ	Wavelength 50% transmission
5	4.56–5.02
9	8.41–9.03
11	10.45–11.9
13	12.5–13.5
18	16.5–19.5[a]

[a] Long wavelength cutoff of 18 μ filter determined by atmospheric water vapor.

associated with the 1964 measurements were almost entirely due to uncertainties in the instrumental response function used to deconvolve the data. To reduce this uncertainty substantially, measurements of a bright star (β Pegasus) were made during the observations of Venus. The star was scanned normal to the slit used for the limb measurements. All the data were recorded on magnetic tape and reduced with an IBM 360-75 digital computer.

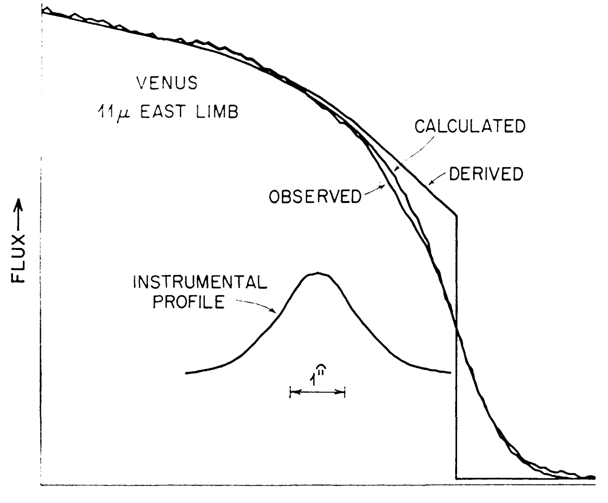

Fig. 1.

https://doi.org/10.1017/S0074180900102621 Published online by Cambridge University Press

Figure 1 illustrates the data collected along part of the east limb of Venus at 11 μ. The data were reduced by the technique described in the earlier paper (Westphal, 1966) and the calculated, observed, and derived limb curves are shown along with the

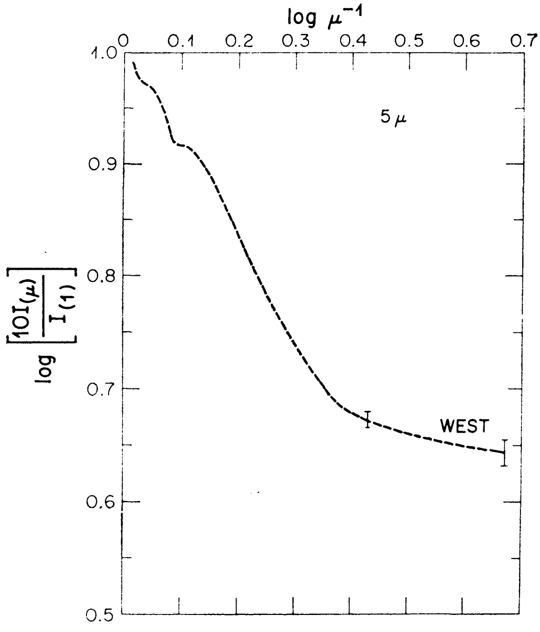

Fig. 2.

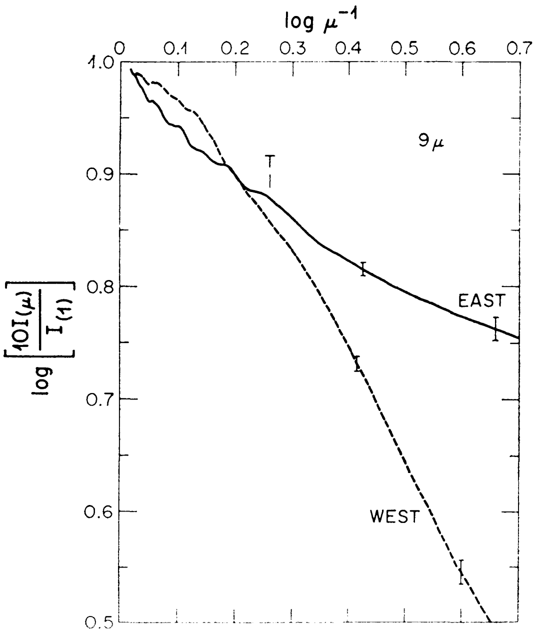

Fig. 3.

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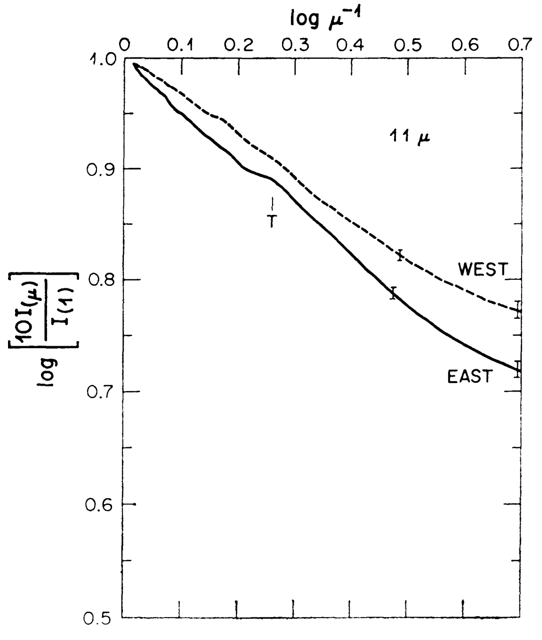

Fig. 4.

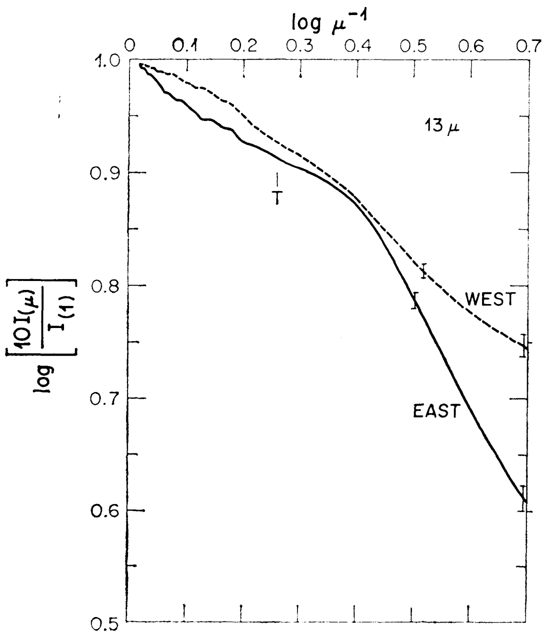

Fig. 5.

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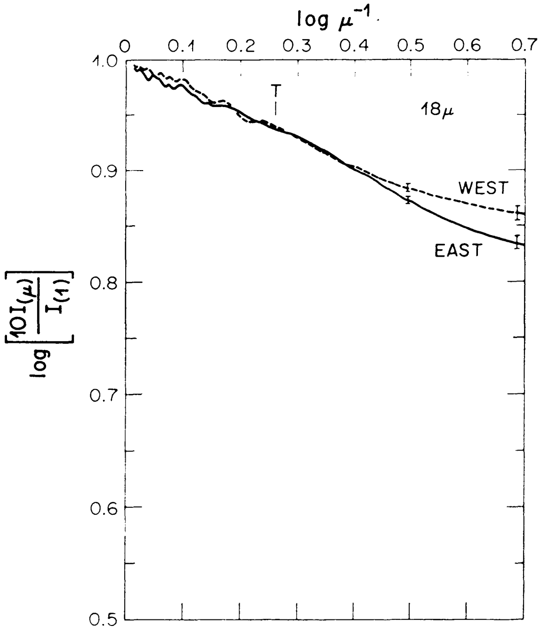

Fig. 6.

instrumental profile. The sensitivity of this deconvolution process is very high and again the errors in the final derived profile are almost entirely due to the uncertainty in the instrumental profile. As was true before, the deconvolution process depends on the assumption of a discontinuous decrease of the flux to zero at the limb. This assumption is very likely satisfactory on the scale of these measurements.

Another important feature of this reduction process is that spatial variations smaller than about $\frac{1}{3}$ of the halfwidth of the instrumental profile are not recoverable. This precludes detection of sizeable departures from a smooth profile very near the edge. Thus although values for the flux are determined to within 0.05 arc sec of the limb, the reliable data extend only to within about 0.6 arc sec of the limb.

Figures 2 through 6 show the reduced data plotted as log flux vs log μ^{-1}, where μ^{-1} is the secant of the local zenith angle. Error bars are shown at two places on each curve, the errors approach zero near the origin. The location of the sunrise terminator is shown on all the east limb curves.

3. Discussion

Detailed interpretation of the data will require calculations based on quite complicated models. In this paper, only a qualitative discussion of the curves will be attempted.

The most striking general characteristic of the data is the gradual decrease of limb darkening with increasing wavelength for zenith angles less than 65° (log $\mu^{-1} < 0.4$). This results, in a general sense, from the change in the Planck function with temperature and wavelength. The data closer than log $\mu^{-1} = 0.4$ to the limb show very complicated

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details and large differences between the east and west sides. As an example, the 13 μ data from the east limb show a very large increase in limb darkening for log $\mu^{-1} > 0.4$. This is a spectral region of high CO_2 opacity and suggests the possibility of horizontal inhomogeneity in either temperature or opacity or both, related to the presence of sunlight.

The 9 μ data from the west limb also shows very strong limb darkening out to the limit of measurement, while the east limb has only moderate darkening. Since this is a region free from CO_2 absorption the differences must reflect changes in the opacity or temperature of the particulate material in the atmosphere.

The 11 μ east limb curve shows a definite increase in flux just at the terminator. Samuelson (1969) has suggested that such an effect could be due to the difference in thermal time constant between the particulate material and the surrounding CO_2 gas as the planet rotates into the sunlight. One would expect that a careful study might determine some of the thermal properties of the particles from this data.

The 5, 11, and 18 μ data from the west limb and the 9, 11, and 18 μ data from the east limb show a marked decrease in limb darkening for values of log $\mu^{-1} > 0.4$. Since such an effect can be caused in several ways, only careful modeling can choose the most likely source of this flattening.

Five micron data is available only for the west limb, since reflected sunlight eastward from the terminator on the east limb profile precludes a unique determination of the thermal flux.

Another feature of the curves is that, at all wavelengths except 18 μ, the west limb is brighter than the east limb for zenith angles less than about 50°. This observation is consistent with the observation that the antisolar point is emitting more flux than the subsolar point in the 8–14 μ wideband measurements previously reported (Westphal *et al.*, 1965) and indicates that the upper part of the atmosphere has essentially a uniform longitudinal temperature structure.

Further high spatial resolution studies should include polarization measurements, particularly at 5 and 9 μ where most of the opacity should be due to the particulate material in the atmosphere.

It should also be possible to make limb darkening measurements at much higher spectral resolution (resolution ≈ 50) in regions of special interest.

4. Summary

The results reported in this paper, along with the in situ measurements from probes and the occultation measurements should allow a rather complete model of the upper atmosphere of Venus to be developed. The complexity of this region is greater than previously known and the likelihood of spatial and temporal inhomogeneities will require careful modeling.

References

Avduevsky, V. S., Marov, M. Ya., and Rozhoestvensky, M. K.: 1968, 'Model of the Atmosphere of the Planet Venus Based on Results of Measurements Made by the Soviet Automatic Interplanetary Station Venera 4', *J. Atmospheric Sci.* **25**, 537.

Chase, S. C., Kaplan, L. D., and Neugebauer, G.: 1963, 'The Mariner 2 Infrared Experiment', *J. Geophys. Res.* **68**, 6157.
Kliore, A., Levy, G. S., Cain, D. L., Fjeldbo, G., and Rasool, S. I.: 1967, 'Atmosphere and Ionosphere of Venus from the Mariner V S-band Radio Occultation Measurement', *Science* **158**, 1683.
Murray, B. C., Wildey, R. L., and Westphal, J. A.: 1963, 'Infrared Photometric Mapping of Venus Through the 8- to 14-Micron Atmospheric Window', *J. Geophys. Res.* **68**, 4813.
Samuelson, R. E.: 1968, 'The Particulate Medium in the Atmosphere of Venus', *J. Atmospheric Sci.* **25**, 634.
Samuelson, R. E.: 1969, private communication.
Sinton, W. M. and Strong, J.: 1960, 'Radiometric Observations of Venus', *Astrophys. J.* **131**, 470.
Vinogradov, A. P., Surkov, Yu. A., Andreichikov, B. M., Kalinkina, O. M., and Grechischeva, I. M.: 1970, this volume, p. 3.
Westphal, J. A., Wildey, R. L., and Murray, B. C.: 1965, 'The 8–14 Micron Appearance of Venus Before the 1964 Conjunction', *Astrophys. J.* **142**, 799.
Westphal, J. A.: 1966, 'The 10-Micron Limb Darkening of Venus', *J. Geophys. Res.* **71**, 2693.