Journal of

GEOPHYSICAL RESEARCH

VOL. 71 JUNE 1, 1966 No. 11

# The 10-Micron Limb Darkening of Venus

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Observations of 8- to 14-μ flux from diametric scans of Venus with the 200-inch Hale telescope have been made. The reduced data indicate an unexpected brightening near the Cytherean limb. The data show a more complicated atmospheric structure than postulated by published models. Horizontal inhomogeneity of the emission complicates the interpretation.

## INTRODUTION

Limb-darkening measurements of Venus have been reported by several workers (see *Pollack and Sagan* [1965] for a review of these data). The extension of such measurements very near the Cytherean limb requires the use of the largest available telescope at a time when Venus is near the earth.

In June 1964, several diametric profiles of the 8- to 14-μ flux from Venus were obtained with the 200-inch Hale telescope operated in the east-arm Cassegrainian mode. These data were recorded with a photometer system described previously [*Westphal et al.*, 1963] as part of a surveillance program [*Westphal et al.*, 1965]. Venus was near inferior conjunction and 52.2 sec of arc in apparent diameter, close to the maximum angular size accessible with the 200-inch telescope. Monitor photographs taken during the recording of the data were used to check the exact positioning of the scans on the apparent disk. These photographs also allow an estimate of the seeing disk in the visible to be made and, by a technique to be described below, an estimate of the instrumental spatial response function. An estimate of the true flux distribution along the profile was made by deconvolving the observed flux profile with the estimated instrument response, utilizing a digital computer.

A comparison of these reduced profiles with profiles predicted by several proposed models indicates that the Cytherean atmosphere is somewhat more complex in structure than any of these models, and that true horizontal variations in the structure are probably confusing the comparisons.

## THE DATA

From the available data, the two right ascension profiles recorded June 4, 1964, near the center of the Cytherean disk were digitized from the original strip chart records.

These profiles have a signal-to-noise ratio in excess of 100 as recorded with an electrical time constant short with respect to changes in the flux during the two minute scan.

## REDUCTION OF THE DATA

The diameter of the theoretical diffraction disk of the 200-inch telescope is about 0.5 sec of arc at a wavelength of 10 μ. This coupled with a seeing tremor disk of 1 to 2 sec of arc and an entrance aperture to the photocell of about 1.0 sec of arc, distorts the flux profile

[1] Contribution No. 1395.

received by the detector by a substantial amount. Since the data most useful for model atmosphere studies are those taken near the limb where the Cytherean atmosphere path is long, it is most important to correct the observed flux profile for the effects of the total instrumental spatial response at the time of observation.

To obtain an estimate of the true flux profile it is necessary to deconvolve the observed profile with the instrumental response. An estimate of the instrumental response was obtained using observations of the limb of the moon when the observed limb was at the subsolar point on the moon, that is, at either first or third quarter. Unfortunately, the quarter moon and Venus near inferior conjunction are not simultaneously available at an equivalent altitude and no exact measure of the 'seeing' at 10 $\mu$ exists. Thus, it was necessary to observe the moon at a different time, and to select data when the visible seeing was about the same as when the Cytherean profiles were made. Also, it was necessary to assume that the 10-$\mu$ seeing is proportional to the visible seeing, and the true flux is zero in the sky and a large uniform value on the moon. The first derivative of the observed flux profile from the photometer then represents the instrumental response at that time. The same time constant and spatial scan rate was used when recording the profiles from both Venus and the moon.

Two extremes of the instrumental response were used. These extremes are the result of computing instrumental responses from lunar data with seeing disks clearly smaller and clearly greater than that shown on the Venus monitor photographs. The half-width of these roughly Gaussian instrumental response profiles were 2.0 and 2.8 sec of arc. The mean of these values is assumed to best represent the true profile. To facilitate the deconvolution procedure, described below, a minimum of smoothing of the observed Cytherean profile was necessary, limited to removal of obvious noise pulses of much higher spatial frequency than the details of the profile.

The Caltech IBM 7094 computer was used to numerically deconvolve the Cytherean profiles. An approximation to the 'true' Cytherean profile was numerically convolved with the instrumental response using Weddle's rule [*Scarborough,* 1962], and the result compared with the observed profile to modify the profile estimate. About 25 successive approximations were necessary before the observed and computed profiles agreed within the noise level of the data. Figure 1 shows the observed and computed profiles and the derived true Cytherean profile for the mean of the instrumental responses.

For a comparison with theoretical atmospheric models it is useful to calculate $\mu$, the secant of the angle between the line of sight and local Cytherean vertical, for each point on the profile. The calculated value of $\mu$ is critically dependent on the location of the edge

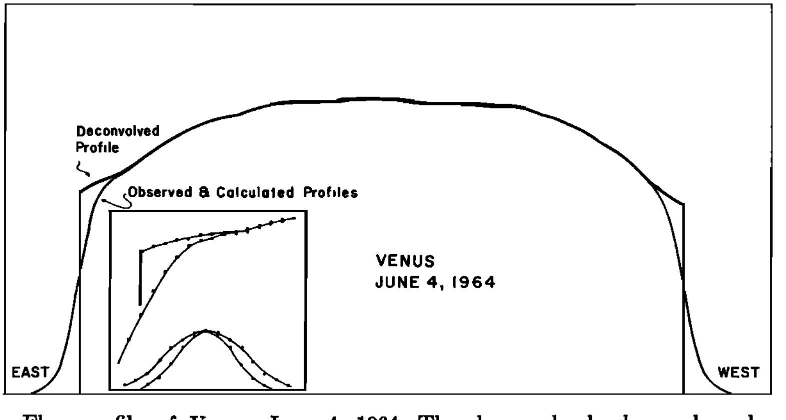


Fig. 1. Flux profile of Venus, June 4, 1964. The deconvolved, observed, and calculated profiles are superposed. The inset illustrates the details of the east limb and the two extreme instrumental response profiles.

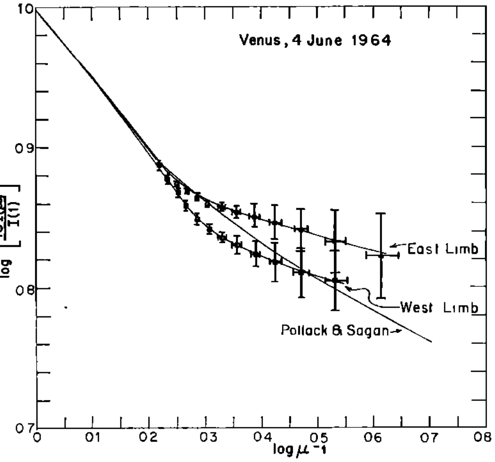


Fig. 2. A plot of the reduced data for the east and west equatorial limbs on June 4, 1964. A prediction of *Pollack and Sagan* [1965] is superposed.

of the planet on the flux profile. In these calculations, the edge was assumed to be a discontinuity beyond which no emission originates. Under this assumption, the edge could be located during the deconvolution within about 1/200 of the planetary diameter. If the edge is 'fuzzy' on this spatial scale, the calculations are invalid since $\mu$ is undefined. Since the theoretical models are also based on the assumption of a discontinuous edge, a comparison may still have meaning.

## Comparison with Model Atmospheres

*Pollack and Sagan* [1965] have proposed several model atmospheres for Venus. To allow a comparison of the data with the limb darkening predicted by these models, the profiles have been replotted in a form of log flux versus log $\mu$. Figure 2 shows the two limb profiles where the points are the mean and the error bars are the extremes derived by use of the two instrumental profiles. Although the two profiles are different from each other, both show a flattening of the slope beyond log $\mu$ = 0.3. The prediction of *Pollack and Sagan* [1965, Figure 3] for their models B($\bar{\omega}_0 = 0$), A1 for $T_0 = \phi$, and A2 is also shown on Figure 2. This prediction also shows a flattening beyond log $\mu$ = 0.3, although the observed flattening is considerably greater. The data illustrated in Figure 2 are tabulated in Table 1.

Since the data for various values of log $\mu$ come from different parts of the atmosphere, horizontally separated, any horizontal nonuniformity in the brightness temperature will appear as a variation in the observed profile. Large-scale horizontal and temporal variations in the observed brightness temperatures are commonly observed on Venus in this wavelength region [*Westphal, et al.*, 1965]. Indeed the present profiles indicate the west side is brighter than the east. This added effect complicates the model comparisons and can only be resolved by measurements over a short time period of a fixed geographical location from various angles of elevation, perhaps from a Venus flyby or orbiter. Since the observed horizontal variations seem to be smooth and large scale, the change in slope near the edge seems likely to represent a general property of the atmosphere, at least on this day.

TABLE 1.

| | $\log_{10} \mu^{-1}$ | $\log_{10}$ 10 $I(\mu)/I(1)$ |
|---|---|---|
| East Limb | 0.00 ± .005 | 1.000 ± .004 |
| | 0.05 ± .005 | 0.975 ± .004 |
| | 0.10 ± .005 | 0.951 ± .004 |
| | 0.15 ± .005 | 0.924 ± .004 |
| | 0.20 ± .005 | 0.899 ± .004 |
| | 0.25 ± .005 | 0.874 ± .004 |
| | 0.267 ± .005 | 0.869 ± .004 |
| | 0.286 ± .005 | 0.865 ± .005 |
| | 0.307 ± .005 | 0.860 ± .005 |
| | 0.331 ± .005 | 0.857 ± .005 |
| | 0.358 ± .007 | 0.853 ± .005 |
| | 0.389 ± .010 | 0.850 ± .008 |
| | 0.427 ± .012 | 0.846 ± .012 |
| | 0.472 ± .015 | 0.840 ± .016 |
| | 0.531 ± .017 | 0.832 ± .022 |
| | 0.614 ± .030 | 0.822 ± .030 |
| West Limb | 0.00 ± .005 | 1.000 ± .004 |
| | 0.05 ± .005 | 0.975 ± .004 |
| | 0.10 ± .005 | 0.951 ± .004 |
| | 0.15 ± .005 | 0.924 ± .004 |
| | 0.20 ± .005 | 0.899 ± .004 |
| | 0.221 ± .005 | 0.887 ± .004 |
| | 0.235 ± .005 | 0.877 ± .004 |
| | 0.251 ± .005 | 0.867 ± .004 |
| | 0.268 ± .005 | 0.858 ± .004 |
| | 0.286 ± .005 | 0.848 ± .005 |
| | 0.307 ± .005 | 0.841 ± .005 |
| | 0.331 ± .005 | 0.835 ± .005 |
| | 0.358 ± .006 | 0.830 ± .006 |
| | 0.389 ± .007 | 0.823 ± .007 |
| | 0.427 ± .010 | 0.818 ± .012 |
| | 0.472 ± .015 | 0.810 ± .016 |
| | 0.531 ± .018 | 0.804 ± .022 |

*Acknowledgments.* I thank Dr. G. Neugebauer for many helpful comments. This work was supported by NASA grant NsG 56-60.

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(Manuscript received January 31, 1966.)