Infrared Photometric Mapping of Venus through the 8- to 14-Micron Atmospheric Window[1]

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Abstract. The 200-inch Hale telescope has been used to obtain high-resolution maps, on four mornings juxtaposed about the Mariner 2 encounter, of the brightness temperature of Venus in the 8- to 14-micron wavelength interval. The resolution was about 1/30 of the disk of Venus. The signal-to-noise ratio was in excess of 100. The maps reveal (1) a general limb darkening, (2) a bilateral symmetry about the planet's orbital plane, (3) a very slight wedging of the contours as the only day-to-night effect, and (4) a transient temperature anomaly in the southern hemisphere.

Introduction. The thermal emission from Venus was first measured by *Pettit and Nicholson* [1924]. The measurements have been reviewed by *Pettit* [1961]. Characteristic brightness temperatures were found, and the interesting discovery was made that the dark part of the disk of Venus was emitting about as strongly as the sunlit part. These observations were made on the 100-inch telescope at Mount Wilson with a vacuum thermocouple. *Sinton and Strong* [1960] have made observations with a spectrophotometer incorporating a Golay cell on the 200-inch telescope. They have recorded the average center-to-limb brightness profile and real departures from blackbody spectral distribution.

In the present study high-resolution brightness-temperature contour maps have been constructed on four successive nights juxtaposed about the Venus encounter of the Mariner 2 spacecraft. Preliminary results have been reported briefly [*Murray, Wildey, and Westphal*, 1963].

The observations. The observations were collected at the east-arm Cassegrain focus of the 200-inch telescope during the morning twilights of December 14, 15, 16, and 17, 1962. The photometer and detector (mercury-doped germanium photoconductor) used have been described by *Westphal et al.* [1963] and more briefly by *Murray and Wildey* [1963*a*]. The reduction and calibration of observations for extended sources are described by *Murray and Wildey* [1963*b*], together with a discussion of the possible systematic errors. The atmospheric extinction correction used in the present study is that adopted previously by *Wildey and Murray* [1963] and is due to Westphal (private communication). It may be an important source of systematic uncertainty. The reduced data are presented in the form of a map of brightness temperature (the temperature for which the measured specific intensity equals a Planck function weighted precisely the same over wavelength).

The telescope's hour-angle drive was adjusted to slightly exceed the earth's rotation rate. Beginning at the north limb of the Venus disk a series of right-ascension scans, separated by small southerly decrements in declination, was thus made. The scans were reproducible, and the signal-to-noise ratio near the center of the disk was about 100 to 1. This is seen in scans 1 and 2 of Figure 2, which correspond to tracks 1 and 2 of Figure 1. The scans were reduced at intervals commensurate with the photometer resolution (about 1.5 seconds of arc, 1/30 of the disk diameter, or 400 km at the Venus subearth point). The resulting brightness temperatures were fixed geographically by translating the scan parallel to right ascension until its length became the chord of a circle whose diameter was preassigned as the length of the scan that bisected the disk. This procedure was necessitated by the lack of precision with which the telescope's declination circles can be read, even

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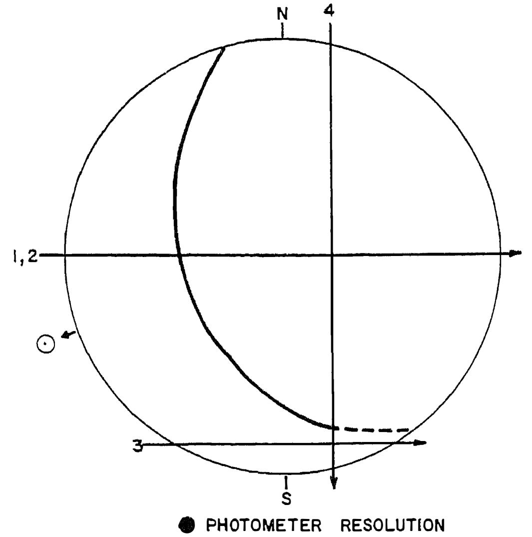

Fig. 1. Index map of scans reproduced in Figure 2. The arrowhead denotes the direction of each scan. Scans 1 and 2 are exactly coincident in order to test reproducibility.

differentially. Approximately 20 per cent of the scans were thrown out as a result. The positional uncertainty produced a north-south crenulation in the contours plotted on the resulting brightness-temperature maps.

The mean brightness temperature for the center of the disk on the four nights was 208°K ± 2° (s.d.), about 28°K lower than the commonly accepted value. This includes night-to-night calibration errors and possible fluctuations in atmospheric extinction. No correction has been made for unknown transmission losses within the telescope, and this may be a serious cause of systematic error. The obscuration of the prime-focus cage (13 per cent) combined with the laboratory reflectivity at 10 microns (0.98) of each of the four mirrors in the telescope optics give an over-all telescope transmission of 0.81. The brightness temperatures would be uniformly increased by 7°K as a result. However, if the reflectivity of each of the four mirrors were only 0.85, perhaps owing to

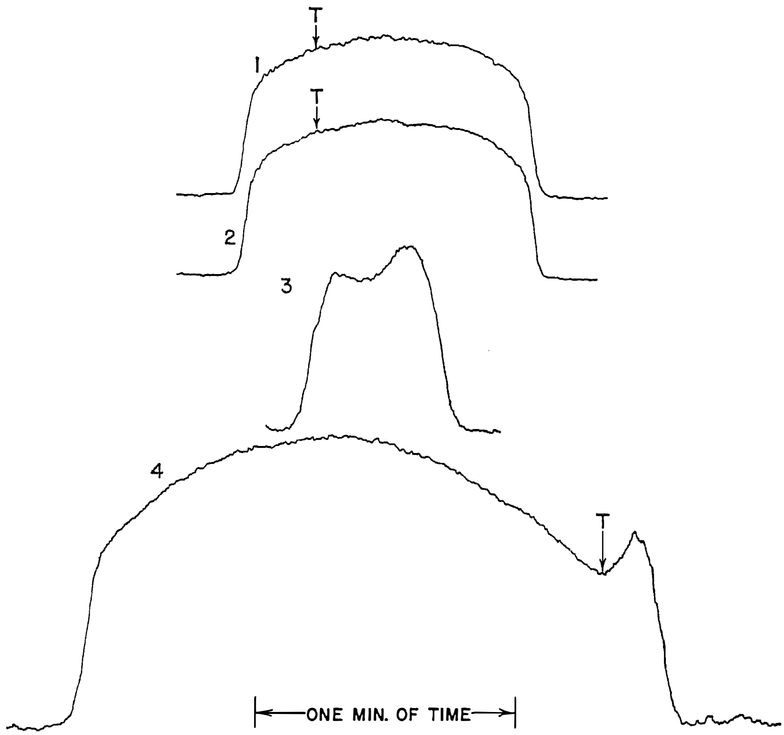

Fig. 2. Tracings of selected strip chart records of output voltage versus time. Scans 1 and 2 from December 13, 1962, illustrate reproducibility; 3 and 4 show closure of a 'hot spot' as observed on December 15, 1962. Scan 3 is a right-ascension scan; 4, a declination scan. *T* indicates terminator crossing.

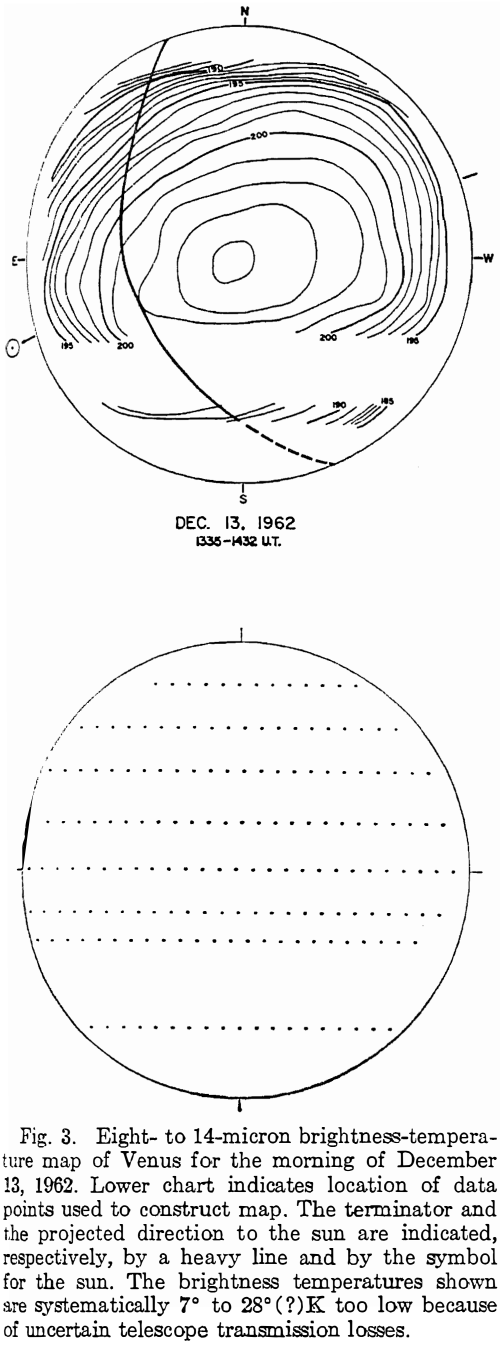

Fig. 3. Eight- to 14-micron brightness-temperature map of Venus for the morning of December 13, 1962. Lower chart indicates location of data points used to construct map. The terminator and the projected direction to the sun are indicated, respectively, by a heavy line and by the symbol for the sun. The brightness temperatures shown are systematically 7° to 28°(?)K too low because of uncertain telescope transmission losses.

thinness of the coatings, the entire 28°K disparity would disappear. The importance of the observations described in this paper is not in the absolute value of the central temperature but rather in the two-dimensional picture of the infrared radiation of Venus. The *differential* accuracy of these brightness-temperature measurements is about 1/3°K.

The brightness-temperature contour maps. Figures 3 to 6 display the brightness-temperature contour maps for the four nights of ob-

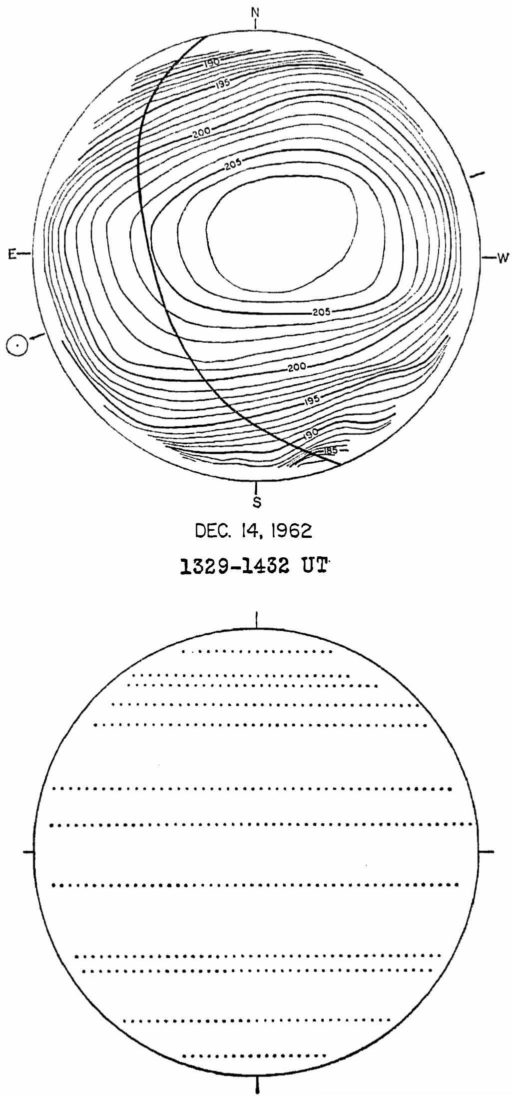

Fig. 4. Eight- to 14-micron brightness-temperature map of Venus for the morning of December 14, 1962. Lower chart indicates location of data points used to construct map. The terminator and the projected direction to the sun are indicated, respectively, by a heavy line and by the symbol. The brightness temperatures shown are systematically 7° to 28°(?)K too low because of uncertain telescope transmission losses.

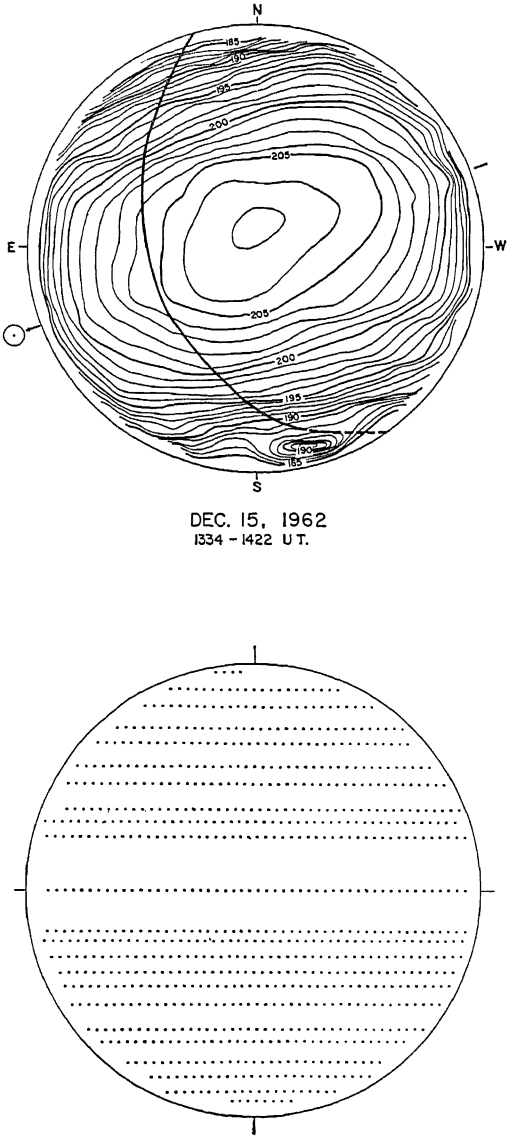

Fig. 5. Eight- to 14-micron brightness-temperature map of Venus for the morning of December 15, 1962. Lower chart indicates location of data points used to construct map. The terminator and the projected direction to the sun are indicated, respectively, by a heavy line and by the symbol. The brightness temperatures shown are systematically 7° to 28°(?)K too low because of uncertain telescope transmission losses.

servation. Immediately beneath each map is shown a chart of the corresponding data points. The projection of the radius vector from Venus to the sun is shown on each map, together with celestial north and east and the line of the terminator.

Features common to all the maps include (1) a general decrease in brightness from center to limb; (2) no night-to-day effect except a very slight wedging of the contours, diverging toward

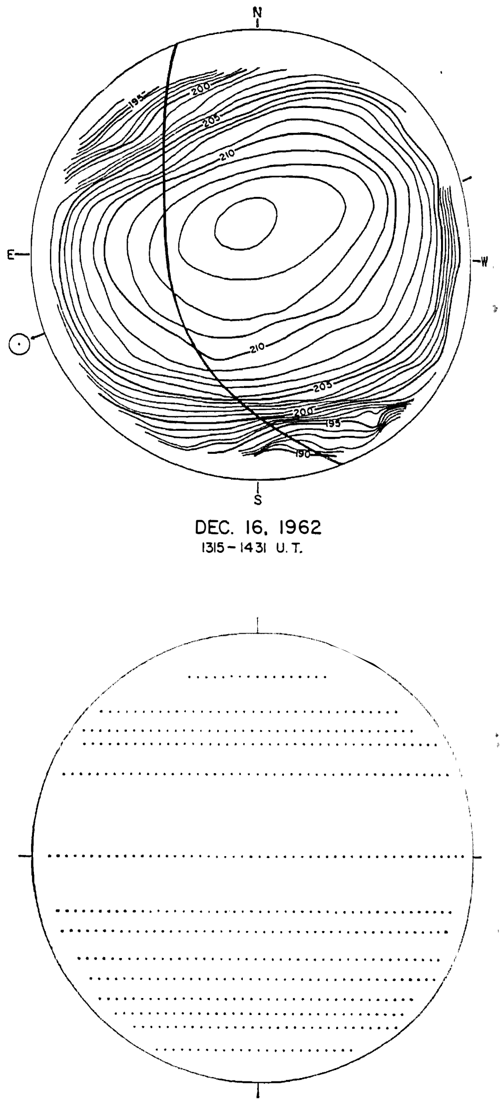

Fig. 6. Eight- to 14-micron brightness-temperature map of Venus for the morning of December 16, 1962. Lower chart indicates location of data points used to construct map. The terminator and the projected direction to the sun are indicated, respectively, by a heavy line and by the symbol. The brightness temperatures shown are systematically 7° to 28°(?)K too low because of uncertain telescope transmission losses.

the dark side; and (3) a bilateral symmetry of the contour pattern about the diameter in Venus's orbital plane. In addition, the map for December 15 shows a well-defined anomalous 'hot spot' whose existence was also evident on a declination scan across Venus the same morning (see scans 3 and 4 of Figures 1 and 2). The maps for the mornings of December 14 and 16 reveal this hot spot to be but one phase of transient phenomena taking place over an extended region in the vicinity of the southern cusp of the planet. Because of the temporal, and presumably geographic, variation of this anomalous feature it fulfills the usual definition of a storm.

Discussion. The general decrease in brightness from center to limb is most obviously explained in terms of the dependence on angle with local vertical of the specific-intensity vector characterizing the emergent radiation field. This phenomenon is analogous to limb darkening as observed in the visible region in the sun, if we assume that the total Venus atmosphere is optically thick from 8 to 14 microns. One is thus led from a consideration, in fairly general terms, of the equation of radiative transfer [*Münch*, 1960; and others] toward the conclusion that the temperature on Venus increases with depth down through the range in the atmosphere from which most of the 8- to 14-micron radiation emerges.

The absence of a strong night-to-day effect in the infrared emission suggests that the temperature of the emitting atmospheric layers is nearly independent of the planetary diurnal insolation variation. Furthermore, the energy loss from the planet in this wavelength band balances about one-third of the total solar energy absorbed on the illuminated hemisphere. Therefore, energy redistribution mechanisms are implied that render a major fraction of the local energy loss on the planet similarly insensitive to diurnal insolation variation.

A second constraint upon the planetary energy redistribution mechanism is strongly implied by the fact that the contours show bilateral rather than radial symmetry. This distribution is suggestive of *real* lateral temperature variations, most simply a latitudinal cooling toward the 'poles' away from Venus's orbital plane. Such a condition is easily visualized as a latitude effect due to solar insolation provided that the planet is allowed to rotate with a period small compared with the thermal relaxation time of its atmosphere and surface materials.

Another global distribution of the planet's atmospheric effective temperature which, when combined with intense limb darkening, can also produce the observed bilateral symmetry is one wherein the emitted flux is at a maximum at the subsolar point, decreases as a function of the great-circle distance away from that point to a minimum value just on the nighttime side of the terminator, and then increases to a second maximum at the antisolar point. This very special distribution is a priori possible for a synchronously rotating planet upon which advective energy transport may be important. However, the two interpretations differ in regard to their prediction of the integral brightness, in the 8- to 14-micron region, viewed as a function of phase angle (sun-Venus-earth angle). The latitudinally dependent flux ('rotational') interpretation should show no particular phase effect, whereas the case of dependence on geodetic distance from the subsolar point, or 'synchronous' interpretation, should display a phase effect of perhaps 5°K. In fact, no phase effect has yet been observed [*Sinton*, 1963; *Sinton and Strong*, 1960]. But the uncertainties in the present data do not permit an unqualified rejection of the possibility of some phase effect (Sinton, private communication). More observations of integral brightness and the apparent distribution of radiation at different phases will be required before the three-dimensional distribution of effective temperature will be completely established on observational grounds alone; however, the latitudinally dependent distribution does seem to be the more likely at present. Thus, for a truly synchronously rotating planet, if the infrared emission is indeed latitudinally dependent, the solar energy must be redistributed within the planetary atmosphere not only with such efficiency that no day-night effect is present but also with such sensitivity to Coriolis forces (as the only latitudinally dependent parameter left) that approximately 20 per cent less energy is radiated away at the poles as at a point on the equator of equal distance from the subsolar point.

Recent radar observations [*Goldstein and Carpenter*, 1963] are interpreted to indicate a

252-day retrograde rotational period (140-day synodic period), and thus the latitudinal dependence may indeed reflect insolation variation. However, the thermal relaxation time of the atmosphere and surface materials of Venus must be long, i.e., measured in years, if both the infrared and radar observations are to be explained adequately. Possibly, high atmospheric pressures and surface temperatures (implying high atmospheric opacity) may account for such a large heat capacity and long relaxation time. Other, completely different explanations of the phenomenon based on the thermal properties of the actual surface are, of course, possible.

The 'storm' or 'storm zone' observed in the southern hemisphere does not correlate with any visible feature on Venus in photographs taken around December 15 [*Smith,* 1963], although its effects are apparent on one of the three infrared scans collected by Mariner 2 on that date [*Chase, Kaplan, and Neugebauer,* 1963]. If the storm zone is a result of topographically induced disturbances in the Venus atmosphere, the 'mountains' in question must cover an extensive area in the southern polar region. If the storm is orographic, it cannot have remained associated with the mountains of its origin unless the rotation period of Venus is approximately between 7 and 9 days. Additional, closely spaced observations of such features may prove to be highly illuminating.

Acknowledgments. We have indeed been fortunate to be able to use the 200-inch telescope for these observations, and we wish to express our gratitude to the Mount Wilson and Palomar observatories.

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