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RADIOMETRIC OBSERVATIONS OF VENUS

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ABSTRACT

Modern infrared techniques were applied to the measurement of thermal radiation and temperatures of planets. The two nearest planets have the maximum of their thermal emission within the 8–13-μ band that is transmitted by our atmosphere with relatively little absorption. The transmission of the atmosphere was determined by extrapolation of observed planetary emission to outside the atmosphere, using the square-root law. Calibration of the equipment was made with black bodies. The method of determining atmospheric transmission was tested in the laboratory with an ammonia cell, to simulate a planetary atmosphere, and a rock, to simulate a planet. Radiation temperatures for the rock within a few degrees of the thermometer temperature were obtained in these tests.

Extensive measurements were made of Venus with the 200-inch telescope in 1953, and further measurements were made in 1954. The temperature at the center of the disk was found to be −39° C. Scans near dichotomy show that the dark side of the disk is nearly as hot as the bright side. There is also substantial limb darkening. A cold region found at the north cusp in 1953 appears to be related to a bright cloud found in ultraviolet photographs taken on the same date.

Spectra of Venus between 8 and 13 μ were obtained with prism and grating spectrometers. A diffuse band at 11.2 μ was found in the spectrum of Venus in addition to a carbon dioxide band at 10.4 μ. The 10.4-μ band was found much weaker than expected.

In pioneering work on planetary radiometry, Coblentz and Lampland (1924, 1925, 1927) and Pettit and Nicholson (1923, 1930, 1936) used compensated thermocouples connected to d.c. galvanometers. Water-cell and glass filters were employed to separate the reflected solar energy from the planetary emission. Calibration was obtained either from the solar energy reflected by the planet or from stellar radiation. An extensive wealth of important planetary facts have been derived from their observations (Coblentz 1924; Menzel 1924; Pettit and Nicholson 1924, 1955; Menzel, Coblentz, and Lampland 1926; Hess 1950; Gifford 1956).

Subsequently the techniques of infrared have been vastly improved. In particular, chopping was first used in the infrared by A. H. Pfund (1929) to eliminate the drift which usually occurs even with compensated thermojunctions. With this method the desired radiation incident upon the detector is interrupted at a regular rate, and some means is provided (in the galvanometer or amplifying circuit) so that only the alternating component of the thermocurrent is measured. For example, Pfund used an underdamped galvanometer that resonated with the alternating thermopile voltage. In recent times the more popular procedure is to amplify the thermoelectric signal with a transformer. By such methods the d.c. part of the signal, along with any slow drift, is eliminated. If two thermocouples are connected in opposition and the chopping is arranged to switch the planetary image from one couple to the other while both couples always observe the sky, there is little or no loss in sensitivity over the use of compensated junctions in d.c. radiometry. We have not used two detectors in our work, so that a loss of about twofold in sensitivity over d.c. radiometry occurs.

The use of filters which transmit only the long-wave infrared constitutes another improvement in technique. The use of these avoids completely the necessity of differencing large deflections to obtain the net infrared emission, as was the case when water-cell filters were used. Besides these old, opaque infrared filters, isolation of bands can now be effected in a number of ways: double monochromators; residual-ray bands of crystals; new silver sulfide filters; and even the newer interference filters. With such means of isolation, the calibration of the isolated band, together with the sensitivity of the detector, may be made through the use of black-body cavities directly at the telescope.

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This report is concerned with the spectroscopy of the warmer nearby planets, observing through the 8–13-μ band of transparency of our atmosphere. Fairly well-resolved spectra of the emission of several of the planets were obtained with a scanning prism spectrometer, while even better spectra were subsequently obtained using a grating.

OBSERVABLE PARAMETERS

One would like to investigate the heat radiation from a planet in respect to its dependence on a number of parameters, including wave length, time, distribution over the disk of the planet, and the polarization. Obviously, when one considers the variation in the intensity with all the parameters, the amount of observing necessary to determine the complete dependence is inordinately large. The obvious way to simplify the observing is to integrate over all the parameters except one or two and then to investigate the dependence of the integrated energy on these one or two parameters. Instead of integrating over the other parameters, another possibility is to use a fixed value for these or perhaps to integrate over just a limited range.

There is another reason for wanting to integrate over the parameters which are not being investigated, and for studies of the heat radiation of planets this reason is almost imperative. It is the increase in signal-to-noise ratio that results from such an integration. The radiation received from the planets is in most cases so feeble and the detectors that are presently available so insensitive that only one or two variables can be investigated at one time, and the others must be integrated over to increase the amount of signal available.

The range of the variables is also restricted. The range of time is limited to times close to the present and generally to times when the planet is close to the earth and when the telescope is available for use. We may, however, investigate the dependence of heat radiation on natural periods of the planetary motion, such as the day and the year.

The range of wave lengths that are available is limited by the transmission of the earth's atmosphere. The region in which the heat radiation is observable is from about 8 to 13 μ. On either side of this band the earth's atmosphere is opaque or nearly so. But in exceptionally dry climates, such as at Flagstaff, Arizona, observations near 20 μ can be made.

The types of observations that we have made in this investigation are of three kinds. First, by taking the radiation from the entire disk of the planet, integrating over 4 seconds of time, and requiring about 15 minutes for a scan, we investigated the spectral distribution between 8 and 13 μ. Second, by integrating the planetary radiation over the 8–13-μ band, we studied the distribution in two dimensions over the apparent disk of the planet. This was done by making drift-curves with a circular or rectangular aperture. The drift-curves made in 1953 were reduced to temperatures by calibration with two black bodies. The observations which were made in 1954 were not standardized in this way but are only relative to one another. For obtaining temperatures from these, a third type of observations was made. Observations of the center of the disk of the planet were made with an aperture larger than that used for the drift-curves and a wave-length band wider than that used for the spectral investigation. This band was chosen at a position where the atmosphere has high transmission, so that less error results from transmission corrections. These observations were calibrated by black bodies and serve to give the temperature of a point on the planet by which the relative curves may be standardized.

EQUIPMENT

In the summer of 1952 we used the 100-inch telescope for a preliminary study of planetary radiation. One of the main purposes of this study was to acquaint ourselves with the problems which arise, so that we could modify our equipment and be well prepared for use of the 200-inch telescope later on.

For the measurement of the total radiation from the planet, filters with sharp cutoffs are desirable for limiting the region of observation to the region of high transmission of the atmosphere. At the time of the observations such filters were not available, but a double monochromator, which affords zero dispersion, is an efficient substitute. A double instead of single monochromator is desirable for this application. The sensitivity of thermal detectors is inversely proportional to the square root of their area, and a considerably smaller thermocouple can be used when the light is condensed to undispersed light by a second monochromator. The jaws of the middle slit of the double monochromator may be set to limit the pass band to 8–13 μ, the region of high atmospheric transmission.

In 1941 a double monochromator with potassium bromide prisms, for this study of planetary radiation, was designed and constructed with a part of the funds granted by the Rockefeller Foundation for the construction of the 200-inch telescope. This monochromator was used for the preliminary study in 1952 and for the work on Venus in 1953. Each half of the monochromator is of the Wadsworth type and has a 60° prism with a clear aperture approximately $1\frac{1}{2}$ inches square. The focal lengths of the telescope and collimator mirrors are 16.5 inches. The exit slit of the monochromator is imaged on the thermocouple by a 6-inch ellipsoidal mirror which provides a sixteen-fold reduction in size of the exit slit. Such a monochromator, when carefully made and accurately aligned, is highly efficient. Just prior to its use for the 1953 work the transmission of the monochromator was found to be 70 per cent when the prisms had a fresh polish and the mirrors were freshly coated. However, when it was used in the 1952 preliminary work, it had been used for several years in laboratory work, and its transmission had deteriorated to 30 per cent.

The monochromator was used at the $f/30$ coudé focus of the telescope. An auxiliary mirror of 12-inch aperture converted the $f/30$ beam to $f/11$ for imaging the planet on the slit of the monochromator, as shown in Figure 1. An aperture at the focal plane of the telescope defined the area of the planet which was measured. A 10-inch-diameter aperture in front of the 12-inch mirror was the aperture stop of the system and effectively masked the 200-inch mirror to 182 inches. Except for the obscuration by the prime-focus cage of the telescope, the solid angle accepted from the black-body sources was the same as that accepted from the planet. The disparity of the solid angles caused by the prime-focus cage was corrected for in the reduction.

The planetary radiation, before passing through the focal-plane aperture, was chopped at 5 cycles per second, and only the alternating component of the voltage produced by the thermocouple was amplified. The chopping was accomplished by a reflecting chopper, which, when in the open position, allowed the planetary image to fall on the aperture. When it was in the closed position, it reflected light from the sky adjacent to the planet into the aperture. In this manner the chopping was between the planet plus sky and the sky alone, and hence theoretically only the planetary part of the radiation was chopped. However, because of the two additional mirrors in the sky beam, the transmission of this beam was reduced, and the cancellation was therefore not perfect. This effect turned out to be far from negligible when spectra of the planet were obtained.

The sensitivity of the apparatus was determined by observations of the emission of two black-body conical cavities at known temperatures. One of the black bodies was immersed in melting ice and the other in warm water contained in a vacuum flask. The cones were made from $\frac{1}{16}$-inch copper sheet, and the inside was blackened. The temperatures of the cones were determined from a thermometer in a well attached to their sides. In order that the sensitivity could be determined for the entire apparatus including the telescope, the optical path for the radiation from the calibrating black bodies was as nearly identical to that of the planetary radiation as practicable. Three additional aluminum mirrors were used in the path from the black bodies in order to compensate for reflection losses of the three aluminum mirrors of the telescope. The chopper mirror, the sky mirror (whose primary purpose will be explained later), and the comparison mirror served this purpose. In the arrangement used at Mount Wilson there was only one extra mirror in the comparison path, since the comparison mirror was in front of the chopper; thus the losses of two mirrors of the telescope were not compensated.

In the preliminary work a standard Farrand thermocouple was used. Its receiver was $\frac{3}{4}$ mm square—much larger than the image of the exit slit upon it. The amplifier used was also made by Farrand Optical Company. Cam-actuated switches performed rectification of the amplifier output. After electrical filtering, the output was registered on a Brown recorder. In the preliminary work a 2-second time constant was used, while in the 1953 work a 4-second time constant was employed. In this later work we employed a special thermocouple of 0.2 × 1-mm area made by the Farrand Optical Company. The reduction in detector area and the use of the longer time constant doubled the signal-to-noise ratio. As a precaution against inadequate vacuum in the thermocouple, we kept liquid nitrogen on the charcoal getter during observations made in 1953. This generally gave only a 10 per cent improvement, proving that the vacuum was indeed very good.

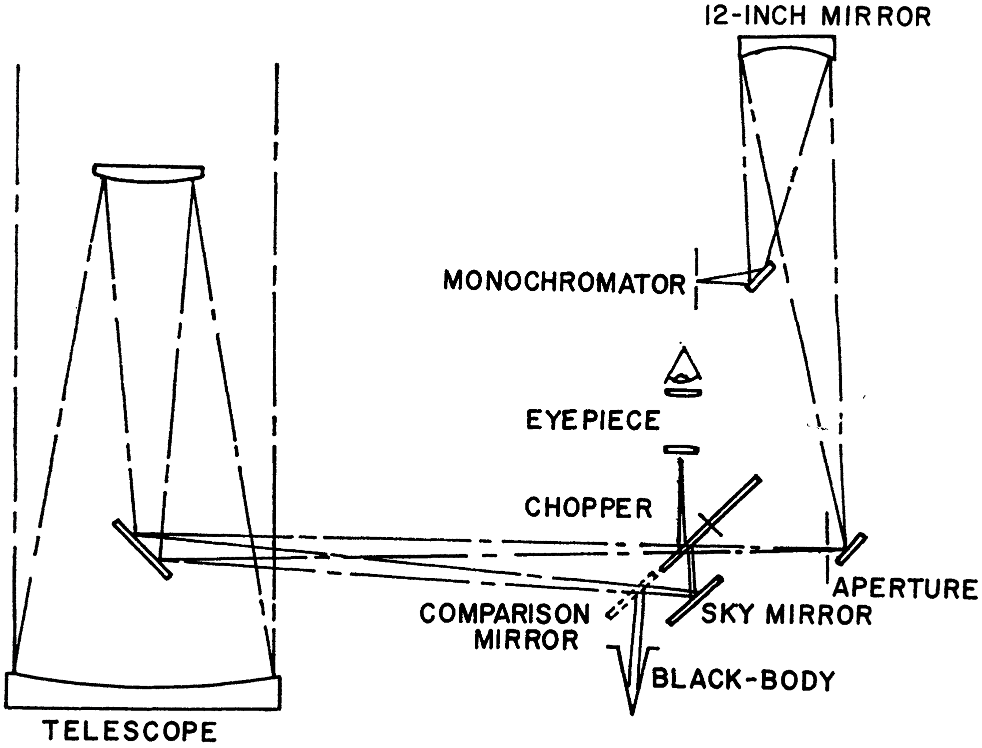

FIG. 1.—The optical apparatus used at the coudé focus of the 200-inch

In 1953, in order to use as much of the planetary image as possible when spectra were being obtained, two image slicers were constructed to slice the round image into three strips and distribute them along the slit. The larger one sliced the entire image, while the smaller one could slice either the light or the dark half of the disk of Venus. The larger slicer provided a $1\frac{1}{2} \times 12$-mm strip at the entrance slit of the monochromator. Since we found slit widths of only $\frac{1}{2}$ mm to give adequate signal-to-noise ratios, about two-thirds of the Venus radiation was wasted at this high spectral resolving power.

METHOD OF REDUCTION

The past methods of reduction fall into two categories, those which measure the ratio of the planetary heat at two wave lengths and those which are based on the Stefan-

Boltzmann law. The latter methods are probably the more accurate. In the first method a small error in the ratio of two wave lengths, as can easily be made by a systematic error in the relative atmospheric transmission of the two bands, makes a relatively large error in the derived temperature. On the other hand, an error in the measurement of the total radiation, the atmospheric transmission, or the determination of the thermocouple sensitivity causes about one-quarter of this error in the temperature. In the older methods based on the Stefan-Boltzmann law, however, the atmospheric transmission has not been adequately evaluated. It has been assumed that the transmission depends exponentially on the air mass penetrated. This law is certain to be inaccurate within broad response bands such as are used.

An improvement in the evaluation of atmospheric transmission can be made by instrumentally restricting the observed band so that it falls within the region of high transparency. The method used in the past—the use of cover-glass and water-cell filters —is not satisfactory because the bands isolated by these filters contain the partially transparent wings of the H_2O and CO_2 bands at 6.3 and 14.9 μ. When these filters are used, we must know exactly how the band wings grow with increasing water vapor and carbon dioxide and the quantity and distribution of these gases in the atmosphere. Therefore, eliminating these regions and confining the observed band to the highly transparent region avoid much difficulty. An effective transmission may then be evaluated for these high-transparency regions. Furthermore, laboratory black bodies at known temperatures can then be used for calibrating the sensitivity of the thermocouple and equipment. From a knowledge of the band transmitted by the filters and the atmospheric transmission of this band, the temperature of the planet may be computed by using integrals of Planck's function over the wave lengths of the band.

ATMOSPHERIC TRANSMISSION

The 7–13-μ region is not completely transparent but contains many lines and bands. These have recently been very well resolved in solar spectra taken at the Jungfrau Joch (Migeotte, Neven, and Swensson 1956). Because of these bands, the transmission of the atmosphere must be ascertained for radiation having the spectral distribution of the planet measured. Since it is impractical to place bodies of known temperature outside our atmosphere, we cannot directly measure the transmission. As a substitute we will use a law of transmission whereby the radiation outside the atmosphere can be determined by extrapolation of observed intensities reaching us through different amounts of air mass (secant of the zenith distance). This procedure is used for visible light. Here a plot of the logarithm of the deflection against the secant of the zenith angle appears to be satisfactory. At the present state of our instrumentation, this plot is not satisfactory in the infrared because the infrared absorption is largely from sharp lines and our spectrometers in conjunction with thermal detectors do not isolate a sufficiently narrow band of wave lengths over which the absorption coefficient can be considered constant. A law which does apply, at least approximately, is the well-known square-root law. This states that the absorption of a gas is proportional to the square root of the amount of gas penetrated. This law was first derived theoretically by Ladenburg and Reiche (1912) for the absorption of a single line having the Lorentz shape. W. M. Elsasser (1938) showed that it also applied to a band of uniformly spaced, equal-intensity lines for path lengths short enough that there is little overlapping of the lines. That this law applies to atmospheric absorption in the 7–13-μ region was demonstrated by John Strong (1941). It was found that if the radiation received from the sun is plotted against the square root of the secant of the zenith distance, a straight line is obtained, while the conventional logarithmic plot does not yield a straight line.

Accordingly, we have reduced our data by assuming that the square-root law applies even when extrapolated to zero path length. An extrapolation to zero air mass of the straight line plotted through the points obtained for a series of air masses yields the amount of radiation assumed to be incident outside the atmosphere. That the temperatures obtained with this extrapolation are very close to the true temperatures has been demonstrated in a laboratory experiment with an atmosphere of ammonia in place of the earth's atmosphere, as will be described later.

INTEGRATION OF PLANCK FUNCTIONS

It has been mentioned that, for calibration of the sensitivity of the equipment, deflections from two black bodies have been impressed on the records. These two deflections do not give sufficient data alone to reduce the planetary observations to temperatures. They serve only to establish the difference between two points of the non-linear temperature scale of the recorder. Since the wave-length region has been restricted by the monochromator, the Stefan-Boltzmann law cannot be used to obtain deflections for other temperatures. In order to determine these deflections, we need to know integrals of the Planck functions over the wave-length band transmitted by the monochromator for all temperatures of interest and to normalize these integrals to the scale established by the deflections produced by the two black bodies. This integration has been done both experimentally and theoretically. Figure 2 shows the fourth power of the absolute temperature plotted against the deflection produced by a black body within the band transmitted by the monochromator, 8.2–12.4 μ. The zero of the deflection scale is taken to be the deflection caused by melting ice, while the deflection caused by 100° C is taken to be 100 on the linear deflection scale. We term a unit of this scale "one-degree radiation" and express it as °*R*. This scale has been chosen following Strong (1939), who defined the monochromatic radiation temperature of a body as the ratio

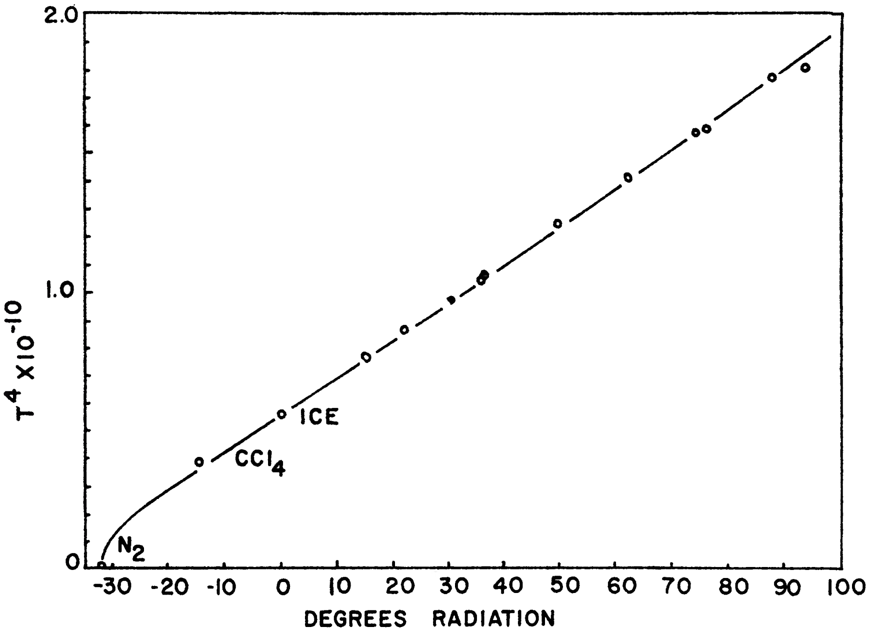

FIG. 2.—Experimental calibration graph obtained with the double monochromator transmitting 8.2–12.4 μ.

$$T_{°R} = \frac{d_1 - d_0}{d_{100} - d_0} \, 100° ,$$

where d_1 is the deflection caused by the temperature $T_{°R}$, d_0 is the deflection caused by a 0° C black body, and d_{100} is the deflection caused by a 100° C black body. All these deflections were caused by the radiation in a narrow band of wave lengths from the bodies. The scale can, of course, be used for a broad band of wave lengths, as in the present investigation.

The points in the graph are experimental measurements. They were obtained by placing one of the cones in liquids at various temperatures. For this purpose liquid nitrogen, melting carbon tetrachloride, melting ice, and water at various temperatures up to boiling were used. The solid line was calculated with the aid of the tables computed by Lowan and Blanch (1940), and the line was adjusted to go through the experimental points at 0° and 91° C. In the calculation of this solid line it was assumed that the cutoff of the monochromator at 8.2 and 12.4 μ was ideally sharp. Actually, the cutoff with 1-mm entrance slit width extended over 0.9 and 0.6 μ at the short- and long-wave-length ends, respectively. It is seen from the graph that the deflection which would be caused by absolute zero is not appreciably different from the deflection obtained from liquid nitrogen, and this point falls at $-32°$ *R*. This point may be taken as the zero point of the absolute radiation scale.

The calibration-curve was used to obtain planetary temperatures after the deflections were corrected for the atmospheric transmission and obscuration by the prime-focus cage and the deflections normalized so that the deflection from the water minus that from the melting ice was identical with their radiation temperatures.

The deflection that is considered to be due to the planetary radiation is the difference between the deflection obtained for the planet and the deflection obtained for the sky adjacent to the planet. The first deflection is actually that of the transmitted planetary radiation plus the emission of the sky, and the second deflection is the emission of the sky alone. It is tacitly assumed that the space beyond the planet has no radiation of its own, that is, it is equivalent to a blackbody at absolute zero. Therefore, the deflection of the planet over that of the sky, after the corrections and adjustments mentioned above have been made, is assumed to be the absolute radiation temperature of the planet. The calibration-curve is then used to obtain the temperature. The temperature obtained in this manner assumes that the planet has an emissivity of unity.

THE MODIFIED METHOD

The method described above was modified to minimize effects of the failure of the square-root law in the strongest absorption bands occurring in the 7–13-μ region such as the ozone band at 9.6 μ and the strong water lines at 11.9 and 12.7 μ. This modified method makes use of the moon as a reference source and assumes that the moon will have a smooth emission spectrum as a function of wave length.

It was desired to obtain the atmospheric transmission as a function of the wave length in order, later, to determine the spectrum of Venus outside the atmosphere. The short period of time available for continuous observation did not permit taking a sufficient number of spectra of the planet at widely different values of the air mass to afford reliable extrapolation of the data to zero air mass. Also the difficulty with strong bands would have been present in this extrapolation too.

To obtain the transmission data, we took spectra of the nearly full moon with a small heliostat placed just west of the 200-inch telescope dome. Here we could observe unrestricted after the moon exposed itself around the dome, and we obtained spectra from before meridian passage until the moon was almost setting. The arrangement of the equipment had no provision for chopping against the sky radiation as was done with the telescope. Hence it was necessary to agument spectra of the moon plus sky with spectra of the sky. The sky adjacent to the moon was observed for the latter spectra, and the values of the zenith distance were taken to be the same as that of the moon.

The spectra were obtained on the night of July 24–25, 1953, one day prior to full moon. The entrance and middle slits were set at 0.5 mm, the same width as that used for the majority of the Venus spectra. The length of the slit was restricted to about two-thirds the diameter of the moon's image, and the moon was centered on this slit. Nineteen spectra were obtained, but some of these were interfered with by clouds and were discarded. The first ones taken were also discarded because it was apparent that the sensitivity was changing as the apparatus cooled to the outside temperature. During the remainder of the night the sensitivity appeared to be constant.

A plot of the deflection against the square root of the air mass was made for ten wave lengths between 8 and 12 μ for both the sky and the moon spectra. Extrapolations were made to zero air mass and to the zenith and interpolations for $\sec^{1/2} z = 1.5$. The difference of the moon-plus-sky and the sky values is considered to be the deflection due to the moon alone. The transmissions found at the zenith and at $\sec^{1/2} z = 1.5$ from these extrapolations are recorded in Table 1. It is assumed that the radiation from the moon is that of a gray body. The extrapolated values of the moon's radiation outside the atmosphere at 8.71, 10.53, and 12.02 μ are assumed to be correct, and it was then found that the radiation from a 60° C gray body would fit these three points quite well.

TABLE 1

ATMOSPHERIC TRANSMISSION OBTAINED FROM LUNAR SPECTRA, 1953

WAVE LENGTH	NET MOON DEFLECTION, $\sec^{1/2} z=$			EXTRAPOLATED TRANSMISSION (PER CENT)	BLACK BODY	TRANSMISSION $\sec^{1/2} z = 1\ 5$ (PER CENT)
	0 0	1.0	1 5			
6 40			0 0		132 1	0 0
7 06			0 2		143 1	0 1
7 65	. .	.. .	5 8	.	143 9	4 0
8 20	122 2	75 1	51 5	61 3	138 8	37 1
8 71	131 2	93 3	74 5	71 2	131 2	56 8
9 25	101 2	75 8	63 1	75 1	122 0	51 7
9 67..	64 0	38 9	26 2	60 8	114 3	22 9
10 14	103 5	70 2	53 6	67 8	105 2	51 0
10 53	98 1	69 5	55 0	70 8	98 1	56 1
10 93	90 3	63 2	49 8	69 9	91 2	54 6
11 30	83 9	56 1	42 4	66 8	84 9	49 7
11 69	72 8	47 8	35 1	65 6	78 8	44 5
12 02	74 1	47 2	33 8	63 7	73 8	45 8
12 40			22 4	..	68 3	32 8
12 74			17 9	..	63 8	28 0
13 08			14 3	.	69 4	24 2
13 41	. .		3 8		55 6	6 8

The transmission at $\sec^{1/2} z = 1.5$ is then obtained by dividing the 60° gray-body spectrum adjusted to the moon at 8.71 μ by the observed moon spectrum interpolated to $\sec^{1/2} z = 1.5$. These transmissions are given in the last column of Table 1 and are assumed to be the standard transmissions of the atmosphere on any given date at an air mass of 2.25. At other values of zenith distance the transmission can be found with the square-root law from the standard values. The essential purpose of determining the transmission in this manner is to avoid the failure to obtain the correct transmission in a strong band.

By using these transmissions and the experimentally determined spectrum of the planet, the actual spectrum of the planet outside the atmosphere was determined. The effective transmission of the atmosphere was then found by taking an average of all the above-determined transmissions at $\sec^{1/2} z = 1.5$ but weighted according to the individual planetary spectrum. The average, of course, extends over the pass band of the monochromator, i.e., from 8.2 to 12.4 μ.

LABORATORY TEST OF THE METHOD

The extrapolation method described above, but without the modification using the moon, is entirely complete within itself and requires no data obtained from other sources or prior knowledge of atmospheric transmission. Furthermore, the extrapolation method can be tested by laboratory measurements to see whether it does give the correct temperature of an object that is never observed directly but only through a gas contained in an absorption cell that simulates the atmosphere. However, a gas different from the atmospheric absorbing gases must be used in order to obtain appreciable absorption within a cell of convenient size. The test was carried out using ammonia as the gas. Its ν_2 band provides strong absorption between 9 and 13 μ. An ammonia-filled cell having rock-salt windows and a path length of $\frac{1}{4}$ inch was mounted so that it could be rotated about an axis parallel to the plane of the cell windows. In this way different values of the angle of penetration (corresponding to the zenith angle for the earth's atmosphere) were obtained. Because of the finite size of the cell, the width of the beam was reduced as the cell rotated to large angles. This, as well as the variation of the reflection losses at the cell windows with angle, made it necessary to make auxiliary measurements with the cell empty, to correct for these effects. With the empty cell, observations were made of black bodies at the temperatures of liquid nitrogen and melting ice for a series of angles between zero and 68°. The measurements with the cell perpendicular to the beam yielded the sensitivity of the apparatus, while measurements at other angles give the correction for the reflection losses and beam-width variation.

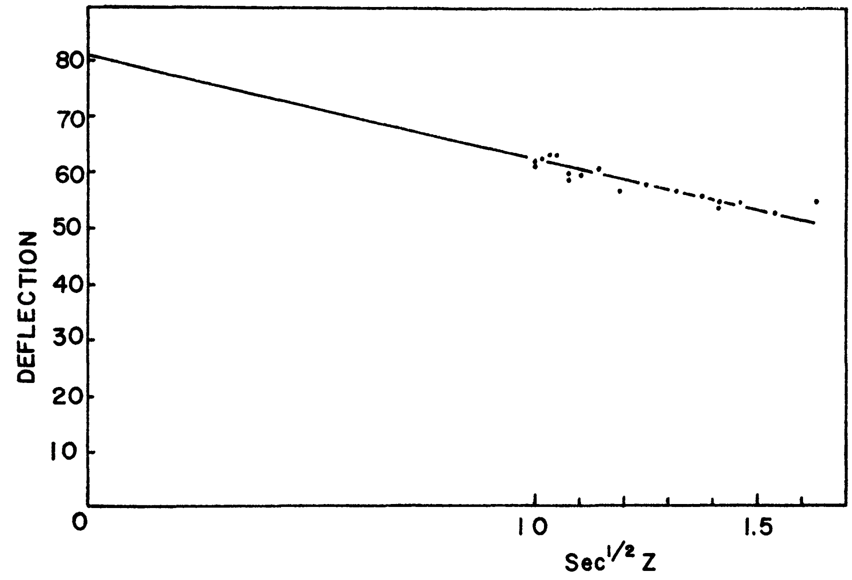

FIG. 3.—Plot which was obtained using an ammonia atmosphere

A piece of granite at room temperature was used to simulate the planet. A black-body cone immersed in liquid nitrogen was exchanged with the rock in order to simulate the observations of the sky adjacent to the planet. The calibration-curve shows that there is essentially no radiation from liquid nitrogen within the monochromator pass band. With ammonia in the cell, observations were made of the rock and of the liquid nitrogen for the same angles as before. Figure 3 shows a diagram of the deflections, corrected for losses due to the cell, plotted against the square root of the secant of the angle. The straight line which best fits the data gives a transmission of 76.5 per cent at the "zenith." A temperature of 21.2° C is obtained for the temperature of the granite.

Its actual temperature was 24.0° C. From this result one may surmise how reliable the method is—it gave a temperature only slightly lower than the true temperature. The test of the method was not a test of the effect of the planet having an emissivity lower than unity, however. The emissivity of the stone did not enter, since it was bathed in radiation at room temperature.

TEMPERATURE MEASUREMENTS

In the summer of 1952 we observed on 14 nights with the 100-inch telescope, which time was shared with other observers. Since we could operate in daylight as well as darkness, we used the telescope from about 4:00 until 7:00 P.M. The night observer used the telescope from then until 4:00 A.M., when we used it again until sunrise. Inasmuch as the 100-inch telescope cannot be conveniently changed from the Newtonian to the coudé focus during the night, we worked during the period of the bright of the moon when observations were being made with the coudé spectrograph. Therefore, our equipment, mounted at the coudé focus, had to be readily removable and replaceable so as not to interfere with the regular astronomer. The change-over from our observations to spectrographic observations or vice versa required about 10 minutes.

The middle slit of the monochromator was opened to 6 mm, and the rotation of the prism tables was set to 10.9 μ wave length, yielding a band pass of from 8.3 to 13.3 μ. The entrance slit of the monochromator was generally set at 1 mm. A different aperture was used for each planet at the coudé focus. These apertures had exactly the diameter of the image of the planet taken from the *American Ephemeris and Nautical Almanac* and were painted a flat white to facilitate guiding the telescope. Except in the case of Jupiter, these apertures, when imaged on the monochromator slit, were smaller than the slit opening. Any error in guiding could be seen from the light thrown on one side of the aperture.

This procedure was modified when it was discovered that the dispersion in the atmospheric refraction became important when zenith distances became greater than 60°. At these large angles the infrared image did not lie in exactly the same position as the visible image but differed from it by a few seconds of arc. The direction of this displacement could be clearly seen by the presence of red and blue fringing of the image. The maximum signal was sought by displacing the image along this direction until maximum deflection was recorded. The proper displacement was noted in terms of the fraction of the planet's diameter, and settings were made using this displacement until a new position of maximum was found. Table 2 shows the differential refraction found by assuming the refraction directly proportional to the index. A table of refraction given by Russell, Dugan, and Stewart (1945), after being corrected to the atmospheric pressure of Mount Wilson—620 mm—was used for the total refraction, and the change in index between visible and infrared was found from the dispersion formula of Edlén (1953). The empirical values found from Venus on September 12 are compared with these calculated values in Table 3.

Deflections were recorded alternately with the planet on the aperture and the sky next to the planet on the aperture. Approximately every half-hour the comparison mirror was put in, and deflections were recorded from black bodies at either ice and boiling-water or ice and dry-ice temperatures.

The most extensive set of observations were made of Venus. On September 12 its emission was measured while the air mass changed from 1.66 to 4.38. The deflection resulting from the extrapolation to zero air mass is 16.7 ± 0.3 p.e. and, when adjusted by means of the calibrating deflections to the thermal calibration chart, yields a temperature of 225° K. The transmission of the atmosphere at the zenith is 71.3 per cent. Time was not available to obtain sufficient data for a similar plot for the other planets. Instead, the transmission of the atmosphere found from Venus at a specific zenith angle was used for correcting the deflections of other planets to outside the atmosphere. The use of

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these transmissions for planets whose spectral distribution differs from that of Venus will give slightly erroneous temperatures. The temperature that is obtained from measurement of the whole disk of the planet is the temperature of a black body of the same size as the planet and yielding the same amount of radiation in the monochromator pass band as does the planet. Temperatures found in this way are listed in Table 4. The last column of the table gives subsolar temperatures derived in the same manner that Pettit and Nicholson (1936) did for Mercury, for those planets that have little or no atmosphere.

MEASUREMENTS OF VENUS

In July, 1953, we devoted all our time with the 200-inch to observation of Venus. Venus was a morning object and was not far from dichotomy, yielding twice the ap-

TABLE 2

DIFFERENCE BETWEEN INFRARED AND VISUAL IMAGE AT 620-MM PRESSURE

z	Δ Refr.	z	Δ Refr	z	Δ Refr
90°	38″8	79°	5″3	60°	1″7
89	27 2	78	4 9	55	1 5
88	20 1	77	4 6	50	1 3
87	15 8	76	4 2	45	1 1
86	13 0	74	3 7	40	0 8
85	10 9	72	3 3	35	0 7
84	9 4	70	2 8	30	0 6
83	8 2	68	2 6	25	0 4
82	7 2	66	2 4	20	0 3
81	6 5	64	2 2	10	0 2
80	5 8	62	2 0	0	0 0

TABLE 3

COMPUTED AND OBSERVED DIFFERENTIAL REFRACTION

z	Observed Δ Refr	Computed Δ Refr	z	Observed Δ Refr	Computed Δ Refr.	z	Observed Δ Refr	Computed Δ Refr
68°4	1″8	2″6	72°6	2″7	3″3	74°6	3″6	3″7

TABLE 4

MOUNT WILSON MEASUREMENTS OF PLANETARY TEMPERATURES, 1952

Date U T	Object	Effective Temp (°C)	Subsolar Temp (°C)
Aug. 29	Mercury	+ 95	+299
	Jupiter	−140	. . .
Aug. 30	Mercury	+ 76	+265
	Jupiter	−143	.
Sept. 11	Mars	− 40	− 7
Sept. 12	Mars	− 31	+ 2
Sept. 12	Venus	− 48	.

parent diameter of the previous year and a relatively long period of observing before sunrise. This larger diameter, along with the larger telescope, gave images of Venus at the same f/number as at Mount Wilson but with four times the diameter. In addition, because of equipmental improvements already mentioned, we could reduce the size of the aperture so that we could now examine the disk of Venus in detail.

It was not practical to observe a zenith angle greater than 60°. Also the dome was closed at sunrise to avoid heating the telescope and dome interior. These limits allowed us the observing period between 3:00 and 5:00 A.M. Since we followed the regular night observer, some time was necessary for change-over and the establishment of some adjustments. This required only about 20 minutes, even when the telescope was being used at the prime focus during the night. Table 5 gives a log of all the observations that we made on Palomar Mountain in 1953. A log of 1954 observations appears in Paper II (Sinton and Strong 1960). Except for July 13 (cloudy) and the last two nights, which were devoted to lunar observations using a heliostat, all nights were devoted to the Venus work.

TABLE 5

LOG OF OBSERVATIONS ON PALOMAR MOUNTAIN, 1953

Date UT July	Object	Type of Observation	Remarks
11	Venus	Temperature	Exploratory, good signal-to-noise
12	Venus	Spectra	1-mm slits, good signal-to-noise
13	.	.	Clouds, no observations
14	Venus	Spectra	0.7-mm slits, 4 spectra
15	Venus	Spectra	0 5-mm slits, 7 spectra
16	Venus	Spectra	0 5-mm slits, 5 spectra
17	Venus	Temperature	Drift parallel to equator
18	Venus	Temperature	Drift parallel to terminator
19	Venus	Temperature	Drift parallel to terminator
20	Venus	Spectra	1-mm slits
21	Venus	Spectra	0 5-mm slits, 3 spectra
25	Moon	Spectra	0 5-mm slits, observed with heliostat
26	Moon	Spectra	0 5-mm slits, first part of night
		Temperature	Drift curves during lunar eclipse remainder of night

The first morning of observation was devoted to measurement of the total radiation from Venus at the center of the bright half. Many changes in gain and time constant were made to determine the signal-to-noise ratios that were available. Subsequently, on July 17, 18, and 19, using this experience, we made drift-curves across the disk of the planet.

The band pass of the monochromator for these curves was 8.2–12.4 μ—a slight shift of the band was made from that used at Mount Wilson to center it better on the atmospheric window. With this band pass the thermal calibration shown in Figure 2 was obtained during the period on Palomar Mountain, and it has been used to reduce these drift-curves.

The drift-curves of July 17 were made perpendicular to the terminator with apertures of 2.73×4.21 and 1.48×4.21 seconds, the long axis of the aperture being parallel to the terminator. It is possible with the 200-inch to alter the driving motion from the star rate by accurately known amounts. In addition, known amounts of motion in the declination axis can be inserted. Thus we could insert motions to follow the planet exactly in right ascension and declination and then insert additional motions to traverse the planet's disk at an arbitrary rate, either perpendicular or parallel to the terminator. The aperture across which the planet's image traverses was ruled with a pair of lines perpendicular to the long axis of the aperture and spaced the radius of the planet from the aperture's center. These lines were used for guiding. The planet's image was kept centered between these lines by pressing either the east-west or the north-south pair of buttons, whichever set moved the planet most nearly perpendicular to the lines; the other set was not touched during a scan.

Unfortunately, no correction was made for atmospheric dispersion, as discussed earlier. The angle betweeen the terminator and the direction toward the zenith along which the dispersion occurs was approximately 50°. At a zenith angle of 60° the infrared image lies 1.7 seconds lower in the sky than the visible image. Thus the actual scans passed approximately 1.1 seconds north of the center of Venus. The July 17 drift-curves will be referred to as "equatorial scans."

On July 18 and 19 drift-curves were made parallel to the terminator with apertures of 1.48 × 4.21 and 0.88 × 4.21 seconds, respectively. These drift-curves will be referred to as "meridional scans." Becasue of the atmospheric dispersion, the actual path was approximately 1.3 seconds west of the center of the disk.

Ultraviolet photographs of Venus usually show cloud formations which change radically from day to day, as was demonstrated by F. E. Ross (1928). Photographs with visible light, except in rare instances, show no structure on the disk. It seemed cogent to obtain ultraviolet photographs on the same days that drift-curves were made, to see whether there was a correlation of structure. These photographs were obtained with a Leica camera body placed in front of the aperture at the coudé focus. Positive motion-picture film and a Corning No. 5840 filter were used to photograph in a band from 3300 to 4000 A. Exposure time was 2 seconds. Figure 4 shows photographs taken on July 17, 18, and 19. The fine diagonal streaks are apparently due to the filter.

The atmospheric transmission, weighted according to the spectrum of Venus through the pass band of the monochromator, was obtained as described under "Modified Method." It was found that the weighted transmission at an air mass of 2.25 was 46.7 per cent. The square-root law is used for finding the transmission at other zenith distances. The temperatures obtained at the centers of all the drift-curves are listed in Table 6. The mean temperatures obtained each day are close to 234° K, in agreement with the results of Pettit and Nicholson (1955).

The average of the last three scans obtained on July 17, after correction for the change in atmospheric transmission during the scans, is shown by curve *a* of Figure 5. The abscissa scale for each curve was obtained as follows: A tangent was drawn to the drift-curves at the points of inflection. The intercept of this tangent with the base line is assumed to be a nominal edge of the disk.

The most striking characteristic of this equatorial scan is the near-equality of the radiation from the day and night halves of the planet, which was previously pointed out by Pettit and Nicholson (1924, 1955). However, it is apparent that the dark side (the west) is not quite so hot as the illuminated side. It is also obvious that there is a falling-off or the radiation toward the limb of the planet similar to the limb darkening of the sun. There are then at least three effects which determine the shape of the equatorial drift-curves: first, the decline of the actual temperature from the bright to the dark side; second, the limb darkening which is the result of emission at a lower temperature of the higher atmosphere observed near the limb; and, third, this curve is modified by the smoothing effects of the finite size of the scanning aperture, the seeing, and the diffraction by the telescope. Though it is not possible from the data obtained uniquely to separate the first two of these components, it will be attempted by making an assumption.

The smoothing effects of the finite size aperture and of seeing and diffraction by the telescope may be eliminated from a knowledge of these effects. The scanning aperture was 1.4 seconds of arc wide or about 0.08 of the diameter of Venus. Diffraction by the

FIG. 4.—Ultraviolet photographs of Venus obtained on July 17, 18, and 19, 1953. North is at the top

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telescope for 10-μ waves amounts to a blurring of about 0.5 seconds, while seeing probably contributes about 1.5 seconds blurring. Since the smoothing by the scanning aperture was the last effect imposed on the curve, it is the first to be eliminated. The graphical method described by Bracewell (1955) has been used. The effects of seeing and diffraction were then removed by using the same method but assuming the combination of the two to have a Gaussian distribution with a half-width of 2.0 seconds. The restored curve is shown as the solid curve in Figure 6.

This curve should have only the effects of limb darkening and the variation of temperature along the equator. It will be assumed that the law of limb darkening is independent of local temperature. If the law is expanded into a power series in x, which represents the abscissa in Figure 5, it will contain only even powers of x. On the other hand, the temperature variation may contain all powers of x. If measurements at widely different phase angles were available, then these two effects could be uniquely separated. In the absence of these measurements, it is assumed that the temperature variation contains no even powers. By averaging the east and west halves of the drift-curves, the odd powers cancel, leaving what we trust represents only limb darkening. Figure 7, *a*, shows the average of the halves compared to a $\cos^{1/2}\theta$ law of darkening, where θ is the angle between the normal to the surface and the line of sight. The data appear to fit this law very well except very close to the limb. The variation in temperature may then be deter-

TABLE 6

TEMPERATURE OF VENUS FROM DRIFT-CURVES, 1953

SCAN NO	TEMPERATURE AT CENTER	EFFECTIVE TEMPERATURE OF WHOLE DISK
	July 17	
1	237.5	230
2	238	230
3	234	226.5
4	232	224.5
5	228	221
Means	233.9	226.5
	July 18	
1	235.5	228
2	234.5	227.5
4	233.5	225.7
Means	234.5	227.1
	July 19	
1	235.2	227.7
2	232.7	225.3
3	233.5	225.5
4	231.0	233.0
Means	233.1	225.4

mined by dividing the curve of Figure 6 by the limb-darkening factor and converting the resulting curve to temperatures with the calibration chart. This has been done in Figure 8, where the absolute temperature is plotted against the angle which the normal to the surface of Venus makes to the sun. The variation in temperature over the apparent disk is seen to be rather uniform. In 1953 the night half of Venus appeared to be only 2° or 3° colder than the day side.

The limb darkening found for the equatorial scan is assumed to apply to the meridian scans as well. In Figure 9 the same procedure has been used to eliminate the limb darkening from the meridional curves of July 18. There is a fall in temperature at the presumed poles, and the southern half is slightly warmer than the northern; but a comparison of the July 18 and 19 curves *b* and *d* in Figure 5 shows that the latter may not have been

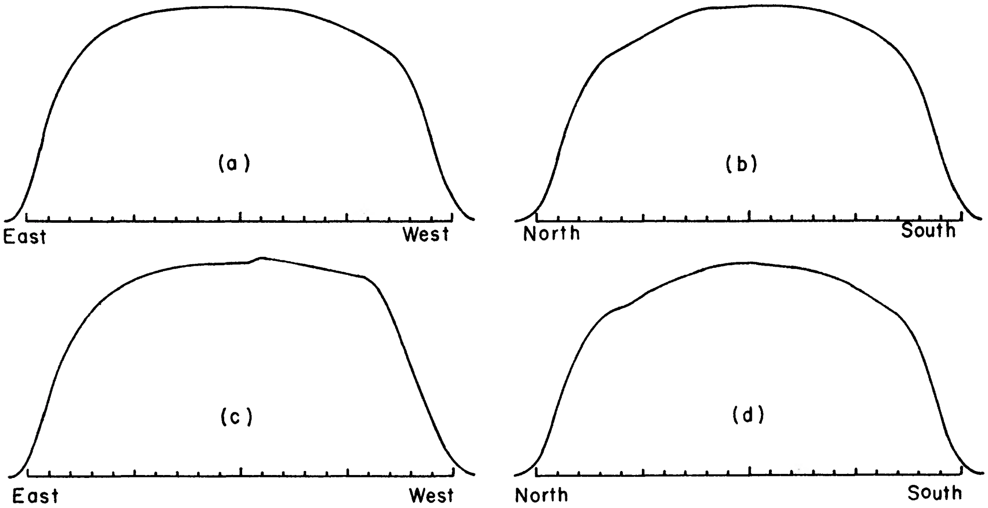

FIG. 5.—Averages of drift-curves obtained on (*a*) July 17, 1953; (*b*) July 18, 1953; (*c*) July 27, 1954; and (*d*) July 19, 1953.

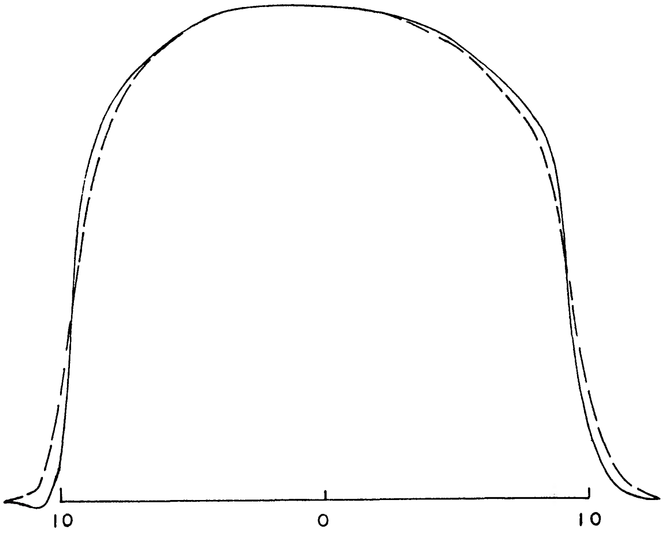

FIG. 6.—Average of scans of July 17 with smoothing effects removed (*solid curve*) compared with uncorrected average curve (*dashed*).

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used in 1953. As these were only relative drift-curves, an absolute measurement was made of the center of the disk with a 5-second aperture on July 29. This measurement yielded 234.5° K. at the center of the disk. Two of the drift-curves were averaged and are shown in Figure 5, *c*, after correction for the changing zenith angle. This curve also fits fairly well to a $\cos^{1/2}\theta$ law of limb darkening (Fig. 7, *b*). After correction for limb darkening the 1954 temperatures are also shown in Figure 8.

SPECTRA OF VENUS

Spectra were obtained of Venus and Mars with the 100-inch telescope in 1952 but only with very poor signal-to-noise ratios. When a number were averaged together, they showed the general shape of the spectrum and even the 9.6-μ ozone band. However, since they do not add any information to that shown in the much better spectra obtained in 1953 and 1954, they will not be presented here.

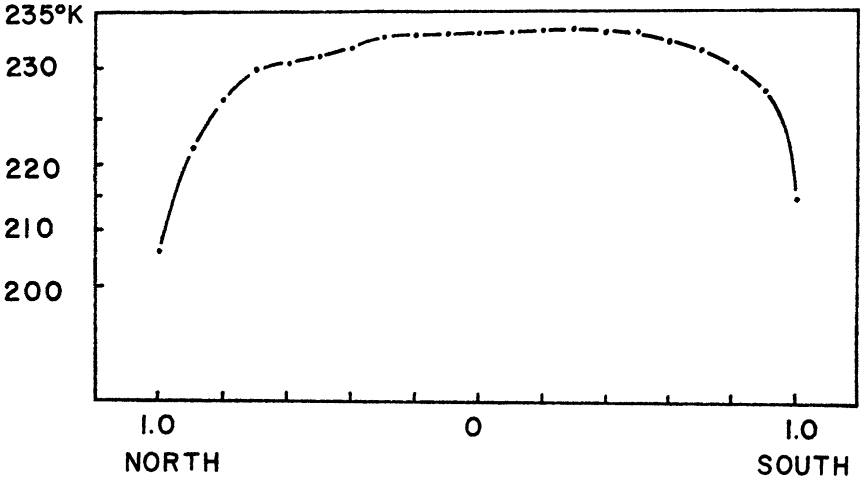

FIG 9.—Average of meridional scans of July 18, 1953, with limb darkening removed

Numerous spectra of Venus were obtained with the double monochromator on the 200-inch telescope in 1953. Spectra with good signal-to-noise ratios could be obtained with the large image slicer and slit widths as narrow as 0.5 mm, corresponding to a resolution of 0.36 μ at 10 μ. Figure 10 shows a spectrum obtained with the image of Venus falling directly on the image slicer, a spectrum obtained with Venus traversing the comparison path before falling on the image slicer, and a spectrum with the sky alone in both paths. The fact that this "sky-sky" spectrum is not a straight line indicates that the two beams were not exactly balanced. The deviation from a straight line can be shown to be just that which would be produced by two additional mirrors with 97 per cent reflectivity in one beam. It was not realized beforehand that such a small imbalance would cause such a large effect. The planetary emission may be obtained from the difference between the direct and the indirect spectra or between a direct or indirect spectrum and the sky-sky spectrum.

For both the direct and indirect spectra a square-root plot was made at each counter number. From the straight lines fitted to these points, the values at $\sec^{1/2} z = 1.5$ were determined. The spectrum of Venus at $\sec^{1/2} z = 1.5$ obtained from the July 15 data is plotted in Figure 11. The spectrum that was obtained from the average of all the Mount Wilson spectra was a generally similar shape but had much poorer resolution.

The atmospheric transmissions obtained from the moon spectra can be applied to the Venus spectrum to obtain the spectrum of Venus outside the atmosphere. This spectrum, the case on July 19. There was a colder region which extended half the radius of the planet from the north pole on both these dates, and its extent agrees with the bright cloud visible on the ultraviolet photographs.

An effective temperature of the entire disk of the planet may be determined if it is assumed that the $\cos^{1/2}\theta$ dependence is valid along any diameter of the disk. Integration of this factor over the disk results in four-fifths of the emission of a uniform temperature disk. The temperatures in the last column of Table 6 were obtained by taking four-fifths of the radiation temperature of the center of the drift-curves. The resulting mean temperature, 226° K, is only a degree from the effective temperature obtained in 1952.

In 1954, when Venus was again near dichotomy but this time as an evening star, a few observations were made of it during the period of Mars observing. Drift-curves were made on July 27 perpendicular to the terminator with an aperture similar to the one

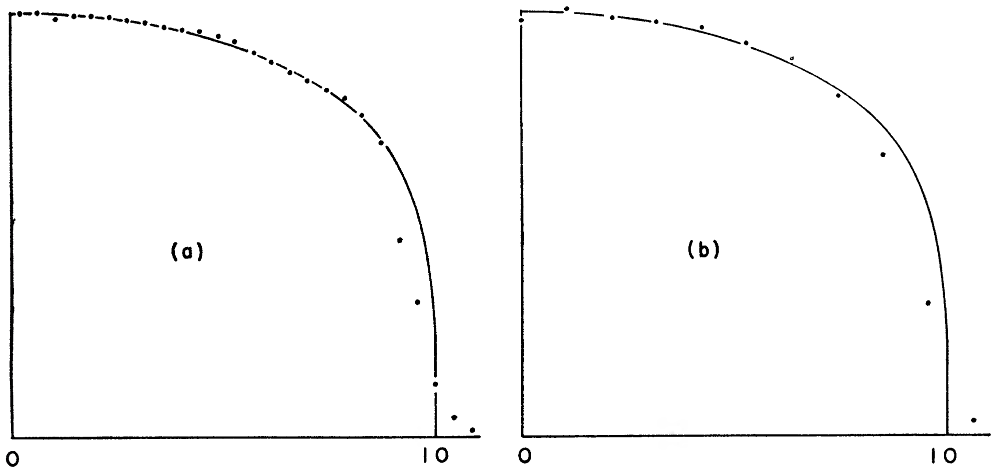

FIG. 7.—Average of east and west halves of equatorial scans (*points*) on (*a*) July 17, 1953, and (*b*) July 27, 1954, compared with $\cos^{1/2}\theta$ (*line*) In both cases there has been a slight adjustment of the abscissa scale for the best fit.

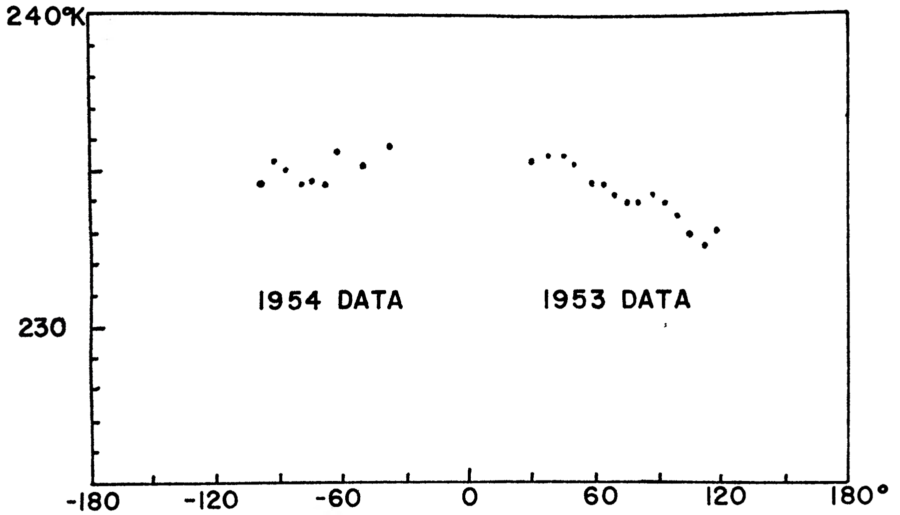

FIG. 8.—Temperatures obtained from equatorial scans plotted against the angle between the surface normal and the sun.

after correction for wave-length variation in dispersion of the monochromator, is shown in Figure 12. This figure also shows black-body curves corresponding to 220°, 225°, and 230° K. The scale of the Venus spectrum has been normalized so that its total area between 8.2 and 12.4 μ is the same as for the 225°-curve.

Prior to obtaining these spectra it was expected that we would find the absorption bands of carbon dioxide at 9.4, 10.4, and 12.6 μ very intense in the spectrum of Venus. It is estimated that there is five hundred times as much CO_2 in the Venus atmosphere above the cloud level as there is in the earth's atmosphere (Kuiper 1952). These bands arise from two excited levels, the transitions being, respectively, $0\ 2^0\ 0$ to $0\ 0\ 1$, $1\ 0^0$ to $0\ 0\ 1$, and $0\ 2^0$ to $1\ 1^1\ 0$. The two lower states, $0\ 2^0\ 0$ and $1\ 0^0\ 0$ are 1285.5 and 1388.1 cm^{-1} respectively, above the ground state of the molecule.

The spectrum in Figure 12 shows no evidence for the 9.4 and 12.6 bands, and the depression at 11 μ extends to too long a wave length to be associated entirely with the band at 10.4 μ. In order to determine more precisely whether the 9.4 and 12.6 CO_2 bands are present, the equivalent widths of the bands at 9.6 and 12.6 μ were determined from spectra of Venus and compared with those determined from spectra of the moon. These widths are plotted against the square root of the air mass in Figure 13. It is seen that there is no systematic difference between the equivalent widths of these bands for the Venus and the moon spectra. The equivalent width was also found for the absorption feature at 11.2 μ in the Venus spectra (Fig. 14). In drawing the envelope for this band, cognizance was taken of a slight absorption feature due to H_2O at 11.9 μ. The equivalent width of the band at 11.2 is 0.06 μ, and there is no corresponding band in the moon spectrum.

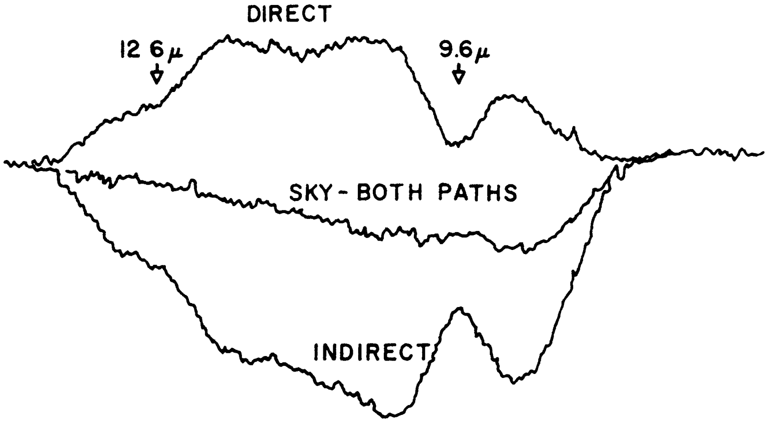

FIG 10 —Spectra of Venus and sky obtained in 1953

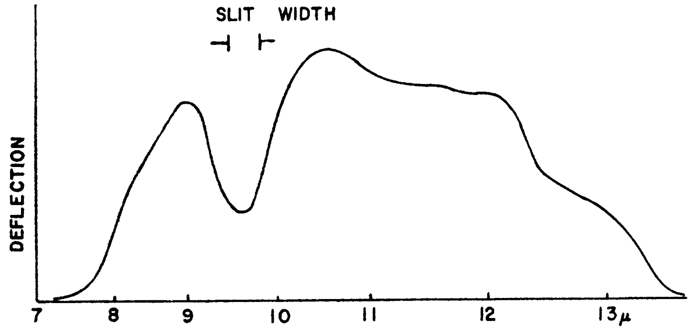

FIG 11.—Spectrum of Venus interpolated to 2.25 air masses

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Figure 15 shows a spectrum obtained in 1954 with a grating spectrometer. It demonstrates a much greater resolution, about 0.08 μ at 10 μ. Unfortunately, no indirect spectra of Venus were obtained. Therefore, it is not possible to say precisely how much the contribution of the imbalance of the two beams was. One cannot reduce the spectrum to outside the atmosphere with much certainty. The 10.4 band of CO_2 is clearly resolved into its P and R branches, and the band appears to be stronger in the spectrum of Venus than in the spectrum of the moon. There is no sharp absorption feature at 11.2 μ, showing that this band that was discovered the previous year must be rather diffuse absorption and is here obscured by the atmospheric absorptions. It is probably present in this spectrum but is a great deal weaker.

The existence of limb darkening in the drift-curves across Venus indicates that the radiation arises from a region of the atmosphere where the temperature is decreasing with altitude. The failure to observe the CO_2 bands in 1953 and the appearance only weakly of the 10.4 band in 1954 indicate that the radiation is being absorbed by a gray

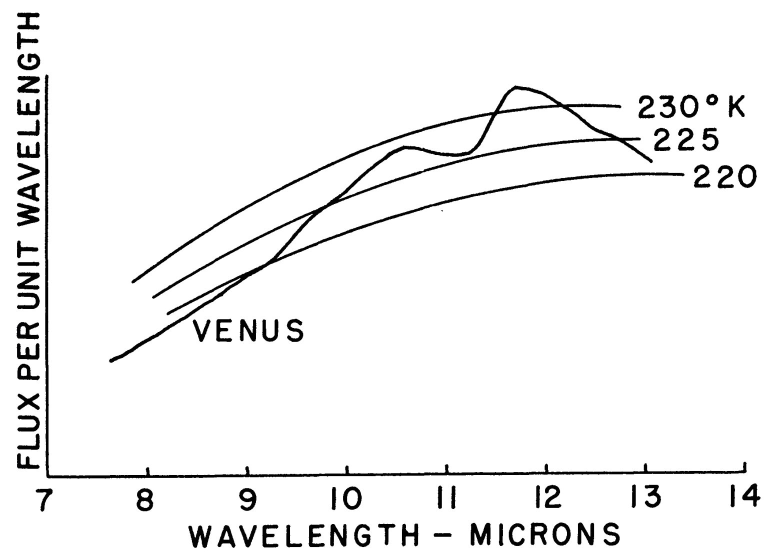

Fig 12 —Spectrum of Venus reduced to outside the earth's atmosphere and compared to black-body emission-curves

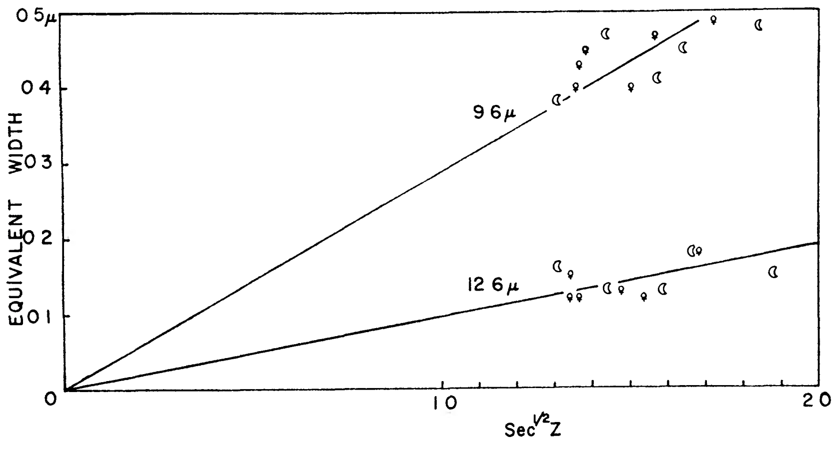

Fig. 13.—Equivalent widths of the bands at 9 6 and 12.6 μ in Venus spectra, ♀, and lunar spectra ☾

material above most of the CO_2. The low radiometric temperature, when compared with the higher temperature corresponding to the top of the cloud level obtained by Chamberlain and Kuiper (1956) and earlier by Adel (1937), also indicates that the radiating level is above the cloud level. It does not appear that dust or other suspended solid or liquid matter would be capable of explaining the gray material, since such material is likely to be penetrated more easily in the infrared than in the visible. The absorption may not really be gray but may be due to gases that just fill in absorption around the CO_2 bands and perhaps have somewhat stronger absorption at 11.2 μ. Hence it appears that the most reasonable way of explaining the observed data is to postulate the existence of a region with a lapse rate sufficient to provide limb darkening, and in this layer there are other gases as well as CO_2 which provide a nearly continuous absorption, at least continuous when averaged over the band pass of our spectrometer.

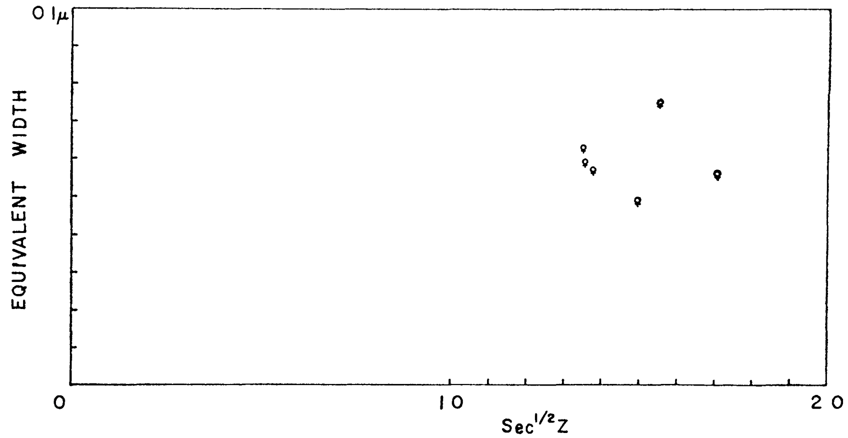

FIG. 14 —Equivalent widths of the band at 11 2 μ in spectra of Venus

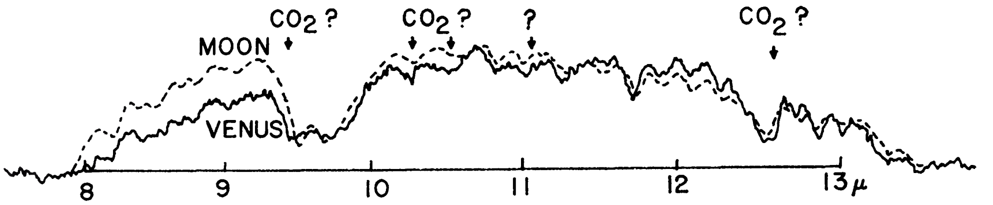

FIG 15.—Spectra of Venus and moon obtained with the grating spectrometer in 1954

One possible molecule for this explanation is carbon suboxide C_3O_2. This molecule has already been suggested by Sinton (1953) and by Kuiper (1957) as a constituent of the Venus atmosphere. Spectra of this gas obtained by Lord and Wright (1937) showed bands at 7.2, 8.2, 8.9, 9.8, 11.0, 11.2, and 12.8 μ; the strongest bands were the ones at 11.0 and 11.2 μ. Carbon suboxide is an unstable molecule and readily polymerizes, on standing, to a reddish or whitish mass. This polymerization may explain the clouds on Venus. Recent spectra by Rix (1954) do now show the 11.0 and 11.2 bands, and it appears now that the bands found by Lord and Wright were due to an impurity. It may well be that the bands were due to the polymerized suboxide.

Thus the clouds may be due to polymerized carbon suboxide, and above these there is a thin haze of the polymer which serves to stop the radiometric, but not the photographic, infrared. The latter region of the spectrum is stopped only at the clouds which have a higher temperature.

It is a pleasure to acknowledge with sincere gratitude the observing time at the 100-inch and 200-inch telescopes made available by the Mount Wilson and Palomar Observatories. We also wish to thank the many observers who shared nights with us for their indulgence and co-operation.

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