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OBSERVATIONS OF VENUS AT 3.15-CM WAVE LENGTH

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ABSTRACT

The observations of radiation from Venus at 3.15-cm wave length on 34 days in May–June, 1956, are described. The apparent black-body temperature for Venus derived from the measurements changed from about 620° ± 110° K (m.e.) in early May to about 560° ± 73° K (m.e.) near inferior conjunction. Two single observations at 9.4-cm wave length are described, which suggest that the radiation follows a thermal spectrum.

I. INTRODUCTION

Thermal radiation from planets has not previously been investigated at radio wave lengths because of the small flux density of radiation at the earth. The strong bursts of long-wave-length radio noise which were first identified with Jupiter by Burke and Franklin (1955, 1956) and subsequently by others (Kraus 1956*a;* Shain 1956) and also later identified with Venus by Kraus (1956*b*, 1957) are presumably associated with some electrical phenomena in the atmospheres of the planets. The flux density of this impulsive radiation from Jupiter apparently falls off rapidly with decreasing wave length and has not yet been measured at wave lengths shorter than about 11 meters (Smith 1955). If the impulsive radiation from Venus has similar spectral characteristics, it should not be an important factor compared to thermal radiation at centimeter wave lengths.

Preliminary estimates indicated that thermal radiation from Venus at inferior conjunction should be easily detectable with the Naval Research Laboratory 50-foot reflector and a sensitive radiometer at a wave length of 3.15 cm. As a result, a series of observations was made during May and June, 1956, a period just prior to and including inferior conjunction, with the object of measuring the flux density of the radiation and the corresponding apparent black-body radiation temperature of Venus at this wave length. The observations were made on 34 days spread over the period May 2 to June 23, so that a variation of the radiating properties with time could also be tested.

Whether the radiation measured at 3.15 cm is all of thermal origin and whether the radiation originates in the atmosphere of Venus or at the surface cannot be deduced from the present measurements without additional data. Two single subsidiary observations of the radiation from Venus at 9.4-cm wave length are described in the appendix. These measurements suggest that the bulk of the received radiation has a spectrum similar to that of thermal radiation, but the precision of the spectral determination is low because of the extremely weak flux densities and the small number of observations at the longer wave length.

II. APPARATUS

a) *Radiometer*

The radiometer used for the measurements was designed around the Dicke system (Dicke 1946). In this case, however, a switched ferrite circulator was used to connect the receiver alternately to the 50-foot antenna and to a small horn antenna pointed at the sky which was used as a comparison source. The comparison antenna had a half-intensity beam width of 37° and was mounted so as always to point at the sky within 45° of the zenith for all orientations of the 50-foot reflector. The switching rate was 30 times a second. The insertion loss of the ferrite circulator was 0.3 db, and the switching ratio was greater than 20 db over the receiver band width. The way in which the ferrite circulator was used in this application has been previously described (Mayer 1954, 1956). The detected 30-c/s modulation applied to the recorder was a measure of the difference between the integrated radiation over the acceptance pattern of the 50-foot antenna and that over the acceptance pattern of the comparison antenna. When only weak sources of radio radiation were included in the main beam of the 50-foot antenna, this difference was small. As a result, two nearly equal power levels were compared, with consequent advantages in the stability and sensitivity of the radiometer. The inherent isolation of the receiver circuits from the source impedance, which was afforded by the ferrite switch, improved the accuracy of calibration and gave further improvement in the stability of the radiometer through the suppression of variable impedance errors.

The ferrite switch was followed by a superheterodyne receiver which accepted power in two bands of frequencies, each 5.5 Mc wide and separated by 60 Mc about a center frequency of 9530 Mc. The double-side-band receiver noise factor measured with a noise source at the antenna terminal was 4.7 in units of power ratio. For intercomparison with single side-band receivers, this figure corresponds to a noise factor of 8.4 (9.2 db). The output time constant of the radiometer was about 5 seconds. The root-mean-square fluctuation in the recorder trace averaged about 0.5° C.

The radio frequency and intermediate frequency circuits were located adjacent to the focus of the reflector so that minimum lengths of rigid transmission line could be used for the high frequencies. The detected 30 c/s modulation was cabled to the control cabin of the antenna mount, where the modulation-frequency amplifiers and the power and recording units were located.

The primary calibration standards for the measurement of received power were two thermal noise sources which were substituted for the antenna feed horn. These sources were used to calibrate a small noise power which was fed to the receiver from an argon discharge tube through a directional coupler in the antenna transmission line. The secondary standard was used so that the calibration of the radiometer could be checked at frequent intervals during the observations. The two thermal noise sources were made from matched resistive terminations in a wave guide, which, with their associated transmission lines, were immersed in agitated water baths. The temperatures of the water baths were measured with precision thermometers. The two sources were connected, in turn, to the feed antenna terminal of the radiometer with a matched termination at ambient temperature substituted for the comparison horn, and the change in the output meter deflection was compared with the change due to the argon discharge noise source. This procedure calibrated out the effect of transmission-line losses and also avoided the receiver-law problem encountered when measurements are made at an antenna temperature level of a few tens of degrees absolute and the calibration is made at a level of a few hundreds of degrees absolute. The coupling ratio of the argon tube coupler was about 30 db, so that only about 0.1 per cent of the antenna power was lost. The effect of the change of impedance when the noise sources were substituted for the antenna feed horn was tested and found to be negligible. The change in the equivalent antenna temperature when the argon discharge was turned on was determined to be 13.8° C, with a mean error of about 2 per cent.

b) Antenna

The general characteristics of the Naval Research Laboratory 50-foot reflector have been described elsewhere (Hagen 1954). For these measurements a small plane-polarized pyramidal horn was located at the focal point of the reflector as the feed antenna. The radiation pattern of the feed antenna was such that the illumination at the edge of the reflector was about 15 db below that at the vertex.

The reception patterns of the 50-foot antenna were measured, using a transmitter mounted in the top of the Washington Monument at a distance of about 25000 feet. The measured half-intensity widths for the main lobe were 0.16° for the horizontal-plane pattern and 0.14° for the vertical-plane pattern. These patterns were measured for both horizontal and vertical polarization, but no differences were found in the main lobe that exceeded the experimental errors. In addition, seven transit drift-curves for the radio source Taurus A were averaged to get an estimate of the horizontal-plane pattern at an altitude angle of 73°. This pattern gave a half-intensity width for the main lobe of 0.145°. No correction was made for the finite size of the source.

The peak gain of the antenna or the corresponding effective area for reception has not been calibrated with high accuracy because of experimental difficulties and because the antenna characteristics apparently change with the elevation angle of the reflector. The variation with elevation angle was checked by making drift scans through the intense radio sources Cas A and Taurus A over a range of altitude angles. The observations were not sufficiently accurate to define the variation in detail, but they indicate that the antenna gain at the average altitude of the Venus observations is about 10 per cent higher than that measured with the reflector pointed at the horizon.

The ratio of the gain of the antenna to the theoretical gain calculated from the geometrical aperture area will be referred to as the "aperture efficiency." The maximum aperture efficiency which could be expected for this reflector geometry and aperture illumination has been calculated as 0.66,[1] assuming no loss in gain from shadowing, reflector distortions, etc.

Several attempts were made to calibrate the gain of the antenna experimentally. The most straightforward measurement was made in June, 1957, with a transmitting antenna at a distance of about 13 miles and a line-of-sight path. The signal received by the 50-foot antenna was compared with the signal received by an accurately calibrated horn antenna which had a gain of about 22 db. The comparison was made by using a superheterodyne receiver as a constant-level detector and attenuators calibrated to about 5 per cent. The main source of uncertainty in the measurement was in the relationship of the field sampled by the standard horn antenna with a representative average field over the aperture of the 50-foot reflector, since the field was not sampled over the whole aperture. The measurement gave a value for the aperture efficiency of 0.56 when corrected to an altitude angle of about 50°. The mean error is estimated as about 11 per cent.

A previous estimate of the antenna gain was made with data gathered during the period of the Venus observations. Drift scans across the moon were made during two lunations in May–June, 1956, with the 50-foot antenna. These observations indicated a nearly uniform brightness distribution over the moon and very little change in brightness over the lunar cycle at 3.15-cm wave length. The antenna gain was estimated by combining the measured antenna temperature when the main lobe of the antenna was centered on the moon with an integration of the average measured antenna reception pattern over the solid angle subtended by the moon. The value for the radiating tem-

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[1] We are indebted to F. Hennessey and J. Foster, of the Antenna Research Branch of this laboratory, for supplying us with this figure.

perature of the moon at 3.2-cm wave length of 183° K reported by Zelinskaya and Troitskiy (1955) was used. This estimate gave a value for the aperture efficiency of the antenna corrected to about a 50° altitude angle of 0.55. The mean error of this estimate is probably about 15 per cent. The more directly measured value of 0.56 was used for the data reduction.

III. OBSERVATIONS

The circumstances of the observations are diagramed in Figure 1 for the period May 2–June 23, 1956. The position of Venus has been plotted, along with the positions of the sun and the Crab Nebula. The change in the position of Venus during the observing period, together with the narrow angular width of the antenna beam, eliminates the possibility of confusion with a radio source fixed in the sky. The close proximity of Venus to the sun from June 20 to June 23 made the measurements more difficult in this interval because solar radio radiation was received in the minor lobes of the antenna diagram. The position of the Crab Nebula, radio source Taurus A, with respect to the path of Venus is noted because this source was used as a pointing object to calibrate the direction of the antenna beam with respect to the control dials.

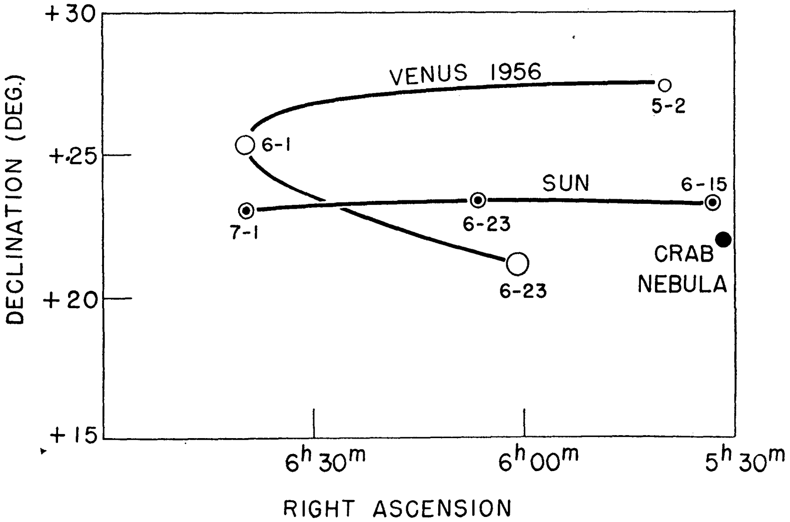

FIG. 1 —The path of Venus over the observing period

The observations of radiation from Venus were made by pointing the antenna in a fixed direction and allowing the rotation of the earth to scan the antenna beam through the position of Venus. The amplitude of the resulting drift-curve was taken as a measure of the change in antenna temperature due to the difference between the brightness of Venus and that of the background in the immediate vicinity. The brightness temperature of the background at this wave length is not accurately known, but it is very small compared with the brightness temperature of Venus. This method of taking data minimized the effect of stray radiation, since the antenna was stationary during a drift-curve. The response of the radiometer as the rotation of the earth scanned the beam of the antenna through the position of Venus is illustrated in Figure 2 for 4 days during the observing period. The four drift-curves are drawn to approximately the same scale and show the increase in the measured flux density as the distance between the earth and Venus decreased. The solid angle subtended by the visible disk of Venus increased by about 3.65 times from May 2 to June 22, inferior conjunction. The sloping base line on the June 23 drift-curve was caused by interference from the sun in the antenna side lobes. The

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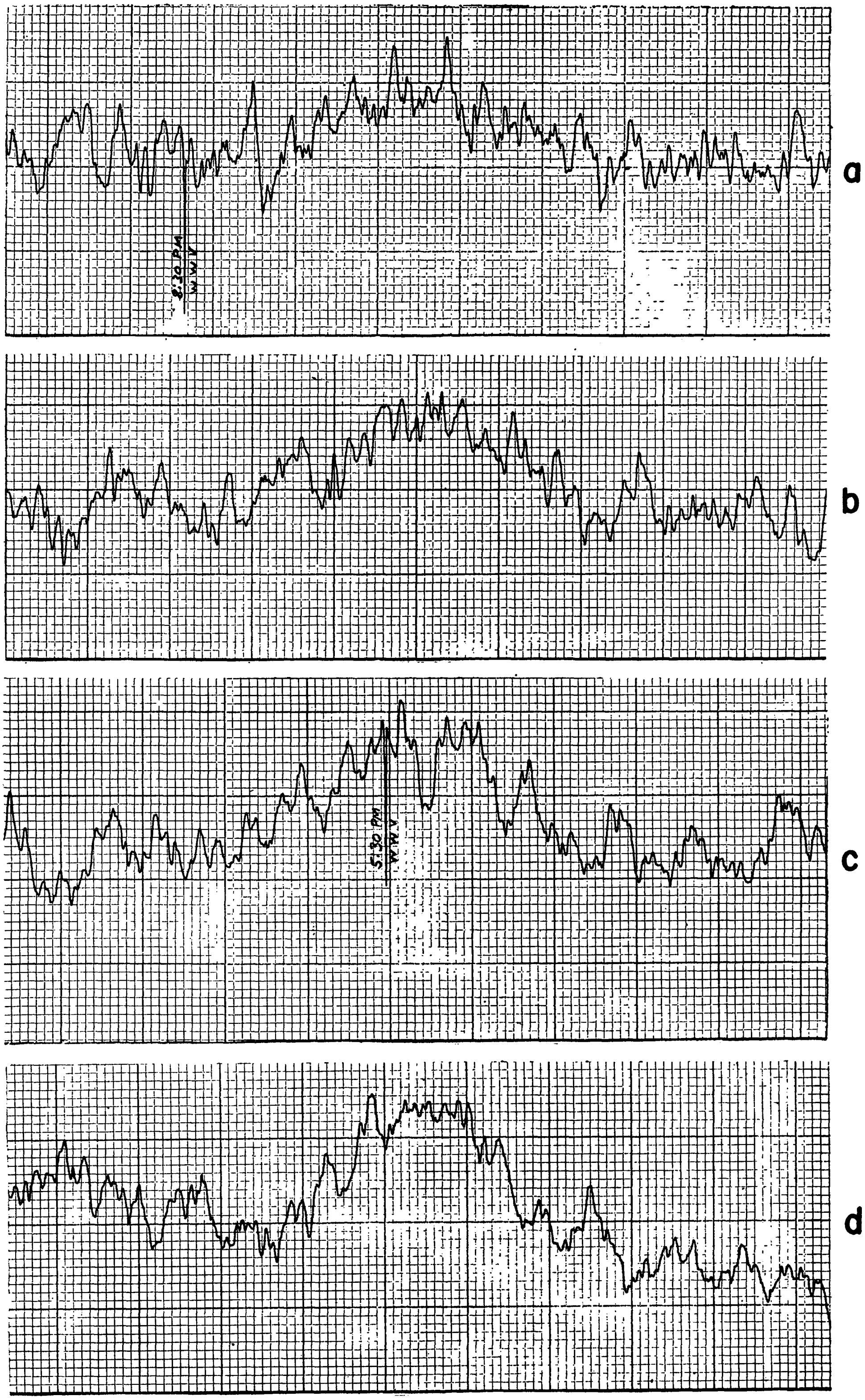

FIG. 2.—Drift scans of the antenna beam through Venus *a*, May 11, 1956; *b*, May 26, 1956; *c*, June 17, 1956; *d*, June 23, 1956.

radiometer response due to a similar scan of the antenna beam through a point source at this declination would have a half-intensity width of about 1.9 divisions on the time axis.

The pointing corrections found from the observations of radio source Taurus A were not relied on completely for the observations of Venus because of systematic pointing errors which depended on the local hour angle and declination of the source. Drift-curves through the indicated dial position of Venus and at declinations above and below this position, usually in 1 minute of arc steps, were made on each of the 34 days of observation. The best declination settings throughout the observing periods were then selected by considering the amplitudes of all the drift-curves. Observations were not made on days when the weather was unfavorable or when obvious radio interference was present. In all, about 1400 drift-curves through or near the declination of Venus were made. Of these, about 600 were selected for which the peak of the antenna beam missed the position of Venus by less than 1 minute of arc according to the control dials. The root-mean-square deviation of the pointing of the antenna beam from the indicated dial position was estimated, from observations of more intense radio sources, to be about 1 minute of arc.

The observations of Venus are summarized in Figure 3. The measurement for May 2 was the average of five drift-curves which were taken in a slight rain and with the antenna pointed off declination; therefore, this value is not included. The peak amplitudes of the drift-curves which were selected as corresponding to proper positioning of the antenna beam to within the limits described above are plotted in Figure 3, *a*, in antenna temperature units. The centers of the circles correspond to the averages for each day. These average points describe a curve which is generally similar to the variation in the solid angle subtended by Venus during the period. Using a random distribution for the antenna-pointing errors and an average of the measured antenna reception diagrams, the possible depression of an average due to antenna-pointing deviations was estimated as about 4 per cent. The flux density of radiation incident on the antenna which corresponds to each of the average values for the measured change in antenna temperature was calculated, with the antenna gain found as described in Section II*b*. The flux density is indicated by the right-hand scale in Figure 3, *a*.

The temperature of a black-body radiator which would subtend the same solid angle as the visible disk of Venus and which would account for the measured flux density of radiation is plotted in Figure 3, *b*. The estimated mean error which is appropriate for relative comparison of the daily averages is indicated by the brackets. The total mean error of the measurement of apparent temperature and flux density is estimated as about 18 per cent from May 5 to May 22 and about 13 per cent from May 22 to June 23.

IV. DISCUSSION

In general, the drift-curves were reproducible to the expected accuracy and exhibited no definite evidence of variability in the received radiation other than that to be expected from noise-type radiation and from variations in antenna pointing. Because of its altitude-azimuth mounting, the plane of polarization accepted by the antenna rotated with respect to the source by about 113° over the range of hour angles observed. In addition, the polarization of the antenna was rotated by 90° on May 17, so that the data before this date were taken with a horizontally polarized antenna and the data after this date were taken with a vertically polarized antenna. In view of this, it is likely that any significant plane-polarized component of the radiation from Venus would have been noticed. It is indicated, therefore, that the bulk of the radiation is either unpolarized or circularly polarized and that the plane-polarized antenna would accept half the incident flux.

The antenna temperature is given (Pawsey and Bracewell 1955) by

$$T_a = \frac{D}{4\pi} \iint_{4\pi} T_b \frac{A}{A_0} \, d\Omega ,$$

where D is the directivity of the antenna at the peak of the lobe, A/A_0 is the normalized reception pattern of the antenna, and T_b is the brightness temperature. In the present case the receiver is alternately connected to the 50-foot antenna and to the small horn antenna pointed at the sky. The output meter reads the difference between the antenna temperatures corresponding to the two antennas. Since the directivity of the sky horn is small and the reception pattern is broad, the antenna temperature corresponding to the sky horn is very nearly constant for all orientations of the antenna and also as a function of time. During the 4-minute interval of a drift-curve the sky-horn antenna temperature can be considered constant. The change in measured antenna temperature

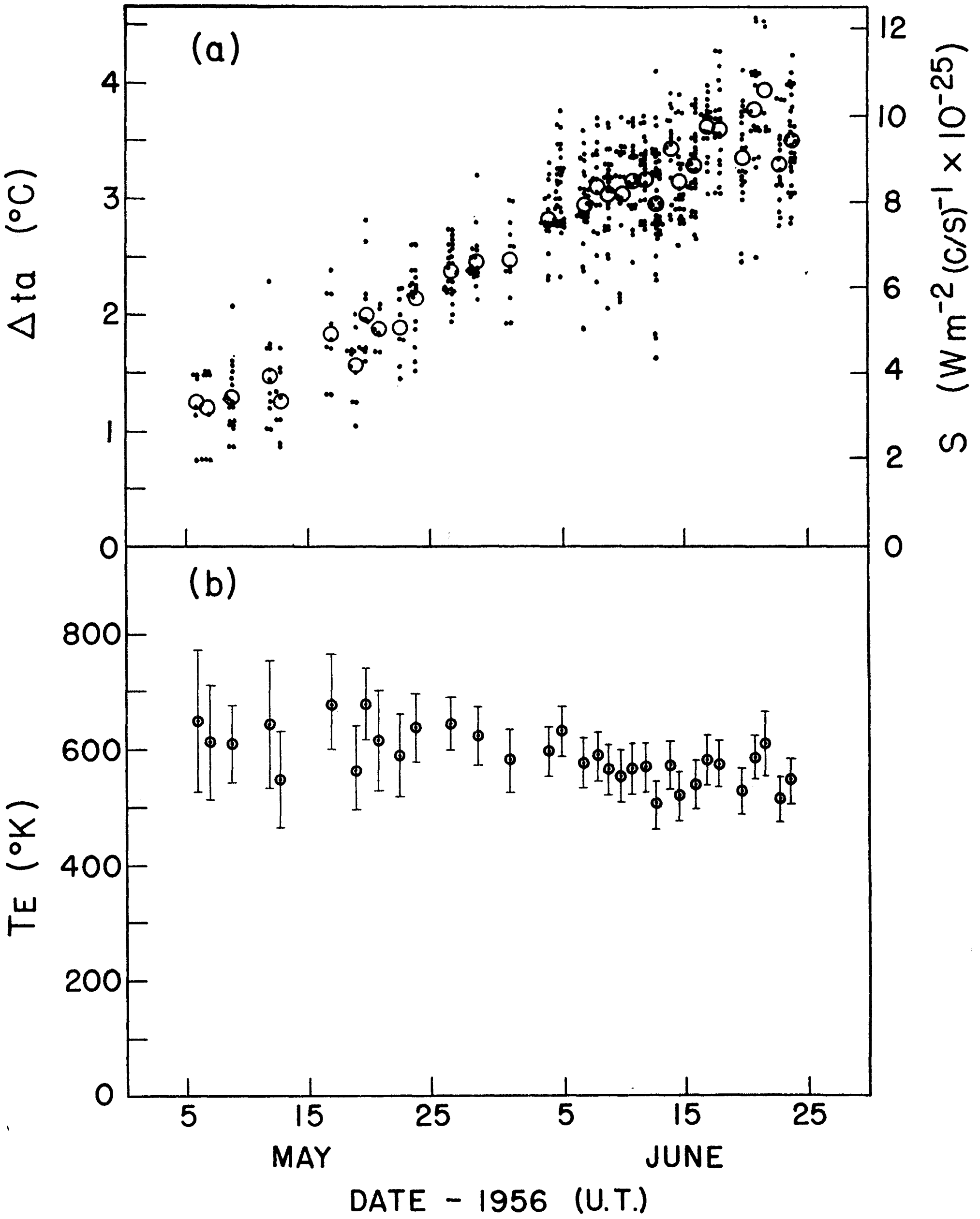

FIG. 3.—Summary of the observations. *a*, Individual measurements and daily averages in units of antenna temperature (Δta) and flux density (S). *b*, The apparent temperature of a black body subtending the same solid angle as Venus, derived from the measured daily averages.

during a drift scan then corresponds to the change in the integral as the source enters and leaves the main beam of the 50-foot antenna. The brightness temperature of the background in the vicinity of Venus is believed negligible compared to the brightness temperature of Venus, except when the sun was nearby. The radiation from the earth which is collected by the antenna is constant during a drift-curve. Therefore, the change in antenna temperature during a drift-curve is a measure of the flux density of the radiation from Venus.

The flux density of unpolarized radiation, S, from a point source is related to the corresponding change in antenna temperature, Δt_a, during a drift-curve by the following formula, where k is Boltzmann's constant and A is the effective area of the antenna for reception:

$$S=\frac{2k\Delta t_a}{A}. \tag{1}$$

The flux density in two polarizations at a wave length, λ, from a uniformly bright black-body radiator at a temperature, T, and subtending a solid angle, Ω, is given with sufficient accuracy for this experiment by the Rayleigh-Jeans approximation:

$$S=\frac{2kT\Omega}{\lambda^2}. \tag{2}$$

In the present case the size of the visible source was small compared to the half-intensity width of the antenna beam, so that the error introduced by the use of equation (1) was estimated to be less than $\frac{1}{2}$ per cent and was neglected. The spacing between the two bands of wave lengths sampled by the radiometer is less than 1 per cent of the central wave length, and the average is a good approximation to the flux density at the central wave length. It is estimated that possible errors due to solar radio radiation reflected from Venus were less than 0.1 per cent.

The measured antenna temperatures have been corrected for absorption in the earth's atmosphere, using values derived by Schulkin (1951) and for the estimated antenna-pointing errors. The absorption correction at the zenith was 1.25 per cent. The solid angle of the radio source is not known, but, for purposes of calculation, it was taken as the solid angle subtended by the visible disk of Venus. Where the solid angle changed appreciably over a group with a common average, a weighted average was used for the solid angle.

The data plotted in Figure 3, *b*, suggest a slight decrease in the apparent temperature of Venus over the measurement period. A change in the radiation level might be correlated with the rotation of Venus or with the phase of solar illumination. During this period the illuminated crescent decreased from about 36 per cent of the disk of Venus to zero. The present observations are not considered adequate to define a correlation.

The results of the radio observations of Venus and the results of other observations may be compared with reservation. Recently reported results of infrared radiometric observations by Petit and Nicholson (1955) and by Sinton (cited from Menzel and Whipple 1955) indicate an apparent black-body temperature of about 235° or 240° K. These measurements probably refer to the top of the cloud layer on Venus. The rotational temperature derived from the CO_2 bands of Venus has recently been reported by Chamberlain and Kuiper (1956) as 285° K. The maximum temperature at the surface of Venus has been estimated by Wildt (1940) from solar heating considerations as 408° K.

The radio observations indicate black-body temperatures considerably higher than these. Because of the uncertain nature of the atmosphere of Venus, no attempt will be made in the present discussion to assign the region of emission of the radio radiation, but it is undoubtedly different from that of the infrared. At least part of the 3.15-cm radiation may be emitted at the surface of the planet, and it is perhaps possible that part may arise in a heavily ionized atmosphere layer, although this seems unlikely, as an electron-density orders of magnitude higher than those found in the earth's atmosphere would probably be required. Also, the radio measurements are not yet complete enough to rule out the possibility that part of the observed radiation might be of nonthermal origin. The two single measurements at 9.4-cm wave length which are described in the appendix were an attempt to put rough limits on the radio spectrum, and the results tend to confirm thermal radiation.

V. CONCLUSIONS

The observed radio radiation from Venus at 3.15-cm wave length over a period covering nearly 2 months showed the characteristics of steady radiation with no apparent linearly polarized component to within the limits of accuracy. The measured flux density of the radiation approximated the inverse-square-law variation as the distance between Venus and the earth decreased but suggests a slight decrease in the radiation level during the period. The apparent black-body temperature of Venus deduced from the measurements was about 620° ± 110° K (m.e.) near the beginning of the period and about 560° ± 73° K (m.e.) near the end of the period. Two single observations at 9.4-cm wave length suggest that the bulk of the radiation follows a thermal spectrum, but, the accuracy of these measurements is low. A more complete series of measurements of the radiation from Venus at different wave lengths will be needed to define the spectrum.

We especially acknowledge the valuable assistance given by J. W. Boland in making the observations and reducing the data. We would also like to thank F. Hennessey for many useful discussions of the antenna-measurement problem.

APPENDIX

An attempt has been made to put rough limits on the spectrum of the microwave radiation from Venus by making two observations at 9.4-cm wave length. This wave length was chosen because a standard Dicke type radiometer was available for installation in the 50-foot antenna. The radiometer was modified by including a ferrite isolator and an argon-discharge calibrator in the antenna line.

This radiometer was installed in the 50-foot antenna on June 24, 1956. The pointing of the antenna beam was calibrated by using radio source Taurus A, and observations of Venus were attempted. The interference caused by the sun in the antenna side lobes was found to be more serious than at 3.15 cm, and no usable data were obtained on June 24. On the morning of June 25 the interference from the sun was still present but was sufficiently lessened to allow four usable drift-curves to be made. When these four drift-curves were averaged, a response at the position of Venus was brought out which had about the right half-width for a drift-curve, but additional uncertainty was present because of a much larger and broader response which occurred 280 seconds later in right ascension and was believed to be caused by sun interference. The response at the position of Venus indicated a change in antenna temperature of about 0.3° C. Assuming an antenna aperture efficiency of 0.60, this would correspond to an incident flux density of 8×10^{-26} watt $m^{-2}(c/s)^{-1}$ and an apparent black-body temperature of about 430° K. The mean error is quite high, perhaps 50 per cent.

Because of the uncertainty due to sun interference, the 9.4-cm radiometer was again installed in the antenna on July 27. At this time a number of drift-curves were made through the position which Venus occupied on June 25. When these drift-curves were averaged, neither the response at the position of Venus nor the larger response 280 seconds later was apparent. In addition, seven drift-curves through the position of Venus on this date were made. When these curves were averaged, a response was brought out at the position of Venus, again with a half-intensity width which approximated the antenna beam width. This response indicated a change in antenna temperature of about 0.25° C. Again assuming an antenna aperture efficiency of 0.60, this would correspond to an incident flux density of about 6×10^{-26} watt m^{-2} $(c/s)^{-1}$ and an apparent black-body temperature of about 740° K with about the same uncertainty as before.

The average of the two 9.4-cm measurements of apparent temperature is 580° K, which compares favorably with the 3.15-cm apparent temperature.

The high uncertainty in the 9.4-cm observations makes it impossible to draw definite conclusions, but these measurements suggest that no great percentage of the 3.15-cm flux has a spectrum very different from that of simple thermal radiation.

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