III Session: PASSIVE RADIO OBSERVATIONS OF VENUS, SATURN, MERCURY, MARS, AND URANUS

Passive Radio Observations of Mercury, Venus, Mars, Saturn, and Uranus [1]

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The radio observations of Mercury, Venus, Mars, Saturn, and Uranus are reviewed and discussed in relation to knowledge of these planets acquired by other means. In the case of Mercury, it is shown that the radio observations imply a temperature of ~ 300 °K for the unilluminated hemisphere, a result which appears to be in sharp disagreement with infrared measurements of Mercury. Two detailed measurements of the Venus spectrum near 1-cm wavelength are presented and compared.

1. Introduction

Astronomical observations at radio wavelengths, say, from 100 m to 1 mm, have given rise to unexpected results in many branches of astronomy, and the planetary studies branch is no exception. The first radio emission from any planet was detected from Jupiter at 13.5-m wavelength by Burke and Franklin [1955], and it was obvious immediately from the intensity and time dependence of the emission that the radiation process could not be ascribed to thermal mechanisms. Long-wavelength studies of Jupiter emission have proceeded at a rapid rate since 1955 and form the major part of the observing programs of several radio astronomy observatories. In 1956, a new phase of planetary radio astronomy was introduced by the detection of thermal radiation from Venus, Mars, and Jupiter by Mayer, McCullough, and Sloanaker at the U.S. Naval Research Laboratory [1958 a, b, c]. Unlike the observations that led to the Jupiter detection, Venus was first observed at 3.15-cm and 9.4-cm wavelength, and all subsequent planetary detections have been made initially at centimeter wavelengths. At the present time, radio emission has been detected from Mercury, Venus, Mars, Jupiter, Saturn, and (perhaps) Uranus.

The fact that planetary radiation has been primarily studied at centimeter and millimeter wavelengths can be readily understood from the basic law of thermal radiation, Planck's law, and the usual radio-frequency approximation, the Rayleigh-Jeans law. The thermal energy emitted per unit time into unit solid angle by a unit area of a perfect emitter at a temperature T in the frequency range between ν and $\nu+d\nu$ is given by Planck's law,

$$I(\nu)\,d\nu=\frac{2h\nu^3}{c^2}\frac{d\nu}{(e^{h\nu/kT}-1)},\tag{1}$$

where h, c, and k are Planck's constant, the velocity of light, and Boltzmann's constant, respectively. In the radio domain, $h\nu/kT \ll 1$, so (1) may be expanded to give the familiar Rayleigh-Jeans approximation,

$$I(\nu)\,d\nu=\frac{2kT\nu^2}{c^2}\,d\nu=\frac{2kT}{\lambda^2}\,d\nu\cdot\tag{2}$$

The power received by a radio telescope having an effective area A_e from a radio source of solid angle Ω_s is given by

$$P_{\text{rec}}=kT_A\Delta\nu=\frac{k\Delta\nu}{\lambda^2}\int\Omega_s\,TA_e d\Omega,\tag{3}$$

where T_A is the "antenna temperature," and a factor 1/2 has been included because only one polarization can be received at a time. The wavelength dependence of (3) shows clearly the advantage of short wavelengths when trying to detect thermal radiation. For all pencil-beam antennas now in use the effective area of the aperature is essentially constant over the solid angle subtended by the source, so (3) may be approximated as

$$P_{\text{rec}}=kT_A\Delta\nu=\frac{k\Delta\nu\,A_e\,\overline{T}_B\Omega_s}{\lambda^2},\tag{4}$$

where $\overline{T}_B$ represents the radio brightness temperature averaged over the hemisphere of the planet visible from Earth.

Equation (4) has been used to compute the values shown in table 1. For the computation of these values we have assumed a parabolic antenna of 30.5-m (100-ft) diameter operating at a wavelength of 3 cm with an aperature efficiency of 0.50. The values of table 1 are only intended to serve as a guide to the typical orders of magnitude involved in planetary radio astronomy. Note that the detection of radio emission from Neptune and Pluto is a formidable task by present standards.

Equation (4) was derived under the assumption that the effective area of the antenna does not vary appreciably over the solid angle subtended by the planet.

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TABLE 1. *Typical values of received power and antenna temperatures for planetary radiation at 3-cm wavelength* [a]

Planet	Solid angle [b]	Mean brightness temperature, $\overline{T}_B$	Antenna temperature	Received power
	Steradian	*°K*	*°K*	*W*
Mercury	2.2×10^{-9}	400	0.36	5.0×10^{-17}
Venus	7.0×10^{-8}	600	17.1	2.4×10^{-15}
Mars	5.9×10^{-9}	200	0.48	6.6×10^{-17}
Jupiter	4.1×10^{-8}	150	2.5	3.4×10^{-16}
Saturn	7.0×10^{-9}	100	0.28	3.9×10^{-17}
Uranus	2.4×10^{-10}	[c] 100	.0098	1.4×10^{-18}
Neptune	8.3×10^{-11}	[c] 100	.0034	4.7×10^{-19}
Pluto	5.0×10^{-12}	[c] 100	.0002	2.8×10^{-20}

[a] A parabolic antenna, 30.5 m (100 ft) in diameter, with an aperature efficiency of 0.50 at $\lambda = 3$ cm, and a receiver bandwidth of 10 Mc/s is assumed.
[b] At mean conjunction or opposition.
[c] Estimated temperature for purposes of comparison.

This is simply another way of stating that with the antenna beam widths that are now in common use one does not have sufficient angular resolution to resolve the planet and to directly measure the distribution of the radio brightness temperature over the planetary disk. In an observational sense, this limitation can be circumvented by three radically different methods: (a) Use of variable-baseline interferometers to determine the Fourier angular spatial-frequency components of the brightness distribution; (b) observation of the diffraction pattern resulting from a lunar occultation of the planet (also to determine the Fourier components of the brightness distribution); and (c) measurement of planetary emission from spacecraft passing close to, or orbiting, the planet. All three methods have been employed in recent years; it is certain that use of these techniques will increase in the future. Variable-baseline interferometric techniques have been applied with great success to Jupiter [Radhakrishnan and Roberts, 1961; Morris and Berge, 1962] and to Venus [Clark and Kuzmin, 1965]; a lunar occultation of Jupiter has been observed at 74-cm wavelength with the Australian 210-ft radio telescope [Kerr, 1962]; and microwave emission of Venus has been measured with high planetary resolution during the fly-by mission of Mariner 2 [Barath et al., 1964].

2. Mercury

Mercury is the smallest of the planets, having a radius of 2420 km, and a mean distance from the sun of 0.387 A.U. It has been generally believed from visual observations that Mercury's sideral rotation period is 88 days, the same as its sideral period of revolution about the Sun; hence it is in synchronous rotation and always keeps the same side toward the Sun. Infrared radiometric observations have led to a determination of the subsolar point temperature of approximately 610 °K, but no measurement of the temperature of the dark hemisphere is available [Pettit, 1961]. It has been generally assumed that Mercury has a very tenuous atmosphere—possibly no atmosphere—and that the temperature of the dark portions of the planet is near 0 °K. Recent observations, however, including radio observations, suggest that these assumptions and values may be in error as we shall show.

Measurement of Mercury's radio emission is difficult for two well-known reasons: (a) The planet is of small angular size, subtending approximately 11 sec of arc at mean conjunction; and (b) the planet's angular distance from the Sun is never more than 28°. The first implies that the radio emission, as measured on the Earth, is very weak, as can be seen from table 1. Actually, table 1 is misleading because of the second difficulty. The values in table 1 were computed for Mercury at conjunction, when the radio energy received on Earth is maximum and when Mercury is at its minimum angular separation from the Sun. Reception of solar radio emission in the wide-angle lobes of the antenna pattern can exceed the radio emission from Mercury, particularly when the planet is separated from the Sun by a small angle, thereby making detection of Mercury a difficult observational problem.

Radio emission was first detected from Mercury, in 1960, at 3.45-cm and 3.75-cm wavelengths by Howard, Barrett, and Haddock [1962], as shown in figure 1. The observations were not of sufficient precision to reveal a dependence of the mean radio brightness temperature on the phase of Mercury, if such a dependence exists, but merely gave an average brightness temperature of 400 ± 80 °K for phase angles near 90°. To compare this value with planetary temperatures determined from the infrared measurements, it is necessary to assume a temperature distribution over the planetary surface. If Mercury has no atmosphere and is in synchronous rotation about the Sun, then a reasonable assumption is that the surface isotherms on the illuminated hemisphere will be concentric circles about the subsolar point. Because practically nothing is known about the temperature on the unlit hemisphere, it is usually assumed that it is at constant temperature, T_D. These statements may be put on a quantitative basis by writing the brightness temperature distribution as

$$\begin{aligned} T(\theta) &= T_D + (T_{ss} - T_D)\cos^n\theta \qquad && 0 \leq \theta \leq 90^\circ \\ T(\theta) &= T_D && 90 \leq \theta \leq 180^\circ, \end{aligned} \tag{5}$$

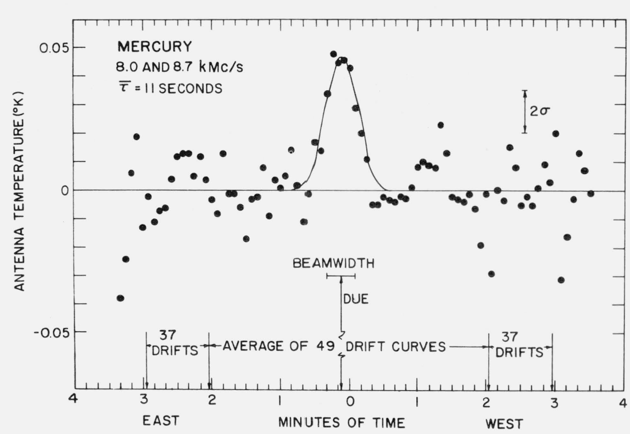

FIGURE 1. *The first radio detection of Mercury.*
Note that it was necessary to average many curves before the Mercury signal was apparent [Howard, Barrett, and Haddock, 1962].

where θ is the polar angle of a point on the surface measured from the planet-Sun axis, and T_{ss} is the temperature of the subsolar point at the depth of origin of the radio emission. The exponent n is unknown but elementary physical considerations for a smooth, nonrotating sphere with no atmosphere would require $n=1/4$. Howard, Barrett, and Haddock [1962] considered $n=0$, 1/4, and 1 with $T_D=0$ °K in the analysis of their results. It must be emphasized that (5) is taken to be the distribution of the radio brightness temperature, although its functional dependence was assumed from considerations of the surface temperature distribution. It can be expected that the brightness temperature will differ from the surface temperature because of the effects of emissivity and escape of the radio energy from below the surface. The coefficients of (5) will, therefore, depend on the physical parameters of the surface and subsurface material, but the functional dependence on θ can be expected to follow closely that of the surface temperature.

The mean value of the radio brightness temperature, $\overline{T}_B$, is found by integrating (5) over the hemispherical surface of the planet that is visible from Earth,

$$\overline{T}_B=\frac{1}{\pi R_M^2}\int T(\theta, \phi) \cos \alpha \, dA, \tag{6}$$

where R_M is the radius of Mercury and α is the angle between the normal to dA and Earth. As written, (6) appears to be independent of the phase angle of the planet, but the limits of the integral will involve the phase angle. Since the temperature distribution assumed in (5) is independent of ϕ, $T(\theta, \phi)=T(\theta)$, and substitution of (5) in (6) gives

$$\overline{T}_B=T_D+\frac{1}{\pi R_M^2}\int_{\text{S.H.}} (T_{ss}-T_D) \cos^n \theta \cos \alpha \, dA, \tag{7}$$

where the integration is now restricted to that portion of the sunlit hemisphere which is visible from Earth and, therefore, the limits of the integral are functions of phase angle. If we adopt the notation of Howard, Barrett, and Haddock [1962], (7) can be written

$$\overline{T}_B=T_D+(T_{ss}-T_D)\, Y(n, i) \tag{8}$$

$$Y(n, i)=\frac{1}{\pi R_M^2}\int_{\text{S.H.}} \cos^n \theta \cos \alpha \, dA. \tag{9}$$

For $n=1$ it is possible to carry out the integration of (9) in closed form to get

$$\overline{T}_B=T_D+\frac{2}{3\pi}(T_{ss}-T_D)\,\{\sin i+(\pi-i) \cos i\}, \tag{10}$$

where i is the phase angle, i.e., the planetocentric angle between the Sun and Earth and restricted to values between 0 and π. Figure 2 shows $Y(n, i)$ as a function of phase angle for $n=0$, 1/4, and 1.

Equations (8) and (9) and figure 2 predict that a large phase effect should be observed in the radio observations if the dark-side temperature of Mercury T_D is low but, as has been pointed out previously, the initial observations by Howard, Barrett, and Haddock [1962] were not of sufficient precision to reveal a phase variation. When interpreted in terms of (8), (9), and figure 2 with $n=1/4$ and $T_D=0$ °K, the results indicated a subsolar brightness temperature of 1100 $\pm$300 °K, which is considerably in excess of the subsolar surface temperature of 610 °K as determined from infrared observations [Pettit, 1961]. The disagreement worsens if allowance is made for the surface emissivity to differ from unity. If a subsolar temperature of 610 °K is adopted, then the observations imply a brightness temperature of approximately 270 °K for the unilluminated hemisphere. Thus the first observations, in spite of their low precision, were suggestive of a temperature of several hundred degrees for the unilluminated surface of Mercury.

Mercury was observed on 10 days in May and June 1964, by Kellermann [1965] at 11.3-cm wavelength, using the Australian 210-ft radio telescope. The observations covered a range of phase angles from 29° to 145° but failed to show any change of the brightness temperature as a function of phase, within the limits of precision of the observations. Furthermore, the results showed that the mean brightness temperature at 11.3 cm was in good agreement with the results of Howard, Barrett, and Haddock at 3.45-cm and 3.75-cm wavelengths. Table 2 shows Kellermann's results. Note that the mean brightness temperature for a phase angle of 29° is only 220 $\pm$160 °K, even though at this angle 94 percent of the planetary disk was illuminated.

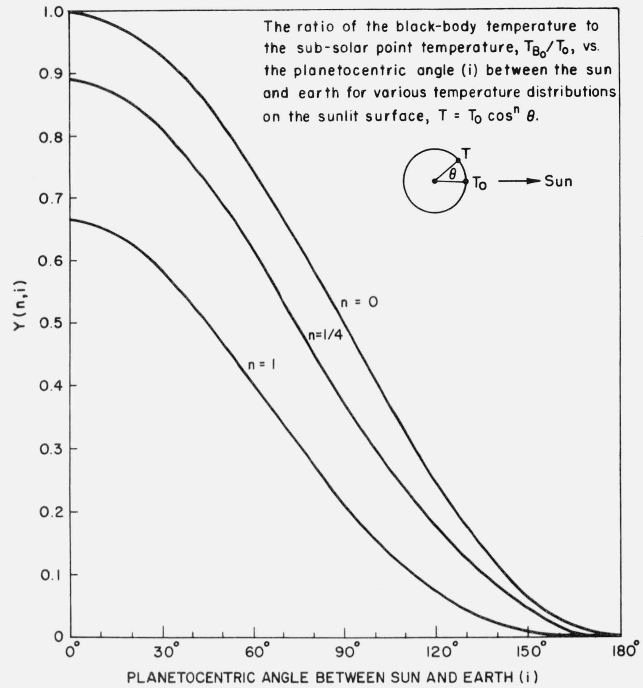

FIGURE 2. *The integral of (9) as a function of phase angle for* n=0, *1/4, and 1 [Howard, Barrett, and Haddock, 1962].*

TABLE 2. *Mean brightness temperature of Mercury at 11.3-cm wavelength as a function of planetary phase angle [Kellermann, 1965]*

Date	Phase angle, i	Mean brightness temperature, $\overline{T}_B$
	Degree	*°K*
May 8, 1964	145	290±30
9	142	320±40
10	140	220±70
11	137	320±70
27	98	330±80
28	96	275±80
June 2	84	300±90
6	74	250±100
18	38	410±150
20	29	220±160

A measurement of Mercury emission at 1.53-cm wavelength has been reported by Welch and Thornton [1965]. These workers report the mean brightness temperature to be 465±115 °K as determined by measuring the ratio of Mercury emission to Jupiter emission and assuming a temperature of 155 °K for the brightness temperature of Jupiter at 1.53 cm. The assumed Jupiter temperature is consistent with the value 144±23 °K, measured at 0.835 cm [Thornton and Welch, 1963]. The average illumination of the disk of Mercury during the 1.53-cm observations was 0.25. Welch and Thornton assume a subsolar temperature of 620 °K, $n=1/2$ in (9) and compute that the mean brightness temperature from the illuminated disk would be approximately 100 °K if the dark side temperature is 0 °K. Since the observed value is 465 °K, this result implies a substantial contribution from the unilluminated hemisphere of Mercury. If (9) is used to compute the brightness temperature of the dark hemisphere, under the assumption of a subsolar temperature of 620 °K, $n=1/2$, and $\overline{T}_B=465$ °K, the result is approximately 440 °K, again demonstrating that a large microwave brightness temperature appears to be required to match the observations.

The existence of an appreciable temperature for the unilluminated hemisphere was only suggested by the first observations, but is also indicated by the 11.3-cm and 1.53-cm observations. A temperature of ~300 °K would satisfy all of the radio observations on the basis of the simple model represented by (5), but, as more refined observations become available, a more complete model that includes thermal damping and microwave attenuation in the planetary subsurface will be required. Of particular interest will be the sign of the temperature gradient in the subsurface material, as determined by frequency dependence of the brightness temperature of the dark hemisphere. If the temperature gradient with depth is negative, an external source of heating is indicated; however, if the gradient is positive, an internal source of heating, such as radioactivity, would be required. External heating, such as solar heating, would have to be coupled with a means of transporting the heat to the unilluminated hemisphere. Possible mechanisums include a tenuous atmosphere and/or a nonsynchronous rotation for Mercury. The implications of an atmosphere on the value of the dark-side temperature were considered briefly by Field [1962]; the problem of internal heating caused by radioactivity was considered by Walker [1961]. Walker's conclusion was that for radioactive heating similar to that in chondritic meteorites the temperature of the unilluminated hemisphere would be only 29 °K, far short of the requirements for the radio measurements.

Two effects related to the motion of the planet have been neglected in the discussion above. Both will have to be considered as more accurate radio measurements are made. These effects are the varying distance between Mercury and the Sun, and the libration of Mercury. The first can amount to ±20 percent in distance, an effect that will perhaps be reduced as $r^{1/2}$ when translated to temperature at the surface of the planet [Pettit, 1961], and the second will provide a source of heating, averaged over 88 days, for a portion of the unilluminated hemisphere. Present observations are insensitive to these effects, but they may become discernible in future observations.

3. Venus

Venus is second only to Jupiter in the number of studies of it made at radio wavelengths. This is due, of course, to the unexpected intensity of the Venusian radiation plus the increased interest in the nearby planets as a result of the implications of contemporary space technology. A review of the radio observations of Venus, made before 1964, and the interpretations thereof, has recently been published by Barrett and Staelin [1964]; therefore, the present review will concentrate on subsequent observations.

The spectrum of radio emission from Venus is well established as a result of many measurements at 0.4-, 0.8-, 3-, and 10-cm wavelengths. The spectrum shows emission that is characteristic of brightness temperatures of approximately 600 °K between 3 cm and 10 cm, and 350 to 400 °K between 0.4 cm and 0.8 cm, as shown in figure 3. This spectrum has led to consideration of many different physical mechanisms of emission and absorption, but two have been most widely discussed. In one model it is assumed that

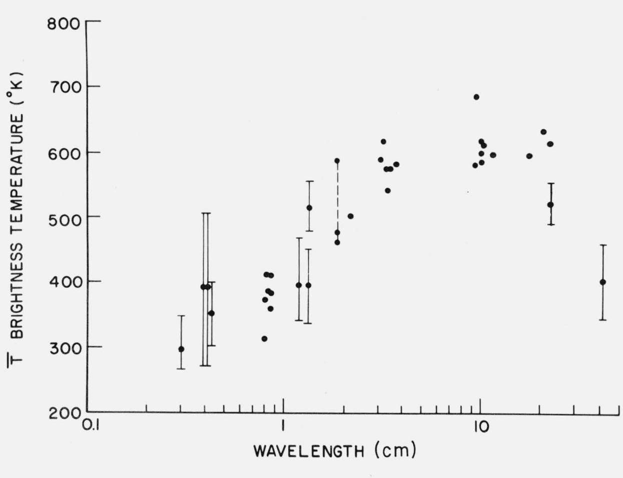

FIGURE 3. *The microwave spectrum of Venus.*
Error bars are omitted where the points cluster closely together, but those shown are generally typical.

the centimeter radiation is a measure of the true surface temperature and that the lower temperature observed at millimeter wavelengths arises from atmospheric absorption [Barrett, 1960, 1961]. In the second model it is assumed that the planet has an ionosphere which is the origin of the centimeter radiation and that the millimeter radiation originates on the surface and passes relatively unattenuated through the ionosphere [Jones, 1961]. Both models were conceived to explain the spectrum, which gave the only available experimental information at the time, and both were successful. With the advent of observations as a function of planetary phase, radar measurements, observations from the Mariner 2 spacecraft, and variable-baseline interferometric measurements, however, the constraints imposed upon the ionospheric model have become severe and it is generally regarded as inadequate at the present time.

It has long been realized that lunar and planetary radio emission will be polarized, provided the surface may be characterized as a smooth dielectric [Troitsky, 1954], and it has been noted that this fact can be exploited to provide information about the surface [Heiles and Drake, 1963; Soboleva and Pariiskii, 1964; Pollack and Sagan, 1965] or to distinguish among various atmospheric models and/or absorption mechanisms [Barrett and Staelin, 1964]. The integrated polarization, averaged over the planetary disk, is very small, however, and has not yet been detected. But, by variable-baseline interferometry, the resolution has been improved and planetary polarization can be detected [Heiles and Drake, 1963; Clark and Kuzmin, 1965]. The one series of observations made with sufficient sensitivity and resolution to detect this effect has been important in discriminating among various planetary models.

An important series of observations has recently been concluded by Clark and Kuzmin [1965], using the California Institute of Technology variable-baseline interferometer at 10.6-cm wavelength. The observations were carried out for baseline spacings up to 6500 λ, and proved to be slightly polarization-dependent, the polarization averaged over the planetary disk being 0.8 ± 0.5 percent. Clark and Kuzmin conclude that the 10.6-cm radiation originates in a compact medium, presumably the surface of Venus, and that the dielectric constant of the medium is 2.2 ± 0.2. The observations also imply that there is a brightness temperature asymmetry amounting to 25 percent at the limbs for orthogonal directions; Clark and Kuzmin attribute the lower temperature to the poles. The actual surface temperatures derived from the observations depend upon the assumed distribution of temperature on the surface of the planet. Clark and Kuzmin consider several models of which the following actual surface temperatures, as opposed to radio brightness temperatures, may be considered typical: 630 °K for the center of the unilluminated disk,[2] 690 °K for the equatorial terminator, and 440 °K for the polar regions. The observations also indicate that the radius of the radio-emitting region may be slightly smaller than the optical disk, as would be expected for a source exhibiting limb darkening at radio wavelengths. The ratio of the radius of the optical disk to the radius of the radio-emitting region is 1.007 ± 0.009, so the difference from unity is not statistically significant. Also, it must be borne in mind that the radius of the optical disk actually refers to the top of the cloud layer, which is estimated to be at a height above the surface of approximately one percent of the planetary radius.

Whereas most of the early measurements of Venus were made at wavelengths near 0.8 cm, 3 cm, and 10 cm, in recent years observations have been made at millimeter wavelengths, at wavelengths near 1 cm, and at wavelengths longer than 10 cm. Measurements now published and not included in an earlier review [Barrett and Staelin, 1964] include a brightness temperature of 534 ± 60 °K at 1.6-cm wavelength [Vetukhnovskaya et al., 1963] and measurements at 0.86-cm, 0.43-cm, and 0.32-cm wavelengths by Tolbert and Straiton [1964a]. Tolbert and Straiton, however, do not report their deduced brightness temperatures in the published paper. The values are given in an unpublished report [Tolbert and Straiton, 1964b] as 375 ± 53 °K at 0.86-cm wavelength, 330, $+56$, -36 °K at 0.43-cm wavelength, and 300, $+57$, -27 °K at 0.32-cm wavelength.

Previous observations had clearly indicated that the wavelength region near 1 cm was the transition region from brightness temperatures near 600 °K at longer wavelengths to brightness temperatures of 350 °K at millimeter wavelengths (fig. 3). During the 1964 inferior conjunction, two series of observations were conducted at several wavelengths between 1.653 cm and 0.835 cm in an effort to better define the spectrum in the transition region. Welch and Thornton [1965] observed Venus at wavelengths at 1.653, 1.456, 1.350, 1.245, 1.158, 0.971, and 0.835 cm, using a 10-ft radio telescope of the University of California. Staelin and Barrett [1965], using a 28-ft radio telescope at Lincoln Laboratory, Massachusetts Institute of Technology, observed Venus at wavelengths of 1.42, 1.37, 1.28, 1.18, 1.01, and 0.926 cm. A comparison of these observations is given in table 3. A proper intercomparison of the observations should be made with due regard for the different ways in which the data were taken. Welch and Thornton used one radiometer that was tuned to the wavelengths indicated, and Venus was observed on the dates shown in table 3. Staelin and Barrett, on the other hand, observed with a five-channel system having a common antenna-feed line, five frequency-selective filters, and five separate radiometers. Thus each observation, in reality, consisted of five simultaneous observations of Venus at five closely spaced frequencies. This system was used for the observations at 1.37, 1.28, 1.18, 1.01, and 0.926 cm. The measurement at 1.42-cm wavelength was performed with a single-channel system and is of low precision because it was near the cutoff wavelength of the antenna-feed line and represents a limited amount of data.

[2] Clark and Kuzmin give this temperature for the "center of the disk" without defining to which disk they refer. In the abstract, however, they refer to this temperature as the "antisolar point temperature," so presumably the disk is the unilluminated disk.

TABLE 3. *Comparison of 1964 observations of Venus near 1-cm wavelength by Welch and Thornton [1965] and by Staelin and Barrett [1965]*

Wavelength	Frequency	Brightness temperature	Date	Observer
cm	*Gc/s*	°*K*		
1.653	18.15	560±51	July 24	W, T
1.456	20.60	595±50	July 25	W, T
1.42	21.1	502±80	July 15, 17, 18	S, B
1.37	21.9	404±28	.........([a])..........	S, B
1.350	22.22	530±45	July 26, 31	W, T
1.28	23.5	450±23	.........([a])..........	S, B
1.245	24.10	451±53	July 27	W, T
1.18	25.5	428±20	.........([a])..........	S, B
1.158	25.92	495±50	July 30	W, T
1.01	29.5	463±32	.........([a])..........	S, B
0.971	30.9	412±55	July 19	W, T
0.926	32.4	430±24	.........([a])..........	S, B
0.835	35.9	390±45	July 20	W, T

[a] Observations made on 13 days between June 5 and July 30.

The entries of table 3 are not plotted in figure 3, because of the compact wavelength scale and the close spacing of the points. Figure 4 shows the entries of table 3 on an expanded scale. Only data of 1964 are shown. Several features are immedately apparent. A point-by-point comparison of the two sets of observations, without regard to the date of observation, shows that sharp spectral features exist in the spectrum of Venus at these wavelengths, or that the observations are in disagreement. Either set of measurements, taken by itself, represents an advance in the frequency resolution with which the Venusian spectrum has been examined. Furthermore, spectral lines arising from molecular resonances are common features of the microwave properties of atmospheric constituents [Barrett, 1962]; therefore, the existence of sharp spectral features cannot be ruled out by physical arguments about the mechanism of emission and absorption. The data of Welch and Thornton, considered by itself and taken at face value, represent smoothly varying function of frequency, while the data of Staelin and Barrett, under similar conditions, can, at best, be taken as independent of frequency between 21.1 Gc/s and 32.4 Gc/s, with steep transitions at each end to match the other observations. This, of course, does not seem likely.

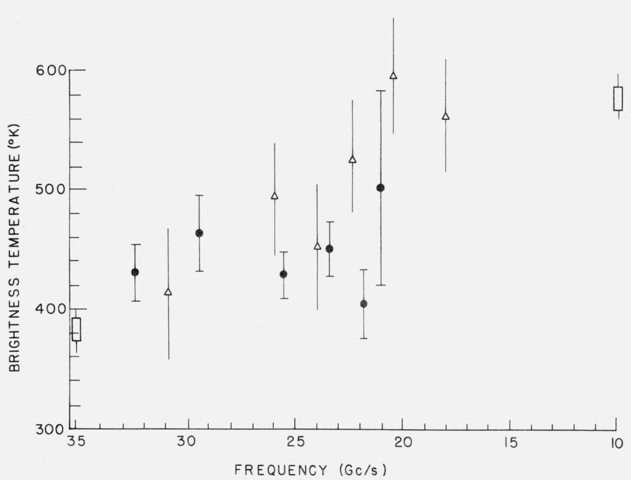

FIGURE 4. *The Venus measurements of Welch and Thornton* [1965] *(triangles) and Staelin and Barrett* [1965] *(dots), as shown in table 3.*
The rectangles at 10 Gc/sec and 35 Gc/sec represent the many previous measurements at these frequencies.

Another interpretation of the data is possible. Note that the worst disagreement between the two sets of data is for frequencies less than 25 Gc/s, and that Welch and Thornton took their data only on single days, late in July. An examination of Staelin and Barrett's data for the same, or neighboring, days shows that brightness temperatures for frequencies less than 25 Gc/s were higher than the average of all other days. In other words, if comparison of the two sets of observations is made only for the interval of time when there are common observations, the disagreement between the two sets of data largely disappears. This suggests that the spectrum of Venus near 1-cm wavelength may be a function of time [Staelin and Barrett, 1965]. This conclusion, if valid, will be extremely important in terms of physical processes in the Venusian atmosphere; however, many more measurements, extending over long periods of time, will be required to definitely establish this effect.

An obvious reason for interest in the spectrum of Venus at wavelengths near 1 cm is the existence of the rotational resonance line of water vapor at 1.35 cm. Calculations have shown that the presence of water may be detectable from detailed measurements of the radio spectrum [Barrett, 1961; Barrett and Staelin, 1964]. A previous measurement of the brightness temperature at 1.35-cm wavelength by Gibson and Corbett [1963] gave a value of 520±40 °K, thereby indicating no appreciable effect of water vapor on the Venusian radio spectrum. Welch and Thornton's measurement at 1.35 cm is in agreement with this value. The observations of Staelin and Barrett suggest that resonant absorbers, of which water vapor is only one possibility, may be important in establishing the spectrum. If the spectrum is time-variant, for example, as would be the case if the illuminated and unilluminated hemisphere had different spectra, then the question will be very difficult to resolve. The best solution will come, undoubtedly, from multifrequency, simultaneous observations of the type performed by Staelin and Barrett, or from high-sensitivity frequency-scanning radiometers.

4. Mars

Mars has been the subject of more study than any other planet in the solar system, undoubtedly because the surface is visible and its distance from Earth is such that moderate detail can be observed in the changing patterns of its surface. But, until recently, the radio observations of Mars have been performed only at wavelengths near 3 cm. During the favorable opposition of September 1956, Mars was observed on 7 days between September 9 and 21 by Mayer, McCullough, and Sloanaker [1958b, c], using the U.S. Naval Research Laboratory 50-ft antenna, operating at 3.15-

cm wavelength. The average brightness temperature deduced from the observations was 218±76 °K. Mars was again observed there at 3.14-cm wavelength by Giordmaine, Alsop, Mayer, and Townes [1959] 6 weeks after the November, 1958, opposition. The mean brightness temperature was 211±20 °K, in excellent agreement with the 1956 observations.

The temperature of the center of the Martian disk in the 8–13 μ infrared "window" has been determined to be 288 °K by Sinton and Strong [1960], and a diurnal temperature variation of approximately 100 °K was detected. In view of these results, it can be said that the 3-cm radio observations are in good agreement with the values to be expected from the infrared results. The radio brightness temperatures will be less than the planetary surface temperatures, as determined by the infrared, for three reasons: (a) The infrared temperature of 288 °K refers to the center of the disk, whereas the 3-cm observations represent an average over the disk and, therefore, will include appreciable fractions of the surface with temperatures less than 288 °K; (b) the microwave emissivity of Mars will be less than unity, thereby lowering the brightness temperature; and (c) the microwave emission may be expected to originate in the subsurface material of Mars where the temperature may be less than that of the surface. A suitable theory that allows for these effects has not been developed specifically for Mars; in fact, at the present time, it is not warranted in view of the limited number of radio observations and the lack of any major disagreement with accepted ideas about the planet.

A very unusual series of observations of Mars at 21.3-cm wavelength has been reported by Davies [1964], using the 250-ft antenna of Jodrell Bank. The mean brightness temperature was reported to be 1150±50 °K, far in excess of any thermal temperature that can be expected from the surface or subsurface of the planet. This result is reminiscent of the well-known nonthermal radiation from Jupiter, which is usually attributed to Jovian radiation belts similar to the terrestrial Van Allen belts. It seems likely, however, that Mars was probably observed at decimeter wavelengths with negative results following the scientific excitement created by the Jupiter decimeter observations; but these negative results, if they exist, have not been published. Nevertheless, it seems premature to speculate about the origin of the strong Martian decimeter radiation until it has been confirmed by further observations.

5. Saturn

As might be expected from the values given in table 1, Saturn is well within the range of detectability of present radio-astronomy techniques and has been observed at a number of centimeter wavelengths. A measurement of Saturn was reported by Drake and Ewen [1958] at 3.75-cm wavelength, but no brightness temperature was deduced and the detection is open to question. In 1960, a series of observations was conducted by Cook et al. [1960], using a maser pre-amplifier and the 85-ft antenna of the University of Michigan; and Saturn was easily seen on each drift scan across Saturn, as shown in figure 5. The mean brightness temperature was determined to be 106 ±21 °K, in good agreement with the infrared radiometric temperature at the cloud-top level. This result suggests a thermal origin for the 3.75-cm radiation, a conclusion that appears to be valid for all of the planets at short centimeter wavelengths.

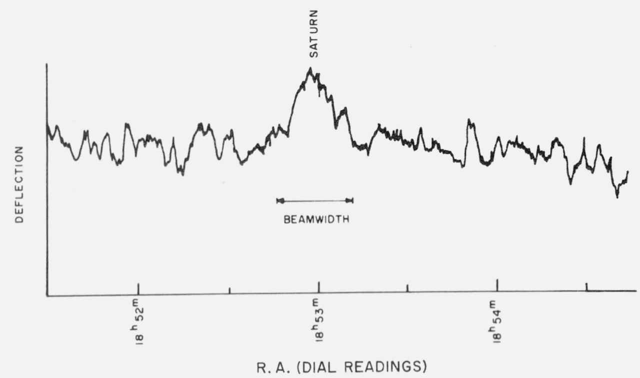

FIGURE 5. *A drift scan of Saturn made with a maser radiometer and the University of Michigan 85-ft radio telescope* [*Cook et al., 1960*].

Three series of observations have been conducted at wavelengths of approximately 10 cm which give results slightly different from the 3.75-cm results. Drake [1962] measured Saturn emission at 10-cm wavelength, using the 85-ft antenna at the National Radio Astronomy Observatory, and determined a brightness temperature of 196 ±44 °K, almost double the 3.75-cm value. This result was suggestive of nonthermal radiation, but could also be explained by thermal processes simply by assuming that the 10-cm radiation was originating from a deeper layer in the atmosphere than the 3.75-cm radiation and that the atmospheric temperature was somewhat hotter at the level of origin. A surprising series of observations was reported by Rose, Bologna, and Sloanaker [1963], using an 84-ft radio telescope at the U.S. Naval Research Laboratory at 9.4-cm wavelength. The mean brightness temperature was 177 °K, in good agreement with Drake's value; however, the 9.4-cm radiation was found to be strongly polarized. If it is assumed that the 3.75-cm results are strictly thermal emission, to evaluate the nonthermal contribution to the observed 177 °K, the thermal component, or 106 °K, should be subtracted from the 9.4-cm result. It then follows from the observations that the nonthermal component of the 9.4-cm radiation is 51 ±22 percent polarized. Furthermore, the observations showed that the electric vector of the emission is parallel to the axis of rotation, whereas the Jupiter decimeter emission shows the electric vector to be parallel to the equator. These observations would imply that the magnetic axis of Saturn is nearly perpendicular to the axis of rotation if the analogy with Jupiter emission is made. It now appears that the observations were in error, the polarization of Saturn's radiation is time-variant,

786-228 O-66-5

or the polarization is an extreme function of frequency. This conclusion is based on measurements recently reported by Davies, Beard, and Cooper [1964]. These workers observed Saturn with the Australian 210-ft radio telescope at 11.3-cm wavelength. The mean brightness temperature was determined to be 182 ± 18 °K, in excellent agreement with both the 10-cm and 9.4-cm observations, but no polarization was detected within an upper limit of 6 percent. The agreement between observations near 10-cm wavelength furnishes an argument against the polarization being strongly frequency-dependent; further measurements are clearly needed to resolve the apparent discrepancy, especially at longer wavelengths.

A recent measurement of Saturn emission at 1.53-cm wavelength has been reported by Welch and Thornton [1965]. As in their Mercury measurements, the ratio of Saturn to Jupiter brightness temperatures was determined to be 0.94 ± 0.15. If the brightness temperature of Jupiter is taken to be 155 °K, this result leads to a value of 146 ± 23 °K for Saturn's brightness temperature at 1.53-cm wavelength. This result is higher than the 3.75-cm temperature, which, if verified by further measurements at both wavelengths, may be attributed to absorption by ammonia in the atmosphere of Saturn.

Note that in all determinations of the mean brightness temperature it has been assumed that the size of the radio-emitting region is equal to the optical disk of Saturn. This assumption implies that the rings of Saturn are not responsible for the emission. This assumption could be checked by observations of high accuracy extending over a long period of time, but the measurements would be quite difficult unless a large portion of the emission originated in the rings.

Finally, mention should be made of attempts to observe decameter burst-like radiation from Saturn, again, analogously with Jupiter. The confidence level of such observations is necessarily low unless Saturn is a strong and frequent emitter at decameter wavelengths, because of the possible confusion with emission of terrestrial origin. At this time, several possible events were noted which could be associated with Saturn, but the observers have not yet claimed a reliable detection at decameter wavelengths. A recent paper on this subject is that of Smith et al., [1965].

6. Uranus

Table 1 shows that detection of radio emission from the remote planets: Uranus, Neptune, and Pluto is a very difficult task. An attempt to detect Uranus at 11.3-cm wavelength has recently been reported by Slee [1964], using the Australian 210-ft radio telescope. Although Uranus was not detected, it appears that a weak radio source was detected near the position of Uranus on February 24, 1964. The presence of the source was checked by making observations on May 2, 1964, when Uranus was in a new position. Observations on May 3, 1964, failed to show any evidence of emission from the planet. The upper limit set by these observations on the mean brightness temperature at 11.3-cm wavelength is 320 °K. The infrared temperature of Uranus is approximately 100 °K; thus the 11.3-cm observations indicate an upper limit to the nonthermal radiation emitted by Uranus.

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Discussion Following Barrett's Paper

D. O. Muhleman: Have the data points in the planetary spectra you presented been corrected to the same phase angle?

Alan H. Barrett: No.

D. O. Muhleman: Wouldn't such a correction decrease the scatter in the points?

Alan H. Barrett: Other uncertainties in the data are certainly larger than the displacements in the points caused by phase effect.

J. A. Roberts: Is the radar rotation period of Mercury sufficiently great to explain the high temperature observed on the dark side of the planet?

Alan H. Barrett: I have not made these calculations.

F. D. Drake: If the surface of Mercury is like that of the Moon, then despite the somewhat greater rotation period we would expect the radio emission behavior to be very much like that of the Moon. As is well known, at the wavelengths at which Mercury has been observed, the dark side of the Moon is nearly as bright as the bright side, and so we would expect the same behavior of Mercury.

J. H. Thomson: R. D. Davies has now determined that the apparently very high brightness temperatures of Mars at 21-cm wavelength observed at Jodrell Bank in 1963 were seriously affected by a confusing cosmic radio source, with the result that the Martian brightness temperature appeared very much higher than it actually was. After correction for this confusing source, the equivalent blackbody disk temperature for Mars at the 21-cm wavelength in 1963 was 320 ±95 °K. Similar measurements during the 1965 opposition produced an equivalent blackbody disk temperature of 225 °K.

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Mars and Venus at 70-cm Wavelength

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Observations of Venus and Mars at a frequency of 430 Mc/s have been made with the Arecibo telescope. An observing technique was used in which the source was observed, and some days later, when the planet had left its previous position, the position was reobserved to determine the flux produced by the background radio sources. The equivalent blackbody temperature measured for Venus at 430 Mc/s was 518±40 °K. The upper limit on its flux density at 1 A.U. was 0.05 $\times 10^{-26}$ MKS units at 195 Mc/s. The upper limit at 430 Mc/s was 0.024×10^{-26} MKS units.

(Paper 69D12–594)