RESULTS OF RADIO OBSERVATIONS OF MERCURY, VENUS, AND MARS

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RADIO and radar astronomy have made possible new kinds of planetary investigations and have led to a number of fundamentally new data regarding the planets. The present paper gives a brief survey of the results of radio observations of the planets, and an account of the present state of the problem of determining their physical conditions from radio data. Since the subject is so broad, the discussion is limited to planets in the terrestrial group: Mercury, Venus, and Mars.

1. MERCURY

Mercury is the planet nearest to the sun.

On the basis of optical observations, it has been assumed that the rotation of this planet is synchronous; in other words, that the period of its rotation about its axis is the same as that of its revolution around the sun, so that it always keeps the same face toward the sun. Mercury's mass is small, and consequently its atmosphere is extremely tenuous (several hundred times less dense than that of the Earth). Measurements of the infrared self-radiation of Mercury, carried out by Pettit and Nicholson[88] during 1923-1925 over phase angles ranging from 30° to 125°, showed that the intensity of this radiation depends on the phase of the solar illumination; this is true also in the case of the Moon. Assuming that the brightness distribution from the center to the limb of the planet is specified by $\cos^{2/3}\theta$, where θ is the angular distance from the subsolar point, they found that the temperature is 613°K at the subsolar point. This agrees well with the calculated equilibrium temperature for the subsolar point on a synchronously rotating planet.

The first radio astronomical measurements of Mercury were made in 1961 by Howard, Barrett, and Haddock[64] at wavelengths of 3.45 and 3.75 cm and at phase angles ranging from 106° to 58°. The weighted mean value of the brightness temperature, averaged over the apparent disk of the planet, was found to be 430°K. In view of the small range of phase angles represented by these observations and the low accuracy of measurement, it was not possible to look for a phase dependence in the brightness temperature of Mercury.

The first measurements of the dependence of Mercury's brightness temperature on the phase of the solar illumination were carried out in 1964 by Kutuza, Losovskiĭ, and Salomonovich[22] at 8 mm wavelength and by Kellermann[68] at 11 cm. The measurements by Kutuza et al. show that, at 8 mm, there is a dependence of the average disk brightness temperature $\bar{T}_{B☿}$ on the phase angle Φ. Calculations of the brightness temperature T_0 at the subsolar point, assuming that the distribution of temperature over the planetary surface is of the form $T_B = T_0 \cos^n\theta$ for the illuminated hemisphere, with $T_B = 0$ in the dark hemisphere, give $T_0 = 660 \pm 120$°K for $n = 1/4$ and $T_0 = 540 \pm 85$°K for $n = 0$. Within the limits of the errors, this agrees with the infrared measurements by Pettit and Nicholson.

These data do not agree, however, with measurements by Epstein[47] in 1965. These also were made in the millimeter wavelength range (3.2 mm) over a full cycle of phase angles. They show no dependence of the average disk brightness temperature on the phase of the solar illumination. A second difference in Epstein's results is the unexpectedly low value of $\bar{T}_{B☿}$, which he found to be only about 200°K. This is appreciably lower than the constant term in the lunar brightness temperature (adjusted to the distance of Mercury from the sun) or the calculated equilibrium temperature.

The anomalously low brightness temperature found by Epstein might be explained by a low radiance of the surface of Mercury in the 3-mm wavelength range. Such an interpretation, however, would not remove the disagreement between Epstein and Kutuza et al. regarding the phase angle dependence $\bar{T}_{B☿}(\Phi)$. A model with a "cold" absorbing atmosphere of the kind suggested for Venus might possibly remove both contradictions if an appropriate choice were made for its parameters.

Further observations by Epstein[50] in April 1966 show, however, that the brightness temperature of Mercury at 3.4 mm wavelength increases from 150°K at phase angle $\Phi = 130°$ to 500°K at $\Phi = 50°$, so there actually is a dependence of $\bar{T}_{B☿}$ on phase at millimeter wavelengths.

Kellermann's phase measurements agree rather well with a temperature distribution of the form $T_B = 250 + 260 \cos^{1/4}\theta$ for the illuminated hemisphere and $T_B = 250$°K for the dark hemisphere. A uniformly bright surface with $T_B = 300$°K would also satisfy the experimental data. Read[92], who made measurements of the radio emission of Mercury at the closely adjacent wavelength of 10.6 cm in 1965, could find no dependence of temperature on phase. He set $\bar{T}_{B☿}$ at

301 ± 25°K, which agrees well with Kellermann for a uniformly bright surface.

Finally, there is a single measurement of the brightness temperature of Mercury at 1.53 cm wavelength, by Welch and Thornton[103]. They found 465 ± 115°K, for $\Phi = 160°$.

The above measurements show that the phase dependence of the brightness temperature of Mercury becomes less with increasing wavelength. This can be explained if, as in the case of the Moon, the radiation at longer wavelengths comes from deeper layers in the planetary surface, where the temperature does not change quickly with variations in solar heating. Considering the fact that, were the Moon placed in Mercury's orbit, one would expect its temperature to increase by a factor of 1.6, it is clear that a mean value of about 300°K for Mercury is in satisfactory agreement with the constant component of the lunar brightness temperature, which is about 220°K.

The above interpretation of the radio astronomical measurements corresponds to a model for Mercury in which the temperature ranges from 600°K at the subsolar point down to about 150°K on the unilluminated side of the planet, with a uniform temperature near 300°K (independent of the solar illumination) at the penetration depth for 10 cm waves. This differs from earlier ideas in that it does not assume the temperature of the unilluminated side of Mercury to be at absolute zero, an opinion which was based on the assumption of synchronous rotation. It also differs in that it calls for a moderate temperature at shallow depths in the subsurface layers of the planet. However, the radio astronomical data on Mercury now available are not a sufficient basis for drawing more definite conclusions regarding the physical characteristics of the planet. Further observations are necessary, particularly measurements of the phase dependence of the brightness temperature, and these should be made over a wider range of wavelengths.

The first radar observations of Mercury were made in June 1962 by Kotel'nikov and his coworkers[11] at the Radiotechnical and Electronic Institute of the Academy of Sciences of the USSR (IRÉ). The effective reflecting area of the planet at 43 cm wavelength was found to be 0.03 to 0.06 times the geometrical area, which is about the same as for the Moon. Similar results were subsequently obtained by Carpenter and Goldstein[31] at 12.5 cm wavelength at the Jet Propulsion Laboratory (JPL) and by Dyce and Pettengill[46,86] at 70 cm at the Arecibo Ionospheric Observatory (AIO).

The similarity of the reflecting properties of Mercury and the Moon is yet another argument in support of the similarity of their surface characteristics.

The most interesting result of the radar measurements of Mercury is their contradiction of the idea that the planet rotates synchronously. Observations by Dyce and Pettengill[46] made during April and August 1965 at AIO have shown the rotation of Mercury is direct and that it has a period of 59.3 ± 2 days rather than 88 days, as was supposed previously. As a result, Rasool, Gross, and McGovern[91] reviewed the optical observations made between 1924 and 1953 by Antoniadi, Lyot, Dollfus, and Baum. They showed that these were consistent with a number of possible rotation periods. The 88-day period found previously is only one of the possibilities. A period of 58.4 ± 0.5 days is also consistent with the optical data, and it agrees with the radar result.

Finally, Colombo[35] has pointed out that, if Mercury has an ellipsoidal figure, a stable rotational period equal to exactly $\frac{2}{3}$ the orbital period is possible, owing to the eccentricity of the planet's orbit. This is 58.65 days.

2. VENUS

Venus is the planet nearest to the Earth, and it is the brightest object in the sky after the Sun and the Moon. Nevertheless, optical observations have been able to show only that it has an atmosphere which differs from our own in having a large carbon dioxide content and relatively small amounts of oxygen and water vapor. Because of the opacity of the atmosphere, only the upper layers of this aerosol-cloud envelope are accessible to optical observation. The pressure at the level of the cloud layer is estimated to be between 0.1 and 0.3 atmospheres. The temperature at this level is about 240°K on both the illuminated and the unilluminated sides of the planet. Optical observations do not reach the surface, and the nature of the atmosphere below the clouds is still a matter of conjecture.

New ways of studying Venus have become available with the advent of radio and radar astronomy. Since the terrestrial atmosphere and clouds are transparent to radio waves, one can expect similar transparency on the part of the cloud layer of Venus. By studying the self-radiation and reflected radiation of the planet in these transparent "windows," one can obtain information on the temperature and surface properties of Venus, as well as on the portion of the atmosphere below the clouds.

The first measurements of the self-radiation of Venus, made in 1956 by Mayer, McCullough, and Sloanaker[75], revealed that the average brightness temperature over the visible disk is near 600°K. This is more than twice the radiometric temperature measured previously in the infrared. Before interpreting this result, however, it was necessary to clarify the mechanism responsible for the radio emission, and to establish whether or not the atmosphere of the planet is in fact transparent.

It is well known that one of the most important characteristics of a radio-emitting mechanism is the spectrum it yields. Measurements of the radio spectrum of Venus have been made in the USSR, USA, England,

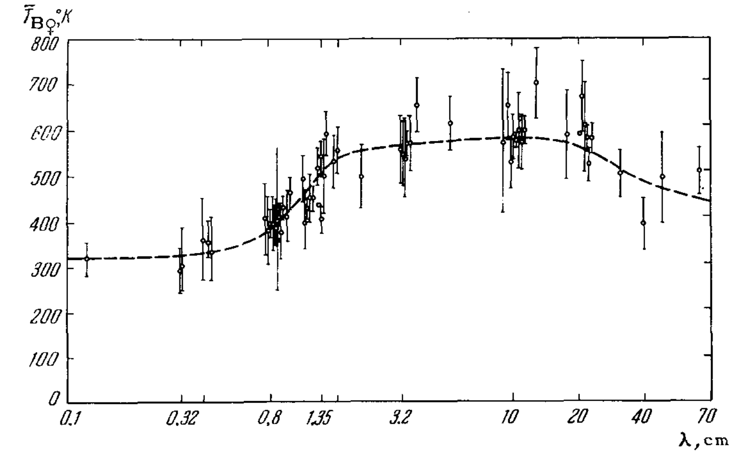

FIG. 1. Average disk brightness temperature spectrum for the unilluminated side of Venus.

and France over a broad band of wavelengths ranging from 1 mm to 70 cm[3,5,8,15,16,20,30,36,37,39,41,42,48,52-55,61,62,68,69,72-74,78,80,96,97,99,101,103]. The results of these measurements are shown in Fig. 1 in the form of average disk brightness temperature $\overline{T}_{B♀}$ as a function of the wavelength λ. The most characteristic features of the radio spectrum of Venus are the approximate constancy of the brightness temperature between 2 and 20 cm wavelength and the considerable decrease at shorter wavelengths. Another interesting but still uncertain detail of the spectrum is the decrease of the brightness temperature at decimeter wavelengths.

Two families of models have been proposed to explain the radio spectrum of Venus: one with a "cold" atmosphere, and one with a "hot" atmosphere.

In the "cold" model, proposed by Kuz'min and Salomonovich[15] and further developed by Barrett[27], Sagan[93], Salomonovich[24], Kuz'min[18], Barrett and Staelin[28], and Basharinov and Kutuza[2], it is supposed that the high radiation temperature of the planet at centimeter wavelengths is due to thermal radiation from a hot ground surface, observed through an atmosphere which is transparent at these wavelengths (Fig. 2). The decrease in brightness temperature at the shorter wavelengths is explained by absorption and reradiation in a cooler atmosphere which is not transparent to millimeter waves.

In the model with a "hot" atmosphere, suggested by Jones[66] and developed by Tolbert and Straiton[100], Scarf[94], Kuz'min[17], Danilov and Yatsenko[6], and Vakhnin and Lebedinskiĭ[4], it is supposed that the atmosphere of Venus contains some kind of electroactive medium which acts as a source of high-temperature radiation at centimeter wavelengths. In the millimeter range, this medium is assumed to be transparent, and the radiation received at the Earth comes from the relatively cool surface of the planet. The contradiction between this model and the radar data for Venus might be resolved by assuming that the radiating medium is semitransparent or that there are "holes" in it.

Analysis has shown that the spectrum is consistent with either kind of model. This is demonstrated by Fig. 3, which shows the spectra we have computed for phenomenological models with "cold" and "hot" atmospheres, along with the measured values of $\overline{T}_{B♀}$.

Therefore, spectral measurements alone do not let one choose between these models, and consequently one cannot determine the physical parameters from such data alone. Supplementary information is needed.

In order to clear up this question, Kellogg and Sagan[7] suggested measuring the distribution of radio brightness over the apparent disk of Venus. It was expected that the model with a "hot" atmosphere would yield a brightness distribution, in the transition part of the spectrum, with the greatest intensity at the edge of the disk owing to the greater optical thickness of the electroactive medium responsible for the high-temper-

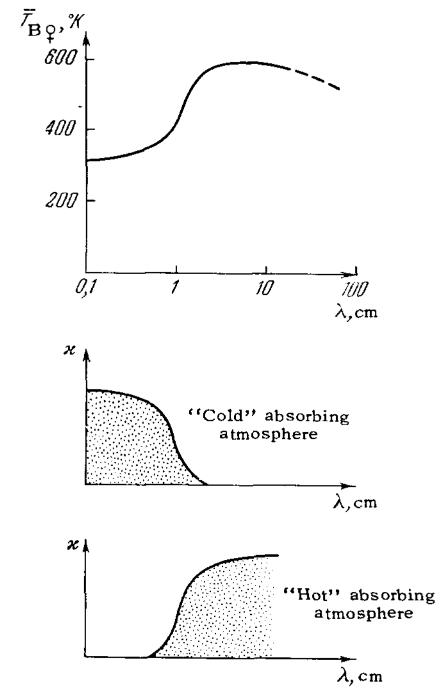

FIG. 2. Schematic representation of the dependence of absorption on wave length for the Venus models with "cold" and "hot" absorbing atmospheres.

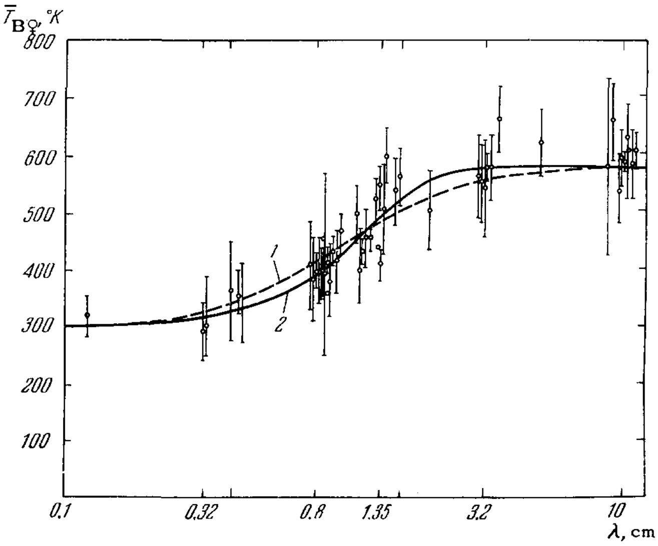

FIG. 3. Computed brightness temperature spectra for Venus: 1—"cold" atmosphere model; 2—"hot" atmosphere model.

ature radiation. On the other hand, the "cold" atmosphere model leads one to expect a darkening toward the edge of the disk because of the increased optical thickness of the absorbing atmosphere (which would be cooler than the surface of the planet).

The measurements have proven to be contradictory, however. Thus the first measurements, made by Korol'kov, Pariĭskiĭ, Timofeeva, and Khaĭkin[9] at a wavelength of 3 cm, and subsequent Mariner 2 observations at 1.9 cm by Barath et al.[26], showed a darkening toward the edge of the disk. But measurements at 1.35 cm, also made from Mariner 2, revealed no darkening, even though the effect should have been much stronger at the shorter wavelength. On the other hand, measurements at the much longer wavelength of 10 cm by Clark and Spencer[34] showed a brightening at the edge. Apart from these contradictions, this experiment does not provide an unambiguous choice between the models. Thus a darkening toward the edge of the planet does not prove that the observed radiation comes from the surface. For example, it might occur if the radiation arises in a dense atmosphere whose temperature drops with increasing height. Radar measurements at a wavelength of 3.6 cm[67,95] show that the reflection coefficient is more than an order of magnitude less than at decimeter wavelengths. This suggests that the atmosphere of Venus may be strongly absorbing at wavelengths of 1.9 to 3 cm, where the limb darkening was found.

An experiment was required which would show unambiguously whether or not the radio emission received from Venus is radiated from its surface. Such an experiment was made by Kuz'min and Clark[20] in 1964 at the Owens Valley Radio Observatory of the California Institute of Technology. The principle of the experiment is this: because of the difference between the Fresnel reflection coefficients for vertical and horizontal polarizations, the radiation from the edges of the apparent disk of the planet should be polarized if it comes from a surface which is sharply distinct from the surrounding medium. On the other hand, if the radiation arises in an ionosphere, a cloud layer, or any other kind of formation lacking a sharp boundary, it will be unpolarized. The high angular resolution required for this experiment was achieved by using a radio interferometer.

The results of the measurements are shown in Fig. 4 as differences between the interferometer visibility functions for polarizations perpendicular ($F_\perp$) and parallel ($F_\parallel$) to the effective baseline of the interferometer. It is evident that $F_\perp$ exceeds $F_\parallel$ by an amount considerably greater than the errors of measurement. This shows that the radiation from the edge of the apparent disk is polarized. Therefore the major portion of the radio emission of Venus at 10 cm (the wavelength used for the experiment) is thermal radiation from a sharply bounded surface, in other words the surface of the planet. It then follows that the model with a "hot" atmosphere must be rejected.

The establishment of the nature of the observed radio emission lets us settle the question of the temperature of the surface of the planet. It follows from the above measurements[20] that the surface temperature at the antisolar point is 650 ± 70°K, while it is 500 ± 100°K in the circumpolar regions. The temperatures on the illuminated and unilluminated sides of the planet do not differ by more than 10%[21,40,69].

The source of the heating is still unclear. It is most likely to be the greenhouse effect, but the matter requires further study.

The radius of the planetary surface, as determined by radio astronomical measurements[20], is 6060 ± 55 km, which is somewhat less than the ephemeris radius of 6100 km.

Successful radar observations of Venus have been made since 1961 in the USSR, the USA, and England[10,12,14,31-33,45,51,58,61,65,67,70,71,81,85,89,90,98].

According to the radio[20] and radar measure-

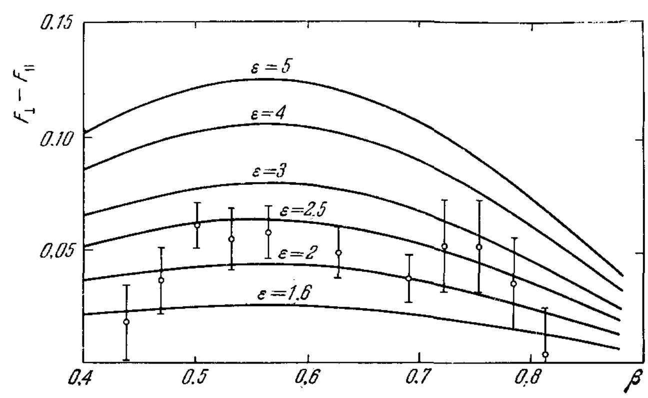

FIG. 4. Difference between the radio interferometric visibility functions measured on Venus for polarizations perpendicular and parallel to the effective interferometer baseline.

ments, the dielectric constant of the surface material of the planet, ϵ, is in the range 3 to 4. This rules out a large water content, and particularly a continuous ocean; it corresponds rather to dry rocks of density $\rho = 1.5-2\ g\,cm^{-3}$, such as sand, granite, diorite, dunite, limonite, and other dry rocks found in the Earth's crust. The radar measurements have shown also that the surface of Venus is much smoother than that of the Moon; the rms deviation of the surface from the horizontal is about 6°.

Radar has made it possible to determine the elements of the rotation of Venus. It turns out that, unlike the majority of the planets in the solar system, Venus rotates in the sense opposite to its revolution about the sun. The rotation is very slow; 247 ± 5 days are required for one turn about its axis.

Goldreich and Peale[57] have pointed out that if the moment of inertia of Venus depends on direction, a stable rotational state is possible such that at each inferior conjunction Venus is oriented in a way that makes its moment of inertia relative to the direction of the Earth a minimum. In order to attain this synchronism between the Earth and the rotation of Venus when the latter is retrograde, the rotational period must be 243.16 days. This agrees with experiment to within the errors of measurement. A more refined determination of the rotational period is needed to settle this very interesting point. Allowing for the orbital motion of Venus, a rotational period of 247 days corresponds to a "Venus solar day" of 118 earth days, which is about half a "Venus year." The rotational axis of Venus is nearly perpendicular to the plane of its orbit; hence the seasons should not be very clearly defined.

Measurements at JPL[32,33,61] and AIO[45] have shown that there are regions on Venus where the reflection of radio waves is enhanced (Fig. 5). One of these, which crossed the central meridian on 23 July 1964, has a meridional extent which may be as great as 3800 km (0.62 Venus radii); this region is less than 900 km wide. The second region is more complicated, and it is larger. Nothing is known as yet about the nature and structure of these areas. In view of the greater reflecting power and the depolarization of the reflection, one can assume that they are rougher than most of the surface.

Unfortunately, the radio and radar data do not give direct information on the properties of the atmosphere of the planet. From the temperatures of the surface and the cloud layer, however, one can estimate indirectly the pressure at the surface. Assuming an adiabatic atmosphere of carbon dioxide and nitrogen, the calculated pressure at the surface should be some 30 times greater than that in the cloud layer; hence it should be 3 to 10 earth atmospheres. If the atmosphere is non-adiabatic, the pressure must be still greater. Attempts to determine the composition of the atmosphere and the cloud layer from radio data

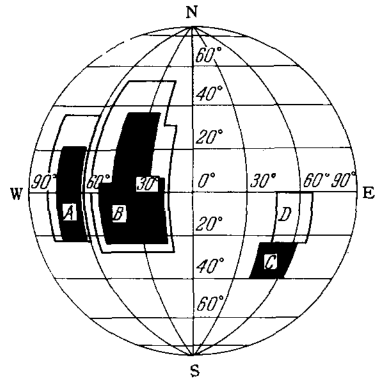

FIG. 5. Locations of the regions giving enhanced radio reflection on the disk of Venus.

do not give unambiguous results since the measured spectrum $\bar{T}_{B♀}(\lambda)$ is consistent with different kinds of liquid polar aerosols, including supercooled water, carbon dioxide gas at pressures of 100 to 200 atmospheres, and possibly other components. Attempts to find the water vapor content of the atmosphere of Venus from observations in the water vapor absorption line at λ = 1.35 cm, by four groups in the USA[42,55,97,103], have given contradictory results, as have the optical data. The only numerical estimate, made by Drake[42], gives an upper limit for the water vapor content which is several tenths of a gram of saturated water per square centimeter.

3. MARS

The first radio observation of Mars was made in 1956 by Mayer, McCullough, and Sloanaker[76]. At 3.15 cm wavelength, the brightness temperature of the planet averaged over the apparent disk was found to be 218 ± 76°K.

During the last ten years, observations of the radio emission of Mars have been made at wavelengths ranging from 1 mm to 1.54 m[23,37,38,49,56,63,68,69,73,83,102].

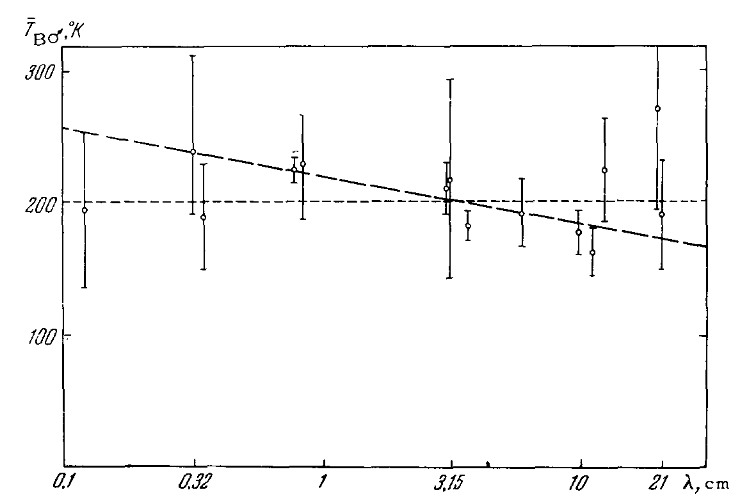

FIG. 6. Average disk brightness temperature spectrum for the illuminated side of Mars.

Figure 6 shows the average disk brightness temperature $\overline{T}_{B♂}$ as a function of the wavelength λ. The figure suggests that $\overline{T}_{B♂}$ becomes less with increasing λ, although a constant temperature $\overline{T}_{B♂} \cong 200°K$ also agrees satisfactorily with the data, considering the large errors of measurement. Either way, the observed radio emission can be interpreted as thermal radiation.

The decrease of $\overline{T}_{B♂}$ with increasing wavelength, if it is real, might be accounted for in the following ways:

a) The presence of a phase trend whose amplitude becomes less with increasing wavelength. Since it is possible to observe Mars from the Earth only at small phase angles, i.e., when most of the visible disk is illuminated by the sun, one would expect the brightness temperature to be higher at the shorter wavelengths where the phase effect should appear more strongly. In this case the temperature on the dark side of Mars should be much less than that on the illuminated side.

b) A decrease in the radiating power of the emitting layer with increasing wavelength.

The first radar observations of Mars were made in 1963 by Kotel'nikov et al.[13] at 43 cm wavelength and by Goldstein and Gillmore[59] at 12.5 cm. The mean reflection coefficient was found to be close to that of the Moon. The spectrum of the reflected radiation indicates that there are fairly flat areas on the Martian surface which extend for several kilometers or more. Regions of enhanced reflecting power were also found.

In 1965, radar observations of Mars were made by Goldstein[60] and Dyce[44] at wavelengths of 12.5 cm and 70 cm. respectively. Charts showing the distribution of the reflecting properties as a function of planetocentric longitude were constructed, and it that there is a correlation between enhanced radar reflection and the dark regions on the Martian surface.

Radio and radar observations of the planets are continuing, and undoubtedly important new data on planetary physics will be forthcoming in the next few years.

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