ICARUS 14, 222–234 (1971)

# The Microwave Spectrum of Mars: An Analysis

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Received December 10, 1970; revised March 23, 1971

A weighted least squares fit to the best available data on the Martian microwave spectrum indicates that the brightness temperature decreases from long to short wavelengths, rather than increasing as expected from the solution of the one-dimensional equation of heat conduction. Reasonable assumptions on the ratio of electrical to thermal skin depths, on internal heat sources, on ferromagnetic materials, on radiative conduction, on compaction with depth, and on surface roughness all fail in reproducing the deduced spectrum. A thin near-surface layer of a material with high dielectric constant and high millimeter wave absorption is needed. Since Mars exhibits marked surface overturn, a condensible material, namely liquid water, seems indicated. A layer of liquid water some tens of microns thick, on the average, localized in the top few millimeters of a Martian epilith with refractive index $\simeq 1.6$ fits the microwave spectrum, and the infrared and radar data as well. The origin of such a layer of liquid water and its possible exobiological significance are discussed. The distribution of water should be nonuniform over the disk and may help explain discordant microwave observations and the anomalous variation of infrared brightness temperature with latitude. Further millimeter wave radio and radar studies of Mars are needed.

## THE OBSERVED MICROWAVE SPECTRUM

The simplest expectation from the solution of the one-dimensional equation of heat conduction is that the brightness temperature of Mars should increase towards short wavelengths: we view essentially the illuminated hemisphere of Mars, where the temperatures near the surface should be significantly greater than the mean surface temperature because of the large diurnal temperature variation. At long wavelengths we are seeing to depths at which the diurnal temperature wave has been attenuated to the mean planetary temperature. At short wavelengths we are seeing to more shallow depths where the impressed diurnal thermal wave has not been so attenuated. The wavelength of the expected turnup in the spectrum was anticipated to be somewhere in the millimeter wavelength range and to give some information on the electrical and thermal properties of the Martian surface material (Sagan and Pollack, 1965).

In the preceding paper, Epstein (1971) has presented a critical review of reliable available microwave observations of Mars. These have been plotted in Fig. 1 along with 1$\sigma$ error bars taken from Table I of his paper. All the disk-integrated brightness temperatures shown have been reduced to the mean solar distance of Mars. The phase angle and the axial inclination of Mars should not significantly affect the observed temperatures. Phase effects have been sought but not detected ($\Delta T \lesssim 20°$K) at 3.3 mm by Epstein *et al.* (1970) and at 3.75 cm by Dent *et al.* (1965).

Due to the presence of polar caps, changes in the axial inclination are difficult to deal with exactly. However, a simple calculation indicates that this effect should change the observed disk-integrated brightness temperature by less than about 20°K. There is no evidence that the data used in Fig. 1 are systematically affected by such an effect.

Also shown in Fig. 1 are a linear and a quadratic least squares fit to the data.

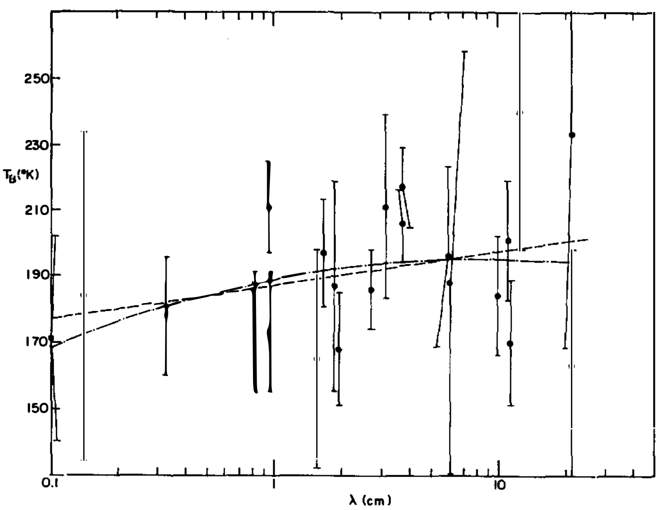


FIG. 1. The observed microwave spectrum of Mars, after Epstein (1971). Shown are the disk-integrated brightness temperatures; the error bars represent $1\sigma$ deviations. Also shown are linear and quadratic least squares fits in which each point is weighted inversely according to its uncertainty.

Each point was weighted inversely by its probable error. The observations suggest a decreasing brightness temperature with decreasing wavelength, or, as an extremely conservative summary of the data, no sign of an increase in brightness temperature with decreasing wavelength. The evidence for a turndown towards short wavelengths is strengthened by Low's (1970) statement that more recent observations of higher reliability confirm the generally low brightness temperature of Mars near 1 mm wavelength reported previously (Low, 1965).

As is evident from Tables I and II of Epstein (1971), some of the data points are in apparent mutual contradiction—which has led Kuzmin *et al.* (1971) to fit two mutually exclusive curves to the data, and which has led Epstein to reassess critically the reliability of the data points. Within the definition of $1\sigma$ error bars, all points in Fig. 1 may be mutually concordant. We do not exclude the possibility of a variation in Martian surface properties with central meridian longitude—although there is at present no evidence for such an effect. In the future observers might wish to plot their observations as a function of central meridian longitude. The difficulties in achieving a theoretical understanding of the microwave spectrum of Mars is illustrated in a variety of ways—e.g., Efanov *et al.* (1971) are compelled arbitrarily to reject disquieting data points. In the following discussion, however, we will accept the full suite of available observations, as reduced to a common basis by Epstein (1971), use his estimates of the reliability of each point, and attempt to understand our least squares fit to the data. Our arguments remain approximately valid so long as the spectrum does not turn up towards short wavelengths.

Contrary to the expectation from a straightforward solution of the equation of heat conduction (cf. Morrison, Sagan, and Pollack, 1969), the observations, as we have seen, indicate a turndown and not a turnup in brightness temperature towards short microwave wavelengths. The objective of this paper is to understand the absence of a turnup towards short wavelengths in terms of the thermal, electrical, or chemical properties of the Martian surface material.

## THE DISTRIBUTION OF SURFACE TEMPERATURE

Morrison, Sagan, and Pollack (1969; henceforth Paper I) have derived daytime equatorial surface temperatures from previously incompletely reduced 8–13 $\mu$ observations of Sinton and Strong (1960) made with the 200-in. Hale telescope. These data can be represented very well by an expression of the form

$$T_s(0) = 197 + 104 \cos(\phi - 7°), \quad (1)$$

where $\phi$ is the hour angle on the equator and $\phi = 0°$ at noon. This expression predicts a sunset equatorial temperature of 209°K and a sunrise equatorial temperature of 185°K, values well within the range of temperatures predicted by the models developed in Paper I. For our present purposes we assume that during the day the equatorial surface temperature is given by Eq. (1), while at night it decreases linearly from 209°K at dusk to 185°K at dawn.

Expanding this temperature variation in a Fourier series we obtain:

$$\begin{aligned} T_s(0) = 230.4 &+ 51.8 \cos(\phi - 12.4) \\ &+ 22.9 \cos(2\phi - 3.7) \\ &-1.0 \cos(3\phi - 33.9) \\ &-3.8 \cos(4\phi - 3.3). \end{aligned} \quad (2)$$

Also in Paper I there is a plot of the observed latitude dependence of surface temperature. This dependence can be described within experimental error by

$$T_s(\psi) = T_s(0) \cos^N \psi, \quad (3)$$

where $\psi$ is the latitude, and $N = \frac{1}{2}$; Eq. (3) is compared with the observations in Fig. 2. It should be noted that the $N = \frac{1}{4}$ dependence implied by the Stefan-Boltzmann equation does not adequately fit the data points. Surface roughness has the effect of *decreasing* the value of $N$: the observed dependence for the Moon, for example, is $N \simeq$ ; (Hafgors, 1970).

Both North of +30° latitude and South of −30° latitude the observed temperatures appear to be systematically below what is expected from a cosine to the one-quarter power law. Or, equivalently, between ±30° latitude, the temperatures are too high for a cosine one-quarter power law. Since this is just the latitude range in which the mean surface temperatures are above the freezing point of water (see Fig. 2) the idea naturally arises that the discrepancy is due to the latent heat of water changing phase on Mars. We will return to the question of water phase changes on Mars later in this discussion. Alternatively, the latitude dependence of brightness temperature might be strongly influenced by a strongly anisotropic emission phase function; but the agreement between groundbased and Mariner 6 and 7 infrared measurements makes this alternative unlikely—a hypothetical strongly anisotropic scattering phase function in the visible would have to just compensate a hypothetical strongly

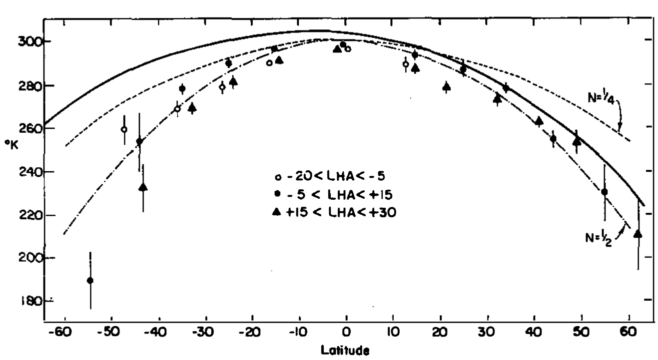


FIG. 2. The variation of surface temperature with latitude on Mars after Morrison *et al.* (1969). The data points are average infrared brightness temperatures for the three ranges of local hour angle indicated. The solid curve is the theoretical peak thermometric temperature for an albedo of 0.25 and a thermal inertia of 0.004 cal cm$^{-2}$ sec$^{-1/2}$ deg$^{-1}$. The two dashed lines represent Eq. (3) for $N = 1/2$ and $N = 1/4$. They have been normalized according to Eq. (1) to a temperature of 301°K at the equator for LHA = 0.

anisotropic emission phase function in the infrared.

## The Homogeneous Surface Model

If the surface of the planet is homogeneous with depth in its thermal and electrical properties, and if these properties are known, then the radio brightness temperature is easily predicted from the surface temperature (see, e.g., Troitskii, 1965). It is sufficient to consider the case of Mars at opposition with the subsolar and subearth points coincident on the equator. Let $\psi$ be the latitude, and let $\phi$ be the longitude measured from the subsolar meridian. Then if the surface temperature is given by

$$T_s(\phi,\psi) = T_{s0}(\psi) + \sum_{j=1}^{\infty} T_{sj}(\psi)\cos(j\phi - \alpha_j), \tag{4}$$

where $\alpha_j$ is the phase lag of the $j$th harmonic of the surface temperature behind the insolation, the brightness temperature at a wavelength $\lambda$ in the microwave region, at a point of the disk where the angle of emission is $\theta_{out}$, will be

$$T(\phi,\psi,\lambda) = [1 - R(\lambda,\theta_{out})]\left\{T_{s0}(\psi) + \sum_{j=1}^{\infty} \frac{T_{sj}(\psi)\cos(j\phi - \alpha_j - \xi_j)}{\{1 + 2\delta_j\cos\theta_{in} + 2\delta_j^2\cos^2\theta_{in}\}^{1/2}}\right\}.$$

In this expression:

$$\theta_{in} = \arcsin[(\sin\theta_{out})/n(\lambda)], \tag{6}$$

$n(\lambda) = [\epsilon(\lambda)]^{1/2}$ = index of refraction,

$R(\lambda,\theta_{out})$ = reflection coefficient of the surface,

$$\xi_j = \arctan\left\{\frac{\delta_j\cos\theta_{in}}{1 + \delta_j\cos\theta_{in}}\right\}, \tag{7}$$

$$\delta_j = j^{1/2} l_e/l_t. \tag{8}$$

The quantity $\delta_1 \equiv \delta$ is the usual ratio of electrical to thermal skin depths. The electrical skin depth $l_e = 1/k(\lambda)$, where $k(\lambda)$ is the absorption coefficient (cross section per unit volume) of the surface at wavelength $\lambda$; and the thermal skin depth

$$l_t = \left\{\frac{2K}{\rho c \Omega}\right\}^{1/2}, \tag{9}$$

where $K$ is the thermal conductivity, $\rho$ is the density, $c$ is the specific heat capacity of surface material, and $\Omega$ is the rotational angular velocity of Mars.

If there is a net thermal flux out of the interior, which gives rise to a gradient $\Gamma$(°K/cm) in the surface layer, then a term $\Gamma l_e \cos\theta_{in}$ is to be added within the curly bracket of Eq. (5). In that expression $\phi = 0$, at noon.

The disk-integrated brightness temperature can now be obtained by integrating over the disk:

$$\langle T(\lambda)\rangle = \frac{1}{\pi R^2}\int T(\phi,\psi,\lambda)\cos\theta_{out}\, dA, \tag{10}$$

where $R$ is the radius of Mars, $dA = R^2\cos\psi\, d\psi\, d\phi$ and $\cos\theta_{out} = \cos\phi\cos\psi$. To carry out this integration we use Eqs. (2) and (3) with $N = \frac{1}{2}$. We perform the calculation using a 36 point Gaussian grid over the disk.

Laboratory and lunar experience demonstrate $l_e$ to be proportional to the wavelength, so that

$$\delta = l_e/l_t = m\lambda. \tag{11}$$

For the Moon, $m \simeq 2.5$ (Hagfors, 1970), and from laboratory measurements by Campbell and Ulrichs (1969) for a wide range of geochemically abundant materials we infer that the likely range is $m = 1$–$3$. Pollack and Sagan (1970) find the real part of the refractive index $n \simeq 1.6$ for the bright areas of Mars between 3.8 and 70 cm. (There are no radar observations of Mars below 3.8 cm.) The presence of dark areas will make the effective value of $n$ for the integrated disk somewhat higher.

Since Mars is considerably smaller than the Earth, it is unlikely to be significantly differentiated. Model calculations by Hanks and Anderson (1969) predict that Mars has no core, and is uniformly colder than the Earth. Even the most optimistic recent calculation deduces only a very

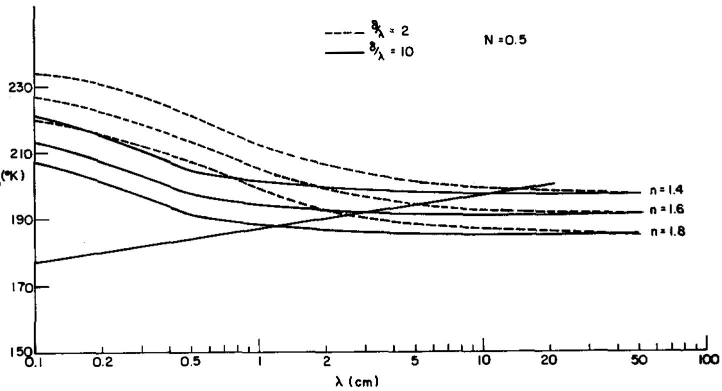


FIG. 3. Predicted brightness temperatures for a homogeneous Martian surface layer with no internal heat sources. A range of values of $n$, the surface refractive index, and $\delta$, the ratio of electrical to thermal skin depths, is shown. The exponent of the latitude dependence of temperature $N$ is taken as 0.5, as the observations suggest. Also shown is the linear least squares fit to the observed brightness temperatures from Fig. 1. Note that large $\delta/\lambda$ flattens the spectrum, but cannot make it decline to short wavelengths.

small core on Mars (Binder, 1969). Thus there is no reason to expect that the internal heat flux will even approach the geothermal value, $1.5 \times 10^{-6}$ cal cm$^{-2}$ sec$^{-1}$ (Stacey, 1969). Accordingly, to a first approximation, we take $\Gamma = 0$.

Figure 3 shows the predicted microwave spectra for a homogeneous surface layer with $n = 1.4$, 1.6, 1.8, $\delta/\lambda = 2$ and 10, and $\Gamma = 0$. Also indicated is the approximate observed spectrum taken from Fig. 1. Clearly the models give the wrong spectral shape: the predicted temperatures are much too high at short wavelengths. In Fig. 3 an $N = \frac{1}{2}$ latitude dependence is used. For a choice of $N = \frac{1}{4}$ the curves are systematically shifted up by about 9°K.

The introduction of an internal thermal gradient does not affect the temperatures in the millimeter range; the only effect is

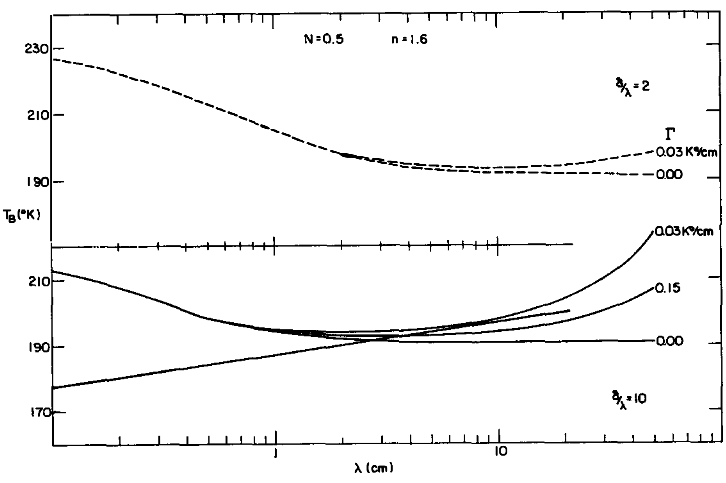


FIG. 4. Predicted Martian brightness temperature as a function of wavelength assuming a real part of the refractive index of the surface material equal to 1.6, values of the ratio of electrical to thermal skin depths, $\delta$, as shown, and $N = 0.5$, for a range of assumed values of the thermal gradient due to internal heat sources on Mars. Also shown for comparison is the linear least squares fit to the observations from Fig. 1. The surface is assumed to be thermally and electrically homogeneous with depth.

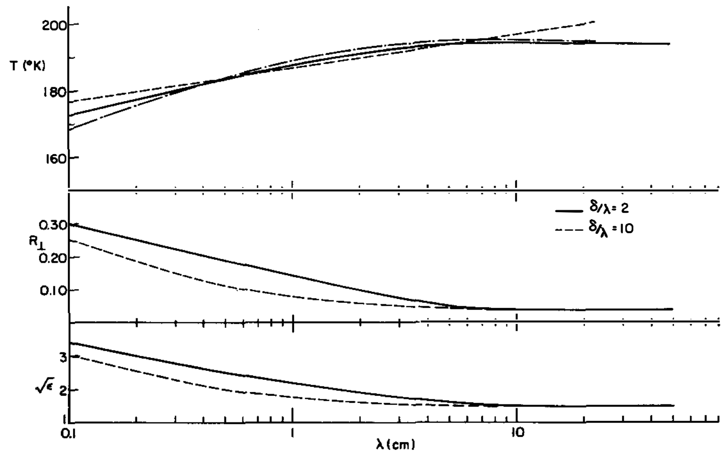


FIG. 5. The top part of this figure shows a possible Martian microwave spectrum (solid line). Also shown for comparison (dashed lines) are the two least squares fits to the observed microwave temperatures taken from Fig. 1. Next is shown the wavelength dependence of the Fresnel reflectivity at normal incidence, $R_\perp$, required to produce this possible spectrum. Finally, the corresponding values of $\sqrt{\epsilon} = n =$ real part of the index of refraction of the surface are shown as a function of the wavelength. The calculations are for homogeneous models and for two representative values of $\delta$, the ratio of electrical to thermal skin depths.

to increase the temperature at long wavelengths. According to Paper I, for Mars $\gamma = (k\rho c)^{-1/2} \simeq 200\ \text{cal}^{-1}\text{cm}^2\text{sec}^{1/2}(\text{K}^\circ)$, and since $c \simeq 0.17$ ergs $g^{-1}$ for most rocks, and $\rho \simeq 1.2\ \text{g/cm}^3$ for the topsoil of Mars (Pollack and Sagan, 1970), the thermal conductivity of the Martian epilith is about $10^{-4}$ cgs. Assuming a heat flux of the same magnitude as the geothermal one, a value probably much too large for Mars as we have already argued, therefore leads to a gradient of about

$$\Gamma = 1.5 \times 10^{-2}\,\text{K}^\circ/\text{cm}.$$

The predicted spectra in the presence of such a gradient, and in the presence of one twice as large, are shown in Fig. 4. In these calculations we use $l_T \simeq 3$ cm (Paper I).

It is clear that fluxes in excess of the geothermal one are needed to alter significantly the microwave spectrum of Mars, and even then the effect is noticeable only at long wavelengths ($\lambda > 10$ cm). It seems clear that the introduction of internal heat sources on Mars does not help to explain the turn-down at short wavelengths of the Martian microwave spectrum.

We can now ask what must be the wavelength dependence of $n(\lambda)$ such that the spectra predicted on the basis of a homogeneous surface model agree with the observations. The answer is displayed in Fig. 5 for $\delta/\lambda = 2$ and 10, where we have assumed that beyond $\lambda = 10$ cm, $n(\lambda) = 1.5$. Radar observations suggest that it would be better to use $n = 1.6$. However, in that case the temperatures beyond 10 cm would fall about 5K° below those suggested by the least squares fit. In view of the large uncertainties in the observations, this is not a serious discrepancy. But, in the spirit of remaining as true as possible to our least squares fit, all of the following calculations are carried out with $n = 1.5$ beyond $\lambda = 10$ cm. We feel that $n = 1.6$ is probably a more appropriate value, but none of our conclusions are affected by our choice of using $n = 1.5$ instead of 1.6.

Thus we reach the following conclusion:

(A) If the Martian surface is homogeneous it must have an index of refraction which increases from its value of 1.5 or 1.6 at long wavelengths to about 3.0–3.4 at 1 mm; or

(B) The epilith of Mars is inhomogeneous in either its thermal properties or its electrical properties, or both.

The required high values of the Martian dielectric constant at millimeter wavelengths could be checked by millimeter radar observation. Indeed this represents a significant space vehicle experiment.

## Possible Influence of Ferromagnetic Materials, Radiative Conduction, Compaction and Surface Roughness

In this section we consider two questions: (1) How can an $n(\lambda)$ of the type shown in Fig. 5 be obtained? (2) In what ways can the epilith of Mars be inhomogeneous?

First we note that, in general, for dielectrics in the microwave region $n = \epsilon^{1/2}$ remains constant or increases slightly with increasing wavelength (von Hippel, 1954; Campbell and Ulrichs, 1969). Thus the behavior shown in Fig. 5 is quite atypical. The introduction of ferromagnetic materials ($\mu \neq 1$) does not alter the situation, because significant departures from unit magnetic permeability occur only at $\lambda > 10$ cm (von Hippel, 1954). [Note added in proof: Dr. Frank Drake has pointed out to us that ~10% cover of metallic iron particles of mm dimensions might preferentially increase mm brightness temperatures. The rapid oxidation of such particles by surface ozone on Mars seems to pose a serious problem for this model.]

Under Martian conditions we do not expect an inhomogeneity due to the temperature dependence (through radiative terms) of the thermal conductivity. In fact, laboratory measurements by Fountain and West (1970) show that for the Martian epilith $K \simeq$ constant, independent of temperature. Similarly for temperatures between 200 and 300°K, the specific heat capacity cannot vary significantly (Hagfors, 1970). If on Mars, as on the Moon, the density of the surface increases with depth [say, from 1.0 to 1.5 g cm$^{-3}$ in the first 5 cm (Jaffe, 1970)], then this will have no significant effect on the thermal conductivity (Fountain and West, 1970). Furthermore, the inhomogeneity introduced into the heat conduction equation by such a variation of density with depth is unlikely to explain the shape of the microwave spectrum, as we now demonstrate.

The mean density of the Martian epilith inferred by Pollack and Sagan (1970) from radar measurements of Mars is 1.2 g cm$^{-3}$. We now compare the thermal structure of a soil of constant mean density 1 g cm$^{-3}$, with another in which the density increases from 0.8 to 2 g cm$^{-3}$ in the first 4 cm. The density gradient is unlikely to be much steeper. Making the soil density increase to larger values would lead to excessive radar reflectivities.

Compaction should have no effect on the specific heat capacity $c$. Also, according to Fountain and West (1970), the change in the thermal conductivity, $K$, is only ~15% in going from $\rho = 0.8$ g/cm$^3$ to $\rho = 1.5$ g/cm$^3$. Below we consider a model in which $K/K_0$ varies from 0.9 at $\rho = 0.8$ g cm$^{-3}$ to 1.4 at $\rho = 2.0$ g cm$^{-3}$ ($K_0 \simeq 10^{-4}$ cgs). (This is a somewhat larger variation than that suggested by the experiments of Fountain and West.)

We have calculated the thermal structure in the soil at the equator of Mars by solving numerically the one-dimensional heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left\{K \frac{\partial T}{\partial x}\right\}$$

using two boundary conditions: (1) that the surface temperature at any time during the Martian day is known, i.e., $T(x=0) = 197 + 104\cos(\omega - 7°)$ during the day, while at night the temperature decreases linearly from 209°K at dusk to 185°K at dawn (cf. Paper I); and (2) $\partial T/\partial x = 0$ at sufficient subsurface depths. Assuming $K_0 = 10^{-4}$ cgs, $\rho_0 c = 0.3$ cgs, and $\rho_0 = 1$ g cm$^{-3}$ we consider 3 models:

*Model 1*

$\rho = 1$ g cm$^{-3}$ = const. for all $x$. $K =$ const. $= K_0$.

*Model 2*

$\rho$ increases from 0.8 g cm$^{-3}$ at the surface to 2.0 cm$^{-3}$ at 4.0 cm; $\rho$ remains constant beyond $x = 4$ cm (see Fig. 6). $K =$ const. $= K_0$.

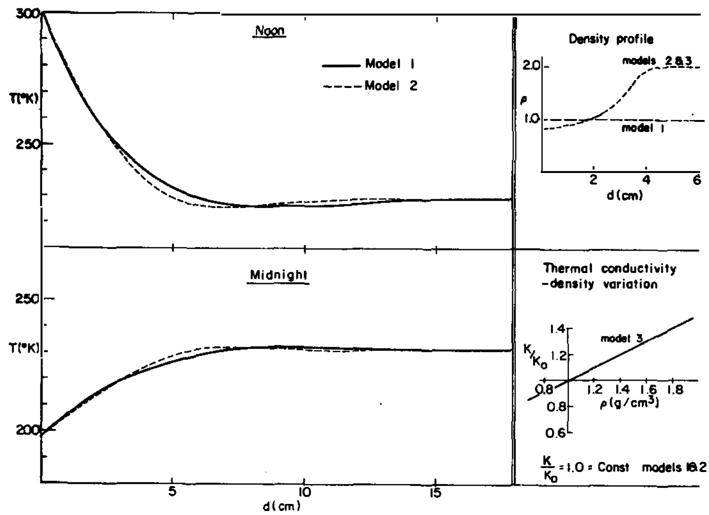


FIG. 6. Variation of temperature with depth at noon and at midnight for the three models described in the text. The assumed variation of density with depth is shown in the inset at upper right. The assumed variation of normalized thermal conductivity with density is shown in the lower right. Curves for Model 3 are not shown in the temperature-depth plots because they lie between the values shown for Models 1 and 2.

*Model 3*

$\rho$ varies as for Model 2, but now $K$ increases with $\rho$, from $K/K_0 = 0.9$ at $\rho = 0.8$ g cm$^{-3}$ to $K/K_0 = 1.40$ at $\rho = 2.0$ g cm$^{-3}$ (see Fig. 6).

Noon and midnight profiles are shown in Fig. 6. The profile for Model 3 is not plotted since it falls between that for Model 1 and that for Model 2. It is clear from the figure that reasonable density variations within the soil do not affect the thermal profiles significantly. We have tried other density variations in addition to the one shown in the figure; the results are similar and very little change in the thermal profile results. Therefore soil compaction alone cannot explain the unusual microwave spectrum of Mars. Soil compaction alone does not significantly alter the thermal structure, but it will increase the reflectivity of the surface at long wavelengths, and this, as we have seen, will only increase the discrepancy between theory and observation. Compaction with depth will tend to *increase* the effective dielectric constant at long wavelengths.

Aeolian erosion on Mars may be rather more efficient at millimeter than at centimeter scales; saltation is likely, at least on occasion, to move mm-sized particles on Mars (Sagan and Pollack, 1969), but not cm-sized particles. If Mars moved rapidly from rough to smooth between centimeter and millimeter scale, the center of the disk would show a higher reflectivity at millimeter wavelengths because shadows would be removed, but the limbs would show a smaller reflectivity because there would be fewer retrodirective reflection elements at the limb. Accordingly the emissivity of the center of the disk would decline but the emissivity of the limbs would increase. Unpublished calculations by Drake and Heiles (1966) show that the center of the disk and limb effects tend to cancel each other out and that it is extremely difficult to achieve any significant change in integrated disk emissivity by a change in roughness. Certainly there is no evidence of any difference in the roughness scale between 3.8 and 70 cm (Pollack and Sagan, 1970). This is another case where millimeter radar astronomy of Mars from Martian orbit would be of great significance.

Thus neither ferromagnetic materials, radiative conduction, compaction with depth, or a variation of surface roughness with scale appear able to account for the anomalous microwave spectrum of Mars.

## Liquid Water on Mars

A possible solution to the enigma posed by the Martian microwave spectrum arises if there is present near the Martian surface a thin layer of a material with high dielectric constant and high absorption coefficient, especially at millimeter wavelengths. Such a layer would be entirely transparent to centimeter wavelength radiation but would strongly influence the millimeter emission. On a planet where winds and meteoritic excavations have circulated surface material to a depth of kilometers, it is difficult to imagine an appropriate material with high complex refractive index which is localized in the top centimeter or so of the Martian epilith.

Solid phase vapor condensates might be concentrated near the Martian surface, but solid water and solid carbon dioxide do not have the requisite refractive indices. We are thus led to consider the possibility that small quantities of liquid water exist near the Martian surface.

Small amounts of water vapor (10–40 $\mu$) are known to be present in the atmosphere (see, e.g., Schorn, 1970). In addition, large amounts of water can be locked up within the surface either as water of hydration (Pollack and Sagan, 1969), or as permafrost (Leighton and Murray, 1966). The presence of a permafrost layer is especially attractive in view of the unusual latitude dependence of the surface temperature which could be due to heat sinks related to phase changes at the boundary of such a layer. The permafrost would not seriously affect the microwave properties of Mars unless the ice melts. The complex dielectric constant of pure ice is similar to that of rock. Only within the topmost few centimeters of the epilith does the temperature ever exceed 273°K, and this occurs only within a cap of planetocentric half-angle 30°–40° from the subsolar point. Thus, under these conditions only about $\frac{1}{3}$ of the projected area of Mars can be covered with liquid water.

There is a debate on the possibility of small quantities of liquid water near the Martian surface. Sagan, Lederberg, and Levinthal (1968), Smoluchowski (1968), and Schorn *et al.* (1969) propose that liquid water can exist for a small fraction of a Martian day in soil interstices. Sagan *et al.* (1968) suggest that diffusion limits the escape of water vapor vaporized after sunrise from frost deposited on the walls of interstices so that the water vapor partial pressure exceeds the triple point in the microstructure of the epilith. Ingersoll (1970) argues that surface frost deposits will vaporize without experiencing a liquid phase. The question must be regarded as still unsettled. All of the foregoing authors appear to agree that liquid water could be present in salt solutions on Mars where eutectic point lowering occurs. With geochemically abundant salts—$MgCl_2$ for example—the freezing point can be lowered many tens of degrees centigrade. The widespread presence of such salts near the Martian surface may not be unlikely even if we put little confidence in the Lowellian hypothesis of evaporites in ancient sea bottoms. Water percolating through the Martian subsurface material during geological time will tend to carry salts of high solubility with it and concentrate them near the surface (Gold, 1970). The sites which tend to exhibit water outgassing may also tend to have preferential concentrations of appropriate eutectic point lowerers. Leovy, Smith, Young, and Leighton (1971) have recently proposed that certain regions of Mars—for example, the so-called W cloud region—are precisely sites of preferential percolation of water through the Martian epilith. And the presence of moisture near the Martian surface is not inconsistent with spectral data on seasonal variations in Syrtis Major (Adams and McCord, 1969). Finally a much more speculative possibility exists—that water-rich Martian organisms are preferentially concentrated near the Martian surface (Sagan, 1970).

This layer of liquid water, whatever its origin, cannot be deeper than a few centimeters, both because of the temperature arguments given above, and for it to have any preferential effect on the millimeter

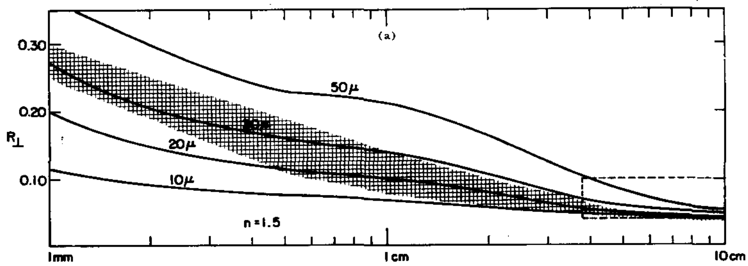


FIG. 7a. The effect of thin layers of liquid water on the Martian microwave spectrum. The normal incidence microwave reflectivity of Mars necessary to explain the observed microwave spectrum is shown in the cross-hatched area. The range of observed radar reflectivities down to 3.8 cm is shown in the dashed box. The curves show the predicted radar reflectivities for thin layers of liquid water of thicknesses ranging from 10 to 50 $\mu$ near the Martian surface. It is assumed that the real part of the refractive index of the underlying surface is constant with depth and has a value of 1.5.

emission. For $\delta/\lambda \sim 1 - 10$ cm$^{-1}$ and $l_T \sim 3$ cm (Paper I), this corresponds to $l_e \sim 0.3 - 3.0$ cm at $\lambda = 1$ mm.

We now consider a Martian surface covered with a thin layer of water of thickness $s$. This layer is thin enough to be invisible to wavelengths longer than 3.8 cm, and the underlying surface is a perfect dielectric with $n =$ constant, determined by radar observations at $\lambda \gtrsim 3.8$ cm.

The actual layer of water can be slightly below the surface, and as long as this depth is less than several millimeters the following conclusions still hold.

The required equations for the reflection coefficient are given by Born and Wolf (1964). The dielectric constants and absorption coefficients for liquid water between 1 mm and 10 cm at 20°C are taken from Goody (1964). Presently we consider supercooled liquid water at lower temperatures. The water layer will be invisible at a wavelength $\lambda$ if

$$s \ll \lambda/4n(\lambda); \qquad (13)$$

for $\lambda \simeq 5$ cm, $n(\lambda) \simeq 8.6$, and $s \ll 0.15$ cm.

Figure 7a shows the results of detailed calculations using $n(\lambda) = 1.5$ for the underlying surface. To be consistent with radar observations the reflectivity beyond 3.8 cm should lie between 0.04 and 0.10. Thus Figure 7 implies that $s < 50\mu$. In fact, to reproduce the reflectivity-wavelength dependence inferred from the microwave spectrum (Fig. 5), and shown as a shaded region in Fig. 7a, a thickness $s \sim 30\mu$ is required. Such a layer raises the reflectivity to a high value at 1 mm, but only slightly affects it beyond 3.8 cm. These conclusions are not strongly dependent on the precise choice of $n$ for the underlying surface, as Fig. 7b shows.

These calculations have been repeated for liquid water at temperatures of 0°C using data tabulated by Gunn and East (1954) and by Goldstein (1951). Unfortunately there appear to be no data available for wavelengths shortwards of 6 mm. The general trend seems to be a decrease of the real part of the refractive

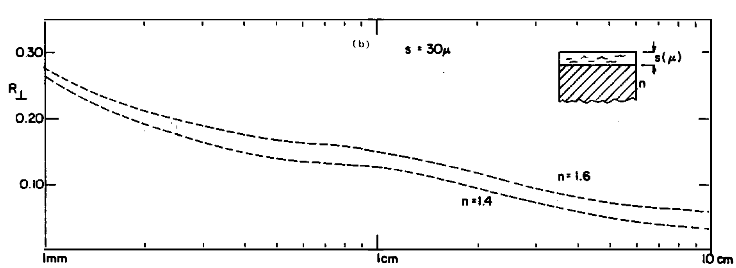


FIG. 7b. An example of the dependence of the predicted reflectivity on the value of the real part of the refractive index of the underlying surface, for one particular value of the water layer thickness.

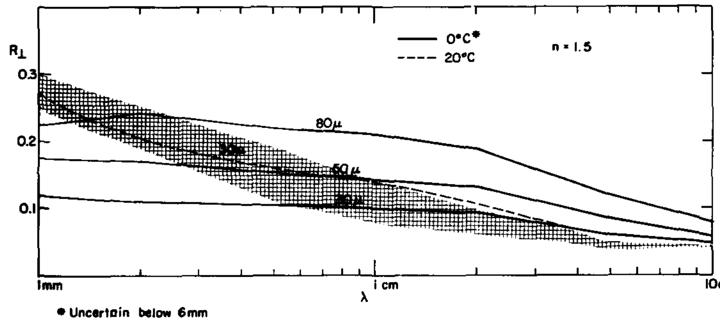


FIG. 8. The effect of layers of liquid water at 0°C and at 20°C on the Martian microwave reflectivity. The cross-hatched region shows the reflectivity necessary to explain the passive microwave observations; the dashed line shows the predicted reflectivity of a 30 $\mu$ layer of liquid water at 20°C near the Martian surface (see Fig. 7a); the solid lines show the case for 30, 50, and 80 $\mu$ layers of supercooled water at 0°C. As in Fig. 7a the real part of the refractive index of the underlying material is assumed to be 1.5.

index with decreasing temperature from +20 to −80°C; and a decrease of the imaginary part of the refractive index with decreasing temperature above this wavelength. An extrapolation of the 0°C data gives the results displayed in Fig. 8. Below 6 mm the curves are rather uncertain. The general conclusion is that a 50-$\mu$ thick layer of liquid water is still compatible with the observed Martian microwave spectrum. The 20°C curves seem to provide a significantly better fit, since at 20°C the dielectric constant of water at millimeter wavelengths is higher than it is at lower temperatures. Considering the range of temperatures actually present in the Martian epilith, the actual situation may be intermediate between the 0°C and 20°C cases.

We conclude that a thin layer of liquid water near the Martian surface could produce the reflectivity curve implied by the microwave spectrum.

If indeed a layer of liquid water is present at times near the surface of Mars, then the epilith is inhomogeneous in both its thermal and electric properties. Thus a simple treatment of the thermal structure, such as that carried out in Paper I, may not strictly apply. The combined problems of the thermal structure and radio emission from a soil entrained with permafrost and in which diurnal melting and refreezing occur will be extremely complicated. We have, however, demonstrated that the epilith of Mars is very likely inhomogeneous if our adopted microwave spectrum is valid; accordingly this problem should be tackled.

The possible presence of some tens of microns of liquid water near the Martian surface is interesting in that the mean equivalent amount of water vapor in the Martian atmosphere (see, for example, Schorn, 1970) is of the same order of magnitude. However, since the absolute value and seasonal modulation of the Martian water vapor abundance may involve mineral-gas equilibria (Pollack, Pitman, Khare and Sagan, 1970) this may be only a coincidence. The ultraviolet flux at the Martian surface has been thought to pose difficulties for any indigenous Martian organisms. If they wish to photosynthesize visible light they run the risk of being photodissociated in ultraviolet light. Sagan and Pollack (1971) have shown, however, that Martian organisms living within the top few centimeters of the Martian epilith —a material which strongly absorbs ultraviolet light—will find themselves in a euphotic zone which has acceptable levels of visible light but in which the ultraviolet radiation has, through multiple scattering, been significantly attenuated. This euphotic zone is compatible with the region of near surface liquid water deduced in the present paper, implying that there may exist a pervasive habitat near the Martian surface suitable both for indigenous Martian organisms and for terrestrial microbial contaminants. This in turn underscores the necessity of sterilizing space vehicles intended for Mars landings (cf. Sagan *et al.*, 1968). In view of the uncertainties in the foregoing discussion and other possible sources of liquid water which present studies suggest, the water in question is not necessarily *within* indigenous Martian organisms; but a mean abundance of $50\mu$ of liquid over the entire surface of Mars would permit, with reasonable patchiness, the presence of a flourishing microbiota and possibly even larger organisms on Mars. Such a patchiness could be examined by mm-wave radio and radar observations as a function of position on the Martian surface. Finally, the presence of even small quantities of liquid water ubiquitously over Mars may provide the missing source of surface erosion required by Mariner photography.

All of the foregoing tentative conclusions are, of course, dependent on the reality of the decline in brightness temperature from cm to mm wavelengths. Further passive microwave measurements of Mars with high precision at all wavelengths are urgently needed.

## Acknowledgments

We are grateful to Eugene Epstein for stimulating and instructive discussions on the reliability of the observational material, to Frank Low for a discussion of his millimeter wavelength observations, to David Jauncey for a discussion of the statistics of Fig. 1, and to Frank Drake and Thomas Gold for important suggestions. This research was supported in part by NASA grant NGR 33-010-082 and NASA grant NGR 33-010-098.

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