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Ever since the discovery of the high brightness temperature, T_B, of Venus at wavelengths greater than 1 cm, considerable reluctance has been exhibited in some quarters to attribute the emission to a hot surface. If the mean surface temperature of Venus is in fact ~ 700°K, indigenous surface life is very difficult to imagine (Sagan 1966), a fact that has certainly contributed to the search for alternative explanations of the microwave emission. Jones (1961) proposed a model in which free-free emission of electrons in a dense Cytherean ionosphere accounted for the spectrum, but the Mariner 2 observations of limb darkening at 19 mm (Barath, Barrett, Copeland, Jones, and Liller 1966) as well as serious theoretical difficulties in understanding the high requisite electron densities (Walker and Sagan 1966) have rendered this model untenable. Vakhnin and Lebedinskii (1966) suggested that the microwave emission is due to glow discharge in rarefied regions of the upper Cytherean atmosphere, where major charge separation between the dark and the bright hemispheres is imagined, and attributed to the slow rotation rate. In this case, the recombination radiation should be strongly concentrated at the terminator, and because of projection effects a marked maximum in the microwave brightness temperature should occur at dichotomy, inconsistent with the observations (see, for example, Pollack and Sagan 1965a). In addition, a pronounced equatorial limb brightening should exist at 10 cm; this is also inconsistent with the observations (Pollack and Sagan 1965b; Clark and Kuz'min 1965). It is clear that alternative models, both thermal and nonthermal, must be able not only to provide a plausible energy source for the emission, but also to explain the phase, polarization, and limb-darkening observations.

A nonthermal mechanism for achieving a spectrum with $T_B \neq T_B(\lambda)$ at $\lambda > 3$ cm and T_B falling with λ for $\lambda < 3$ cm was proposed by Tolbert and Straiton (1962), who attributed the radiation to electrical discharges between adjacent cloud particles. This model has recently been revived by Plummer and Strong (1965, 1966), who believe that it also provides a straightforward explanation of the microwave polarization data. Drake (1967) has shown, in a straightforward theory of the discharge physics, that pure water droplets have far too low an electrical resistivity for discharges between them to reproduce the Venus microwave spectrum. Atkinson and Paluch (1966) have nevertheless reported laboratory detection of electrical discharges between adjacent pure water droplets with small enough characteristic times of discharge to simulate the Venus microwave spectrum; however, they do point out that their discharge times are several orders of magnitude smaller than those typically given in the literature. Plummer and Strong (1967) have concluded that the results of Atkinson and Paluch refute Drake's calculations. The primary purpose of this note is to test the consistency of the electrical discharge model with the Mariner 2 microwave observations, within the constraints set by ground-based measurements; however, we begin by briefly discussing the question of agreement with polarization data.

Plummer and Strong (1966) contend that the discrepancy between the dielectric constant of Venus found from interferometric polarization studies (Clark and Kuz'min 1965) and the larger value obtained from the radar data (Carpenter 1964; Goldstein 1964) provides support for the discharge model: The discharge component of the total microwave emission is unpolarized, and would contribute to a lower dielectric constant for the passive observations. However, while Clark and Kuz'min have corrected their interferometric dielectric constant for depolarization due to surface roughness comparable to a wavelength, they have not allowed for the deviation of local surface facets, such as mountains and valleys, from alignment with the local geoid. The radar measurement of the dielectric constant depends chiefly on the reflection from the vicinity of the subterrestrial point. It is therefore unaffected by moderate variations in slope. But the interferometric polarization measurements are dependent in large part on polarization due to features near the limb (Heiles and Drake 1963). Elevations near the limb, intercepting the line of sight, result in a lower contribution to polarization; normals to these elevations make a smaller angle with the line of sight than would be the case for a perfect sphere. Such large-scale depolarization effects have been observed for the Moon (Baars, Megger, Savin, and Wendker 1965). A discrepancy exists for the Moon between radar and passive dielectric constants; this discrepancy is of the same magnitude and the same sign as the Venus discrepancy, and is probably due at least in part to large-scale limb-depolarization effects. Therefore, it seems unlikely that the existence of such a discrepancy for Venus is significant evidence in favor of the discharge model.

The optical thickness, τ_d, of the discharging dipoles in the electrical discharge model is estimated as follows: In order for electrical discharges to simulate a thermal spectrum at $\lambda > 3$ cm, the characteristic emission time must be $\lesssim 10^{-10}$ sec (Atkinson and Paluch 1966; Drake 1967). Atkinson and Paluch have estimated that some 10^2 discharges sec^{-1} cm^{-2} between adjacent water droplets having net charges comparable to those of terrestrial raindrops are required to produce the observed microwave flux from Venus. Accordingly, during a given discharge, they will be fewer than 10^{-8} dipoles cm^{-2} lying above the discharging dipole. Each dipole will have an absorption cross section less than its geometrical cross section $\sim 3 \times 10^{-2}$ cm^2 and so $\tau_d < 3 \times 10^{-10}$. Evidently, reasonable variations in the choice of parameters for droplet size, etc., will not change the conclusion that $\tau_d << 1$. For small values of τ_d, the formal solution of the equation of radiative transfer reduces to

$$I_\nu = \int S_\nu \exp(-\tau_d/\mu)\, d\tau_d/\mu \simeq \mu^{-1}\int S_\nu\, d\tau_d \quad , \tag{1}$$

where S_ν is the source function for the discharge, and arccos μ is the angle between the line of sight and the local planetary normal. Since at radio frequencies T_B is proportional to the specific intensity I_ν, T_B will have a μ^{-1} dependence for the discharge components of the total microwave emission. This derivation assumes that S_ν is isotropic, or equivalently, that the discharging dipoles have a random orientation, an assumption we will later reexamine. Since $\tau_d << 1$, the surface thermal radiation will in general also contribute to the total observed spectrum.

We consider the following representation of the discharge model: Radiation is produced by the planetary surface, at a temperature T_s; by the discharges, at effective temperature T_d; and in the form of thermal emission, by the clouds, at a temperature of T_c, to the extent that the clouds are opaque. The decline in the brightness temperature below 3 cm may be attributed either to the nonthermal character of the discharge mechanism (Tolbert and Straiton 1962) or to an opacity source characterized by optical depth τ that we will initially attribute to the clouds. In agreement with the view that the discharge occurs in raindrops, we assume that the source of the discharge lies generally below the level of maximum cloud opacity. The total brightness temperature produced in a given area of the planet in direction μ is then given by

$$T_B(\mu) = (1 - R)T_s e^{-\tau/\mu} + T_d\mu^{-1}(1 + R)e^{-\tau/\mu}$$

$$+ T_c(1 - e^{-\tau/\mu})(1 + Re^{-\tau/\mu}) \quad . \tag{2}$$

Here R is the reflectivity and 1 - R is the emissivity of the surface at the wavelength of interest. Equation (2) allows for reflection both of the discharge and of the cloud thermal emission from the surface. Radar observations indicate that the surface of Venus is very smooth at microwave frequencies (see, e.g., Carpenter 1964), suggesting that the reflectivity can be obtained with good accuracy from the Fresnel equations once the dielectric constant ϵ is known. The Mariner 2 radiotelescope accepted that component of the radiation field with the electric vector perpendicular to the plane formed by the line of sight and the local normal ; R is evaluated accordingly, and will increase with μ. Apart from interferometry, existing ground-based telescopes cannot resolve Venus; instead they measure the disk-averaged temperature $\overline{T}_B$. Carrying out a solid-angle averaging of equation (2) we find

$$\overline{T}_B = 2(1 - \overline{R})T_s E_3(\tau) + 2T_d(1 + \overline{R})E_2(\tau) + T_c[1 - 2(1 - \overline{R})E_3(\tau) - 2\overline{R} E_3(2\tau)] , \quad (3)$$

where E_n is the exponential integral of order n.

We now discuss the initial choice of parameters in these equations. At decimeter wavelengths, radar observations indicate $\epsilon \simeq 3.6$ (see, e.g., Carpenter 1964). The lower radar reflectivity at 3.6 cm may be attributed either to a smaller effective dielectric constant of 1.45 at the subsurface level responsible, or to a temperature-dependent atmospheric absorption (Pollack and Sagan 1965a). For the 1.9-cm observations of the Mariner 2 spacecraft we will employ both $\epsilon = 1.45$ and $\epsilon = 3.6$. For $\lambda \geq 3$ cm, $\overline{T}_B$ has an approximately constant value of 620° K; thus, $\tau(\lambda \geq 3 \text{ cm}) \simeq 0$. For a given choice of T_s, T_d may then be found from equation (3). We will consider two values for T_s of 300° K and 450° K. This is the range considered plausible by Plummer and Strong, and is the range of potential biological interest for Venus. Higher values of T_s would imply that almost all the observed radiation arises from the surface. We take $T_c \simeq 250°$ K in accord with infrared temperature measurements of the clouds (Sinton and Strong 1960), and with the necessity for supercooled liquid water to supply the microwave attenuation in view of the negligible microwave opacity of ice. Finally, the maximum value of τ(8 mm) can be obtained from equation (3) by setting $\overline{T}_B$(8 mm) equal to the observed value of 425° K, and assuming that T_d has not yet begun to decline with decreasing wavelength. We then find τ(8 mm) to lie between 0. 3 and 0. 4 for the two choices of dielectric constant and of surface temperature. If we scale τ with λ, as is appropriate for either ordinary liquid or supercooled water using the relations of Basharinov and Katuza (1965), we find $0.05 \leq \tau(19 \text{ mm}) \leq 0.1$. In the calculations below we will consider $\tau(19 \text{ mm}) \leq 0.2$. The initial models to be discussed assume that all the foregoing parameters are independent of latitude and longitude. We will later consider the effect of variations of these parameters with position, within the constraints imposed by ground-based observations.

Theory and observation of limb effects at 19 mm are compared in Table 1, where the brightness temperatures found at the center of each of the three scans of the planet by the Mariner 2 spacecraft are exhibited (Barath et al. 1964; Jones 1964, 1965). The errors reflect the internal scatter in the data set; the uncertainty in the absolute values is estimated to be some 35 K°(Jones 1964, 1965). These peak brightness temperatures have much higher intrinsic reliability than the individual temperature measures along each of the three Mariner 2 scans of the disk. Also shown are values of μ^{-1} and the location of the scan with respect to the terminator on the disk of Venus. We see from the theoretical calculations represented by Cases 1 through 4 that a homogeneous discharge model leads to gross inconsistencies with the Mariner 2 observations. The absolute value of T_B for the terminator is too low; instead of significant limb darkening there is limb brightening. This is directly attributable to the μ^{-1} dependence of the discharge component, which overcomes the limb darkening produced by cloud absorption and the decline of emissivity.

TABLE 1

COMPARISON OF THE MARINER 2 MICROWAVE OBSERVATIONS WITH THE PREDICTIONS OF THE DISCHARGE MODEL

a) Mariner 2 Observations

μ^{-1}	Location	Latitude	Longitude	T_B
1.00	terminator	-18°.7	88°.3	595 ± 12
1.49	dark side	-6°	137°	490 ± 11
2.04	bright side	-13°.6	27°	511 ± 14

b) T_B for the Discharge Model

	Case 1			Case 2			Case 3			Case 4		
	T_s = 300° K, ϵ = 3.6			T_s = 300° K, ϵ = 1.45			T_s = 450° K, ϵ = 3.6			T_s = 450° K, ϵ = 1.45		
μ^{-1}	τ = 0	τ = 0.1	τ = 0.2	τ = 0	τ = 0.1	τ = 0.2	τ = 0	τ = 0.1	τ = 0.2	τ = 0	τ = 0.1	τ = 0.2
1.00	447	430	414	459	439	421	515	492	471	546	518	493
1.49	526	494	464	537	501	464	537	504	473	593	543	503
2.04	634	575	522	628	561	505	577	528	484	635	567	510

	Case 5		Case 6	Case 7	
	ϵ = 1.45, τ = 0.1		ϵ = 1.45, τ = 0.1, T_s = 536° K	τ = 0.1, T_s = 536° K	
μ^{-1}	T_s	T_B	T_B	ϵ	T_B
1.00	450	518	595	1.45	595
1.49	350	512	615	1.45	615
2.04	550	572	632	3.6	577

We next allow, within the constraints of ground-based observations, for variations in the foregoing parameters with position on the disk. Basharinov, Vetukhnovskaya, Kuz'min, Kutuza, and Salomonovich (1964) have found that the disk-integrated brightness temperature is somewhat larger on the bright than on the dark side of Venus at 8-mm wavelength, and that the phase variation at this wavelength is about half that found by Mayer, McCullough, and Sloanaker (1963) at 3 cm. These results imply, for the discharge model, little positional variation in τ. The decline in the absolute value of the 8-mm brightness-temperature phase variation corresponds to a relative decline in the contribution of the discharge and surface terms to the total brightness temperature by about a factor 2. For fixed τ_d both the electric discharge contribution and the surface contribution are decreased; at the same time the contribution from thermal emission of the clouds (which shows little phase effect at infrared frequencies) is increased. If the optical depth in the illuminated hemisphere were a factor of 2 higher than over the terminator, it is easy to show that the 8-mm brightness temperature at superior conjunction would be significantly less than at dichotomy. Variations greater than about 50 per cent at τ are probably excluded by these observations. From Table 1 we see that allowable variations in τ produce at most a 25 K° variation in the values of T_B, when the millimeter absorber is liquid water in the clouds.

We might seek to invoke a 19-mm absorber other than liquid water in the clouds. Because the surface temperatures are low in the discharge model, the clouds will be close to the surface, and the surface pressures will be small. It is therefore very improbable that pressure-induced dipole transitions of CO_2 or N_2 can cause any significant opacity at these frequencies — ~ 100 atmospheres are required (see, e. g., Ho, Kaufman, and Thaddeus 1966). If atmospheric water vapor were the opacity source, its strong resonance line at 13.5 mm should be prominent at these low pressures (Barrett and Staelin 1964), contrary to observation. Furthermore, carrying out analyses similar to those where the clouds were the opacity source, we find that the optical depth at 19 mm of a pressure-induced dipole or water-vapor opacity source would lie between 0.1 and 0.2. Thus, contradictions between predicted and observed limb darkening would result that are quite similar to those found for absorbing clouds.

Let us next consider positional variations in T_s and T_d. We will take as our starting point the model that is able to secure closest agreement with the Mariner 2 observations, and is in reasonable agreement with ground-based observations, viz., $T_s = 450° K$, $\epsilon = 1.45$, and $\tau = 0.1$. The results of these exercises are shown in Table 1, in Cases 5 through 7. A substantial variation of surface temperature from dark to bright side, as seems physically reasonable, is considered in Case 5. Agreement with observations is improved only slightly. In Case 6, we retain the same values as before of $\overline{T}_s$, $\overline{T}_d$, and $\overline{T}_B$, and set the discharge temperature at the terminator point equal to $\overline{T}_d$. The surface temperatures at each scan position are equated, but not to $\overline{T}_s$; rather they are chosen in such a way as to secure agreement with the terminator scan value of T_B in the Mariner 2 experiment. A very steep decline of surface temperature from equator to pole is required in this case in order to maintain $\overline{T}_B \simeq 620° K$. Had we raised T_d as well as T_s, the limb brightening would have been enhanced. The results are still in pronounced disagreement with the Mariner 2 observations. We have thus far neglected phase variations of $\overline{T}_B$. The introduction of the reported phase effect into the calculations would enhance the peak brightness temperature of the bright-side scan, and decrease T_B for the dark-side scan, each relative to the terminator; agreement with observations would then be even poorer.

We have assumed the surface to be essentially smooth at 19 mm, as we know it to be at decimeter wavelengths. If the surface is in fact rough at 19 mm, the limb brightening would be enhanced. This can be seen in equation (2), where the decline in 1-R with increasing μ^{-1} for a smooth surface makes greater contribution to limb darkening in the first term than the R factor contributes to limb brightening for the second and third terms. Observations of Venus over a period of many months around several inferior conjunctions have shown little time variability in the 12.5-cm reflectivity and therefore little change in the surface dielectric constant at this wavelength. These observations suggest that at 12.5-cm wavelength the dielectric constant does not vary markedly with position on the surface of Venus. However, let us generously assume that at 19 mm, $\epsilon = 1.45$ applies for the terminator and the dark-side points of the Mariner 2 observations, while the value of $\epsilon = 3.6$ applies to the bright-side point. The entry for Case 7 of Table 1 shows the results of this set of assumptions: The discharge model is still in considerable disagreement with the observations. If we now allow for a phase variation in $\overline{T}_B$, good agreement with observations still cannot be secured because the bright-side temperature would be increased by approximately the same amount as the dark-side temperature would be decreased.

Finally, let us consider possible positional variations in the discharge temperature T_d. We might suppose that T_d is characterized by erratic fluctuations in time, and that at the moment of the Mariner 2 observations, T_d was anomalously high at the terminator or anomalously low at the bright- and dark-side points. But observations by Drake (1964) at 10 cm that show excellent agreement in both the absolute value of $\overline{T}_B$ and the variations of brightness temperature with phase for two consecutive apparitions of Venus imply that the discharges do not fluctuate significantly in time. Similarly, to the best of our knowledge, there are no cases of significant day-to-day fluctuations in the Venus brightness temperature. We have assumed the discharging dipoles to have random orientation. If they are preferentially aligned, the intensity of the discharge in the directions of the alignment would decline. But beginning, e.g., with the results of Case 7, a very marked alignment would be required to achieve agreement between the discharge model and the Mariner 2 observations. The dipoles would have to be preferentially aligned normal to the local vertical, whereas the dipole moments of falling charged drops would appear to be aligned along the local vertical, leading to enhanced limb brightening instead of limb darkening. However, even if alignment of the appropriate sign and magnitude were to be achieved, it would imply strongly polarized radiation while the observations point to polarizations of 1 per cent or less (Pollack and Sagan 1965b;

Clark and Kuz'min 1965; Dickel 1967). In fact, the starting point for Plummer and Strong's discharge model is the assumption of a nonpolarized, discharge component to explain the fact that lower values of ϵ are found interferometrically than by radar observations.

Thus, after considering a wide range of possible variations of parameters, we conclude that a discharge model with surface temperatures of 450° K or less is incompatible with the Mariner 2 microwave observations at 19 mm. It follows that only a small discharge component can be present in the Venus microwave emission.

Having subjected the discharge model to a careful scrutiny, we must now inquire whether a hot-surface model can quantitatively account for the various radio observations of Venus. We will consider liquid water in the Cytherean clouds to be the source of the microwave opacities below 3-cm wavelength. On the order of 0.1 gm cm^{-2} of liquid water can supply the needed opacity and reproduce the observed spectrum of Venus within observational uncertainties (Sagan and Giver 1961; Salomonovich 1964; Deirmendjian 1964); this is only a small fraction of the total water probably present in the Venus clouds as ice (Sagan and Pollack 1967).

Mayer et al. (1963) have reported a sizable 3-cm phase effect with the brightness temperature of the illuminated side about 150 K° hotter than on the unilluminated side. Drake (1964) has detected a 10-cm phase effect but with about half the temperature amplitude of the 3-cm results. These observations are reminiscent of similar phenomena on the Moon, and are comprehensible in a straightforward manner from the simultaneous solution of the one-dimensional equation of heat conduction and the equation of radiative transfer: The diurnal thermal wave is damped with depth, and long wavelengths arise from greater depths. The Venus phase observations can be understood quantitatively in terms of electrical and thermal parameters of the surface that are typical of common terrestrial materials (Pollack and Sagan 1965a). The minimum brightness temperature in both cases is achieved slightly after inferior conjunction, implying retrograde rotation, a result that has been deduced independently from the radar observations. Assuming water clouds are the source of the 8-mm opacity, it is possible to predict from the 3- and 10-cm phase effects what the 8-mm phase effect should be. These predictions (Pollack and Sagan 1965a) are in very good agreement with the 8-mm phase effect found by Basharinov et al. (1964). Since the observations allow a variation of more than 100 K° between the day and night hemispheres, it is reasonable to expect an equator-to-pole gradient of similar magnitude (Pollack and Sagan 1965b). Such a temperature variation has been found by Clark and Kuz'min (1965) at 10 cm with the Owens Valley interferometer. These observers also find a temperature difference between the antisolar point and the equatorial limb of about 60 K°, which is consistent with the phase effect found by Drake at the same wavelength. Note that for a discharge model, a much larger variation should be found because of the μ^{-1} dependence of the discharge term. At the beginning of this note, we discussed the consistency of the dielectric constant implied by radio interferometry and that obtained by the radar measurements. Finally, the hot-surface model with absorption in the clouds can quantitatively explain the Mariner 2 observations with a longitudinal temperature gradient consistent with that implied by ground-based phase-effect observations (Pollack and Sagan 1967).

We conclude that the electrical discharge model of the Venus microwave emission is in strong disagreement with the Mariner 2 observations, while the model of the planet invoking a hot surface overlaid by water clouds is consistent not only with the Mariner 2 observations, but also with the microwave phase and interferometric observations and the radar data.

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