The Astrophysical Journal, Vol. 150, December 1967

THE ATMOSPHERE AND SURFACE TEMPERATURE OF VENUS
A DUST INSULATION MODEL*

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Received March 13, 1967; revised May 6, 1967

ABSTRACT

A dust insulation model for the atmosphere of Venus is proposed in which the high surface temperature results primarily from a shielding of energy escaping from the planetary interior. The insulation is provided by micron-sized dust particles which may be kept airborne by mild turbulence. For an outflow of planetary heat of the same order as that on Earth, the required infrared opacity of the dusty atmosphere is $\sim 10^5$ and the same atmospheric structure accounts for the observed microwave spectrum. The dust insulation model predicts a systematic variation of radar reflectivity with wavelength and the observations are in good agreement. The otherwise anomalously low value of the differential polarization measured at 10 6 cm is expected in this model due to atmospheric absorption. The results indicate that the microwave phase effect is primarily an atmospheric phenomenon and hence the conclusions which have been drawn from it on the assumption that it is a subsurface effect are in doubt. If the cloud particle properties observed in the visual region (high particle albedo and strong anisotropy of scattering) exist throughout the atmosphere then it is possible for the incident solar energy to cause a small surface temperature variation despite the huge optical thickness of the atmosphere.

I. INTRODUCTION

It is now well known (Fig. 1) that from 3 cm longward the radio emission from Venus has a brightness temperature of about 600° K in sharp contrast to the 235° K temperature determined from bolometric measurements in the infrared and the 235° K expected for radiation balance with absorbed solar energy (for a bolometric albedo of 0.73).

Our meager knowledge of the atmospheric and surface conditions on Venus has permitted vastly different hypothesis for the origin of this high brightness temperature. The ionosphere model, proposed originally by Jones (1961) attributes the centimeter emission to bremsstrahlung radiation from a Cytherean ionosphere, but this model has various weaknesses such as the required high electron density ($\sim 10^9$ cm^{-3}), the limb-darkening observed at 1.9 cm by Mariner II (Barath, Barrett, Copeland, Jones and Lilley 1964), the relatively constant value of the radar reflectivity with wavelength for $\lambda \geq 12$ cm (§ IV), and the differential polarization measured at 10.6 cm (§ V). In the aeolosphere model proposed by Öpik (1961) the visible clouds are composed of particulate matter held in the atmosphere by a continuous dust and sandstorm and it is assumed that 2 per cent of the solar radiative input is dissipated by friction at the surface of the planet. The mechanism by which this heat engine operates was not worked out by Öpik, but recently circulational models have been calculated by Goody and Robinson (1966) and by Hess (1967) for optically thick atmospheres; these indicate that the wind speeds at the surface would be much too mild to cause the frictional heating. Since it is difficult to construct an effective greenhouse model in the form originally proposed, Sagan and Pollack (1965, 1967) favor a cloud-greenhouse model in which the cloud particles enhance the greenhouse effect and provide the microwave opacity.

* This research was supported in part by the National Science Foundation under grants GP-4742 and GF-207.

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However, we find in §§ IV and V that the radar reflectivities and the differential polarization at 10.6 cm indicate that the microwave opacity is concentrated most heavily near the planetary surface and not in a low temperature cloud region. The nonthermal mechanisms which have been proposed for the microwave emission have not been justified by experimental or theoretical studies showing that they can duplicate the observations.

Although the hot surface models have been considered the most promising, they have a common difficulty in trying to explain how the atmosphere can simultaneously transmit incident solar energy and trap planetary thermal radiation. It is the purpose of this paper to examine the possibility of a source internal to Venus providing the energy to heat the surface. A heat source comparable to that on Earth is assumed, and the required infrared optical thickness of the atmosphere in that case is great enough to suggest that the opacity is provided by dust particles. Some characteristics of the dust insulation model which cannot otherwise be accurately determined are specified by the requirement that the predicted centimeter brightness temperatures for that model corresponds to observations. The remaining observables are then used to test the hypothesized model.

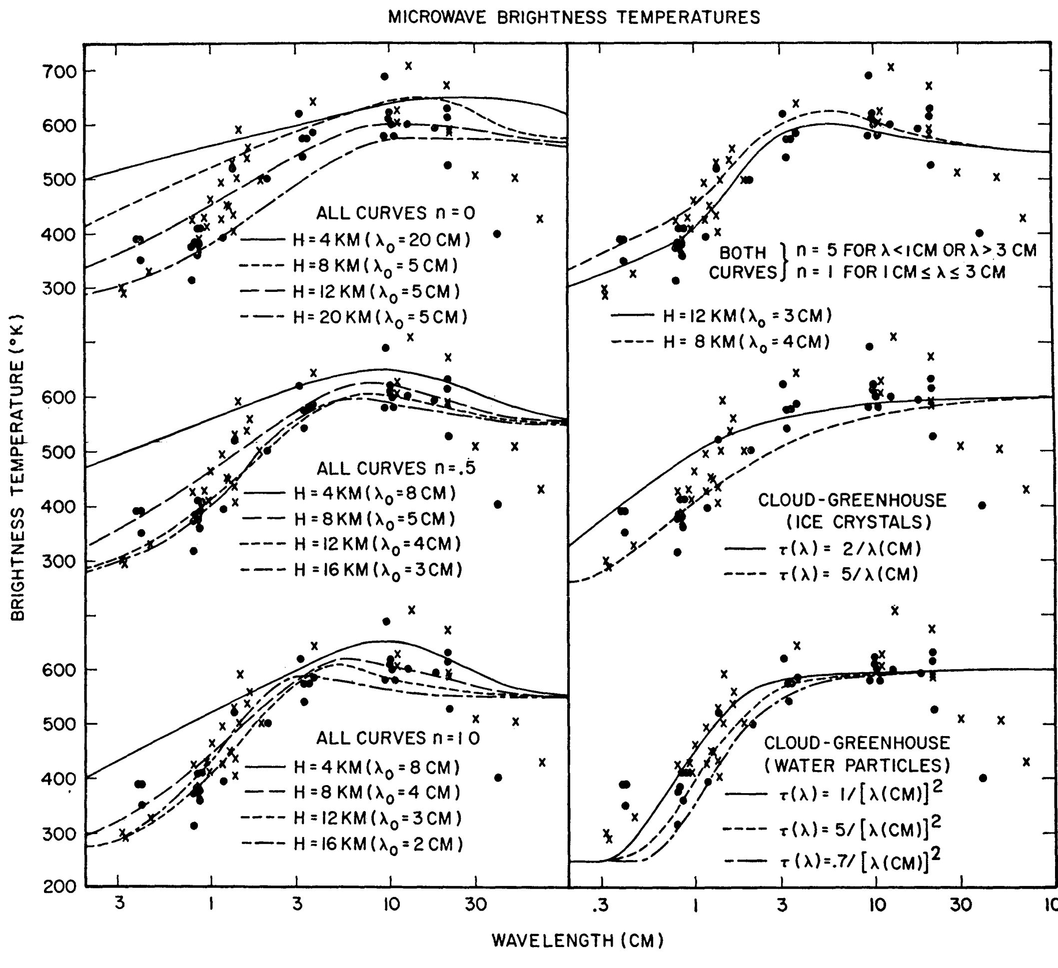

FIG 1.—Observed and theoretical microwave brightness temperatures of Venus The dots correspond to values tabulated by Barrett and Staelin, 1964, while the crosses are values published subsequently and listed by Hansen (1967). *H* is the scale height for the dust distribution, *n* is the exponent giving the wavelength dependence of the loss tangent, and λ_0 is the wavelength at which the optical thickness of the atmosphere is unity.

II. DUST INSULATION MODEL

The brightness temperature measurements, including those of polarization (§ V), strongly suggest that most of the flux observed at wavelengths greater than approximately 3 cm is of thermal origin and originates at the planetary surface. If the ultimate energy source is the Sun, it is difficult to understand how the atmosphere can allow solar energy to reach the surface and at the same time prevent the thermal energy from moving in the opposite direction in any significant quantity. For this reason Deirmendjian (1964) and Kuzmin (1965) suggested, in connection with cloud models, the possibility of the energy source being below the atmosphere, that is, within the planet itself. Although an arbitrarily large source of energy within the planetary interior could cause any surface temperature, we have little basis for hypothesizing an energy source much greater than that on Earth. For a small energy source to heat the planetary surface significantly the atmosphere would have to be much more opaque than in any of the present models, and for the anticipated surface pressure it is not possible for known molecular constituents to provide the required opacity. But particulate matter, due to its essentially unlimited screening ability, can provide a very large opacity. Water and ice particles exist in Earth's atmosphere but not in quantities sufficient to cause the effect in which we are interested and the observations suggest that water is less abundant on Venus. However, the absence of condensates would raise the strong possibility of there being a considerable quantity of solid particulate matter, i.e., dust, in the atmosphere of Venus, since it is the continual process of water-vapor condensation upon dust nuclei that keeps Earth's atmosphere swept reasonably clean of dust. Moreover, the absence of water on the surface of Venus would allow the ground to be a very efficient source of aerosols as compared to Earth, where water causes the formation of minerals which play the role of cement and transform dust particles into coherent rock. Although we do not observe extreme dustiness on the other planets or satellites, another requirement for the existence of an extensive amount of airborne dust is the presence of an atmosphere dense enough to hold up the dust and to contribute to the grinding and fragmentation of the particles.

Thus, we make the following proposition: There is a quantity of dust in the Cytherean atmosphere such that it provides an optical depth of unity at the knee of the radio frequency brightness temperature curve ($\lambda_0 \sim 3$ cm). It is not possible to define precisely the structure of the dusty atmosphere on only the above assumption, but some of the unspecified parameters may be determined by examining the shape of the microwave brightness temperature spectrum.

The most essential of the unknown characteristics are the vertical distribution of the particles and their extinction coefficient as a function of wavelength. To determine the first of these it is helpful to specify the mechanism which keeps the dust particles or aerosols suspended. We will find that the total mass of aerosols above each square centimeter required to fulfil the condition of unit optical depth at the knee of the brightness temperature curve is on the order of 10 gm/cm^2. Although the accretion of meteorites and zodiacal dust might supply this mass in $\sim 10^7$–10^8 years (Millman 1952), a 1-μ particle would fall to the surface in $\sim 10^2$ years and hence this source of particles would be insufficient without some means of continuously relifting the particles. Volcanoes also appear to be an inadequate source since only on the rare occasion of a major eruption on Earth does their contribution exceed that of meteorites.

Thus we will assume that for the atmosphere of Venus to be in a continual state of extreme dustiness there must be a balance between particle sedimentation and uplifting by turbulent or eddy diffusion. Average velocities an order of magnitude or so greater than the particle sedimentation velocity should be sufficient for the eddy diffusion process to be efficient, and this would require velocities only on the order of a centimeter per second for micron sized particles. It is also necessary for particles which sediment out to be replaced at some time by lifting from the surface and this requires a certain minimum "drag velocity," $v*$, which is a characteristic velocity associated with the turbulent air motion. On Earth if $v*$ exceeds about 15 cm sec^{-1} and if there are grains present on the surface of optimum size ($\sim$0.01–0.1 mm) then grain motion results and smaller-sized dust particles may become airborne (Gifford 1964; Ryan 1964). However, the required value for $v*$ may easily be an order of magnitude less on Venus since it is proportional to $\rho^{-5/6}$, where ρ is the surface air density (Gifford 1964). $v*$ may be converted to the horizontal wind speed at 1 meter altitude if the degree of surface roughness is known. For $v* = 1.5$ cm sec^{-1} and a roughness characteristic of Earth the required horizontal wind speed on Venus is 10–20 cm sec^{-1} (Gifford 1964). Since the depolarization of radar signals reveals some areas of extreme roughness the required wind speed may be still less and this wind speed would only need to occur in occasional "gusts."

The vertical distribution of the particles is approximately determined by the assumption of a balance between particle sedimentation and turbulent uplifting. If the dust particles are well mixed with the molecular constituents then they would have an approximately exponential distribution with a scale height of 15–20 km near the surface. Although particle fallout would prevent complete mixing, it might be possible to approximate the true distribution by using some smaller value of the scale height. The theoretical calculations of Junge, Chagnon, and Manson (1961) for the distribution of particles in the terrestrial atmosphere under an equilibrium between eddy diffusion and sedimentation yielded an approximately exponential distribution with a scale height of $\sim$4 km for a particle size of 0.15 μ and an eddy diffusion coefficient $\sim$2000 cm^2 sec^{-1}. Also an approximately exponential distribution with a scale height $\sim$3.3 km has been found in an analysis of the dust distribution in Earth's atmosphere by Matsushima (1967) which was based on direct samplings of aerosols by Rosen (1964). Under similar circumstances on Venus the scale height would be perhaps twice as large due to the larger molecular scale height.

The size distribution of the particles is determined largely by the simultaneous action of sedimentation, which controls the upper size limit, and coagulation, which controls the lower size limit. We may again examine Earth's atmosphere since these processes would not be too seriously affected by changes in the atmospheric conditions. In the terrestrial case under normal conditions the atmospheric aerosols have a fairly sharp upper limit for the size distribution at a radius of about 20 μ over both land and sea (Campen 1961), and theoretical computations by Junge (1963) indicate that this limiting size does not change greatly when the eddy diffusion coefficient, the surface roughness, and the mean wind speed are varied. Hence it seems safe to conclude that there are few solid particles larger than $\sim$50 μ suspended in the atmosphere of Venus. For the present computations of microwave observables the upper size limit and the total volume of particles above unit area are the only characteristics of the size distribution required.

We may now estimate the extinction coefficient for the dust particles. For scattering in the microwave range the Rayleigh approximation is valid since $\lambda \gg a$ (a = particle radius), and hence the scattering cross-section of a single spherical particle is

$$\sigma_S = \tfrac{2}{3}\pi^5 \frac{(2a)^6}{\lambda^4}\left|\frac{\epsilon_c - 1}{\epsilon_c + 2}\right|^2 \text{cm}^2 , \tag{1}$$

where $\epsilon_c = \epsilon_r - i\epsilon_i$ is the complex dielectric constant of the particle. The cross-section for absorption by the same particle is

$$\sigma_A = \frac{3\pi^2(2a)^3}{\lambda} \frac{\epsilon_i}{(\epsilon_r + 2)^2 + \epsilon_i^2} \text{cm}^2 . \tag{2}$$

Below we show that for plausible constituents of the Cytherean surface

$$0.001 \lesssim \epsilon_i \lesssim 1 \tag{3}$$

and

$$3 \lesssim \epsilon_r \lesssim 10 \tag{4}$$

and hence

$$\frac{\sigma_S}{\sigma_A} \simeq \frac{2}{9}\left(\frac{2\pi a}{\lambda}\right)^3 \frac{(\epsilon_r - 1)^2}{\epsilon_i}. \tag{5}$$

From expressions (3)–(5) it is apparent that in the region of interest $\sigma_S \ll \sigma_A$ and hence the optical thickness above unit area is closely approximated by

$$\tau(\lambda) \simeq \int_0^\infty \int_0^\infty n(a,h)\sigma_A(a,\lambda,\epsilon_c)\,da\,dh \tag{6}$$

$$= \frac{\epsilon_i}{\lambda\{(\epsilon_r + 2)^2 + \epsilon_i^2\}} \int_0^\infty \int_0^\infty c' n(a,h)\,da\,dh\,, \tag{7}$$

where c' is a constant, independent of both λ and ϵ_c. The latter form neglects the possible dependence of σ_A on h and although this is not strictly legitimate since ϵ_c may be temperature dependent, we do not have theoretical or experimental data on $\epsilon_c(T)$ at the wavelengths of interest adequate for a more detailed consideration. Using equation (7) we can determine the optical thickness of the atmosphere as a function of wavelength from a knowledge of the complex dielectric constant of the absorbing particles along with the condition that $\tau = 1$ at $\lambda = \lambda_{\text{knee}} \equiv \lambda_0$.

Equation (7) indicates the dependence of the absorption coefficient of the dust particles upon ϵ_c and hence upon the composition of the dust. Since we do not have measurements of ϵ_c for all possible dust constituents we note the physical significance of the dielectric constant (see, e.g., von Hippel 1954*a;* Pollack and Sagan 1965*a*). The real part of the dielectric constant, ϵ_r, is a measure of the polarizability of the material and the four primary sources, electronic, atomic, orientation, and space charge polarization, have characteristic frequencies in the ultraviolet and visible, in the infrared, in the microwave, and in the radio frequency regions, respectively. Since in a solid the molecular dipole moment is not free to rotate, orientation polarization does not operate in dust particles, and ϵ_r must be independent of wavelength in the microwave region.

Although ϵ_i is generally much less than ϵ_r, its value and wavelength dependence are as significant as those of ϵ_r. Barrett and Staelin (1964) implicitly assumed that ϵ_c was wavelength independent for dust particles and Kuzmin (1965) explicitly made that assertion. To determine the possible wavelength dependence of ϵ_i we resort to the few experiments which have been made in the microwave domain. The results have generally been expressed in terms of the loss factor k defined by

$$k = \frac{\sigma}{\nu}, \tag{8}$$

where ν is the frequency and σ the electrical conductivity. Since σ is treated as a measure of all energy loss mechanisms it includes a magnetic dissipation term, but for nonmagnetic materials k is the same as ϵ_i and hence we will examine k directly for wavelength dependence.

Using the measurements of k made at wavelengths 10, 3, and 1.2 cm (von Hippel 1954*b;* Westphal 1963) we can determine an exponent $n(\lambda_1,\lambda_2)$ specifying the average wavelength dependence over the interval λ_1 to λ_2

$$\frac{k(\lambda_1)}{k(\lambda_2)} = \left(\frac{\lambda_1}{\lambda_2}\right)^{-n(\lambda_1,\lambda_2)}. \tag{9}$$

For a number of materials having the required measurements of k available we have calculated n and tabulated the results in Table 1; at least some of the materials may be relevant to Venus. The table also includes values of k_3 cm. If the primary constituent has a small value of k, then impurities may be very important in determining the correct value of k and its wavelength dependence. The measurements upon which Table 1 is based were made at room temperature, but k may have a significant temperature dependence. At higher temperatures k would be larger (Pollack and Sagan 1965*a*), but laboratory measurements in the microwave region are not available. It appears from Westphal's (1963) measurements at lower frequencies, though, that n is probably smaller at higher temperatures and it would be desirable to have the requisite measurements performed. We note here that for most of the materials n is in the range $0 \lesssim n \lesssim 1$ and may differ significantly from zero.

TABLE 1*

MATERIAL PROPERTIES IN THE MICROWAVE REGION

Material	References†	3 cm Loss Factor $k \times 10^4$	$n_{1\ 2-3\ cm}$ (eq. [9])	$n_{3-10\ cm}$ (eq [9])
Sulfur (sublimed)	(a)	1.5	. . .	1 09
Magnesium silicate	(a)	26	0 42	0 30
AlSiMag (93% Al_2O_3, 6% SiO_2, 1% MgO)	(a)	9 7	0 40	. . .
Magnesium titanate (titanium alloy)	(a)	28	0 92	0 31
Aluminum oxide	(a)	27	. . .	0 43
Glass (96% SiO_2)	(a)	9 4	0 36	0 27
SiO_2 (fused quartz)	(a)	1	1 00	0 43
Soda-silica glass (20% NaO, 80% SiO_2)	(a)	200	0 37	. . .
Selenium (amorphous)	(a)	6 7	0 72	1 09
Mica glass	(a)	48	0 57	0 19
Limonite (powder, $2Fe_2O_3$ $3H_2O$)	(b)	3700	.	0 31
Magnetite soil (Fe_3O_4)	(b)	810	. .	0 58
Enstatite (ceramic, $MgSiO_3$)	(b)	300		0 31
Wollastonite (ceramic, $CaSiO_3$)	(b)	170	. . .	0 31
Steak (round)	(a)	3700	0 09	0 17

* The values in this table apply for room temperature.

† (a) von Hippel, 1954*b*
(b) Pollack and Sagan, 1965*a*.

III. MICROWAVE BRIGHTNESS TEMPERATURES

In computing the brightness temperature spectrum a method similar to that used by Barrett and Staelin (1964) was employed. The planetary surface was assumed to be smooth and to have a dielectric constant of 6. The first assumption is accurate at long wavelengths as shown by radar reflections (§ IV), and although the planet becomes rougher toward the shorter wavelengths of interest, the error introduced would not be important since at those wavelengths almost all of the observed radiation originates in the atmosphere and not from the planetary surface. The value used for the dielectric constant is also a result of the radar measurements (§ IV) and since the low values of the reflectivities indicate that the Cytherean surface material is not a good conductor, we could use the following expressions (Stratton 1941) to specify the angular dependence of the surface reflectivities

$$\rho_r(\theta) = \left[\frac{(\epsilon - \sin^2\theta)^{1/2} - \epsilon\cos\theta}{(\epsilon - \sin^2\theta)^{1/2} + \epsilon\cos\theta}\right]^2 \tag{10}$$

and

$$\rho_l(\theta) = \left[\frac{\cos\theta - (\epsilon - \sin^2\theta)^{1/2}}{\cos\theta + (\epsilon - \sin^2\theta)^{1/2}}\right]^2, \tag{11}$$

where ρ_r and ρ_l are the reflectivities for waves having the electric field vector respectively perpendicular and parallel to the surface. In these expressions the dielectric constant, ϵ, is the ratio of the permittivity of the surface to the permittivity of free space and θ is the angle between the direction of incidence and the surface normal. The above reflectivities were also used to determine the surface emissivities, e_r and e_l, by Kirchhoff's law.

For each atmospheric model the computations were made as follows. From the cloud tops, where $T_c = 235°$ K, to the planetary surface, where $T_s = 700°$ K, the atmosphere was divided into layers each 1 km thick. The flux density incident upon the surface was then calculated in terms of the brightness temperature of the downward-moving radiation by means of the following equation valid for pure absorption

$$T_{r,l}^{\downarrow}(h-\Delta h,\theta) \simeq T_{r,l}(h,\theta)\,e^{-\Delta\tau} + T\left(h-\frac{\Delta h}{2}\right)[1-e^{-\Delta\tau}] \tag{12}$$

where

$$\Delta\tau = \Delta\tau(h,\theta) = \int_{h-\Delta h}^{h} \kappa(h,\theta)\,dh \tag{13}$$

and κ (h, θ) is the absorption coefficient per vertical kilometer. At the planetary surface $T_{r,l}^{\downarrow}(0, \theta)$ and ρ (θ) were used to find the amount of energy reflected upward and this was added to the thermal energy emitted by the surface;

$$T_{r,l}^{\uparrow}(0, \theta) = T_{r,l}^{\downarrow}(0, \theta)\,\rho\,(\theta) + e\,(\theta)\,T_S\,. \tag{14}$$

The flux of radiation emerging from the top of the atmosphere was then calculated by means of an equation similar to (12).

The optical thickness of the atmosphere was taken as

$$\tau(\lambda) = t\lambda^{-1-n(\lambda)} \tag{15}$$

with t a constant. The temperature optical depth relation in the atmosphere was specified obliquely by temperature-altitude and optical depth-altitude relations. In the dust insulation model, at least the lower atmosphere should be in a dry adiabatic state (§ VII), so that

$$\frac{dT}{dh} = \frac{-g}{c_p}; \tag{16}$$

since the variation of c_p with temperature and pressure is not large, dT/dh was taken to be constant with a value (8.7° K/km) appropriate for nitrogen. Any error in dT/dh would have a small net effect since it would only modify the angular factor in $\Delta\tau$ (see below). Finally, $d\tau/dh$ was found from

$$\frac{d\tau}{dh} \propto e^{-h/H} \tag{17}$$

as discussed in § II.

This method yielded the brightness temperature at points on the disk specified by the angle θ for each of the two linear polarizations, $T_r(\theta)$ and $T_l(\theta)$. The brightness temperature for a triangular slice of the planet's disk, was then found by weighting the brightness temperature at each θ by the solid angle seen at Earth:

$$T_{r,l} = \int_0^{\pi/2} T_{r,l}(\theta)\sin 2\theta\,d\theta\,. \tag{18}$$

Then, for an isothermal planetary surface, the average temperature which would be observed over the entire disk was the arithmetic mean of T_r and T_l.

In the calculation of $\Delta\tau(h,\theta)$ the effect of planetary curvature on the path lengths through each layer was accounted for as follows: From Figure 2 we see that, neglecting refraction, the correct angular factor is sec $(\theta - \alpha)$ but α must be put in terms of the variables of the problem. From the triangle including $\theta - \alpha$

$$d\alpha/\tan(\theta - \alpha) = dh/(R_v + h) ,$$

where R_v is the radius of Venus. Integrating from $h = 0$ to $h = h$

$$\sec(\theta - \alpha) = \left[1 - \left(\frac{R_v \sin\theta}{R_v + h}\right)^2\right]^{-1/2} . \tag{19}$$

In some of the computations $n(\lambda)$ was assumed to be constant over the frequency range of interest. In Figure 1 are given the results of the brightness temperature computations for $n = 0$, and it is seen that regardless of which vertical distribution is used for the particles, the steep rise in the observed spectrum cannot be reproduced. From Figure 1 we see that $n = 0.5$ cannot necessarily be ruled out, although $n = 1$ seems to provide

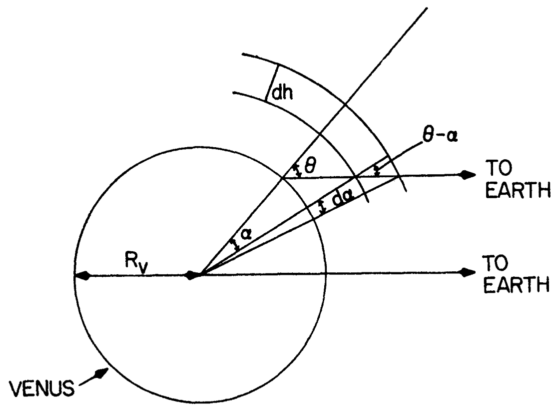

FIG. 2.—Coordinate system used for the derivation of the term giving the angular dependence of the absorption optical depth.

a better fit to the observations. In both cases the models with $H = 12$ km and $H = 16$ km fit the observations about equally well but it is apparent that small values of H (<8 km) cannot be correct.

The approximation $n =$ constant was examined. Figure 1 shows the computed brightness temperatures for

$$n = 0.5 \quad \text{for} \quad \lambda < 1 \text{ cm and } \lambda > 3 \text{ cm} ,$$

$$n = 1.0 \quad \text{for} \quad 1 \text{ cm} \leq \lambda \leq 3 \text{ cm} ,$$

which corresponds approximately to the measured values for SiO_2 at room temperature (Table 1). The results indicate substantial agreement with the observations and when other values of n were used for $\lambda < 1$ cm and $\lambda > 3$ cm it was found, as might have been anticipated, that these changes had little effect on the computed brightness temperatures. Hence, as far as the microwave brightness temperatures are concerned, it is probably sufficient to take n as a constant equal to its value in the 1–3 cm range.

It may be noted in Figure 1 that a certain decrease in the brightness temperature occurs in the dust model for $\lambda > 10$ cm and the observations suggest that such an effect does exist. It occurs in the dust model since the emissivity of the ground is less than unity and since the radiation in the interval 3–10 cm arises mainly from the atmosphere just above ground level where the temperature is nearly equal to the surface temperature, but a cloud model would not produce such an effect.

Thus, we see that it is possible for the dust insulation model to provide an adequate fit to the observations of brightness temperature and this conclusion differs from the results obtained earlier by other investigators for a dusty atmosphere (Barrett and Staelin 1964; Kuzmin 1965). Our calculations differ in this respect primarily because we include a variation with wavelength of the imaginary part of the dielectric constant, and we have shown that such a variation could be expected. In the process of showing that the insulation model can match the observed spectrum we found that the unknown parameters, H and n, are probably in the ranges

$$8 \text{ km} \lesssim H \lesssim 16 \text{ km} \tag{20}$$

and

$$0.5 \lesssim n \lesssim 1 \tag{21}$$

and these are within the ranges which we found in § II to be the most likely.

IV. RADAR CROSS-SECTIONS

In Figure 3 we have plotted the published radar cross-sections of Venus obtained during the 1962 conjunction and subsequently. The two very low values between 3 and 4 cm are in agreement with a previous unsuccessful attempt by Karp to measure the re-

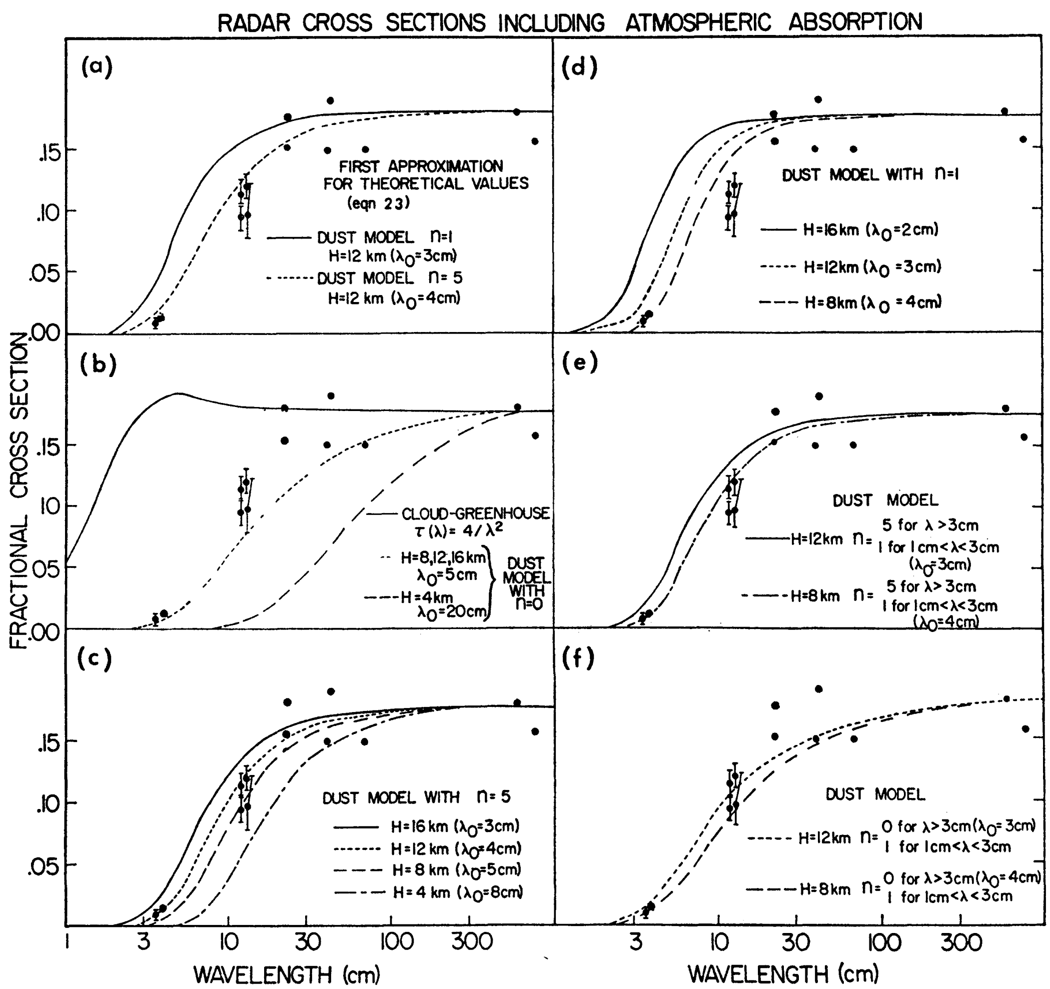

FIG. 3.—Observed and theoretical radar cross sections of Venus. H, n, and λ_0 are the same as in Figure 1. The two curves in the upper left were determined from equation (23) while the remaining curves include the effect of scattering from the entire disk.

flectivity at 3.6 cm (Barrett and Staelin 1964) which established an upper limit of 1 per cent. The difficulty in finding planetary surface materials to provide such a low intrinsic reflectivity and the much higher reflectivities measured at longer wavelengths together suggest atmospheric absorption as the primary cause of the low reflectivity.

The reflectivity at long wavelengths should correspond to the intrinsic reflectivity of the planetary surface material as a consequence of the fact that all the atmospheric models predict negligible absorption in that region. In addition, at long wavelengths it is expected that the planet should appear smooth in which case the measured reflectivity would be equal to ρ (0), the reflectivity at normal incidence. From equations (10) and (11)

$$\rho_r(0) = \rho_l(0) = \left(\frac{\epsilon^{1/2} - 1}{\epsilon^{1/2} + 1}\right)^2 \equiv \rho(0). \qquad (22)$$

Then from the measured value for ρ (0) the reflectivities at any angle may be found by expressing ϵ in terms of $\rho(0)$ in equations (10) and (11). The radar cross-sections as they would be measured on Earth may then be obtained provided that the absorption coefficient of the atmosphere is known at each wavelength. The problem is complicated somewhat by the fact that at shorter wavelengths the Cytherean surface appears rougher, and hence part of the reflection is returned from even the limb region. Since the atmospheric absorption is greater for the slant paths, the distribution of reflected power over the planetary disk must be obtained at each wavelength.

We may make a first-order approximation by assuming that the planet is a smooth sphere, in which case all of the reflected radar signal would be returned from near the center of the disk. Then the measured cross-section is given by

$$\frac{\sigma}{\pi a^2} = \rho(0)\, e^{-2\tau(\lambda)}, \qquad (23)$$

and in Figure 3, *a*, we have graphed this function for the insulation model and for the cloud-greenhouse model assuming that the reflectivity of the solid surface at normal incidence is approximately wavelength independent in the region of interest, ρ (0) = 0.18.

The assumption of a smooth surface, which introduces an error which is a function of wavelength, may be eliminated if the distribution of reflected power over the planetary disk is specified. This has been done by Hansen (1967) who assumed that a fraction, f, of the reflected radiation was scattered quasi-specularly and the remaining part was scattered diffusely. This f was determined at each wavelength having sufficient observations available, and the results of numerical calculations for the reflectivity are shown in Figure 3, *b–f*. These results do not differ greatly from those obtained using the simpler equation (23), and this is largely a consequence of the fact that there are two effects in the more detailed approach which work in opposite senses. Toward shorter wavelengths the increased planetary roughness causes more reflection from the limb region and hence more atmospheric absorption of the signal, but at the same time the backscattering function for the diffuse component reflects preferentially toward the radar. The absorption effect is generally larger and hence the more exact theory reduces the predicted cross-section, but the change was significant only at short wavelengths where it was assumed that almost all of the reflected energy was scattered diffusely (e.g., at $\lambda = 5$ cm the detailed computations reduced the fractional cross-section from 9 to 6.5 per cent). Moreover, the most recent observations (Evans, Ingalls, Rainville, and Silva 1966) indicate that the surface roughness at $\lambda < 12$ cm is much less than that used by Hansen and hence equation (23) should be adequate.

From Figure 3, *b*, we see that $n = 0$ predicts a too low reflectivity at all wavelengths and this model had previously been rejected on other counts. Figure 3 shows that the dust insulation model is in good agreement with the observed radar reflectivities if n

averages 0.5 to 1 in the 1–10-cm range and if $H \sim 12$ km and these values are just those demanded by the brightness temperatures (§ III). We note finally that radar measurements in the 3.6–12.5-cm transition region would be helpful in determining the atmospheric properties and additional measurements are needed at long wavelengths to better define the reflectivity for no absorption.

V. POLARIZATION OF THERMAL EMISSION

Measurements of differential polarization over the surface of Venus were made recently at a wavelength of 10.6 cm by Clark and Kuzmin (1965). The absolute fringe visibilities were limited to an accuracy of 3 per cent by gain variations, but the differences between perpendicular measurements had a probable error only one tenth as great, and hence we will consider the differential polarization measurements.

In the following we first consider Venus as being a smooth homogeneous planet having a uniform temperature T, a dielectric constant ϵ, and a magnetic permeability equal to that of free space. In this approximation we may use the brightness temperatures in two polarizations computed in § III, $T_r(\theta)$ and $T_l(\theta)$. We will compute the brightness temperature T_r' or T_l', which would be observed by a radiotelescope accepting a single linear polarization oriented on the planet's disk at an angle φ_0 with respect to the planet's equator. The planet's equator is defined by the orbital plane. T_r' and T_l' are each a linear combination of T_r and T_l depending upon the location of the baseline projected onto the disk:

$$T'_{r,l}(\theta,\varphi) = T_{r,l}(\theta,\varphi) \cos^2 (\varphi - \varphi_0) + T_{l,r}(\theta,\varphi) \sin^2 (\varphi - \varphi_0) . \tag{24}$$

Rectangular coordinates on the apparent disk of Venus are also defined with the origin at the center of the disk. The y direction is specified by the angle φ_0 and the z-direction is orthogonal to the y-axis and in the plane of the apparent disk. Then the fringe visibility, F, which is the ratio of the brightness temperature seen by the interferometer to the brightness temperature of the unresolved disk, is given by (Heiles and Drake 1963; Pollack and Sagan 1965*b*):

$$F_{r,l} = \frac{\int_{\text{disk}} T'_{r,l}(\theta,\varphi) \cos[\gamma(y/R_v)]\, d\Omega/\Omega}{\int_{\text{disk}} T'_{r,l}(\theta,\varphi)\, d\Omega/\Omega}, \tag{25}$$

where

$$\gamma \equiv \frac{2\pi b}{\lambda} \frac{R_v}{D} .$$

D is the distance from Venus to the observer, R_v is the radius of Venus, b is the interferometer spacing projected onto Venus, and Ω is the solid angle subtended by Venus at the observing point.

The measurements of Clark and Kuzmin, in the form $F_r - F_l$, are plotted in Figure 4. In the same figure we have plotted the differential visibility functions for an atmosphereless planet with different values for the surface dielectric constant, and according to Clark and Kuzmin a least-squares fit of the observational results with the calculated functions yields

$$\epsilon = 2.2 \pm 0.2 .$$

This value would be raised somewhat by considerations of surface roughness and nonuniform surface temperatures, but these effects should be small (Clark and Kuzmin 1965) and a spatial variation of ϵ could not be expected to have an effect much different from that due to a variation of T. Hence, there is clearly a serious discrepancy between the values of ϵ as determined by the visibility functions and as determined by the radar reflections ($\epsilon = 2.2$ corresponds to a reflectivity of only 3.75 per cent), and it is of interest to examine whether the inclusion of atmospheric effects will reduce the discrepancy.

Using the values for T_r and T_l calculated in § III we computed the values of F_r and F_l corresponding to the model atmospheres considered in that section. It should be noted that since we expressed the equations for F_r and F_l in terms of T_r and T_l, rather than in terms of the surface temperature and emissivity, the effect of the atmosphere was automatically included. The differential polarizations shown in Figure 4 were obtained from equations (24) and (25). Since at 10.6 cm the atmospheric absorption is negligible in the cloud-greenhouse model, the results shown in Figure 4 for no atmosphere apply to that model. For the dust model the low values for the fringe visibilities are due to atmospheric absorption and Figure 4 reaffirms that the most probable value for the scale height is $H = 12 \pm 4$ km. Thus, we conclude that the differential fringe visibilities which are predicted by the insulation model are in substantial agreement with the observed values.

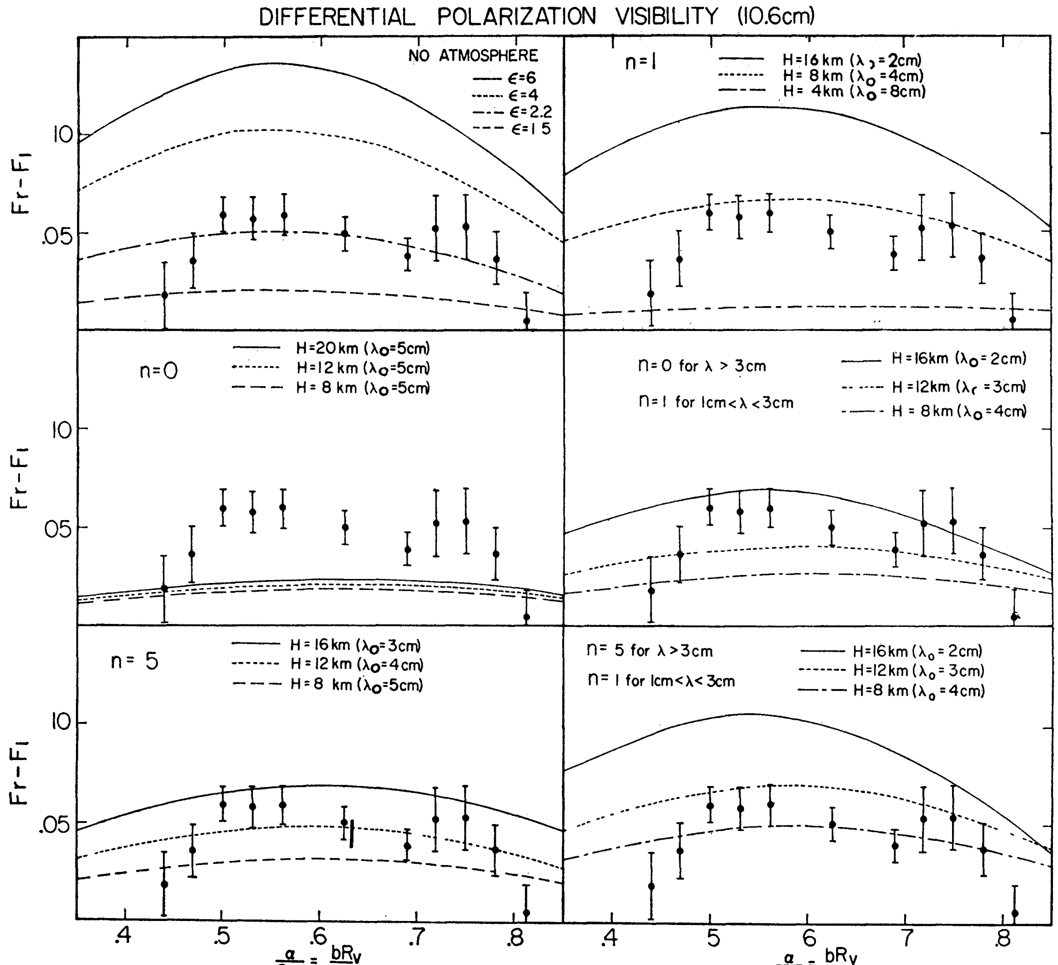

FIG. 4.—Observed and theoretical differential fringe visibilities of Venus at 10.6 cm. H, n, and λ_0 are the same as in Figure 1 and ϵ is the dielectric constant of the surface. In all curves ϵ is taken as 6, except those in the upper left.

VI. MICROWAVE PHASE EFFECT

The microwave phase effect provides another potential source of information about the Cytherean surface. If the brightness temperature as a function of phase angle Φ is expressed as

$$T_B(\lambda) = T_a + T_b \cos(\Phi - \Phi') ,$$

where T_a, T_b, and Φ' are independent of phase angle, then the published values for the phase amplitude T_b, with a minus sign indicating a lower temperature on the illuminated side of the planet, are: T_b (3.4 mm) $= -12°$ (Wilson, Epstein, Oliver, Schorn, and Soter 1966); T_b (8 mm) $= 41°$ (Basharinov, Vetukhnovskaya, Kuzmin, Kutuza and Salomonovich 1964); T_b (3.15 cm) $= 73°$ (Mayer, McCullough and Sloanaker 1963); T_b (3.75 cm) $= 60°$ (Dickel 1966); T_b (10 cm) $= 41°$ (Drake 1964); T_b (10.6 cm) $< 15°$ (Kuzmin 1966); and T_b (21.2 cm) $< 12°$ (Davies and Williams 1966). The probable errors given by the authors are generally small, but there are possibilities of systematic errors perhaps even as large as the phase amplitudes themselves.

It has generally been assumed that the phase effect should be interpreted mainly in terms of the properties of the surface of the planet. A temperature variation at the surface would be communicated to the subsurface region but with depth it would be damped in amplitude and thus, since the longer wavelengths are generally less penetrating, the decrease of the phase amplitude toward longer wavelengths would be qualitatively accounted for. However, we have shown that the systematic variation of radar reflectivity with λ (§ IV) and the unexpectedly low value of the differential fringe visibility at 10.6 cm (§ V) together argue forcefully that there is non-negligible atmospheric absorption not only at 3 cm, but also at 10 and 12 cm regardless of whether it is provided by dust particles or some other opacity source. Another reason for rejecting the unmodified subsurface interpretation is the sharp decline of the phase amplitude T_b from 3 to 20 cm. If the subsurface interpretation is valid and if the thermal parameters estimated by Kuzmin (1966) are accepted, then a brightness temperature amplitude of 60° K at 3 cm would imply amplitudes of $\sim$50° and $\sim$40° at 10.6 and 21.2 cm, respectively, in contradiction to the observations. Moreover, the quantity of excess heat stored in the atmosphere of the hot hemisphere is at least on the same order as that radiated from the dark hemisphere in one Cytherean night if the temperature difference between the two hemispheres is only $\sim$50° K and if the surface pressure is $\sim$10 atm, and hence it is not necessary to assume that thermal waves from the subsurface communicate or store any of the radiated energy.

For the above reasons we believe that the microwave phase effect should be interpreted as primarily an atmospheric phenomenon with the surface conditions entering as perturbations. For the atmospheric opacities found in §§ IV and V and for reasonable surface thermal parameters it follows that at wavelengths great enough for the emission to penetrate that atmosphere it comes from a depth where the thermal wave is already damped to a negligible value. Consequently the decrease of the phase amplitude toward long wavelengths is a result of the decreasing optical thickness of the atmosphere toward large λ and the sharp drop from 3 to 21 cm is more readily understood.

Although the inverse phase effect found at 3.4 mm is a surprising result, it is easier to interpret in the dust model than in most of the others. A greenhouse model with CO_2 or H_2O as the microwave absorber would predict a strong positive phase amplitude since the absorption coefficients of these gases depend on an inverse power of the temperature. However, the absorption in dust particles increases with temperature, and hence it may be that on the dark side of the planet we see to a greater depth and hence a higher temperature. The actual situation, however, may be considerably complicated by changes in the lapse rate and in the cloud altitude between the bright and dark hemispheres.

We emphasize finally that the conclusion drawn from the microwave phase effect on the basis of its subsurface interpretation are not necessarily valid. In particular the differences of several hundred degrees in the surface temperature deduced by Pollack and Sagan (1965*a*) are not required if the phase effect refers mainly to the lower atmosphere rather than to a subsurface level where the thermal wave is damped and where the emissivity is less than unity.

VII. SURFACE TEMPERATURE

For the calculations in § IV to § VI it was assumed that the surface temperature of Venus is on the order of 700° K. In order to test the self-consistency of the dust insulation model, it is necessary to examine whether the same model which was found to produce the observed spectrum in the microwave region would indeed cause the planetary surface to have a high temperature. For this purpose we would like to find the temperature distribution in an atmosphere which is bounded below by a surface supplying a constant flow of thermal energy πf (ergs cm^{-2} sec^{-1}) while the upper boundary of the atmosphere receives solar radiation in the visible region of amount πF (ergs cm^{-2} sec^{-1}) normal to the direction of incidence. We may neglect conduction since the energy transferred by that means would be small (see, e.g., Kuzmin 1965). Although some convection must operate and in fact we have argued that the existence of turbulent or eddy diffusion is required in order for the atmosphere to maintain its dusty state, the energy transferred by this process need not be large. With a strictly adiabatic lapse rate there would be no heat transfer by turbulence even if it were serving to relift dust particles. Hence we will consider the case of radiative equilibrium. Then in regions in which the lapse rate is calculated to exceed the adiabatic value, the true gradient must be near the adiabatic one and a certain amount of heat must be transferred by the turbulence. We will here neglect the atmospheric heat capacity and possible horizontal advection although the model for the atmospheric circulation proposed by Goody and Robinson (1966) will be mentioned below.

Even with the above restrictions the problem is complex, but we will make simplifications in two directions: (*a*) exclude scattering, include absorption and internal heat source; (*b*) exclude internal heat source, include scattering and absorption. We will then argue that the two resulting solutions may be combined for an approximate evaluation of the surface temperature.

We first consider the case of pure absorption which was recently treated by Wildt (1966) in a paper on the greenhouse effect. Wildt finds the temperature distribution in the case of pure absorption in an atmosphere in which both the absorption coefficients for incident solar radiation and escaping planetary radiation are gray although their ratio, n, may differ from unity. In fact the gray approximation should be more nearly correct in the dust insulation model than in the greenhouse model since the absorption by a size distribution of dust particles is not such a strong function of wavelength as molecular absorption.

In the problem considered by Wildt a parallel insolation flux, πF, is incident at an angle θ_0 to the surface normal of a semi-infinite plane-parallel atmosphere which has absorption coefficients k_v and k_i in the visible and thermal infrared. The local rate of isotropic emission is given by

$$4\pi k_i B(\tau,\mu_0) = 4k_i\sigma T^4(\tau) ,$$

where

$$\tau = \int_x^\infty k_i dx .$$

Then the solution for the source function is (Wildt 1966)

$$B(\tau,\mu) = \tfrac{3}{4}h(\tau)f + ng(\tau,n/\mu_0)F \tag{26}$$

where

$$h(\tau) = \tau + q(\tau)[0.577 \leq q(\tau) \leq 0.710] \text{ and } g(\tau,n/\mu_0)$$

is the normalized Neumann solution of the non-homogeneous Milne equation. In equation (26) we may replace $h(\tau)$ by τ since the atmosphere of Venus is optically thick in the infrared region. Since Venus radiates with nearly the same efficiency from both hemispheres, we may write πF in terms of the effective temperature of the incoming solar radiation T_e such that

$$\pi F = \sigma T_e^4 = \sigma T_\odot^4 R_\odot^2(1 - A_b)/4d^2 , \tag{27}$$

where $T_\odot$ is the effective temperature of the Sun, $R_\odot$ the solar radius, d the distance from Venus to the Sun, and A_b the bolometric albedo of Venus. For $A_b = 0.73$ (Rasool 1963) we find $T_e = 235°$ K.

If the energy escaping from the planetary interior is represented by a parameter α such that

$$\pi f = \alpha\sigma T_e^4 , \tag{28}$$

then from equations (26)–(28)

$$T/T_e = [\tfrac{3}{4}\alpha\tau + ng(\tau,n/\mu_0)]^{1/4} . \tag{29}$$

The first of the two terms inside the brackets gives the contribution of the internal heat source to the atmospheric temperature while the second term represents that due to a greenhouse effect. Although a greenhouse effect may contribute partially to the high surface temperature and although forward scattering can cause a similar effect (see below), we would like to see if the internal source may provide the major contribution to the high surface temperature. Hence we temporarily put $g = 0$ in equation (29) and find that in order to cause $T \sim 600°$ K the product $\alpha\tau$ must be ~ 50. For an outflow of heat similar to that on the earth (2×10^{-6} cal/cm^2 sec, Allen 1963) $\alpha = 5 \times 10^{-4} \equiv \alpha_1$ and hence the infrared optical thickness required for the dust model to "explain" the high surface temperature is $\sim 10^5$. If we consider a heat flow 10 times that on Earth, α_{10}, the requisite infrared optical thickness of the atmosphere becomes $\sim 10^4$.

The principal question which we must examine is whether the same atmosphere which agreed with the microwave measurements actually predicts this huge infrared opacity which is required for the insulation effect to operate. For spherical particles we may write the infrared optical thickness of the atmosphere as (since we are considering the case of pure absorption)

$$\tau_{IR} = \int_0^\infty N(a)\pi a^2 Q_A(a)\,da , \tag{30}$$

where $N(a)da$ is the number of particles above unit area with radii between a and $a + da$ and $\pi a^2 Q_A(a)$ is the cross-section for absorption by the particle of radius a. For monodisperse aerosols of radius a_m

$$\tau_{IR} = N_0 \pi a_m^2 Q_A(a_m) . \tag{31}$$

If $x_m = 2\pi a_m/\lambda \gtrsim 1(a_m \gtrsim 1\mu$ for λ in the thermal infrared) then Q_A is on the order of unity, and we can write

$$\tau_{IR} = 3V/4a_m , \tag{32}$$

where V denotes the total volume of particles above unit area.

From equations (2) and (6) the value of V which satisfies the condition that $\tau = 1$ at the knee of the brightness temperature curve is given by

$$V = \frac{\lambda_0[(\epsilon_r + 2)^2 + \epsilon_i^2]}{18\pi\epsilon_i}. \tag{33}$$

For aerosols on Earth ϵ_r is $\sim(1.5)^2$ (Junge 1963) and it most likely differs by less than an order of magnitude on Venus, but ϵ_i has a rather wide range of plausible values and we will consider 1, 0.1, 0.01, and 0.001 which cover that range sufficiently well.

Although there would actually be a continuous range of particle sizes, we may estimate τ_{IR} if we know approximately the radius interval within which the true volume distribution is concentrated. Polarization (Lyot 1929; van de Hulst 1952) and infrared reflectivity measurements (Sagan and Pollack 1967) indicate that the atmospheric particles are at least in the micron-size range, but sedimentation would prevent the existence of many particles larger than 10 μ so that the single particle sizes $a_m = 1\ \mu$, and 10 μ should be representative of probable conditions. For these values we find (eqs. [32] and [33], $\lambda_0 = 3$ cm) the folowing values for the infrared optical thickness of the atmosphere.

	$\epsilon_i = 0\ 001$	$\epsilon_i = 0\ 01$	$\epsilon_i = 0\ 1$	$\epsilon_i = 1$
$a_m = 1\ \mu$	$\tau_{IR} \sim 5\times10^6$	$\sim 5\times10^5$	$\sim 5\times10^4$	$\sim 5\times10^3$
$a_m = 10\ \mu$	$\tau_{IR} \sim 5\times10^5$	$\sim 5\times10^4$	$\sim 5\times10^3$	$\sim 5\times10^2$

The above values agree approximately with the value $\tau_{IR} \sim 10^5$–10^4 found to be necessary for the insulation effect to cause the high surface temperature and the model is hence consistent in this respect.

In equation (29) if n is smaller than $\sim$0.01, then $ng(\tau, n/\mu_0)$ is comparable to the values we expect for $3a\tau/4$ in the dust insulation model, and in that case temperature variations of $\sim$100° K could exist over the planetary disk. Even if the particles do not absorb more strongly in the infrared than in the visible, the greater forward scattering in the visible would cause a similar effect. Samuelson (1967) has determined the greenhouse effect in an atmosphere which both absorbs and scatters (anisotropically) when there is no internal heat source. For complete forward scattering in the visible and isotropic scattering in the infrared the greenhouse effect is approximately the same as in an absorbing atmosphere, but with n replaced by $(1 - \omega_0)Q_E(\mathrm{Vis})/Q_E(IR)$, where the Q's are extinction efficiency factors of the dust particles. With realistic deviations from complete forward scattering no solar photons will reach the surface, but the surface temperature is nevertheless increased significantly by the scattering greenhouse effect (Samuelson 1967). We will use equation (29) to estimate the surface temperature distribution for a strongly forward scattering atmosphere with n primarily a measure of $(1 - \omega_0^{\mathrm{vis}})$ since $Q_E(\mathrm{vis})$ and $Q_E(IR)$ would be on the same order of magnitude for particles having $a \gtrsim 1\ \mu$. For the particles scattering the visual radiation, $\omega_0 \gtrsim 0.99$ at least in the upper atmosphere (Hansen 1967), and hence n should be at least as small as 10^{-2} but less than complete forward scattering in the visible would reduce the greenhouse effect so that it is doubtful that the maximum greenhouse contribution to the surface temperature could be any larger than that given by $n = \frac{1}{100}$.

We may estimate the temperature lapse rate expected in the dust insulation model by calculating the gradient appropriate for radiative equilibrium. Neglecting the second term in (29) and assuming $\tau = \tau_0 \exp(-h/H)$ we find

$$\frac{dT}{dh} = -\frac{T_e}{4H}\left(\frac{3a\tau_0}{4}\right)^{1/4} e^{-h/4H}. \tag{34}$$

For $T_e = 235°$ K, $\alpha\tau_0 = 50$, and $H = 10$ km, we find

$$\frac{dT}{dh} = \left(\frac{dT}{dh}\right)_0 e^{-h/4H}, \tag{35}$$

where $(dT/dh)_0 \sim 14.5$ km. Although the values for α and τ_0 are uncertain, they occur only as a product which must have a value $\sim$50 if the insulation effect is to operate. Moreover, since $\alpha\tau_0$ occurs as a fourth root it appears quite definite that in the dust insulation model the radiative lapse rate exceeds the adiabatic value [$\sim$7° K/km (Barrett and Staelin 1964) depending on the atmospheric composition] at the planetary surface, and hence the true lapse rate should be nearly adiabatic at least in the lowest several kilometers. These conclusions imply the existence of mild turbulence near the planetary surface and thus at least qualitatively justify the requirement of moderate surface winds. Since dT/dh decreases with altitude it is possible that a level may be reached below the cloudtops at which the atmosphere becomes radiative. Since convection is required to support the airborne dust, the dusty region in that case would have an upper limit at that altitude and a relatively clear region would exist from there up to the clouds. If the visible clouds are in fact dust then there should be no clear region.

We note finally that we have not attempted to derive a model for the global circulation. Due to the possible large heat capacity of the atmosphere, it is not necessary for the circulation to have a dominant influence on the atmospheric temperature structure. On the other hand, even if we were to assign a dominant role to the global convection, we should note that almost all of the computations which we have made may still have application. For example, the circulational model of Goody and Robinson (1966) requires the atmosphere to be completely opaque to both solar and planetary radiation and such a condition is certainly supplied by our dusty atmosphere. By incorporating their model, however, the existence of a subsurface heat source is less important, since the surface temperature may be maintained by the forced adiabatic temperature gradient. Although the average surface wind velocity in the model of Goody and Robinson is negligible, the dust may be initially raised at the antisolar point where downward vertical velocities of $\sim$10 m sec^{-1} are obtained. The existence of an internal heat source with the requirement of constant net flux could also contribute in this model to the raising of dust. It is also clear that many of the computations may be considered as applying equally well to the aeolosphere since the properties of the dust were not specified in detail by Öpik.

VIII. CONCLUSION

Although there is considerable evidence that the surface of Venus actually is at a high temperature, the atmospheric models which include this have a difficulty in explaining how the solar energy can reach the planetary surface, and hence we have examined the possibility of an internal heat source providing the main contribution to the high temperature. It is assumed that the required atmospheric opacity is provided by dust particles, and the model is based on the assumption that the quantity of airborne dust is sufficient to cause an optical thickness of unity at the knee of the brightness temperature curve. The required volume of dust is $\sim 4a_m\tau_{IR}/3$ cm^3 above unit area (eq. [32]) and, since τ_{IR} must be $\sim 10^5$ ($\sim 10^4$ for a heat flow ten times that on Earth) for the insulation effect to cause the high surface temperature, the dust quantity may be of the order of 10 gm assuming $a_m \sim 1\ \mu$. If the surface pressure is $\sim$20 atmospheres, then 10 gm would represent a mass about 0.05 per cent as large as that of the atmosphere above unit area.

The distribution of dust in the atmosphere is taken as exponential and the scale height and the absorption coefficient of the dust particles as a function of wavelength are established by requiring agreement with the observed microwave brightness temperatures. The derived scale height (10 km $\lesssim H \lesssim$ 15 km) and absorption coefficient (0.5 $\leq$

$n_{3\text{ cm}} \leq 1$, where absorption $\propto \lambda^{-1-n(\lambda)}$) are within the ranges which were anticipated on physical grounds, and the agreement they provide with the observed brightness temperature curve differs from the expectation of Kuzmin as well as of Barrett and Staelin primarily because they assumed that there was no wavelength dependence ($n(\lambda) = 0$) in the imaginary part of the dielectric constant. This dust insulation model predicts a significant atmospheric absorption of centimeter waves, and it is shown that the radar reflectivities and differential polarization visibilities strongly support the existence of the amount of absorption predicted. The evidence indicating significant absorption throughout the centimeter range suggests that the microwave phase effect is largely an atmospheric effect.

Thus in the dust model the surface temperature results from a blanketing of radiation by the dusty atmosphere, although a small variation of temperature over the disk may occur due to forward scattering by the dust particles. The temperature lapse rate is adiabatic from the ground to the top of the dust layer, but the latter is probably located beneath the visible clouds. The turbulent velocities within the dusty region are probably quite small partly because of the expected absence of any destabilizing condensing gas. It is possible for this model to operate on a small energy source since, as opposed to cloud models, it is not necessary to supply latent heat.

It is a pleasure to thank our colleagues at the Universities of Kyoto and Tokyo for their hospitality during the year 1965–1966 where a part of this research was carried out. We also sincerely appreciate the helpful suggestions, constructive criticisms and encouragements offered by Drs. D. Deimendjian, A. Dollfus, S. L. Hess, E. J. Öpik, J. Pollack, C. Sagan, R. E. Samuelson, D. H. Staelin, P. Thaddeus, and S. Ueno on a first draft of this paper.

Note added in proof.—The most crucial question for the dust insulation model is whether significant wind speeds may exist near the planetary surface. S. L. Hess (1967 and private communication) has recently applied numerical hydrodynamics to the circulation problem on Venus assuming a dusty atmosphere. He concludes that the wind speeds would be too small for Öpik's frictional explanation of the surface temperature to be valid, but he is not able to conclude that surface wind speeds of a few tens of cm sec^{-1} can be ruled out. Hess also states (private communication) that it may be possible for the heat from the planetary interior to have a significant effect if the atmosphere is highly opaque to infrared radiation, as it would be in the dust insulation model, but he feels that this question is too subtle for application of the present numerical methods.

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