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Structure of the Lower Atmosphere of Venus[1]

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If the centimeter microwave emission from Venus arises from its surface, the radar reflectivities and microwave brightness temperatures give mean darkside surface temperatures of about 640° K. Extrapolations of the phase data to small phase angles indicate mean brightside surface temperatures of about 750° K. If the cloudtop pressures and temperatures are known in both hemispheres, the surface pressures and darkside subadiabatic indices can be derived. A reanalysis of the CO_2 absorption bands near 0.8 and 1.6 μ and of the Regulus occultation data indicates: (1) that the same cloud level, at $T_c \simeq 234°$ K, is responsible for the reflection and emission throughout the visible and infrared, and (2) that the brightside cloudtop pressure is at least as great as the darkside cloudtop pressure, the most probable values being 0.6 atm and 90 mb, respectively. Even with a small phase effect these cloudtop pressures give surface pressures $\simeq 50$ atm. The darkside lapse rates are substantially subadiabatic, in contradiction to the Aeolosphere Model. Failure of the Urey equilibrium on Venus results in surface pressures of this order or greater; and similar values are obtained from the atmospheric structure deduced from Spinrad's measurements of the near infrared CO_2 band at 7820 Å. The altitude of the cloudtops on the dark side is then $\simeq$80 km, and is possibly even higher in the bright hemisphere. The surface pressures and phase effect lead to a sidereal period of rotation which exceeds 170 days, and is quite possibly equal to the period of revolution. For nonsynchronous rotation, the specific heat capacity of the atmosphere controls the nocturnal cooling. There is a smaller contribution from subsurface conduction. For synchronous rotation, the atmospheric circulation must supply the radiation emitted to space from the dark hemisphere. The effect of Rayleigh scattering on a cloudless day on Venus is to yellow the sky and redden the sun. The radiation scattered back to space will also have a yellow cast, and may explain the apparent color of Venus. The color index should therefore be a function of phase. In short visual wavelengths, the surface of Venus cannot be seen from space, even on a cloudless day. The observations of permanent dark markings at these wavelengths possibly represent clouds connected with surface features far below; they cannot be the surface features themselves. But near infrared photography has the promise of detecting surface markings on Venus. The high surface temperatures and pressures lead to melting and vaporization of surface material, and to greatly enhanced infrared opacities, facilitating the operation of the Greenhouse Effect on Venus. Direct exploration of the surface of Venus would seem to be a very difficult engineering problem.

INTRODUCTION

Three models have been proposed to explain the origin of the microwave emission from Venus: the Greenhouse and Aelosphere Models, wherein the centimeter brightness temperature $T_B \sim 600°$ K arises from the planetary surface, and the Ionospheric Model, in which the high temperature emission arises from free–free transitions of electrons in the Cytherean ionosphere. (For a general and critical

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discussion of these models, see Kellogg and Sagan, 1961, and references given there). In these models, it has been customary to assume an adiabatic lapse rate from the cloudtops to the surface in the dark hemisphere. The surface pressure is then obtained from the Poisson equation. For the Greenhouse and Aeolosphere Models, surface pressures of a few atmospheres are derived in this manner; for the Ionospheric Model the value is 1 atm or less, because of the lower surface temperature.

Barrett (1961) has suggested that to explain the 8 mm brightness temperatures by pressure-induced dipole transitions of CO_2, surface pressures as high as 30 atm might be required. However, a revision of his computation, based on more recent data, suggests that the millimeter microwave emission cannot be explained consistently by CO_2 absorption alone (Sagan and Giver, 1962).

A reconsideration of the structure of the lower Cytherean atmosphere seems indicated, because the darkside temperature gradient is quite possibly less than the adiabatic. Direct evidence that such is the case lies in recent indications of a phase variation in the centimeter wavelength brightness temperatures. Until recently, almost no data on Cytherean microwave emission existed between superior conjunction and dichotomy. Therefore the brightness temperatures in the illuminated hemisphere of Venus had to be derived from extrapolation of the data for large phase angles. These extrapolations gave the following results for $T_B{}^\circ$, the integrated brightness temperature for the illuminated hemisphere: 661° K (Drake, 1962*a*, 10 cm); 694° K (Mayer, McCullough, and Sloanaker, 1962, 3.15 cm); $<750°$ K (Kuzmin and Salomonovitch, 1962, 4 mm, 8 mm, 3.3 cm). More recently Drake (1962*b*) has obtained 10 cm brightness temperatures near superior conjunction which are consistent with his previous extrapolation. The difference between integrated brightness temperatures in the two hemispheres of Venus is then $\Delta T > 70$ K°, for all sets of observers; the estimates are $\Delta T = 78$ K° (Drake, 1962*a*); $\Delta T = 146°$ K (Mayer, McCullough, and Sloanaker, 1962); and even higher values for Kuzmin and Salomonovitch (1962). The most recent observations rule out the possibility that the brightside $T_B{}^\circ \simeq 1000°$ K.

The arguments to be presented in the following section indicate that the pressure at the cloud level in the illuminated hemisphere of Venus is at least as great as the cloudtop pressure on the unilluminated hemisphere. If the surface pressure is the same in the two hemispheres, then the phase effect shows that the temperature gradient on the dark side must be much less steep than on the bright side.

This argument and the calculations to follow provide evidence against the Aeolosphere Model, in which the surface is heated by friction in a stirred atmosphere and where the temperature gradient must be very close to adiabatic even on the dark side (Öpik, 1961). In the Ionospheric Model, part of the phase effect must be due to increases in the electron density and electron temperature on the bright side (Sagan, Siegel, and Jones, 1961); the departure from adiabaticity on the dark side will therefore be correspondingly decreased. But on the Greenhouse Model the full effect of the phase variation on the darkside temperature gradient will be felt, and it is for this model that most of the following computations apply.

In the next section, values for the cloudtop pressures in the bright and dark hemispheres are derived. The consequent atmospheric structures are described in the following section. Independent and supporting evidence for high surface pressures and subadiabatic lapse rates are presented in the fourth section. The connection between the microwave phase effect and the period of rotation is discussed in the fifth section. The next to last section investigates Rayleigh scattering and surface visibility in the derived model atmospheres. Surface characteristics and other properties of Venus which follow from the previous discussion are presented in the final section.

Estimates of Cloudtop Pressures

Estimates of the pressures in the upper Cytherean atmosphere can be made by using light of various wavelengths. The possibility exists that a different level is observed at each wavelength. For this to be the case on a cloud-covered planet, we would require a series of clouds at different pressure and temperature levels, each being transparent at some wavelengths and opaque at others. Using the data then available, Öpik (1961) proposed the existence of at least two cloud layers, one at $T_c = 234°$ K and $P_c \sim 0.10$ atm; the other at $T'_c = 340°$ K and $P'_c \sim 1$ atm, corresponding to the visible clouds. However, more recent observational and theoretical work, to be discussed presently, does not support the necessity for several such cloud layers; instead it points to a single cloud layer, at a temperature $\simeq 230°$ K, which, when unbroken, is responsible for almost all Cytherean radiation reflected and emitted to space between the visible and 13 μ.

Infrared bolometry of Venus in the 8 to 13 μ window in the terrestrial atmosphere leads to a brightness temperature of about 234° K on both the illuminated and unilluminated hemispheres (Pettit and Nicholson, 1955; Sinton and Strong, 1960). This temperature is quite constant in time; what secular variations do exist, Sinton (1962) is inclined to attribute to breaks in the 234° K cloud deck. A recent determination of the brightness temperature of Venus at 3.75 μ gives a mean value of 236° K in the unilluminated hemisphere (Sinton, 1962).

A reanalysis of old Mt. Wilson spectra in the 8000 Å CO_2 band region by Spinrad (1962), to be discussed in more detail in the section on independent estimates, gives a variation of pressures and temperatures from plate to plate. There is a general trend for higher pressures to go with higher temperatures, and the obvious interpretation is that the observations are made through a variable Cytherean cloud cover, so that on some days light is received from deeper atmospheric depths than on others. Then, the lowest temperature observed should correspond to the temperature in the vicinity of the clouds. This temperature is 214° K at 7820 Å.

Observations of the occultation of Regulus by Venus analyzed by de Vaucouleurs and Menzel (1960), give a value of the scale height H_{occ} at the occultation level on the dark side of 6.8 ± 0.2 km. An independent analysis of the same data by Martynov and Pospergelis (1961) yields $H_{occ} \simeq 6$ km, with no probable error quoted. In an atmosphere with a known volume mixing ratio of α CO_2 to $(1-\alpha)$ N_2, the temperature at the occultation level can be derived from the value of H_{occ}. From a study of the 1.6 μ CO_2 bands, Kaplan (1961) has derived a value of $\alpha \simeq 0.15$; from a study of the 7820 Å band, Spinrad derives $\alpha \simeq 0.05$ with a probable error of about a factor of two (Spinrad, 1962; and private communication). The latter value is probably the more reliable of the two (Kaplan, private communication, 1962); the reason for the discrepancy will be discussed below.

These values of α apply to the region far below the occultation level. The occultation level is approximately at optical depth unity in the CO_2–photodissociating ultraviolet, $\lambda \leqslant 1692$ Å (Sagan, 1961*a*). Thus the assumption of constant mixing ratio up to the occultation level will lead to maximum values of the temperature at the occultation level, $T_{occ} = mg\, H_{occ}/k$. The range of values of T_{occ} is then obtained by pairing the extreme values of H of de Vaucouleurs and Menzel with the extreme values of α of Spinrad, as shown in Table 1. The most probable value of T_{occ} is seen to be 203° K. Utilization of a somewhat lower value of H (Martynov and Pospergelis, 1961) leads to lower temperatures; $\alpha = 0.15$ (Kaplan, 1961) leads to slightly higher temperatures. On the Gold-Humphreys model, the temperature of a stratosphere in radiative equilibrium with an opaque cloud layer is $T_{occ} \simeq 2^{-1/4}\, T_c$. For $T_{occ} \simeq 203°$ K, we find $T_c \simeq 240°$ K. In actuality the stratosphere will be in radiative equilibrium with the CO_2 between the cloud surface and the stratosphere; much of the radiation emitted by the clouds escapes between the carbon dioxide bands directly to space. The effect of this correction is to increase T_c somewhat (see, e.g., Mintz, 1961).

TABLE I
ATMOSPHERIC PARAMETERS ABOVE THE CLOUDTOPS

$\bar{H}$● (km)	$\bar{\alpha}$	$\bar{\mu}$	$\bar{T}$ (°K)	Adopted R♀	h_0 (km)	$h_0 + 1.34\,H$ (km)	P_{occ}● (mb)	P_c● (mb)
6.6	0.025	28.42	195°	[a]	78	87	2.4×10^{-3}	1200
6.8	0.05	28.82	203°	[a]	70	79	2.6×10^{-3}	280
6.8	0.05	28.82	203°	[b]	55	64	2.6×10^{-3}	31
7.0	0.10	29.62	216°	[b]	47	47	2.9×10^{-3}	2

[a] Ephemeris value.
[b] Revised value of de Vaucouleurs (private communication, 1962).

The fact that the clouds on both the bright and the dark sides of Venus at 8 to 13 μ, the clouds on the dark side at 3.75 and the bright side at 0.8 μ, and the tropopause clouds on the dark side are all sensibly at the same temperature argues strongly that the same cloud layer is observed at all these wavelengths.

In the following discussion, therefore, we will assume a single cloud layer at $T_c \simeq 234°$ K, which is the primary source of the visible and infrared radiation reflected and emitted from both hemispheres of Venus. There may be breaks in the cloud layer, and there may be other reflecting layers in the lower atmosphere of Venus, but there seems to be only one cloud layer of importance in those upper parts of the Cytherean atmosphere which are most easily and directly accessible by visible and infrared techniques.

We are now in a position to compare the cloudtop pressures on the dark and bright hemispheres of Venus. For the occultation of Regulus on 7 July, 1959 ingress occurred in the unilluminated hemisphere. De Vaucouleurs and Menzel (1960) derived a pressure at the occultation level of $P_{occ} = 2.6 \times 10^{-3}$ mb $\pm 1.3 \times 10^{-4}$ mb, assuming $\alpha \geqslant 0.50$. For the present paper a recomputation of P_{occ} has been performed, corresponding to more likely values of α and T_{occ}. The results are given in the eighth column of Table I, and differ only slightly from the values of de Vaucouleurs and Menzel. The original estimate of the altitude of the occultation level was $h = 70 \pm 8$ km above the visible cloudtops, as determined with a micrometer from the position of the limb. This value of h is based on the Ephemeris radius of Venus. De Vaucouleurs (1962, private communication) has recently reinvestigated the existing data on the radius of Venus. His revised figure gives a new altitude of the occultation level of 55 ± 8 km. Öpik (1961) has pointed out that, due to scattering along an oblique light path through a hazy cloud layer, the micrometer limb is at a higher level than the visible clouds when observed at vertical incidence. Öpik estimates that the effective altitude of the cloudtops is some 1.34 scale heights below the micrometer limb. If, however, the cloud layer has a sharp upper boundary this correction vanishes, and the cloudtops and micrometer limb are at identical altitudes.

To compute the darkside cloudtop pressure from the barometric equation $P_c = P_{occ}e^{h/H}$ with the above data, we will first need to know the mean value of H between the occultation level and the cloudtops. With $T_c = 230°$ K and $\alpha = 0.05$ at the cloudtops, $H_c = 7.6$ km. The value of H at the occultation level is less than at the cloudtops because of the interplay of two effects. The expected temperature will be lower, but the expected molecular weight will be also lower. It is easy to see that the effect of the molecular weight will be small. By coincidence, the occultation level is at approximately optical depth unity in the ultraviolet radiation $\lambda \leqslant 1692$ Å which photodissociates CO_2 (Sagan, 1961a). If α is the ordinary carbon dioxide mixing ratio at lower altitudes, and β is the fraction of CO_2 dissociated at the occultation level, the mean molecular weight at the occultation level will be given to first order by

$$\mu_{occ} = (1 - \alpha)\mu_{N_2} + \alpha(1 - \beta)\mu_{CO_2} + \alpha\beta(\mu_{CO} + \mu_{O}). \quad (1)$$

With $\alpha = 0.05$ and $\beta \simeq 0.5$, $\mu_{occ} \simeq 28.8$. Because of the small value of α, the results do not depend sensitively on the choice of β. The observed value of H_{occ} then gives $T_{occ} = 203°$ K, quite close to the value of the occultation temperature previously derived under the assumption of constant mixing ratio up to the occultation level. As mentioned above, this temperature is of the order expected in a stratosphere overlaying an opaque cloud deck at temperature $\simeq 240°$ K or somewhat higher. In the following derivation of darkside cloudtop pressures, we will adopt $H = 6.8 \pm 0.2$ km, the occultation value, as the mean scale height between cloudtops and occultation level. Comparison with the atmospheric scale height at the cloudtops shows we are adopting a minimum value of H; the resulting values of darkside cloudtop pressures will therefore be maxima.

Table I gives extreme values of $P_c^\bullet$, the cloudtop pressure on the unilluminated hemisphere. (Throughout the remainder of the present paper the superscript $\bullet$ refers to mean conditions on the unilluminated hemisphere of Venus; the superscript $\circ$ to mean conditions on the illuminated hemisphere.) The maximum value of h corresponds to the Ephemeris radius of Venus and a hazy cloud deck: $78 + 1.34 \times 7.0 = 87$ km. The two intermediate values correspond to the Ephemeris radius and to de Vaucouleurs' revised radius, both with hazy cloud decks. The minimum value corresponds to de Vaucouleurs' radius and a sharp cloud deck. The maximum and minimum pressure values of 1200 and 2 mb result from straining all probable errors in alternate directions. The most probable value lies between 31 and 280 mb, depending primarily on the choice of Venus radius. In the following discussion we will adopt $P_c \sim 90$ mb, remembering that the uncertainty is at least a factor of 3.

Having now some estimate of the magnitude and uncertainty of the cloudtop pressure on the dark side of Venus, we desire to make comparisons with the cloudtop pressures on the bright side. From his analysis of the near-infrared CO_2 line contours Spinrad finds that the pressure corresponding to $T = 214°$ K is 1.1 to 1.5 atm (Spinrad, 1962; see also the fourth section of the present paper). These are the lowest pressures recorded by this method. From the preceding discussion it therefore appears that, to the extent Spinrad's pressures and temperatures refer to the same atmospheric level, the cloudtop pressures in the illuminated hemisphere are in the neighborhood of 1 atm. The best adiabats drawn through all of Spinrad's (P, T) points intersect $T = 234° K$ at P between 0.53 and 0.83 atm (cf. fourth section).

Kaplan (1961) has discussed the pressure broadening of the 1.6 μ carbon dioxide bands in Venus. He finds that the pressure at the effective reflecting surface for 1.6 μ photons is given by

$$P_{rs} = 0.13 \left[\frac{1 + 0.57\alpha}{\alpha + 0.3\alpha^2}\right]^{1/2} \text{atm}, \quad (2)$$

where α, as before, is the CO_2 volume mixing ratio. For $\alpha << 1$, as Spinrad's (1962) work leads us to believe, Eq. (2) reduces to

$$P_{rs} \simeq 0.13\alpha^{-1/2}. \quad (3)$$

For $\alpha = 0.025$, 0.05, and 0.10, P_{rs} is, respectively, 0.83 atm, 0.59 atm, and 0.42 atm, from Eq. (2). This is just the range of brightside cloudtop pressures deduced from the adiabats drawn through Spinrad's (P, T) points, and suggests that the effective reflecting surface at 1.6 μ is the visible cloud bank itself. The need for a second reflecting surface below the visible clouds to explain the 1.6 μ pressures is thereby obviated. Kaplan (1961) concluded that the effective reflecting surface at 1.6 μ was at a pressure some four times greater than were the visible clouds; but the conclusion was based on a comparison of 1.6 μ data which refer to the illuminated hemisphere and data from the occultation of Regulus which refer to the unilluminated hemisphere.

The preceding discussion strongly suggests that the brightside cloudtop pressures on Venus are at least as great as the darkside cloudtop pressures. Indeed, with the most probable values $P_c^{\bullet} = 90$ mb, and $P_c^{\circ} = 0.6$ atm, the pressures are some six times greater on the illuminated hemisphere at the level of the clouds.

Atmospheric Structure with a Subadiabatic Lapse Rate

If the true temperature lapse rate is η^{-1} the adiabatic lapse rate, then

$$(\partial T/\partial h) = -\frac{g}{\eta c_p(P,T)}, \tag{4}$$

where g is the acceleration due to gravity, and c_p, the specific heat capacity at constant pressure, is itself a function of pressure and temperature. The variation of pressure with temperature is then given by a modified Poisson equation,

$$P = P_c(T/T_c)^{\eta\gamma(P,T)/[\gamma(P,T)\,-\,1]} \tag{5}$$

where γ is the ratio of specific heats and is also a function of pressure and temperature. P_c and T_c are reference pressures and temperatures, here taken at the cloudtops. The run of pressure and temperature with depth below the clouds must be performed in small steps, with continual readjustment of the values of c_p and γ on the basis of the ambient pressures and temperatures found in the previous step. Following the discussion of the second section, a darkside cloudtop pressure and temperature of $P_c^{\bullet} = 90$ mb, and $T_c^{\bullet} = 234°$ K was adopted. In the computations leading to Fig. 1, a constant volume mixing ratio of 20% CO_2/80% N_2 was assumed for the lower atmosphere. This is a value in the range suggested by Kaplan (1961). More recent evidence of Spinrad (1962) shows that α is closer to 0.05. However, for $\alpha < 0.20$, γ and c_p are quite insensitive to the choice of α, and the calculations should be accurate as they stand for $\alpha \simeq 0.05$. We have assumed that in the region from just below the visible clouds to just above the surface there is no water vapor condensation. Finally, we neglect the small effect on the over-all atmospheric structure of possible condensation and crystallization of water inside the visible clouds.

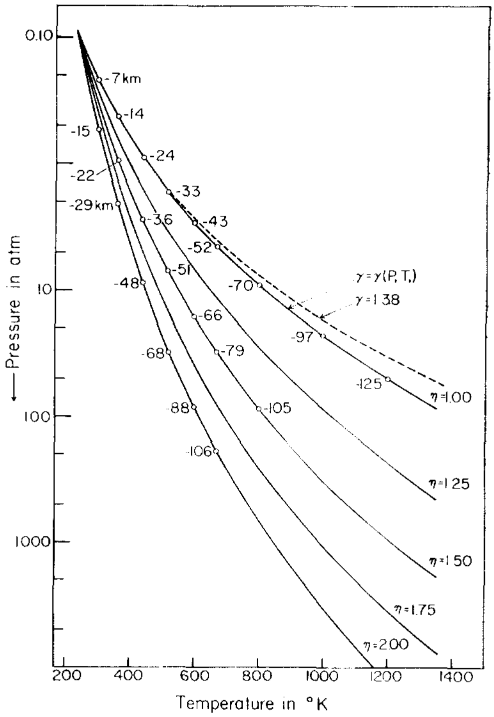

Fig. 1. Structure of the lower atmosphere of Venus for five assumed values of the subadiabatic index, η. The curves converge at the adopted darkside cloudtops, $P_c^{\bullet} = 90$ mb, $T_c = 234°$ K. The numbered points show distances below cloudtops in km.

Under these assumptions, the variation of pressure with temperature illustrated in Fig. 1 has been computed for five values of the subadiabatic index $\eta^{\bullet}$ between 1.00 and 2.00. The altitudes of selected (P, T) values are indicated. For $\eta^{\bullet} = 1.00$, the difference between the cases in which $\gamma =$ constant and in which $\gamma = \gamma(P, T)$ is exhibited. The variation of c_p and γ with P and T was obtained from National Bureau of Standards Circular 564. For other values of T_c and P_c, Fig. 1 can be used, to first approximation, as a nomogram. The apex of the fan of curves should be moved to the desired cloudtop parameters, the coordinate axes remaining fixed.

A mean brightness temperature for the unilluminated hemisphere of Venus at 10 cm is $T_B^{\bullet} \simeq 590°$ K (see, e.g., Drake, 1962*a*). If the emissivity is less than unity, then the surface temperature of Venus will be even higher. Recent radar contact with Venus at 12.5 cm, 43 cm, and 68 cm all place the reflectivity at about 0.10 ± 0.02 (Victor, Stevens, and Golomb, 1961; Kotelnikov, 1961; Pettingill, 1961). By Kirchhoff's law the microwave emissivity is therefore $\epsilon \simeq 0.90$, and, in the absence of atmospheric attenuation of centimeter wavelength emission, the mean surface temperature of the dark hemisphere, $T_s^{\bullet} \simeq 660°$ K. (The corresponding value of T_s° is 740° K; from the observations of Mayer, McCullough, and Sloanaker (1962) at shorter centimeter wavelengths, we would obtain $T_s^{\bullet} \simeq 610°$ K and $T_s^{\circ} \simeq 770$ °K.) Thus from Fig. 1, with $\eta^{\bullet} = 1.00$, the minimum value of the surface pressure is

$$(P_s)_{min} = 4.5 \text{ atm.}$$

The existence of a phase effect in the centimeter brightness temperatures suggests that $\eta^{\bullet} > 1$ on the unilluminated hemisphere, and that, probably, $P_s >> 4.5$ atm.

The dependence upon brightside surface temperature of the lower bounds on $\eta^{\bullet}$ and the surface pressure is illustrated in Fig. 2. The ordinate shows (1) a wide range of suggested brightness temperatures at centimeter wavelengths in the illuminated hemisphere, and (2) the corresponding mean surface temperatures on the bright side, taking $\epsilon = 0.90$. If there is microwave attenuation at $\lambda \geqslant 3$ cm, the surface temperatures will be even greater. The upper curve in Fig. 2 exhibits the run of P_s with T_s°, assuming $\eta^{\circ} = 1.00$. If the thermal gradient is subadiabatic on the bright side, or if the cloudtop pressures are greater on the bright side than on the dark side, the surface pressures will also be greater. The lower curve of Fig. 2 gives the subadiabatic index in the unilluminated hemisphere required for the surface pressures to be the same in the two hemispheres. It

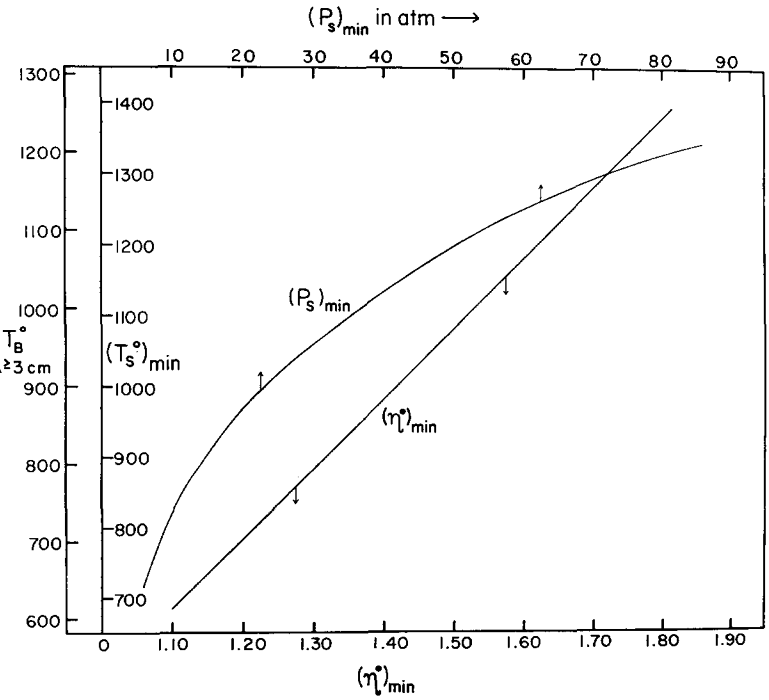

FIG. 2. Minimum values of the surface pressure and of the darkside subadiabatic index as functions of the brightness temperature at centimeter wavelengths in the illuminated hemisphere and the corresponding minimum value of the brightside surface temperature. A microwave emissivity of 0.9 is adopted from radar reflection data. If $P_c^{\circ} > P_c^{\bullet}$, the values of P_s and $\eta^{\bullet}$ will be greater.

is a minimum value for the same reasons.

For a centimeter wavelength phase effect $\Delta T \sim 50°$ K, $\eta^{\circ} = 1.00$, and $P_c^{\circ} = P_c^{\bullet}$, we find $P_s \simeq 8$ atm and $\eta^{\bullet} = 1.14$. $\Delta T \sim 50°$ K, $\eta^{\circ} = 1.00$, and $P_c^{\circ} = 6\ P_c^{\bullet}$ give $P_s \simeq 50$ atm. For $\Delta T \sim 300°$ K, $\eta^{\circ} = 1.00$, and $P_c^{\circ} = P_c^{\bullet}$, $P_s \simeq 22$ atm and $\eta^{\bullet} = 1.42$. Under the conditions just stated, but with $P_c^{\circ} = 6P_c^{\bullet}$, the surface pressure is 132 atm. Thus, despite some uncertainty in the value of T_B° for $\lambda \geqslant 3$ cm and in the ratio $P_c^{\circ}/P_c^{\bullet}$, it seems clear that the surface pressure and the darkside subadiabatic index are both substantially greater than has generally been suggested heretofore.

Independent Estimates of the Atmospheric Structure

Because of the uncertainty in the values of T_B° and of $P_c^{\circ}/P_c^{\bullet}$, it would be very useful to have some other means of fixing the atmospheric parameters. Either an independent estimate of the surface pressure, or one other (P, T) point below the clouds would suffice. Unfortunately no high-accuracy estimate exists for either datum. However, two independent arguments may be invoked; although each is fairly crude, the fact that each represents an independent approach serves to increase the reliability of the total picture.

Failure of the Urey Equilibrium

Carbon dioxide outgassed from the Earth's interior reacts with silicates in the presence of liquid water, and is deposited as carbonates in an equilibrium process first emphasized by Urey (1952). If the Urey equilibrium applied on Venus, it would be easy to compute the CO_2 abundance. For example, in the magnesium Urey equilibrium,

$$MgSiO_3 + CO_2 \overset{H_2O}{\rightleftarrows} MgCO_3 + SiO_2, \qquad (6)$$

the free energy difference between reactants and products, $\Delta F^{\circ} = -6.94$ kcal mole^{-1} (National Bureau of Standards Circular 500). At equilibrium,

$$\Delta F^{\circ} = -RT \ln K_p,$$

where R is the universal gas constant, T the absolute temperature, and K_p the equilibrium constant of the reaction. All reactants and products besides carbon dioxide in reaction (6) are solids and have unit activity. Hence the CO_2 partial pressure, $P_{CO_2} = 1/K_p$. If the mean surface temperature were 670° K, the partial pressure of CO_2 would be 3×10^{-3} atm. If CO_2 comprises 5% by volume, the surface pressure would then be 4×10^{-2} atm. If the mean surface temperature were 1330° K, $P_{CO_2} = 2.5 \times 10^{-2}$ atm, and $P_s \simeq 0.3$ atm. Similar results apply to other choices of T_s and to other cations in reaction (6). In every case, the surface pressure is several orders of magnitude less than the corresponding surface pressures given in the upper curve of Fig. 2, and is often even less than the pressure at the cloudtops.

However, for the Urey equilibrium to be established, liquid water is required both as a catalyst and as a weathering agent to expose fresh surface material. In the absence of liquid surface water, the Urey equilibrium is expected to fail on Venus (Urey, 1952). Then, almost all carbon dioxide outgassed from the Cytherean interior remains in the atmosphere. If we assume that Venus and Earth were endowed with equal amounts of CO_2 precursors in their early history, then the quantity of CO_2 bound as carbonates in the terrestrial crust will give some indication of the partial pressure of CO_2 in the present atmosphere of Venus. (It should be noted that the assumption of equal endowments is *prima facie* a risky one: the abundance of water on Venus is almost certainly less than that on Earth. If water were preferentially depleted on primitive Venus, carbon dioxide might also have been depleted. However, if all the carbon on Venus went through a stage as abiologically synthesized organic matter, as is possibly the case on Earth (Sagan, 1961*b*), this approximation will be valid.) The procedure described was first used by Dole (1956), using geochemical data of Goldschmidt (1933). We here revise the calculations on the basis of more recent geochemical information and Spinrad's (1962) conclusions on the concentration of carbon dioxide on Venus.

The known carbon in the terrestrial sedimentary column falls into two categories, oxidized carbon fossilized as carbonates, and reduced carbon fossilized as argillaceous sediments; both originate from atmospheric CO_2 (Hutchinson, 1954). Using the method of geochemical balances, Rubey (1951) has computed that the carbon dioxide equivalent of the sedimentary fossil carbon arising from these two sources is about 18,000 gm cm^{-2}. The same quantity of carbon dioxide in the present Cytherean atmosphere yields a partial pressure of 16 atm. If the atmosphere is 20% CO_2 and 80% N_2 by volume, the total surface pressure is then 55 atm. For $\alpha = 0.05$, $P_s \simeq 210$ atm. With $T_s^\bullet = 670°$ K, the corresponding value of $\eta^\bullet$ is approximately 2.0.

Rotational Structure of the 7820 Å Band

After a draft version of the present paper was in circulation, the very interesting recent results of Spinrad (1962) became available. Spinrad has reduced spectra of the Cytherean carbon dioxide absorption band at 7820 Å obtained by Adams and Dunham in the 1930's. Temperatures are obtained from the distribution of intensities of the rotational components of the band; values consistent with other measurements are obtained if it is assumed that the Cytherean cloud deck has a sharp upper boundary. If it is assumed that the distribution of scatterers follows the distribution of absorbers, the derived temperatures are far too low. These derived temperatures represent integrations over the light path. Pressures are obtained from the contours of the rotational lines, and increase with the value of the rotational quantum number of the line. The pressures also represent an integration over the light path. The pressures and temperatures vary greatly from plate to plate, but, in general, the higher pressures accompany higher temperatures. The situation is quite suggestive of a variable cloud cover, with radiation arising from different optical depths on different days. Although the plates cover a range of 60° in phase angle, there is no detectable phase effect in either temperature or pressure.

The general run of Spinrad's results give rather high rotational temperatures and line contour pressures. Figure 3 shows his

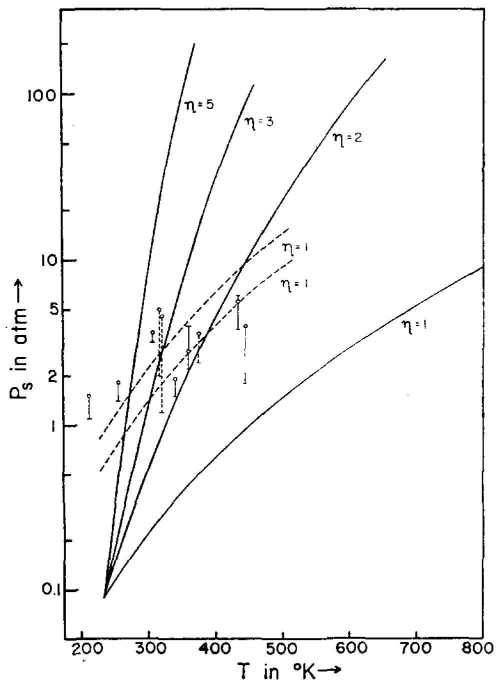

FIG. 3. Pressure and temperature observations at 7820 Å below the clouds (Spinrad, 1962). The circles represent average values of the pressure for rotational quantum number $\bar{J} = 22$. The range of pressure shown varies from values for $\bar{J} = 6$ to (in two cases) $\bar{J} = 33$. The four dashed lines represent observations made between superior conjunction and dichotomy; the remaining solid lines to observations made between dichotomy and inferior conjunction. The solid curves represent an adiabat and three subadiabats for brightside cloudtops at $P_c = 90$ mb, $T_c = 234°$ K. The dashed curves represent adiabats for higher values of the brightside cloudtop pressure.

data on a pressure–temperature diagram, on which are also plotted, as solid lines, the adiabat and three subadiabats for $P_c = 90$ mb, $T_c = 234°$ K. The dashed curves are adiabats corresponding to $P_c^{\bigcirc} > 90$ mb. The range in pressure for each datum corresponds to a range in mean rotational quantum number from $\bar{J} = 6$ to $\bar{J} = 22$ (and in two cases to $\bar{J} = 33$). The circles correspond to the best average values, for $\bar{J} = 22$, in the middle of the band. Because the integration over the light path will have different weighting functions for pressure and for temperature, the pressures and temperatures do not necessarily refer to precisely the same atmospheric level. The four dashed lines correspond to plates taken at phase angles $> 90°$; the others to plates taken at phase angles $< 90°$. Temperatures as high as 440° K, and pressures as high as 6 atm are explicitly exhibited. The temperatures at the bottom of the effective CO_2 absorbing layer will be substantially greater than these integrated results. Using the Curtis approximation, Spinrad finds that the pressures at the bottom of the effective CO_2 absorbing layer are certainly in excess of 10 atm, and in one case approach 18 atm. These pressures and temperatures make the Ionospheric Model of the Venus microwave emission very unlikely.

Of the solid curves drawn in Fig. 3, the points lie most nearly near the ones for $\eta^{\bullet} = 2$ or 3, but the fit is certainly extremely poor. The least squares fit to the points shown gives a curve which is superadiabatic for $P_c^{\bigcirc} = 90$ mb and $T_c^{\bigcirc} = 234°$ K.

It is much more likely that the lapse rate on the illuminated hemisphere is adiabatic, but that the cloudtop pressures exceed 90 mb. The two dashed curves are adiabatic fits to Spinrad's data. The lower of these adiabats is more heavily weighted by the high temperature and high pressure points. The corresponding brightside cloudtop pressures are 0.53 atm and 0.83 atm. It is clear that these high pressure adiabats are in much better accord with the observations. Some scatter of the points should be expected. The fact that observations made on different days see to different depths is suggestive of a turbulent atmosphere and variable clearing of the cloud cover. The spectrometer slit was probably left by Adams and Dunham to drift over the disk of Venus. The result is therefore an integration over clouds and holes between the clouds. Since the observations were made over several years, and a wide range of phase angles, since different cloud covers are presented for each observation, since there is some uncertainty in relating pressure and temperature to the same level, and since the region of the clouds is probably quite turbulent, it is not altogether surprising that the scatter about the high pressure adiabats is as large as it is. Furthermore, for 7800 Å with sec $\theta \simeq 3$, the incident light is extinguished by Rayleigh scattering by a factor of about 0.5 for each passage to and from the 6 atm level. There will be no effect on the relative intensities of the rotational lines, and therefore no effect on the computed rotational temperatures. But the Rayleigh scattering will tend to obscure the wings of the line profiles. Consequently, Spinrad's high pressures will be somewhat underestimated.

Extension of the two high pressure adiabats of Fig. 3 to high temperatures gives $P_s = 27$ and 42 atm for $T_s^{\bigcirc} = 670°$ K; and 55 and 82 atm for $T_s^{\bigcirc} = 800°$ K. Even if we assume that the structure of the lower atmosphere is subadiabatic with a brightside cloudtop pressure of 90 mb, it will be impossible to derive surface pressures below about 30 atm.

The Phase Effects and the Period of Rotation

The phase effect provides direct evidence that, on a nonsynchronously rotating Venus, the surface cools at night. The same must be true of the lower atmosphere. What prevents the surface and lower atmosphere from cooling even more during the long Cytherean night? If Venus rotates synchronously, what is the energy source which maintains the surface temperature of the dark side? Similarly, why are the cloud temperatures very nearly the same in the illuminated and in the unilluminated hemisphere? It is apparent that these questions are closely tied to the value of the period of rotation, and it is of some interest to see how they are coupled.

To begin, we consider the microwave phase effects for nonsynchronous rotation. What is the maximum period of rotation which could maintain the observed phase effects by subsurface heat conduction? We assume that the net radiation flux $S(0)$ leaving the ground at night is just balanced by the heat conducted to the surface from underground. We neglect conductive thermal exchanges between the ground and the lower atmosphere. The radius of curvature of the Cytherean surface is large enough so that horizontal conduction can be neglected. The problem then reduces to the one-dimensional solution of the differential equation of heat conduction. The boundary conditions are that Newton's law of cooling applies at the surface, and that the temperature gradient goes to zero at very large depths. The solution of this problem in the meteorological context is due to Brunt (1944). If we assume that the time of nocturnal cooling is ⅓ the period of rotation, we find that the synodic period of rotation of Venus is

$$\tau_{syn} = \tfrac{3}{4}\pi\rho^2 c_p^2 \kappa [\Delta T/S(0)]^2. \qquad (7)$$

In Eq. (7), ρ, c_p and κ are, respectively, the density, specific heat capacity at constant pressure, and thermal conductivity of the Cytherean surface; and ΔT is the nocturnal cooling of the surface, as given by the centimeter microwave phase effects. An average value of the product $\rho c_p \kappa^{1/2}$ for medium fine, dry quartz sand is 0.0140 cal $(\mathrm{K}^\circ)^{-1}$ cm^{-2} $\mathrm{sec}^{-1/2}$. The maximum value of the net flux at the ground is

$$S(0)_{max} = \epsilon\sigma T_s^{\bullet 4}. \qquad (8)$$

Equation (8) assumes—quite unrealistically for Venus—that there is no downward flux from the atmosphere to the surface at night. With $\epsilon = 0.9$, $T_s^{\bullet} = 640^\circ$ K, and any reasonable value of ΔT at all, Eqs. (7) and (8) give, for a sandy surface, absurdly low values of the synodic period of rotation. That is, under the assumed conditions, the surface of Venus will cool extremely rapidly, and the predicted dark-side temperatures will be much lower than the observed.

A more realistic approach is to make a standard assumption in the theory of stellar atmospheres, *viz.*, constant net flux. Then

$$S(0) = \sigma T_e^4, \qquad (9)$$

where T_e is the effective temperature at which Venus radiates to space from the top of its atmosphere, 234°K. It is observed that T_e is approximately constant during the Cytherean night. This new choice of effective surface radiating temperature gives much higher synodic periods, because the period of rotation is inversely proportional to the eight power of this temperature. For quartz sand again and $\Delta T = 50$°K, Eqs. (7) and (9) give $\tau_{syn} = 20$ hours. But high values of the phase effect give much longer synodic periods, e.g., 13 days for $\Delta T = 200$°K. Furthermore, if the thermal properties of the Cytherean surface resemble sandy clay with a 15% moisture content more closely than dry quartz sand, these values of the synodic period will be increased by a factor of 6.5. For the thermal properties of other ground types, the reader is referred to the compilation by Lettau (1951).

It therefore appears that conduction in the Cytherean surface can explain the phase effect under the following circumstances: the moderate phase effect of Drake (1962*a*) and of Mayer, McCullough, and Sloanaker (1962), is consistent with rotation periods < 20 days; very large phase effects are consistent only with a rotation period > 100 days. If the phase effect is moderate and the period of rotation long, or the phase effect large and the period of rotation short, then subsurface conduction will be unable to account for the observations.

An alternative explanation of the microwave phase effects for nonsynchronous rotation can be found in the specific heat capacity of the Cytherean atmosphere. If we know both the extent of lower atmospheric nocturnal cooling, and the surface pressure, then an estimate of the period of rotation can be derived under the assumption that the heat reservoir is the entire atmosphere, as first suggested by Öpik (1956). The synodic period of rotation is then given approximately by

$$\tau_{syn} \simeq \frac{3\bar{c}_p\overline{\Delta T}P_s}{\sigma T_c^4 g}. \qquad (10)$$

Here $\bar{c}_p$ is the mean specific heat capacity at constant pressure of the atmosphere, $\overline{\Delta T}$ is the mean nocturnal cooling of the atmosphere, P_s is the surface pressure, σ is the Stefan-Boltzmann constant, and g is the acceleration due to gravity. The value of $\bar{c}_p$ was taken for $T = 600°$ K, $P = 40$ atm, and $\alpha = 0.20$; however, within the range of accuracy of Eq. (10), any other reasonable choice gives substantially the same values of $\bar{c}_p$. Since we expect the lower atmosphere of Venus to have appreciable opacity in the infrared, the mean atmospheric cooling must be comparable to that deduced from the microwave phase effects $\overline{\Delta T}$ and P_s are coupled as discussed in Section 3. From the microwave phase data we certainly expect $\overline{\Delta T} \geqslant 50\,\mathrm{K}°$. In Öpik's original discussion, $P_s \sim 1$ atm and $\overline{\Delta T} \simeq 3\,\mathrm{K}°$ were assumed. With the present values, the run of synodic and sidereal periods of rotation with $\overline{\Delta T}$ (and with P_s) is shown in Fig. 4. The values of P_s used are minimum values, as discussed in the third section of this paper. In addition, the values of P_s shown for each $\overline{\Delta T}$ will be minimum values because advection will replace heat radiated to space from the dark hemisphere. If the more probable value of $P_c{\circ}/P_c{\bullet} = 6$ instead of 1 is adopted in the derivation of Fig. 4, all synodic periods will also be increased by a factor of 6.

The results show that the sidereal period of rotation is very likely greater than 170 days, and quite possibly approaches the sidereal period of revolution of Venus, 224.7008 days. Under the assumptions of the derivation, the sidereal period of rota-

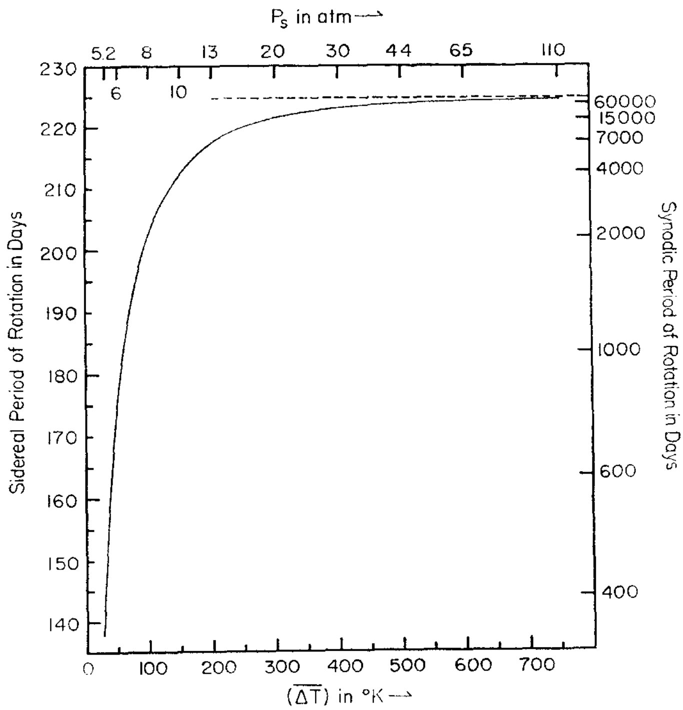

FIG. 4. Sidereal and synodic periods of rotation of Venus as a function of the microwave phase effect and the surface pressure. It is assumed that the specific heat of the Cytherean atmosphere is the nocturnal thermal reservoir, and that the planet rotates nonsynchronously. The dashed horizontal line corresponds to an infinite synodic period, i.e., synchronous rotation. The values of surface pressure shown are minima.

tion exceeds 210 days if $P_s > 30$ atm, essentially independently of the exact choice of $\overline{\Delta T}$. The mean rate of change of surface temperature is then a few degrees per day.

The curve of Fig. 4 asymptotically approaches synchronous rotation. Small departures from synchrony are not significant because of the contributions from subsurface conduction and atmospheric advection, and because of the use of minimum values of P_s.

The conclusion is strongly against sidereal rotation periods of a few tens of days as some photographic studies (Ross, 1928) and the Soviet radar results (Kotelnikov, 1961) indicate; it supports periods approaching synchronous rotation, as some visual studies (Danjon, 1943; Dollfus, 1955) and the United States radar results (Victor, Stevens, and Golomb, 1961; Pettingill, 1961) suggest. The derivation of Eqs. (7) and (10) depends on the assumption of *nocturnal* cooling, i.e., nonsynchronous rotation. Therefore, the assumption of nonsynchronous rotation leads directly to very long periods of rotation, approaching, if not actually reaching, synchronous rotation. We now proceed to the problem of the phase effect for synchronous rotation.

The existence of a sizeable phase effect implies an appreciable horizontal temperature gradient in the lower Cytherean atmosphere, and, therefore, interhemispheric advection. The wind velocities must decline with altitude, because the cloudtop temperatures on the bright and dark sides are sensibly the same (Pettit and Nicholson, 1955; Sinton and Strong, 1960). On a slowly rotating planet, the expected circulation scheme should have a component which is radial from the subsolar point (see, e.g., Mintz, 1961; Kellogg and Sagan, 1961); and there is some hint of this on visual (Dollfus, 1955, 1961) and photographic (Ross, 1928) representations of the appearance of Venus. However, another circulation mode also appears (Ross, 1928; Kuiper, 1954; Richardson, 1955; Dollfus, 1955); this is a set of parallel bright and dark stripes. When these are interpreted as weather bands, the requirement that the linear velocity of rotation of the planet exceed the random wind velocity gives a period of rotation of several tens of days (Ross, 1928; Öpik, 1956) for characteristic terrestrial wind velocities. Now the existence of two circulation modes suggests that the period of rotation is greater than the period required to explain the weather bands alone. Furthermore, the horizontal thermal gradient between the bright side and the dark side will force a circulation pattern which may mimic the weather bands, and calculations based on *random* wind velocities will be in error. Hence the existing observations of the general Cytherean circulation do not seem inconsistent with very long, and possibly synchronous, periods of rotation.

In the case of synchronous rotation, the outward radiation flux from the night hemisphere must be balanced by an energy flux from the day hemisphere provided by the atmospheric circulation. If one were to consider only the heat flux of kinetic energy across the terminator the required mean residual wind velocity from bright side to dark side would be $\sim$150 mph. In actuality, the situation is dominated by contributions from the gravitational potential energy of advected air, from the temperature difference between winds entering and leaving the dark hemisphere, and from the specific heat of the atmosphere. Mintz (1962) has considered these terms and finds, for the atmospheric model of the present paper, that very low velocity winds, $\bar{v} \sim 0.3$ mph, can account for the nighttime radiation losses.

Winds near the cloud level would also help explain the near-equality of cloudtop temperatures in the illuminated and unilluminated hemispheres. In the case that the specific heat of the atmosphere provides the heat reservoir, the nighttime cloud temperatures are maintained radiatively from the underlying atmosphere; and a similar circumstance must prevail when the surface nocturnal cooling is governed by ground conduction alone. Application of Eqs. (7) and (9) to the clouds shows that the condition $T_c^{\bullet} \simeq T_c^{\circ}$ would not be fulfilled were thermal conduction within the clouds the only source of heat to maintain cloud temperatures. Similarly, the specific heat of the clouds themselves cannot provide an adequate heat reservoir for the clouds.

To summarize this section:

(*a*) For nonsynchronous rotation, subsurface conduction in sandy soil can explain $\overline{\Delta T} \sim 50°K$ for rotation periods $\sim$ 1 day, 200°K for $\sim$10 days, and 400°K for $\sim$50 days. Soils with higher moisture content give longer rotation periods.

(*b*) For nonsynchronous rotation, the specific heat capacity of the atmosphere can explain the microwave phase effect, provided the sidereal period of rotation exceeds 170 days. The most likely atmospheric parameters give periods approaching very closely to synchronous rotation. Were the period of rotation shorter than 170 days, the atmospheric thermal reservoir would prevent nocturnal cooling from being as large as it actually is.

(*c*) For synchronous rotation, the atmospheric circulation must transport from the bright hemisphere the energy radiated to space on the dark hemisphere.

In actuality, all three mechanisms must operate. Under these circumstances the period of rotation of Venus must be quite close to the period of revolution.

Rayleigh Scattering in the Atmosphere of Venus

The preceding discussion has provided evidence for Cytherean surface pressures of at least several tens of atmospheres. Rayleigh scattering by this amount of gas will produce optical effects somewhat different from those observed in the terrestrial atmosphere. The extinction coefficient for Rayleigh scattering can be expressed as

$$\beta_o = \frac{32\pi^3}{3n\lambda^4} \sum_i \alpha_i(m_i - 1)^2 \frac{2 + q_i}{2 - q_i} \quad (11)$$

(see, *e.g.*, van de Hulst, 1952), where λ is the wavelength of the incident light, n is the number density of molecules at some reference level in the atmosphere, α_i is the volume mixing ratio of the ith atmospheric constituent, m_i is the index of refraction of the ith constituent, and q_i is the Cabannes depolarization coefficient of the ith constituent. The error introduced by replacing the quantities behind the summation sign by the corresponding values for the terrestrial atmosphere is much smaller than the uncertainty in our knowledge of the surface pressure on Venus. Accordingly, we can use the extinction coefficients tabulated by van de Hulst (1952) for the construction of Fig. 5. The figure gives the transmission of the Cytherean atmosphere to incident sunlight in the absence of clouds as a function of wavelength for five combinations of surface pressure and solar zenith angle, θ. For sec $\theta = 1$, the sample surface pressures chosen are 10, 20, 50, 100, and 200 atmospheres.

It is evident for surface pressures of several tens of atmospheres that very little violet, blue or green light is transmitted in the incident beam. For $P_s = 20$ atm, 10% of the incident beam is transmitted only at 5250 Å; for $P_s = 50$ atm, at 6500 Å; and for $P_s = 100$ atm, at 7750 Å. Thus, even at the zenith the sun would appear a deep red on a cloudless day on the surface of Venus. As the sun approaches the horizon, its color will become a deeper and deeper red; depending on the actual value of P_s, the sun may be extinguished by Rayleigh scattering long before it reaches the geometrical horizon. The light scattered out of the beam of incident sunlight is the source of the coloration of the sky. Thus, the sky on Venus will not be a pure blue. With $P_s = 20$ atm, the sky should have a yellow-green cast when the sun is at the zenith, and take on an increasingly orange hue as the sun approaches the horizon. For larger surface pressures the coloration of the sky becomes increasingly reddened.

Whether these fairly spectacular color effects could actually be observed from the Cytherean surface depends in large part on the opacity and extent of the cloud cover. Both visual and photographic studies (see, e.g., Dollfus, 1961) and near infrared spectroscopy (Spinrad, 1962) show that the visual cloud cover in the upper atmosphere

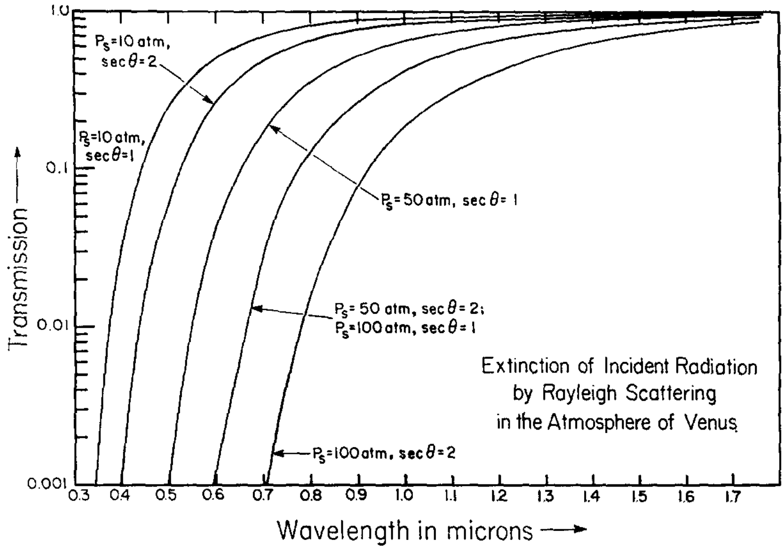

FIG. 5. Extinction of incident radiation by Rayleigh scattering in the atmosphere of Venus. Five choices are shown of the product of surface pressure and the secant of the solar zenith angle.

is variable in time. While the near-equality of infrared brightness temperatures at 3.75 μ and at 8–13 μ (Sinton, 1962) shows that the cloud cover must on the average be some 99% complete, the secular temperature variations which have been observed in the 8–13 μ region (see, e.g., Sinton, 1962) indicate that moments of clearing do occur. It is difficult to say very much at the present time about the possible existence and opacity of clouds in the lower atmosphere, and especially near the surface. The effect of neutrally colored clouds will be to wash out the coloration of both sky and sun. This is apparent on an overcast day on Earth. If the Cytherean clouds are reasonably thick as we expect, an overcast day on Venus may be extremely dark. The contrast which a day of clearing would provide would then be quite striking.

Rayleigh scattering must also have an effect on the color of the light emerging from the top of the Cytherean atmosphere. The computations of Deirmendjian and Sekera (1954) on multiple scattering in a Rayleigh atmosphere of terrestrial mass have shown that, for the sun near the zenith, the radiation scattered by the atmosphere to space has two maxima, one in the near ultraviolet and the other in the violet. Thus, we expect that Earth has a violet cast superposed on its ordinary coloration when seen from space.

The effect of more massive atmospheres on the emerging light can be seen from the work of Coulson (1959; especially his Fig. 2). Coulson computes the spectral distribution of the flux emerging from the top of the terrestrial atmosphere for zero surface albedo, and for values of sec θ as large as 50. As the air mass increases, the ultraviolet and violet peaks are suppressed, and a new peak in the blue ($\lambda \simeq 4600$ Å) appears. For sec $\theta = 50$, the blue peak is also suppressed, and we are left with a mound of very shallow slope and major spectral contributions in the green, yellow, and orange. Thus, the possibility arises that the well-known pale lemon yellow hue of Venus is due to Rayleigh scattering in the bulk of the Cytherean atmosphere.

Coulson (1959) notes that the radiation emerging from the top of a Rayleigh atmosphere will be bluer than the skylight. If the yellow coloration of Venus is due to Rayleigh scattering, then the cast of the sky will be on the red side of yellow, as we have already concluded. It should also be noted that the relative peaks in the violet and ultraviolet tend to remain as the air mass is increased, although their absolute intensity and their intensity compared with other features tends to decline. As a result, even for large air masses, a pronounced relative minimum exists near 3900 Å (and at other short visual wavelengths) in the flux emerging from a Rayleigh atmosphere.

There is a simple test of this hypothesis. At inferior conjunction the light emerging from the top of the Cytherean atmosphere has passed, on the average, through a greater air mass than at, say, dichotomy. Thus, the color index should be a function of phase. Venus should be redder at small phase angles. Moments of clearing in the cloud cover should also be accompanied by an increase in the color index. There would seem to be a need for a program of continuous multicolor photometry of Venus coupled with photographic and bolometric monitoring.

There is one further consequence of the Rayleigh extinction. The surface of Venus cannot possibly be seen in the blue and violet, even through breaks in the clouds. Observations in the green and yellow will be difficult at best. Accordingly, the dark markings seen visually through breaks in the Cytherean cloud deck (Danjon, 1943; Dollfus, 1955) cannot be surface features. This is especially borne out by the observations of Camichel (see Dollfus, 1961) that markings in the photographic ultraviolet correspond closely to the markings observed visually at about the same date.

On the other hand, these same visual observations have led to a period of rotation comparable to the period of revolution. The United States radar results (Victor, Stevens, and Golomb, 1961; Pettingill, 1961) and the considerations of the preceding section support this conclusion. If the period of rotation is truly synchronous, then the visually observed low-level dark markings and their fixed distance from the terminator cannot be explained by diurnal cloud patterns. Thus, if the rotation is synchronous, there must be a cloud pattern in the lower Cytherean atmosphere which is somehow connected with the underlying surface features. The remarkable fact is that these lower clouds can be photographed in the ultraviolet. The washout of features in the photographic ultraviolet by Rayleigh scattering becomes severe at pressure levels of 10 atm and higher. If the surface pressures on Venus are several tens of atmospheres, the lower cloud pattern must extend at least some 40 or 50 km above the surface (cf. Fig. 1), and still be connected with surface features. There must also be sizeable breaks in the lower cloud pattern.

We have concluded it will be very difficult to see the surface of Venus in visible light, because of Rayleigh scattering. However, near infrared photography of Venus should receive light from the lower atmosphere, and quite possibly from the surface. We already know that the 6 atm pressure level can be reached (Spinrad, 1962) *in an absorption band.* Tombaugh (1961) finds a suspicion of markings on Venus in photographs taken at 1.1 μ. Infrared photography of Venus—especially from flyby vehicles—would appear to be a very promising endeavor.

Further Discussion

The general range of parameters deduced in the preceding discussion has several further consequences. The existence of a substantially subadiabatic temperature gradient on the dark side is in direct contradiction to the fundamental requirement of the Aeolosphere Model (Öpik, 1961); namely, that an adiabatic lapse rate exist to provide convective transport of dust from the lower atmosphere to the clouds. In the absence of condensation in the Cytherean atmosphere below the clouds, a subadiabatic temperature gradient will tend strongly to resist convection, and the primary means of vertical energy transport in the lower atmosphere must then be radiative. However, if the visual clouds are composed of water, substantial convective instability can be expected in the region of the clouds.

The high temperatures and pressures imply conditions on the surface of Venus which are quite extraordinary by terrestrial standards. At temperatures of 750° K and greater, the surface of Venus in the illuminated hemisphere will be at red heat. The melting points of lead, zinc, aluminum, magnesium, bismuth, and tin may be reached, and it is possible that liquid pools of molten surface material cover much of the bright side. Because of the high pressures, many substances which would ordinarily be vaporized by the high temperatures may still remain in liquid states. Figure 6 gives the vapor pressure

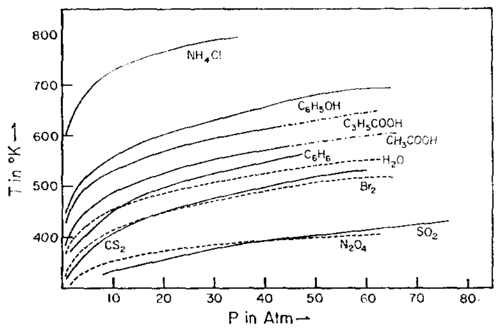

FIG. 6. Vapor pressures of some common materials in the pressure and temperature range expected on the dark surface of Venus. When the vapor pressure equals the ambient pressure for a given temperature, the boiling point is reached. The alternating dots and dashes represent extrapolations of the data.

curves of some common materials in the pressure and temperature regime of interest, as given in the International Critical Tables. It is apparent that, especially at the dark pole, several possible constituents of the lower atmosphere may condense out. Drake (1962) estimates the temperature at the dark pole to be 540° K. Liquid water could then exist at the pole if the surface pressure exceeds 60 atm; liquid benzene, if $P_s > 38$ atm; liquid acetic acid, if $P_s > 26$ atm; liquid butyric acid, if $P_s > 13$ atm; and liquid phenol, if $P_s = 8$ atm. If these and similar substances are present, the surface pressures appear to permit the existence of a polar sea on Venus. It is not anticipated that such a polar sea will have a very large area, because we expect the Urey equilibrium to fail on Venus. Ammonium chloride, if present, will condense out over most of the dark hemisphere. At the pressures and temperatures discussed in this paper, the production of surface organic matter can be expected from the reaction of N_2, CO_2, and H_2O. Clouds of exotic materials may exist in the lower atmosphere. Carbon dioxide and nitrogen remain in the gas phase and well below the critical point at all times.

The high surface pressures and temperatures suggested in the present paper will result in very high opacities throughout the infrared. The thermal excitation of low-lying rotational states, and the pressure-broadening of line contours will contribute to substantial absorption in wavelength intervals which are normally window regions in the terrestrial atmosphere. Pressure-broadening of CO_2 should give high opacity in, for example, the 3.5 μ and 10 μ regions which are normally transparent in the Earth's atmosphere. It is possible that pressure-induced dipole transitions will also make substantial contributions to the over-all opacity. Volatilization of surface material may lead to currently unsuspected infrared absorbers in the lower atmosphere.

These considerations tend to support the Greenhouse Model of the origin of the microwave emission. But it is now clear that the situation is much more complicated than in the original formulation of the Greenhouse Model (Sagan, 1960). Due to cloud opacity and near infrared CO_2 absorption much less incident sunlight reaches the lower Cytherean atmosphere than had been originally thought. The attenuation of outgoing infrared radiation due to the clouds and the increased atmospheric extinction just mentioned will also be much greater than had been originally thought. Another attempt at detailed calculations of the Greenhouse Effect must await a better specification of the composition and opacity of the visible clouds and a better knowledge of the composition of the lower atmosphere.

CONCLUSIONS

Arguments from the microwave brightness temperature phase effects from the failure of the Urey equilibrium, and from the rotational structure of the near infrared CO_2 bands each give surface pressures of at least several tens of atmospheres on Venus. Each argument suffers from the lack of completely adequate observational material. But the existence of three independent approaches all leading to the same result tends to reinforce the conclusions. The following parameters lead to a self-consistent (but not necessarily exclusive) model of the lower Cytherean atmosphere:

(*a*) There is one principal effective reflecting surface from the visible to the far infrared, *viz.*, the visible cloud layer at a temperature $\simeq 234°$ K.

(*b*) The cloudtop pressures are at least as great on the bright side as on the dark; the most probable values are $P_s^{\bullet} = 90$ mb, and $P_s^{\circ} = 0.6$ atm.

(*c*) The mean surface temperature of the dark side is $\sim 640°$ K; on the bright side, $T_s^{\circ} \sim 750°$ K.

(*d*) The surface pressure is $\geqslant 30$ atm, with an outside chance of being as high as several hundred atm.

(*e*) The subadiabatic index in the lower atmosphere on the dark side is $\eta^{\bullet} = 1.5 \pm 0.4$.

(*f*) The high carbon dioxide partial pressures are due to the failure of the Urey equilibrium. No explanation is proposed for the high nitrogen partial pressures.

(*g*) The altitude of the cloudtops in the dark hemisphere is 80 ± 20 km; if $P_c^{\circ} >> P_c^{\bullet}$ the clouds will be even higher in the bright hemisphere.

(*h*) Substantial turbulent motion exists in the region of the clouds.

(*i*) The sidereal period of rotation is greater than 170 days, and is quite possibly synchronous with the period of revolution. For synchronous rotation, the atmospheric circulation must supply the energy radiated to space from the dark hemisphere.

By terrestrial standards the surface conditions are extreme. The temperatures are much higher than the maximum temperatures of ordinary ovens and the surface may be at red heat. The pressures correspond to those at several hundred meters depth in the terrestrial oceans. Substantial amounts of surface material may have liquified or vaporized. Consequently, the exploration of the surface of Venus by unmanned vehicles or by manned exploration teams appears to represent a very difficult engineering problem.

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