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The Radiation Balance of Venus

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PREFACE

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ABSTRACT

Recent microwave observations of Venus give brightness temperatures near 600°K. The spectrum precludes an origin as synchrotron or cyclotron radiation from a Cytherean Van Allen belt; the emission must be thermal and probably arises from just beneath the surface of Venus. The radiation temperature of an airless planet with Venus' color-corrected albedo and solar distance is ~250°K if the period of rotation is much less than the period of revolution or if there is appreciable interhemispheric circulation; it is ~350°K if the two periods are comparable. It is evident that a surface temperature of 600°K demands a very efficient greenhouse effect. From the radiation balance, the effective absorptivity of the atmosphere, integrated over all wavelengths, is $\alpha \simeq 0.995$ for nonsynchronous rotation; the equivalent atmosphere is opaque between 1.5 and 40 μ. Water is the only molecule which is likely to be abundant on Venus and which absorbs in the region longward of 20 μ.

If there is 1 km-atm of carbon dioxide above the effective reflecting layer for the λ8000 bands, the total carbon dioxide abundance in a convective Cytherean atmosphere is 18 km-atm; the total surface pressure is ~4 atm. Extrapolation to long paths of CO_2 and H_2O emissivities at elevated temperatures shows that ~10 g cm^{-2} of water vapor is required for a nonsynchronously rotating Venus and ~1 g cm^{-2} for a synchronously rotating Venus in order that the required greenhouse effect be achieved. As a check, the method was applied to Earth; the correct terrestrial water-vapor abundance was predicted. The Venus model atmosphere has an ice-crystal cloud layer about 36 km above the surface. For nonsynchronous rotation, the predicted cloud layer is at the thermocouple temperature but at saturation has five times more water vapor above it than observed by Strong; for synchronous rotation, the cloud layer is 14 K° cooler than the thermocouple temperature but has 2×10^{-3} g cm^{-2} of water vapor above it, as observed by Strong. More precise agreement with the observed thermocouple temperature and water-vapor abundance cannot be expected, because of CO_2 band emission from warmer regions above the cloud layer, and because of the possibility that ultraviolet photodissociation reduces the water-vapor abundance below saturation values. If the mean cloud albedo is >0.75, the overcast is <0.90. At gaps in the clouds, there are

ABSTRACT (Cont'd)

windows near 8.7 μ and also at many wavelengths in the near infrared and visible regions.

The absence of surface liquid water inhibits the establishment of the Urey equilibrium, and, incidentally, greatly reduces tidal friction. If the Earth had been placed in the orbit of Venus soon after its formation, roughly the same atmospheric carbon dioxide content as on Venus would have resulted, but the surface temperature and water-vapor abundance would have been much greater; thus, Earth must have been formed with $>10^4$ times more water than was Venus. Because of the high temperature and the absence of liquid water, it is very unlikely that contemporary indigenous organisms exist on the surface of Venus.

I. INTRODUCTION

The radiation balance of Venus was first discussed by Wildt (Ref. 1), who showed that the amount of carbon dioxide then believed to exist above the cloud layer could cause a moderately efficient greenhouse effect. For a slowly rotating Venus, Wildt calculated that the tropical noontime surface temperature would exceed 400°K. In this Report, the inverse procedure is adopted. The surface temperature is taken from recent radio observations, and the properties of the atmosphere are deduced. In Sec. II, the radio spectrum and the possibility of nonthermal emission are discussed; the resulting model atmosphere for carbon dioxide is given in Sec. III. The requirements for atmospheric absorption in the far infrared, imposed by the radiation balance, are described in Sec. IV. Semi-empirical equations of radiation balance are derived in Sec. V, where applications are made to the atmospheres of both Venus and Earth, the latter as a test of the reliability of the equations. Section VI describes a model of the Venus cloud layer and a comparison of the model with observations. Finally, the origin of the derived Venus atmosphere is treated in Sec. VII.

II. THE SURFACE TEMPERATURE OF VENUS

A. Thermocouple and Rotational Temperatures

Before 1956, two methods were used to determine the temperature of Venus: thermocouple observations, and analysis of the rotational fine structure of carbon dioxide bands in the photographic infrared. The thermocouple temperatures, derived from Cytherean emission through the 8- to 13-μ window in the terrestrial atmosphere, are between 234 and 240°K (Ref. 2 and 3). The most reliable rotational temperatures, derived from the λ8000 bands of CO_2 by assuming radiative transfer in an optically thick plane-parallel atmosphere, are 285 ± 9°K (Ref. 4). Carbon dioxide bands at 9.4, 10.4, 12.7, 13.5, and 13.8 μ will make an appreciable contribution to the thermocouple temperature. The 10.4-μ band has been observed directly by Strong and Sinton (Ref. 3). It is clear, therefore, that both thermocouple and rotational temperatures are composite quantities, arising from an integration of contributions from various levels in the atmosphere of Venus. Consequently, there is no *a priori* reason to expect the bolometric and rotational temperatures to agree with the temperature of the Cytherean surface.

B. Radio Brightness Temperatures

In 1956, centimeter wavelength radio emission from Venus was detected with the 50-ft reflector of the Naval Research Laboratory by Mayer, McCullough, and Sloanaker (Ref. 5). The derived brightness temperature of the integrated disk of Venus was approximately 600°K, with a mean error of about 100°K. Subsequently, other observations have been performed, all at or near inferior conjunction and at wavelengths ranging from 8.6 mm to 21 cm. The brightness temperatures corresponding to these observations generally agree closely with the values of Mayer *et al.* The data available to date are presented in Table 1, and the resulting radio spectrum is plotted in Fig. 1. Probable errors are displayed, except for the 3.15-cm observations, where mean errors are shown.

The low brightness temperature at 0.86 cm may be the result, in part, of the signal-to-noise ratio being less than unity, and the emission not being detectable in individual observations. The same sources of error exist for the 9.4-cm observations. The large probable error at 21 cm

Table 1. Radio observations of Venus

λ, cm	Time of observation	No. of observations	Instrument	T_B, °K	Reference
0.86	Inferior conjunction 1958	15	10-ft NRL	410 ± 160 p.e.	6
3.15	Dichotomy 1956	13	50-ft NRL	620 ± 110 m.e.	5
3.15	Inferior conjunction 1956	20	50-ft NRL	560 ± 73 m.e.	5
3.37	Dichotomy 1958	2	50-ft NRL + maser	575 ± 58 p.e.	7, 8
3.4	Inferior conjunction 1958	9	50-ft NRL	575 ± 60 p.e.	9
3.75	Inferior conjunction 1959	26	85-ft NRAO	585 ± ~50 p.e.	10
9.4	Inferior conjunction 1956	11	50-ft NRL	580 ± 160 p.e.	5
10.2	Inferior conjunction 1959	11	84-ft NRL	600 ± 65 p.e.	11
21	Inferior conjunction 1959	—	84-ft NRL	750 ± 375 p.e.	12

is attributed to the high background at that wavelength and to interference from the Sun.

In addition to the measurements listed, there has been one observation of Venus made at 68 cm by Drake (Ref. 10) near inferior conjunction in 1959. The sensitivity was too poor to detect 600°K black-body emission at this wavelength, but a brightness temperature considerably in excess of 600°K, such as exists for Jupiter, was not observed.

C. Possibility of Nonthermal Emission

The radio brightness temperatures are considerably greater than the bolometric, the rotational, or the theoretical radiation temperatures of Venus. It is natural to inquire whether or not the emission from Venus may be nonthermal in origin.

The most likely alternative to black-body emission is cyclotron or synchrotron radiation from charged particles trapped in a Cytherean Van Allen belt. This interpretation has been proposed as an explanation of the radio emission from Jupiter (Ref. 13, 14, and 15).

The relation between brightness temperature and frequency for a Van Allen belt of uniform relativistic electron density in a longitudinal cross section through the belt is given by

$$T_B(f) \propto f^{-2} \int_{E_c}^{\infty} n(E)\, P(f)\, dE \qquad (1)$$

where the synchrotron emission spectrum of a single particle $P(f)$ can be written as

$$P(f) \propto E^{-2/3} f^{1/3} \qquad (2)$$

and f is the frequency of emitted radiation, E the particle energy, and E_c the cutoff for a charged-particle energy distribution $n(E)$ (Ref. 15). If we observe that

$$E_c \propto f^{1/2} \qquad (3)$$

and assume

$$n(E) \propto E^{-s} \qquad (4)$$

we obtain, by substituting Eq. 2, 3, and 4 in Eq. 1 and integrating,

$$T_B \propto \lambda^{(s+3)/2} \qquad (5)$$

In order to ensure convergence of the integral, we must have

$$s > \tfrac{1}{3} \qquad (6)$$

The restriction inequality 6 on the exponent s can be removed by artificially introducing a high-energy cutoff as well as a low-energy cutoff. However, if Venus has a magnetic-field strength of a few gauss, centimeter wavelength synchrotron radiation requires electron energies in the Mev-range and proton energies approaching 1 erg/particle. At such energies, it would be very unlikely for s to be negative. [For comparison, the electrons in the Earth's Van Allen belt have an energy distribution given by $s = +5$, as measured by *Sputnik III* (Ref. 16)].

With $s \geqq 0$, T_B is proportional to the 3/2, or higher, power of the wavelength; i.e., the brightness temperature at 20 cm is more than 90 times that at 1 cm. It is evident that even the most extreme curve through the probable errors of the Venus observations shown in Fig. 1 does not approach the synchrotron radiation spectrum. The most extreme spectrum consistent with the Venus observations is perhaps $T_B \propto \lambda^{1/3}$. The corresponding energy distribution would be $n(E) \propto E^{+7/3}$, which is unlikely. It is concluded that the Venus radio emission is not due to

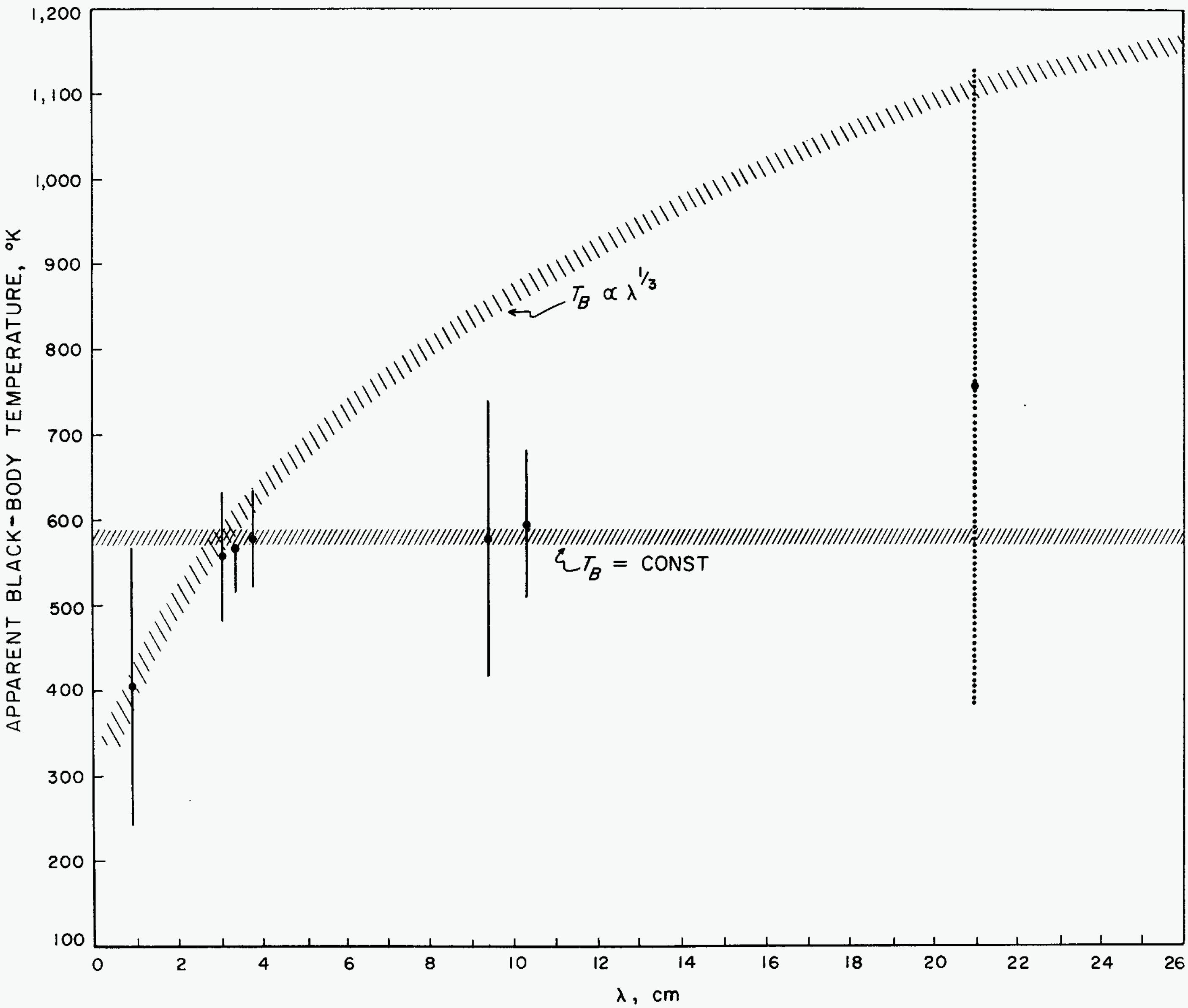

Figure 1. Microwave observations of Venus

synchrotron radiation from a Cytherean Van Allen belt. A similar conclusion applies to free–free transitions in the Cytherean ionosphere, for which, in optically thin regions, $T_B \propto \lambda^2$, and to cyclotron radiation in a dipole field, where $T_B \propto \lambda^{7/3}$ (Ref. 17). The negative result at 68 cm, given by Drake (Ref. 10), the absence of bursts of radio noise, and the lack of a strong plane-polarized component of the emission (Ref. 5) all tend to corroborate these conclusions. In addition, there is a suggestion of a phase effect for Venus, higher temperatures prevailing near dichotomy than near inferior conjunction (Table 1, lines 2 and 3). This is expected if the emission is due to thermal radiation from a surface heated by the Sun. On the other hand, if there were terrestrial values of the magnetic field strength, and of particle energies and densities, electrons trapped in a Cytherean Van Allen belt should drift through 360° in longitude in a few days at most, and no such phase effect would exist.

D. Microwave Absorption and Adopted Surface Temperature

The Venus radio emission, therefore, is probably thermal in origin, with T_B independent of λ. At those microwave frequencies for which the atmosphere of Venus is transparent, the thermal radiation probably arises from just beneath the planetary surface. There is also the bare possibility that the emission is thermal, but arises from a Cytherean ionosphere with electron temperature $\sim 600°$ K. However, it is easily shown that electron densities at least 10^3 times greater than those of the terrestrial ionosphere are required to explain the microwave spectrum. Especially since there is every reason to expect the Cytherean magnetic field strength to be of the same order of magnitude as the terrestrial magnetic field strength, such high electron densities are implausible, and an ionospheric origin of the thermal emission appears untenable. Of the gases in the terrestrial atmosphere, only oxygen and water vapor have appreciable absorption coefficients in the microwave region, relative maxima existing for oxygen near 0.5 cm and for water vapor near 1.4 cm (Ref. 18 and 19). The absorption coefficients decline rapidly at wavelengths exceeding these maxima; water, in particular, becomes essentially transparent beyond a few centimeters. There is a pressure-induced dipole transition of CO_2 in the microwave region, but carbon dioxide transparency is also expected beyond a few centimeters (see, e.g., Ref. 20). In addition, microwave attenuation is produced by liquid and solid particles such as cloud droplets, rain, hail, sand, and dust, provided the particle radius $a \gtrsim \lambda/2\pi$. For common terrestrial conditions, there is effectively no attenuation from these causes beyond a few centimeters (Ref. 21 and 22). There is no evidence indicating the presence of oxygen on Venus. The particles in the Cytherean cloud layer have radii in the range 1 to 10 μ (see, e.g., Ref. 23), and at present there is no reason to believe that particles of much greater size exist, regardless of composition. However, some water is known to exist (Ref. 24; see also Sec. IV-B); therefore, radio brightness temperatures measured at wavelengths shortward of about 2 cm should be lower than those at longer wavelengths. The low T_B at 0.86 cm is probably attributable, at least in part, to this cause. Ultimately, it should be possible to determine directly the total amount of water vapor in the Venus atmosphere by a comparison of brightness temperatures at short microwave wavelengths, allowing for terrestrial absorption. However, at present, the instrumental accuracy is not sufficient to make good quantitative estimates. Barrett (Ref. 20) has attempted to carry out this program with the 0.86-cm brightness temperatures now available. He finds that, for surface pressures of a few atmospheres, the fraction of water vapor in the atmosphere of Venus must be 5% or more. However, Barrett has made no allowance for attenuation in the Cytherean cloud layer; this would tend to reduce considerably the required atmospheric water abundance.

The mean of the most reliable brightness temperatures given in Table 1 lies somewhat below 600°K. Radiation at centimeter wavelengths arises from perhaps a few tens of centimeters below the surface. By terrestrial analogy, the coefficient of thermal conductivity at the surface is so low that very little temperature difference exists between the surface and some decimeters below the surface. Judging from the observations near dichotomy, the mean temperature of the illuminated hemisphere should not be more than a few tens of degrees higher than the mean temperature of the unilluminated hemisphere. Accordingly, for future use, a mean surface temperature is adopted for Venus, averaged over the surface and the seasons, of 600°K. If this temperature is assumed, it remains to be seen whether or not a workable greenhouse effect can be found to explain it.

III. ATMOSPHERIC STRUCTURE

A. Atmospheric Convection and the Period of Rotation

The classic ultraviolet photographs of Venus presented by Ross (Ref. 25) show the presence of extremely time-dependent variable bright and dark areas; band patterns sometimes can be discerned extending from the terminator onto the disk. A set of three bright and three dark bands roughly perpendicular to the position of the terminator was found in the ultraviolet photographs taken by Kuiper (Ref. 26) and by Richardson (Ref. 27). A common explanation of the banded structure is atmospheric circulation arising from planetary rotation. Then the speed of equatorial rotation must exceed that of random atmospheric winds (see, e.g., Ref. 28); this implies a period of rotation of a few weeks, at most. The minimum value for the period of rotation is obtained from the absence of a rotational doppler shift at the planetary limb (Ref. 29), and is of the order of several days.

Visual observations, dating back to Schiaparelli, have suggested the presence of dark markings which show no apparent motion with respect to the terminator over periods of weeks. These have been interpreted as surface features seen through stable gaps in the cloud layer; the apparent constancy in position of the dark markings has suggested to these observers that the period of rotation of Venus is equal to its period of revolution, viz., 225 days. In recent years, Danjon (Ref. 30) and Dollfus (Ref. 31) have supported this view. However, the rapid day-to-day changes in the form, intensity, and position of the ultraviolet markings led Ross (Ref. 25) and others to question the interpretation of visual observations which claim to follow the same feature for many weeks. Kuiper (Ref. 32) has pointed out that, on a slowly rotating planet, cloud patterns near the terminator will bear a constant relation to the terminator, just as characteristic cloud patterns appear at a given time of day on Earth.

Ross also took the approximate equality of day and night thermocouple temperature (Ref. 2) to indicate that the period of rotation must be much shorter than the period of revolution; otherwise, he argued, the illuminated hemisphere would grow much warmer than the dark hemisphere. However, mass transport would prevent an excessive interhemispheric temperature gradient. Thus, either Venus rotates nonsynchronously, or there is appreciable interhemispheric circulation.

Other evidence for a convective atmosphere can be adduced from Dollfus' observations of rapid changes in the polarization and position of regions examined polarimetrically (Ref. 33). Kuiper's observations of very large day-to-day variations in the equivalent width of the λ8689 band of CO_2 (Ref. 23) are suggestive of violent vertical convection of some interposed absorbing material. Strong and Sinton (Ref. 3) also found the intensity of the unidentified 11.2-μ feature to be variable in time.

In the remainder of this Report, no attempt will be made to differentiate between the short (5- to 30-day) and long (225-day) period of rotation (although the observations favor the former), but both will be carried in the calculations. In the light of the evidence just reviewed, it is assumed that a convective atmosphere is in adiabatic equilibrium from the region of the cloud layer down to the surface. The adiabatic gradient should be maintained by incident visible solar radiation penetrating to the surface, as on Earth, and also by a vertical component of the interhemispheric convection. The possibility that the true temperature gradient is strongly superadiabatic can be investigated (see, e.g., Ref. 34, p. 49, Eq. 7.7). If we approximate the convective mixing length by the scale height and take the incident flux from the Cytherean solar constant and albedo, we find an excess of the true temperature gradient over the adiabatic gradient of about 10^{-7} K° cm^{-1}. The absolute value of the adiabatic gradient, as determined in the following subsection, is about 10^{-4} K° cm^{-1}, and it is concluded that the extent of superadiabaticity is negligible. It also follows (Ref. 34, p. 51) that the mean velocity of the convective elements in the Cytherean atmosphere is about 10^3 cm sec^{-1}, and that their mean lifetimes are of the order of ¼ hr.

B. Carbon Dioxide Model Atmosphere

For an atmosphere in adiabatic equilibrium, the temperature gradient is

$$\frac{\partial T}{\partial h} = -\frac{g}{c_p} \tag{7}$$

where g is the acceleration due to gravity and c_p is the specific heat at constant pressure of the atmosphere. The pressure and temperature are related by Poisson's equation,

$$\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\gamma/\gamma-1} \tag{8}$$

where γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume. A surface temperature of 600°K has been adopted. In order to specify the temperature and pressure at all altitudes by Eq. (7) and (8), it suffices to know the pressure and temperature at one point above the surface.

Long path-length laboratory spectra of carbon dioxide taken at pressures of 1 atm or less have very closely reproduced the intensity of the Venus bands at $\lambda\lambda$8689, 7883, and 7820 without excessive pressure broadening (Ref. 35). The amount of Cytherean CO_2 traversed by a light ray at one of these wavelengths is concluded to be about 2×10^5 cm-atm; therefore, the amount of carbon dioxide above the point at which the ray effectively reverses its direction is of the order of 1 km-atm. This point of reversal is often referred to as *the* cloud layer, but it is evident that different levels are observed in the ultraviolet, the visible, and the infrared, and that, therefore, there are several cloud layers or reflecting layers, depending on the nature of the observations. Most of the absorption and scattering occurs at the deepest level of penetration of the incident light, but it is perfectly conceivable that the bulk of the scattering particles which comprise the visible and ultraviolet cloud layer lie at a deeper level.

If an incident photon suffered extensive multiple scattering in the dense regions of the atmosphere near the point of path reversal, the true CO_2 abundance would be less than the value deduced from laboratory intensity-matching; scattering will increase the gas path traversed by an individual photon. However, from observations of the prolongation of the cusps at inferior conjunction, it is known that the visible cloud layer has a scale height which is much less than the scale height of the atmosphere at that level (Ref. 36). An incident photon will be scattered primarily near the top of the cloud layer.

In general, the number of scattering events will be small, the additional path traversed because of multiple scattering being only a small fraction of the total path through the atmosphere, and no substantial revision of existing CO_2 abundances will be required. From diffusion theory, the total net displacement during a three-dimensional random walk is given approximately by $\xi = \lambda N^{1/2}$, where λ is the mean free path and N is the total number of scattering events suffered by the photon over its entire path. This equation has a coefficient of the order unity, which is well-determined if N is large; but for small N, a precise value of the coefficient is meaningless. The integrated path traversed by the photon is $R = \lambda N$; consequently,

$$\xi \simeq R N^{-1/2}$$

The true carbon dioxide abundance above the reversal point in the λ8000 bands is proportional to ξ, whereas the equivalent laboratory path deduced by Herzberg (Ref. 35) is proportional to R. For $N \leq 10$, the CO_2 abundance is still of the order of 1 km-atm. An uncertainty in the carbon dioxide abundance of an order of magnitude will not affect the radiation-balance arguments which follow. Therefore, it is assumed that there is 1 km-atm of carbon dioxide above the effective path reversal point for the λ8000 bands. Of course, the amount of CO_2 above the visible cloud layer should differ from this amount.

Fortunately, Chamberlain and Kuiper (Ref. 4) have computed the rotational temperature for exactly those bands for which the carbon dioxide path has been estimated. The greatest contribution to the rotational temperature arises from those layers in which the greatest absorption occurs. Near the bottom of these layers, the temperature will be greater than near the top. From considerations of pressure-broadening in an adiabatic atmosphere, Kuiper (Ref. 37) has concluded that the temperature near the bottom of the layer is about 320°K. The temperature along the integrated path of the light ray is near 285°K. Therefore, at the atmospheric depth above which there is 1 km-atm of carbon dioxide, the temperature is in the neighborhood of 300°K. No other estimate of temperature and pressure referring to the same level exists. The 8- to 13-μ brightness temperature has no known associated pressure, and the polarimetric pressure has no known associated temperature.

The most likely major constituents of the Cytherean atmosphere are carbon dioxide and nitrogen. It will be shown that the total amount of CO_2 in the atmosphere of Venus is several times greater than the amount of N_2 in the terrestrial atmosphere. For purposes of computing the atmospheric structure, it is assumed that the Cytherean water-vapor abundance is low relative to the abundance of carbon dioxide and nitrogen; the justification for this assumption will become evident in the subsequent Sections. The ratio of specific heats for CO_2 is approximately constant at 1.30 between 230°K and 600°K. Over the same range for N_2, $\gamma \simeq 1.41$; and for H_2O, $\gamma \simeq 1.3$. An abundance of w cm-atm corresponds to a pressure of

$$P = \frac{w \mu L g}{N_A} \quad \text{dynes cm}^{-2} \tag{9}$$

where μ is the molecular weight of the gas in question, and L and N_A are, respectively, Loschmidt's and Avogadro's numbers. Thus with $g = 860$ cm sec^{-2}, 1 km-atm corresponds to a CO_2 pressure of 0.17 atm above the effective reflecting layer in the λ8000 bands. With $T_1 = 600$°K, $P_2 = 0.17$ atm, and $\gamma = 1.30$, Eq. (8) yields, for the surface carbon dioxide partial pressure of Venus, $P_s = 3.4$ atm. With the other values the same and $\gamma = 1.4$, $P_s = 1.9$ atm. If the Cytherean nitrogen abundance is comparable to the terrestrial nitrogen abundance, the appropriate value of P_1 lies nearer the former value than the latter. The corresponding carbon dioxide abundance is 18 km-atm. With a terrestrial N_2 partial pressure, the surface atmospheric pressure of Venus is about 4 atm.

For the relevant temperature range, $c_p(CO_2) \simeq 0.84$ joule g^{-1} (K°)$^{-1}$ and $c_p(N_2) = 1.04$ joule g^{-1} (K°)$^{-1}$. The former value gives, by Eq. 7, a dry adiabatic lapse rate of -10.3 K°/km, and the latter gives -8.2 K°/km. We adopt

$$\left(\frac{\partial T}{\partial h}\right)_{\rm dry} = -10\ \mathrm{K°/km}$$

(If the water abundance is non-negligible, the lapse rate is less because the specific heat is greater.) It then follows that the effective reflecting layer in the λ8000 bands is approximately 30 km above the surface. If the water abundance is appreciable, this layer will be even higher. The ultraviolet and visible cloud layers should be at somewhat lower depths. From the preceding discussion, the pressure and temperature can then be computed for any altitude between the surface and the λ8000-band effective reflecting surface.

IV. FAR INFRARED ABSORPTION

A. Radiation Temperatures

From the value of the solar constant, and the assumption that the surface radiates as a black body of unit emissivity, it is easy to show that the temperature at the sub-solar point of an airless planet which always keeps the same hemisphere facing the Sun (synchronized rotation) is

$$T_r = 394 a^{-1/2} (1 - A)^{1/4}\ °\mathrm{K} \tag{10}$$

where a is the distance from the planet to the Sun in AU, and A is the effective visual albedo of the planet, corrected for departures from gray-body reflection. A planet with nonsynchronized rotation distributes the same energy of insolation over four times more area; the corresponding temperature will then be $4^{1/4} = 2^{1/2}$ less, or

$$T_r = 279 a^{-1/2} (1 - A)^{1/4}\ °\mathrm{K} \tag{11}$$

The visual albedo of Venus is given by Danjon (Ref. 38) as 0.64. It is a time-independent parameter. As Venus has a pale yellow coloring, the albedo must be corrected for selective reflection before the radiation temperature can be determined. From the color index of Venus, Kuiper (Ref. 37) has estimated the effective albedo corrected for selective reflection as $0.64 \leqq A \leqq 0.71$. The mean distance of Venus from the Sun is 0.723 AU. Since the eccentricity of the orbit is 0.007, and since a appears as the square root in Eq. 10 and 11, a can be taken as constant in determining the radiation temperature. The range of radiation temperatures for a synchronously rotating airless planet with Venus' effective albedo and solar distance is then

$$359°\mathrm{K} \geqq T_r \geqq 340°\mathrm{K} \tag{12}$$

The corresponding radiation temperature range for a nonsynchronously rotating airless Venus, or for one with appreciable interhemispheric circulation, is

$$254°\mathrm{K} \geqq T_r \geqq 240°\mathrm{K} \tag{13}$$

Both the color index and the visual albedo of Earth, as determined from observations of Earthlight reflected from the Moon, are functions of time. An average effective albedo is probably near 0.40 (Ref. 39). With $A = 0.40$ and $a = 1.00$, Eq. 11 yields, for the radiation temperature of Earth,

$$T_r = 246°K \tag{14}$$

B. Required Far Infrared Absorption for the Venus Greenhouse Effect

Since the radiation temperature of Venus is far below the radio surface temperature of 600°K, it is evident that a very efficient greenhouse effect is required. A lower bound to the absorptivity of the Cytherean atmosphere can be obtained as follows:

An equation of radiation balance previously applied to Venus by Wildt (Ref. 1) is derived by setting the absorbed incident energy flux equal to the sum of the energy flux emitted by the effective radiating layer of the atmosphere, and the energy flux emitted directly through the atmosphere to space by the surface. Assuming that the absorptivity of the layer responsible for most of the absorption of radiation emitted by the surface is equal to the absorptivity of the layer responsible for most of the atmospheric emission to space, and assuming Kirchhoff's Law, Wildt's equation applies:

$$T_r^4 = \alpha T_A^4 + (1 - \alpha) T_s^4 \tag{15}$$

where T_A is the temperature of the effective atmospheric emitting layer, T_s is the surface temperature, and α is the effective absorptivity of the atmosphere, integrated over all wavelengths. Equation 15 is a simplified form of the equation of radiation balance first applied to the Earth by Simpson (Ref. 40). When Eq. 15 is rewritten as

$$\alpha = \frac{T_s^4 - T_r^4}{T_s^4 - T_A^4} \tag{16}$$

it is clear that T_A cannot exceed T_r, since α cannot exceed unity. Hence, $T_r \geqq T_A > 0$, and, from Eq. 16,

$$1 \geqq \alpha > 1 - \left(\frac{T_r}{T_s}\right)^4 \tag{17}$$

Inequality 17 will also follow from more general equations of radiation balance derived in Sec. V, where departures from Kirchhoff's Law are taken into account. The limits on α set by inequality 17 are very useful because the value of T_A for Venus, as defined above, is not well-determined.

For a synchronously rotating Venus and a representative $T_r = 350°K$ (inequality 12), inequality 17 yields

$$1 \geqq \alpha > 0.884 \tag{18}$$

whereas, for a nonsynchronously rotating Venus and a representative $T_r = 247°K$ (inequality 13),

$$1 \geqq \alpha > 0.971 \tag{19}$$

Integrated absorptivities of this order have some interesting implications for the far infrared absorption of the atmosphere. Infrared observations of Venus, both at wavelengths less than 1 μ and in the 8- to 13-μ region, make it clear that the Cytherean atmosphere is almost opaque at these wavelengths. Hence, it is reasonable to ask how far into the infrared the atmosphere must absorb completely in order to give the integrated absorptivities of inequalities 18 and 19. This critical frequency is given by

$$\int_{\infty}^{\nu_c} B_\nu (T_s)\, d\nu = (1 - \alpha)\, \sigma T_s^4 \tag{20}$$

where $B_\nu (T_s)$ is the specific intensity of the radiation emitted from the surface at temperature T_s. Assuming the surface to radiate as a black body, $B_\nu (T_s)$ is given by the Planck distribution function. Graphical integration of Eq. 20 shows that, for $\alpha = 0.884$, complete absorption must extend shortwards of $\lambda_c = 13\,\mu$; whereas, for $\alpha = 0.971$, the corresponding wavelength is $\lambda_c = 23\,\mu$. Using the extreme values of inequalities 12 and 13 instead of the mean values changes λ_c by less than 1 μ.

Now, complete absorption from the near infrared to 13 μ is at least conceivable in a pure carbon dioxide atmosphere of very great depth, since the very strong ν_2 band of the CO_2 vibration-rotation spectrum is centered at 15.0 μ. In Sec. V, this possibility will be examined in more detail. However, opacity out to 23 μ is impossible for a pure carbon dioxide atmosphere. At room temperature or below, even 20 km-atm of carbon dioxide are transparent beyond 18 μ. As an extreme case, if all 20 km-atm were at the surface temperature of Venus, absorption in the wings of ν_2 would not be appreciable beyond 20 μ (Ref. 41, 42, and 43). It is also recalled that with $T_A = 0$ in Eq. 16, α is larger and, therefore, λ_c is also larger. In Sec. V, it will be found that, for nonsynchronous rotation, the correct value of α is about 0.995; the corresponding $\lambda_c \simeq 40\,\mu$. Consequently, it is evident that a nonsynchronously rotating Venus must have molecules other than carbon dioxide in its atmosphere.

It is unlikely that the required opacity beyond 20 μ could be provided by a scattering cloud layer. Visual observations have been made of occasional breaks in the clouds. If the clouds preferentially scatter light, breaks in the cloud layer should be more frequent in the infrared than in the visible, and complete opacity out to 23 μ

would not be provided. As a second argument, it is noted that the rotational temperature in the $\lambda 8000$ region exceeds the 8- to 13-μ brightness temperature. Thus, the penetration of light into the Cytherean atmosphere at these wavelengths is limited by CO_2 absorption, and not by particle scattering (Ref. 37); the layer of scattering particles cannot be opaque if T_{rot} arises from lower depths than does the thermocouple temperature.

Accordingly, the attenuation required beyond 20 μ if Venus is nonsynchronously rotating must arise from molecular absorption. No common molecules have vibration-rotation bands at these wavelengths. The absorption must be due to a pure rotation spectrum. Spherical top molecules (e.g., N_2, A, CH_4) have no permanent dipole moment and no pure rotation spectrum. Linear molecules (e.g., CO_2, CO, C_3O_2) have no pure rotation spectrum at these wavelengths, although the possibility of such a spectrum in the very far infrared has not been excluded. The only major category of molecules with a pure rotation spectrum in the 20-μ region is that of the asymmetric top molecules, of which water is the most common example. Other molecules, such as aldehydes and alcohols, also absorb at these wavelengths, but it would be very surprising if the abundance of such molecules on Venus approached the abundance of water; furthermore, the most likely origin of alcohols and aldehydes is water itself. Although their far infrared spectra have not been examined in detail, it is possible that some of the nitrogen oxides, especially NO, absorb in this region; however, their abundance on Venus should be extremely low. NO arises primarily from collision of N, O, and a third body, and is very rare in the terrestrial atmosphere (see, e.g., Ref. 44). Atomic oxygen in the terrestrial atmosphere originates mainly in the photodissociation of O_2. In the absence of Cytherean molecular oxygen, O must arise on Venus from carbon dioxide photolysis, which takes place at much shorter wavelengths and, therefore, much lower intensities than does O_2 photolysis on Earth. Atomic oxygen could also be supplied by water-vapor photolysis, which occurs at longer ultraviolet wavelengths, but then H_2O would be much more abundant than NO. Similar considerations apply to the other nitrogen oxides, and suggest that water is the most likely molecule for absorption beyond 20 μ. Consequently, if Venus rotates nonsynchronously, or has appreciable interhemispheric circulation, there must be water in its atmosphere. If we trace back the steps of this argument, we find that the presence of water vapor on a nonsynchronously rotating Venus is a necessary consequence of the high surface temperature and the radiation balance. This conclusion is independent of any assumptions concerning the nature of the cloud layer or the origin of the atmosphere and was reached before direct observations of water vapor on Venus (Ref. 24) had been made.

C. *Minimum Water Abundance for a Nonsynchronously Rotating Venus*

It is desirable to compute the quantity of water required for opacity in a given wavelength region. The water molecule has the peculiarity that its pure rotation spectrum is retained, and indeed enhanced, in the liquid and solid phases. A liquid water abundance of 10^{-2} g cm^{-2} is adequate to provide an integrated absorptivity greater than 0.99. For an average terrestrial cloud, this corresponds to a depth of about 50 meters (Ref. 45). Thus, a liquid water or ice-crystal cloud layer on Venus need contain only 10^{-2} g cm^{-2} of water to give the necessary absorption in the 20-μ region and the required integrated absorptivity. However, such a cloud layer demands appreciably more water in the vapor phase in the underlying atmosphere. As will be shown in Sec. VI, this required water vapor would itself be sufficient to give the necessary absorption. Therefore, in the following, the presence of a cloud layer is ignored, and all the water is assumed to be in the vapor phase. For this reason, and because a minimum value of α was used in Eq. 20, the derived water abundance will be a lower limit.

Elsasser (Ref. 46 and 47) has derived a curve of growth for a molecule in which the Lorentz line shape is assumed for equally spaced, equal-intensity components of the band spectrum. The expression is of the form

$$\alpha_\lambda = \mathrm{erf}\,[\mathrm{const}\,(\gamma w)^{1/2}] \tag{21}$$

where α_λ is the absorptivity for a small wavelength interval around λ, γ is the line width, w is the path, the constant is a function of λ, and the error function is defined by

$$\mathrm{erf}\,x = 2\pi^{-1/2}\int_0^x e^{-z^2}\,dz$$

Since $\gamma \propto PT^{-1/2}$, Eq. 21 can be written

$$\alpha_\lambda = \mathrm{erf}\left[\frac{\beta_\lambda}{2}\left(\frac{\pi w P}{P_0}\right)^{1/2}\left(\frac{T_0}{T}\right)^{1/4}\right] \tag{22}$$

The values of β_λ for water vapor at STP have been conveniently tabulated by Cowling (Ref. 48). Up to $\alpha_\lambda = 0.85$ or 0.90, Eq. 22 reproduces the experimental curve of growth for water vapor with excellent accuracy. Beyond this value, Eq. 22 gives somewhat too intense an absorption for an irregular distribution of rotational components, as is the case for water (Ref. 47). Therefore, in a third way, the computed water abundance will be a minimum.

Beyond about 10 μ, β_λ is approximately a monotonically increasing function of λ. Thus, if α_λ is close to unity at, say, 19 μ, it will be even closer to unity at all greater

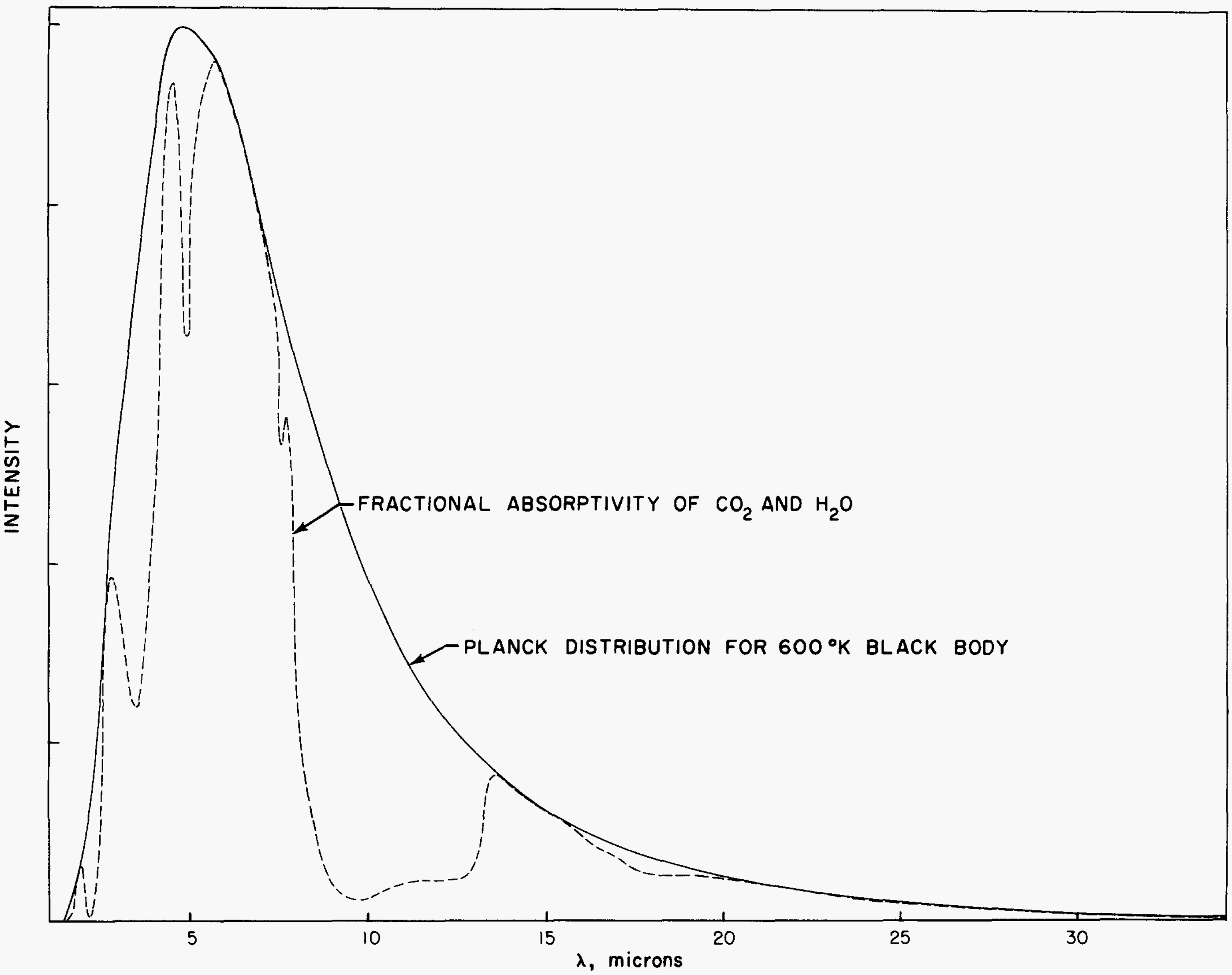

Figure 2. Infrared absorption by CO_2 and H_2O in the Earth's atmosphere if the surface temperature of the Earth were 600°K

wavelengths out to the microwave region. Hence, opacity between 19 and 23 μ essentially implies opacity at all $\lambda > 23\ \mu$. It follows that windows must exist in the Venus atmosphere at shorter wavelengths. This question will be discussed more fully in Sec. V. For the present, assuming the extreme case of complete absorption by the ν_2 band of carbon dioxide out to 20 μ, it is assumed that $\beta\,(20\ \mu) = 2.1$ (Ref. 48). Two cases will be considered, one in which all the water in the Venus atmosphere is considered concentrated in the effective reflecting layer for the $\lambda 8000$ bands ($P = 0.17$ atm, $T = 285°$ K), and the other in which all the water is considered concentrated at the surface ($P = 4$ atm, T = 600°K). For $\alpha_\lambda = 0.990$, say, at 20 μ,

$$5.6\ \text{g cm}^{-2} \gtrsim (w_w)_{\min} \gtrsim 0.34\ \text{g cm}^{-2} \qquad (23)$$

for the two cases. The result is relatively insensitive to the exact choice of α_λ. Note that this quantity has been minimized with respect to four parameters: T_A, the CO_2 absorption, the cloud layer, and the assumptions leading to Eq. 22. The mean water abundance in the Earth's atmosphere is about 1 g cm^{-2}. Thus, it seems safe to conclude that, provided Venus rotates nonsynchronously, there is at least as much water vapor in the atmosphere of Venus as in the atmosphere of Earth. Figure 2 shows the emissivity which would be produced by the CO_2 and H_2O in the terrestrial atmosphere if the surface temperature were 600° K.

V. RADIATION BALANCE

The classic studies of the radiation balance of the Earth are by Sir George Simpson (Ref. 49, 40, and 50). In Simpson's first paper, integrated absorptivities of water vapor were used, based on the then very fragmentary experimental data. The radiation flux emitted from the surface through the atmosphere was added to the radiation flux emitted to space by the atmosphere; Simpson found the sum to be of the same order of magnitude as, but about 40% less than, the absorbed radiation flux from the Sun. A much better agreement between incoming and outgoing intensities was achieved in Simpson's second paper, in which some account was taken of the differential transmissivity of the atmosphere at various wavelengths. At wavelengths for which the terrestrial atmosphere is transparent, Simpson assumed the radiation to arise from the surface; where the atmosphere was opaque, from the tropopause; and at wavelength intervals of intermediate transmissivity, from an arbitrary level intermediate between surface and tropopause.

In this Report, radiation balance for Venus is assumed and the properties of its atmosphere are derived. Since at this stage in the investigation the total water-vapor abundance in the Cytherean atmosphere is not yet known, the wavelength intervals of relative transparency cannot be predicted with accuracy. There are two courses open. The upper atmosphere of Venus can be assumed to be opaque in those wavelengths for which about 1 km-atm of CO_2 is opaque, and the radiation at all other wavelengths to come from some other deeper level to be determined. Alternatively, Simpson's first method, employing improved experimental values of integrated absorptivities and emissivities, can be utilized. In the following, both approaches will be used.

A. Maximum Water-Vapor Abundance on Venus

Assume that the radiation in the carbon dioxide bands is emitted from some region, characterized by a temperature T_A, at or above the λ8000 effective reflecting layer. The radiation at other wavelengths will come from deeper levels, characterized by some temperature T_x. Then, if a fraction f of the emission is contained in the CO_2 bands,

$$T_r^4 = f\,T_A^4 + (1-f)\,T_x^4 \tag{24}$$

If it is assumed that all the radiation not emitted by CO_2 is emitted by H_2O, a maximum water-vapor abundance can be derived from Eq. 24. Actually, there may be other emitting molecules, and radiation emitted by the surface may escape directly to space at certain wavelengths.

Long paths of CO_2 at or somewhat below room temperature will completely fill in the ν_2 and ν_3 bands, as well as the bands in the 10-μ region. Hence, the regions $18\ \mu \geqq \lambda \geqq 9\ \mu$ and $5.5\ \mu \geqq \lambda \geqq 3.5\ \mu$ should be approximately opaque. The intervals $\lambda \geqq 18\ \mu$ and $9\ \mu \geqq \lambda \geqq 5.5\ \mu$ will be relatively transparent for paths approaching 1 km-atm, only the far wings of the carbon dioxide bands causing any absorption. For $\lambda \leqq 3.5\ \mu$, the spectrum shows a number of weak bands. The fraction of the total emission of a black body at 250°K, which is contained in the intervals $18\ \mu \geqq \lambda \geqq 9\ \mu$ and $5.5\ \mu \geqq \lambda \geqq 3.5\ \mu$, is $f = 0.49$. The value of f does not depend sensitively on the temperature; as shown below, the true value is somewhat smaller than 0.49.

In order to minimize T_x, T_r must be minimized and T_A maximized. With $T_r = 240°\text{K}$, $T_A \simeq 234°\text{K}$, and $f = 0.49$, Eq. 24 yields $T_x = 247°\text{K}$. The value of T_x is extremely insensitive to the choice of f. Now, if the water-vapor emission comes from a depth characterized by $T_x = 247°\text{K}$, there must be enough water vapor above this level to give nearly complete opacity. In reality, different wavelengths in the water emission will arise from different depths. But the bulk of the water emission will be in the ν_2 band centered at 6.28 μ. The wings of this band (at $\lambda = 5\ \mu$ and $\lambda = 7.5\ \mu$) have a $\beta_\lambda \simeq 2$ (Ref. 48). Therefore, by Eq. 22, with $\alpha_\lambda = 0.990$, $P = 0.15$ atm, and $T = 247°\text{K}$, $w = 7\ \text{g cm}^{-2}$. If there are 7 g cm^{-2} of water vapor above the level characterized by T_x, then from Eq. 8 and 24, with $\gamma = 1.3$, the total water-vapor abundance in the Cytherean atmosphere is $w = 300\ \text{g cm}^{-2}$. Since, as has already been noted, Eq. 23 tends somewhat to underestimate w,

$$(w_w)_{\max} = 500\ \text{g cm}^{-2} \tag{25}$$

is adopted. Had a value of β_λ appropriate to the center of the ν_2 band been chosen, w would have been much less; e.g., at 6.1 μ, $\beta_\lambda = 8$ (Ref. 48) and the corresponding $w = 20\ \text{g cm}^{-2}$. The small fraction of the total emission which is between 8 and 9 μ has been neglected; it will arise from greater depths because of the transparency of water vapor in this region. It is concluded that the total amount of water vapor on a nonsynchronously rotating Venus is between 0.3 and 500 g cm^{-2}.

For a synchronously rotating Venus, the maximum water abundance is obtained in the same manner, but with $T_r = 340°\text{K}$; then $T_x = 393°\text{K}$, $w = 45\ \text{g cm}^{-2}$, and $(w_w)_{\max} \simeq 75\ \text{g cm}^{-2}$.

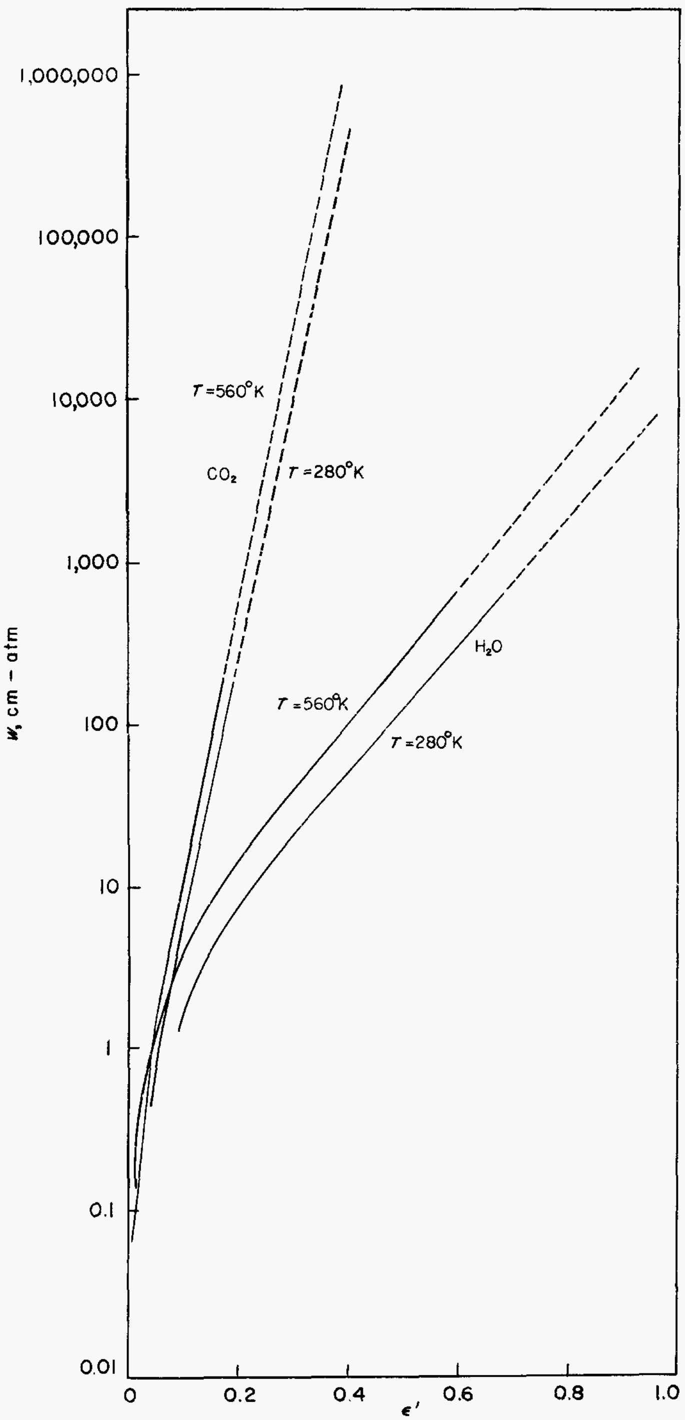

Figure 3. Pressure-uncorrected emissivity of CO_2 and H_2O as functions of temperature and path length

It is clear from these maximum abundances that models of the lower Cytherean atmosphere based upon the saturation vapor-pressure curve of water will be considerably in error. If there are 500 g cm^{-2} of water in the atmosphere of Venus, even though there will be much more water than in the terrestrial atmosphere, the relative humidity at the 600°K surface will be only 0.4%.

B. Long-Path Emissivities of Carbon Dioxide and Water Vapor

The most comprehensive data on the emissivity of carbon dioxide and water vapor at long paths and elevated temperatures exist in the mechanical and chemical engineering literature. Wildt (Ref. 1) has made the only previous application of this information in an astronomical context. Since that time, more detailed information has become available in the work of Hottel and Egbert (Ref. 51 and 52); its use in studies of the radiation balance of Venus represents one of the few astronomical applications of boiler and furnace technology.

In Fig. 3, the solid lines indicate measured values of the emissivities of CO_2 and H_2O as a function of the path w (here in cm-atm), and at two representative temperatures, 280°K, and 560°K. For a given path, at these temperatures, the emissivity is observed to decrease with increasing temperature. This is a simple consequence of the perfect gas law; the Lorentz line width is, at constant pressure, proportional to $T^{-1/2}$ (see also Eq. 22). At the longer paths, the emissivity becomes proportional to log w, since, with the major bands filled in, further absorption with increased path occurs primarily in the wings of the major bands. Especially for a molecule with a spectrum dominated by one or two strong bands, such as CO_2, this relation should extend to very long paths, provided the emissivity does not approach unity too closely (see, e.g., Ref. 47). Accordingly, we have extrapolated the CO_2 data to the 10^6 cm-atm range appropriate to the Cytherean atmosphere. A more modest extrapolation has been performed for H_2O. The extrapolations are shown as dashed lines in Fig. 3.

The emissivities ε' of Fig. 3 are uncorrected for the effects of partial and of total pressure; because of pressure-broadening, these corrections may be considerable. The pressure-corrected emissivity is here written as $\varepsilon = C\,\varepsilon'$. Approximate values of the correction factor C are given by Hottel and Egbert (Ref. 52).

This Report is concerned with the emissivities of carbon dioxide – water mixtures. There must be a further correction for redundant absorption. This can be allowed for by writing

$$\varepsilon_{tot} = C_c \varepsilon'_{CO_2} + C_w \varepsilon'_{H_2O} - \Delta\varepsilon \qquad (26)$$

where C_c and C_w are the pressure-correction factors for carbon dioxide and water and $\Delta\varepsilon$ is that fraction of the total emissivity at the gas temperature which is overlapped by the bands of the two gases. For the relevant values of w, $\Delta\varepsilon$ will have to be estimated directly from the spectra; the values given by Hottel and Egbert (Ref. 52) are only for short paths.

In the application of these data, Kirchhoff's law should not, in general, be expected to hold closely. Non-monochromatic radiation is being considered, and the emitting surface of Venus is hotter than the absorbing atmospheric layers. It is observed experimentally that the absorptivity of a layer of gas at temperature T_l and thickness w, when illuminated by a surface at temperature T_s, is given by

$$\alpha(w) = \varepsilon\left(w\frac{T_s}{T_l}\right)\left(\frac{T_l}{T_s}\right)^n \tag{27}$$

i.e., $\alpha(w)$ is related to the emissivity not of a layer of thickness w, but of a layer of thickness $w\,T_s/T_l$. The value of n for water vapor at the temperatures with which we will be concerned is 0.51 or somewhat higher; for CO_2, $n = 0.65$ to good accuracy (Ref. 51 and 52). As ε approaches unity, the gas layer becomes approximately a black body, and α approaches ε. Uncritical application of Eq. 27 will yield absorptivities or emissivities in excess of unity.

Where ε is not too close to unity, the following discussion applies: For long paths,

$$\varepsilon(w) = a + b\log w$$

Thus,

$$\varepsilon\left(w\frac{T_s}{T_l}\right) = \varepsilon(w) + b\log\frac{T_s}{T_l}$$

Substituting in Eq. 27 yields

$$\alpha(w) = \left[\varepsilon(w) + b\log\frac{T_s}{T_l}\right]\left(\frac{T_l}{T_s}\right)^n \tag{28}$$

The values of $b = (\delta\log\varepsilon)/(\delta\log w)$ can be determined from Fig. 3. For carbon dioxide, $b_c \simeq 0.067$, and for water vapor, $b_w \simeq 0.28$ in the linear parts of the curves.

Assembling the data yields the total absorptivity of the gas mixture,

$$\alpha = \left[C_c\varepsilon'_c(w_c) + 0.067\log\frac{T_s}{T_l}\right]\left(\frac{T_l}{T_s}\right)^{0.65} + \left[C_w\varepsilon'_w(w_w) + 0.28\log\frac{T_s}{T_l}\right]\left(\frac{T_l}{T_s}\right)^{0.51} - \Delta\varepsilon_s \tag{29}$$

where the subscripts c and w refer to carbon dioxide and water, respectively (Ref. 52); $\Delta\varepsilon$ is determined from the band overlapping at the surface temperature. Where ε_{tot} approaches unity, Eq. 29 simplifies to

$$\alpha = C_c\varepsilon'_c(w_c) + C_w\varepsilon'_w(w_w) - \Delta\varepsilon_s \tag{30}$$

C. Applications to Earth and Venus

From the previous discussion, it follows that most of the emission to space in the Cytherean atmosphere arises from high altitudes; whereas, most of the absorption of radiation emitted by the surface occurs at low altitudes. If the radiating level of the atmosphere emits as a black body at some temperature T_A, the appropriate equation of radiation balance is

$$\sigma T_r^4 = \sigma T_A^4 + (1-\alpha)\sigma T_s^4$$

or

$$\alpha = 1 - \left(\frac{T_r}{T_s}\right)^4 + \left(\frac{T_A}{T_s}\right)^4 \tag{31}$$

Note that for $T_A = 0$, Eq. 31 reduces to inequality 17. With α determined from Eq. 31, $\varepsilon'_w(w_w)$ can be derived from Eq. 29 or 30, whichever is appropriate, and the corresponding water-vapor abundance read from Fig. 3.

To give some idea of the accuracy of this method of water-vapor abundance determination, it is first applied to the terrestrial atmosphere. The assumption of black-body emission by the top of the atmosphere is much more likely to be in error for Earth than for Venus.

The atmosphere is considered to radiate from the tropopause. Then, at the equator, $T_A = 200°K$ and $T_s = 299°K$; at latitude 50°, $T_A = 218°K$, and $T_s = 280°K$. With the Earth's radiation temperature given by Eq. 14, $\alpha = 0.74$ at the equator and 0.78 at 50° latitude. At a total pressure of 1 atm, $C_c = 1$ (Ref. 52). For $w_c = 220$ cm-atm, Fig. 3 gives $\varepsilon'_c = 0.21$ near T_s. With $T_l = T_A$ and $\Delta\varepsilon_s = 0.05$, Eq. 29 yields $C_w\varepsilon'_w(w_w) = 0.71$ at the equator and 0.59 at 50° latitude. When the partial pressure of water vapor is much less than the total atmospheric pressure, $C_w = 1$ (Ref. 52). Figure 3 then gives w_w of the order of 800 cm-atm and 200 cm-atm for the two cases; i.e., a water-vapor abundance in the absorbing layer of about 0.6 g cm^{-2} for the equator and 0.2 g cm^{-2} for 50° latitude. Although, for illustrative purposes, we have carried the computation for two latitudes, only the equatorial abundance is valid, because the radiation temperature is defined in terms of the insolation at the equator. The final result of 0.6 g cm^{-2} is within a factor of two or three of the mean total water vapor in the terrestrial atmosphere; considering the nature of the assumptions made, this is very good indeed. Thus, the application of Eq. 31 to the Cytherean atmosphere, where it is more likely to be appropriate, can be expected to give the correct order of magnitude for the water-vapor abundance.

The effective radiating temperature of the upper layers of the Cytherean atmosphere should be near the 8- to 13-μ brightness temperature. Figure 3 shows that 18 km-atm of CO_2 at a temperature near 600°K has a pressure-uncorrected emissivity of 0.415. At the long paths and high pressures obtaining near the surface of Venus, the correction factors for the effects of partial and total pressure are unity. The maximum value of $\Delta\varepsilon_s$ is 0.415. The precise value depends on the water abundance, the determination of which is the goal of the present calculation. Therefore, a preliminary value, say 0.21, half the maximum is adopted and the water-vapor abundance derived. With this, $\Delta\varepsilon_s$ can be computed and a procedure of successive approximations employed. Uncritical use of these values in Eq. 29 yields emissivities in excess of one. The reason for this inconsistency is that ε_{tot} is close to unity, the absorbing atmosphere is approximately a black body, and the allowance for departures from Kirchhoff's law, Eq. 27, is invalid. The correct procedure is to use Eq. 30 with 31.

For example, taking $T_s = 600°K$, $T_A = 234°K$, $T_r = 254°K$, $C_c = C_w = 1$, $\varepsilon_c'(18 \text{ km-atm}) = 0.415$, $\Delta\varepsilon = 0.21$, and the high-temperature water curve of Fig. 3 yields $\alpha = 0.991$ and $w_w = 2700$ cm-atm = 2.1 g cm^{-2}. In the region between 9 and 14 μ, which is completely filled in by CO_2 bands, 2.1 g cm^{-2} will provide an absorption of only about 0.60, from Eq. 22 and the tabulations of Cowling (Ref. 47). About 0.17 of the total radiation emitted by a 600°K black body lies between 9 and 14 μ. Thus, because of the partial transparency of water vapor in this region, $\Delta\varepsilon_s$ is less than its maximum value by $0.40 \times 0.17 = 0.07$. Making similar estimates for other regions of incomplete absorption by water vapor gives a new value of $\Delta\varepsilon_s = 0.28$; the corresponding $w_w = 4.2$ g cm^{-2}. Successive approximations converge near $\Delta\varepsilon_s = 0.38$ and $w_w = 9$ g cm^{-2}. Proceeding in a similar manner for other radiation temperatures, values of α and w_w as given in Table 2 are obtained. Because of the steep slope of the carbon dioxide emissivity (Fig. 3), the value of w_w is quite insensitive to the choice of w_c. Because T_s appears in the denominator of both positive and negative terms in Eq. 31, variations in T_s as great as 100°K have little effect on the final results, especially for nonsynchronous rotation. Our previous maximum and minimum water-vapor abundances are also shown in Table 2. It follows that the actual abundances are closer to the minimum than to the maximum values. For both synchronous and nonsynchronous rotation, a Venus atmosphere composed of H_2O, CO_2, and N_2, with its upper layers radiating approximately as a black body, should have a total water-vapor abundance of several g cm^{-2}. It will be noticed that the values of α for a nonsynchronously rotating Venus are greater than the minimum values derived in Sec. IV; the argument presented there that water vapor is necessary to provide atmospheric absorption in the far infrared is thereby reinforced.

Table 2. Derived total water-vapor abundances for the atmosphere of Venus

	Nonsynchronous rotation		Synchronous rotation	
A	0.64	0.71	0.64	0.71
T_r, °K	254	240	359	340
α	0.991	0.998	0.894	0.921
w_w, g cm^{-2} (Sec. V-C)	9	9	1	2
$(w_w)_{min}$, g cm^{-2} (Sec. IV-C)	0.3 to 5		—	
$(w_w)_{max}$, g cm^{-2} (Sec. V-A)	500		75	

D. Windows in the Venus Atmosphere

It is of some interest to determine at which wavelengths there are windows in the Cytherean atmosphere (cf. Fig. 2). In the region just shortward of 9.0 μ, 18 km-atm of CO_2 at 600°K should be almost transparent. Between 8.4 and 9.0 μ, β_λ for water vapor is 0.25 (Ref. 48), and Eq. 22 indicates that the absorptivity by 10 g cm^{-2} of water vapor is about 0.90. Consequently, in the absence of clouds, we should expect to see deep into the Cytherean atmosphere at $8.4\ \mu \leq \lambda \leq 9.0\ \mu$, but very little energy should come directly from the surface. In case there is only about 1 g cm^{-2} of water vapor, the absorptivity is approximately 0.38, and the surface should be visible in this wavelength interval.

In the near infrared, a slight extrapolation of the data presented by Elder and Strong (Ref. 53) shows that between the Ψ and Ω bands of water vapor, the Ω and χ bands, and the χ band of water vapor and the ν_3 band of CO_2, 10 g cm^{-2} of H_2O has an absorptivity between 0.45 and 0.55. The values given by Elder and Strong refer to room temperature and atmospheric pressure. There seems no simple way to determine the absorptivities at 600°K and 4 atm pressure from these values, but an inspection of Fig. 3 and of the correction factors given by Hottell and Egbert (Ref. 52) suggests that the corrected absorptivities will not be very much greater. Long-path spectra of CO_2 in the near infrared have been obtained by Herzberg and Kuiper. Published spectra with 2×10^4 cm-atm (Ref. 35) show many regions of low absorptivity between 1.0 and 2.5 μ. Unpublished longer-path spectra, kindly made available for this purpose by Dr. G. P. Kuiper, also show such regions. Spectra at 2 atm pressure and 4 km-atm path show regions of particularly low absorptivity (<0.10) between 1.54 and 1.52 μ, 1.32 and 1.23 μ, and 1.11 and 1.00 μ. There are many broader intervals between 1.0 and 2.5 μ with absorptivities less than 0.5, and, outside of the water bands and ν_3 of CO_2, the entire wavelength region shortward of about 3.5 μ should be fairly transparent in the lower atmosphere of Venus.

Observations of breaks in the visual cloud layer suggest that similar rifts exist in the infrared cloud layer; other evidence supporting this conclusion was presented in Sec. IV. It is therefore possible that a properly instrumented balloon observatory, planetary probe, or artificial satellite could obtain information on the lower atmosphere and surface through infrared observations at the designated wavelengths. Some surface detail might also be evident in the visible and in the photographic infrared.

VI. THE CLOUD LAYER

A. Saturation in the Model Atmosphere

Whatever the total water-vapor abundance is in the atmosphere of Venus, saturation will occur at the level for which the saturation vapor-pressure curve of water overtakes the partial pressure curve. Figure 4 gives a quantity proportional to the partial pressure—w, the number of grams of water vapor in a square-centimeter column extending from the level in question to the top of the atmosphere—as a function of the atmospheric temperature. Three total abundances are assumed, bracketing the values derived in Sec. V; and Eq. 8 with $\gamma = 1.30$ is employed. It is seen from Fig. 4 that saturation exists at 220°K for $w_w = 1$ g cm^{-2}, at 225°K for $w_w = 3$ g cm^{-2}, and at 233°K for $w_w = 10$ g cm^{-2}.

Condensation occurs at the saturation point only if appropriate condensation nuclei exist; in the absence of such nuclei, the partial pressure may exceed the vapor pressure by a factor of five or more without the occurrence of condensation. However, at temperatures below 233 $\pm$ 1°K, in an atmosphere saturated or supersaturated with respect to ice, ice crystals will form spontaneously, without the presence of any special isomorphic sublimation nuclei; it is believed that a few small ice crystals forming at these temperatures themselves act as nuclei for further sublimation (Ref. 54, 55, and 56). Thus, the temperatures at which saturation occurs in the atmosphere of Venus are frost points. Small amounts of liquid water may exist near the saturation level, but under the assumptions in this Report, there is an ice-crystal cloud layer on Venus at an altitude of about 36 km, and no water-droplet clouds.

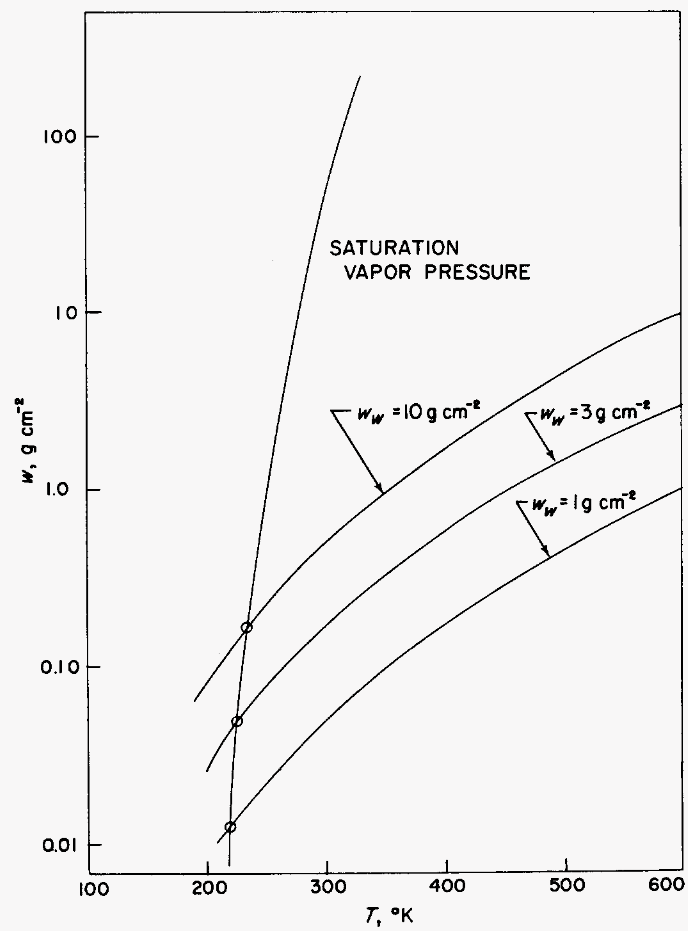

Figure 4. Occurrence of water saturation in the Cytherean atmosphere as a function of total water abundance

In Sec. III it was concluded that the existing evidence favors nonsynchronous rotation, although the opposite case was also carried in the calculations. In Sec. V it was shown that the most probable total water-vapor abundance for a nonsynchronously rotating Venus is about 9 g cm^{-2}. Figure 4 shows that a Cytherean atmosphere with 9 g cm^{-2} reaches the frost point at 232°K. This is within two degrees of the thermocouple temperature of Venus (Ref. 3); i.e., the effective radiating temperature in the 8- to 13-μ region. This strongly suggests that the ice-crystal cloud layer of our model is to be identified with the observed cloud layer of Venus. However, the coincidence should not be overemphasized. Bands emitting from above the cloud layer make some contribution to the thermocouple temperature. If the radiation in the bands comes from levels of higher temperature, the thermocouple temperature will be higher than the cloud-layer temperature. On the other hand, there is relatively little detail in the far infrared spectra of Sinton and Strong, and there is some reason to believe that, in analogy with the Earth, the cloud layer is at the tropopause, and the temperature increases only slowly above it. The latter point should be especially valid in the absence of an ozone layer. We cannot definitely exclude the case of synchronous rotation by these considerations, but it appears even less plausible as a result of them. Alternatively, the assumption of a water cloud on Venus—either solid or liquid—gives a total water-vapor abundance between 1 and 10 g cm^{-2}.

B. Observable Consequences of an Ice-Crystal Cloud Layer

The possibility that the clouds of Venus are composed of water has, of course, been proposed before. By terrestrial analogy, it is a natural assumption, and was widely believed until accurate spectroscopy from the ground gave no evidence for the presence of water vapor. More recently, Menzel and Whipple (Ref. 57) have argued for liquid water clouds, while Öpik (Ref. 28) and Kuiper (Ref. 37) have presented evidence to the contrary. The discussion has revolved around the polarization, the albedo, and the color index of the Cytherean cloud layer and the amount of water vapor above it. These observables are discussed in the present context.

The polarization curve of Venus was first obtained by Lyot (Ref. 58), who attempted to reproduce it in the laboratory, employing a wide range of substances. He found that, for fine mists of water, decreasing the droplet size caused the polarization curve increasingly to resemble that of Venus. However, before even a rough fit was obtained, the droplets became unstable. Lyot therefore prepared colloidal suspensions of bromonaphthalene, which have the same differential index of refraction as water in air, and found that droplets of radii $\simeq 2\ \mu$ were required to give an approximate fit with the Venus observations. However, the fit was not very good; for certain phase angles even the signs of the laboratory and Cytherean polarizations disagreed. Furthermore, Kuiper (Ref. 37) found that the near infrared polarization curve of Venus differed markedly from the theoretically predicted curve for liquid water droplets. Thus, the polarimetric evidence argues against a liquid water cloud layer on Venus.

Lyot also made a few measurements on the polarization of ice-crystal clouds; the crystals were large, and the polarization curve bore little resemblance to that of Venus. However, van de Hulst (Ref. 59) and Dollfus (Ref. 60) have pointed out that small transparent crystals would probably give a polarization curve similar to that of Venus. The variation of polarization over the disk of Venus (Ref. 33) is to be expected for a sublimation-product cloud layer; it is particularly interesting that regions of high (negative) polarization are localized in the apparent polar regions. There have been no theoretical calculations, nor any observations, of the near infrared polarization of nonspherical ice crystals (e.g., the crystals composing terrestrial cirrus clouds are hexagonal prisms); thus, no disagreement with the infrared observations of Venus exists. At the present time, the possibility that the polarization of Venus is caused by an ice-crystal cloud layer is not inconsistent with the evidence. The possibility should also be kept in mind that the Venus polarization curve is composite, the result of contributions from several different sources.

Venus has a distinct yellow coloration, while terrestrial clouds are white. The difference is easily seen when Venus is observed in daylight with terrestrial clouds nearby (Ref. 61). Ice-crystal clouds are as white as water droplet clouds. De Vaucouleurs (Ref. 62) has suggested that Rayleigh scattering above a perfectly white cloud layer may explain the yellow coloration. Otherwise, relatively small amounts of some deep yellow or yellow-brown impurity would suffice to explain the coloration, as has been stressed by Urey (Ref. 63) and others. A likely coloring material, proposed by Groth and Harteck (see Ref. 37), is the polymer of carbon suboxide. The probable synthetic sequence is

$$CO_2 + h\nu \rightarrow CO + O \qquad \lambda < 1692\text{Å}$$

$$2CO + CO_2 + h\nu \rightarrow C_3O_2 + O_2$$

$$nC_3O_2 \rightarrow (C_3O_2)_n$$

Carbon suboxide polymers prepared in the laboratory have a yellow-brown color. Their albedo is rather low, and it is unlikely they are a major constituent of the Cytherean cloud layer. Other substances which may contribute to the coloration of Venus include ammonium nitrite (Ref. 64) and nitrogen dioxide, but their abundance is expected to be low.

If the cloud layer is composed of ice-crystals as the preceding discussion indicates, then it is easy to compute the equilibrium saturation water-vapor pressure above the cloud layer. An integration of the vapor-pressure curve over ice has been performed by Menzel and Whipple (Ref. 57). The amount of water vapor in g cm^{-2} above a layer of ice at temperature T_0 is

$$Q = 4 \times 10^{-7} P_0 T_0 \qquad (32)$$

where P_0 is the vapor pressure in dynes cm^{-2} corresponding to temperature T_0. Values of Q corresponding to the range of likely total water-vapor abundance, as derived in Sec. V, are presented in Table 3.

Table 3. Theoretical water-vapor abundance above the cloud layer

Water vapor above the surface of Venus, g cm^{-2} w_ω	Corresponding temperature of the cloud layer, °K T_0	Water vapor above the cloud layer, g cm^{-2} Q
1	220	2.4×10^{-3}
3	225	4.5×10^{-3}
10	233	1.2×10^{-2}

As pointed out by Menzel and Whipple (Ref. 56), the value of Q corresponding to T_0 equal to the 8- to 13-μ brightness temperature is below the upper limits of water vapor detectable by ground-based spectroscopic observation (see Ref. 64). The recent balloon observations by Moore and Ross have detected the 1.13-μ band of water vapor in the Cytherean atmosphere; the deduced water-vapor abundance above the cloud layer is between 1.5×10^{-3} and 3.0×10^{-3} g cm^{-2} (Ref. 24). Comparison with Table 3 shows these values of Q to correspond to the low total water-vapor abundances derived for a synchronously rotating Venus with no interhemispheric circulation (see Table 2). We thus have the interesting result that synchronous rotation and the observed value of Q are compatible if the cloud layer is 14 K° cooler than the thermocouple temperature; or, alternatively, that nonsynchronous rotation and a cloud layer temperature equal to the thermocouple temperature are compatible if the true value of Q is one-fifth that given by Eq. 32. For the former case, the possibility that emission from the CO_2 bands in the 8- to 13-μ region arises at altitudes and temperatures higher than those characterizing the cloud layer has already been mentioned. The composite thermocouple temperature would then be less than the temperature of the cloud layer. For the latter case, a mechanism is needed to reduce the abundance of water vapor in the high atmosphere below saturation values. In the Schumann ultraviolet, N_2 does not absorb and CO_2 absorbs only below λ1692. But H_2O has a weak photodissociation continuum extending shortward of λ2400, the absorption coefficients becoming as large as 2×10^{-18} cm^2 before λ1692 is reached. It therefore appears possible that the observed water-vapor abundance is less than the saturation abundance because of photodissociation.

C. Cloud Albedo and Overcast

The visual albedo of Venus, uncorrected for selective reflection, is 0.64 (Ref. 38); the corresponding albedo of the Earth is 0.40 (Ref. 39). The mean albedo of all terrestrial clouds is 0.50 to 0.55 (Ref. 66). It is clear that even if the Venus cloud cover is complete, the clouds cannot be of the same mean albedo as those on Earth. However, the mean albedo of terrestrial clouds is an average over a wide range of cloud type and thickness. For example, airplane observations by Luckiesh (Ref. 67) indicated an albedo for the tops of thin clouds between 0.36 and 0.40; for very dense clouds of extensive area and great depth, the albedo was approximately 0.78. Similarly, Aldrich (Ref. 68), in one observation of a low-lying thick stratus, obtained an albedo of 0.78. The most common thick water-crystal clouds on Earth are the cirrostratus. A few airplane observations by Fritz (Ref. 69) give albedos for moderately thick cirrostratus ranging up to 0.64. There appear to be no observations of the albedos of cirrus clouds, which, although much thinner than cirrostratus clouds, seem to have very high albedos in their denser parts. Thus, it is possible that thick water-crystal clouds can account for the observed albedo of Venus.

There is evidence for a haze layer composed of small ice crystals in the atmosphere of Mars (see, e.g., Ref. 23); nevertheless, the albedo of Mars—especially at shorter wavelengths—is very low. It is probable that the Venus clouds are much thicker than the Martian haze, but it is clear that the difference in albedos of the two planets must be better understood before ice crystals can be firmly established as the source of the Cytherean albedo.

Some estimates of the mean Cytherean overcast by a method somewhat similar to that applied by Simpson (Ref. 40) to the Earth are now given. The incident radiation absorbed and transmitted by the terrestrial atmosphere is found to be approximately a linear function of the cloud overcast, reaching a maximum in cloudless skies. A similar relation will be assumed for Venus. If some area of Venus were cloudless, its radiation temperature would be given by Eq. 10 and 11, where $A = A_s$ is now the albedo of the surface of Venus. For illustrative purposes $A_s = 0.25$, a value characteristic of terrestrial deserts (Ref. 70), is adopted. Similarly, if some area of Venus were completely overcast, the radiation temperature would be obtained by using Eq. 10 and 11, now with

$A = A_c$, the cloud albedo. According to the discussion of the previous paragraph, $0.64 \leqq A_c \leqq 0.78$ is adopted. The solid lines in Fig. 5 can then be constructed, plotting radiation flux against overcast. The dotted horizontal lines in Fig. 5 give the radiation flux to space from Eq. 10 and 11, this time using the observed planetary albedos, corrected for selective absorption; the proper outward flux is given only at the correct value of the overcast. Thus, values of the Cytherean overcast can be read from the intersection of dotted and solid lines. For example, if the color-corrected albedo of Venus is 0.64, if $A_c = 0.78$, and if the planet rotates nonsynchronously, the mean overcast is 0.73; if Venus rotates synchronously, if the color-corrected planetary albedo is 0.71, and if $A_c = 0.78$, the mean overcast is 0.87. For comparison, the mean overcast of the Earth is about 0.50. On the other hand, if both planetary and cloud albedos are 0.64, then the overcast is unity. It is interesting to note that if the mean cloud albedo is 0.75 or greater, then the overcast is less than 0.90, and observations through the cloud layer should be possible. Arguments have already been presented that the cloud cover is not complete, and it seems likely that the mean cloud albedo is high. The need for balloon, satellite, or space-probe observations of Venus is again evident.

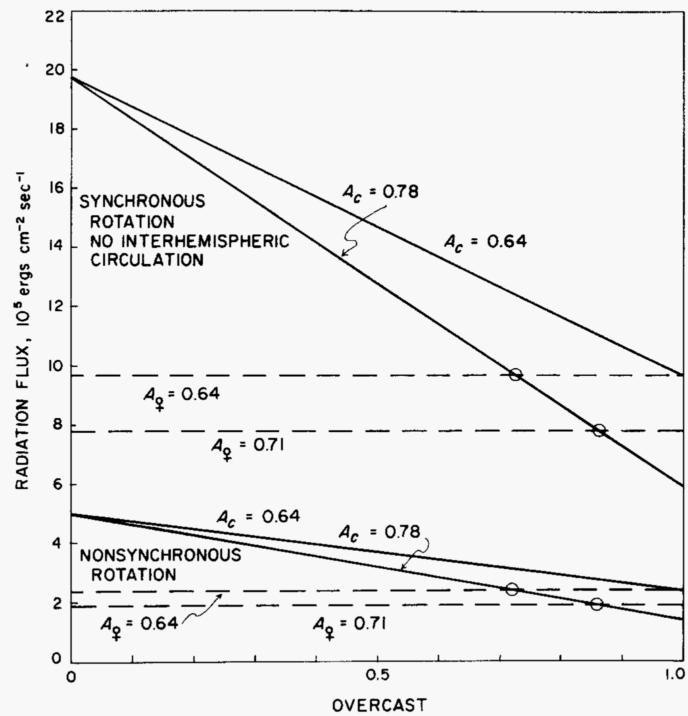

Figure 5. Modified Simpson diagram for the Venus overcast

VII. THE ORIGIN OF THE ATMOSPHERE

Urey (Ref. 71) proposed that on a planet having both surface silicates and surface water, the carbon dioxide partial pressure is maintained by equilibrium reactions such as

$$MgSiO_3 + CO_2 \overset{H_2O}{\rightleftarrows} MgCO_3 + SiO_2 \tag{33}$$

and

$$CaSiO_3 + CO_2 \overset{H_2O}{\rightleftarrows} CaCO_3 + SiO_2 \tag{34}$$

The equilibrium partial pressures near room temperature for reactions 33 and 34 are about 10^{-5} and 10^{-8} atm, respectively, and it is believed that the low CO_2 partial pressures on the Earth and Mars result from such reactions. Liquid water is required both as a catalyst and as a weathering agent to expose fresh silicates.

The surface partial pressure of carbon dioxide on Venus is 3 atm $>> 10^{-5}$ atm, and the question naturally arises as to why the Urey equilibrium fails on Venus. Urey's original explanation (Ref. 71), according to the then current belief, was that there is no water on Venus. An alternative possibility, that the surface is covered by a universal ocean preventing access of CO_2 to silicates (Ref. 57), is no longer tenable in view of the high surface temperature. The correct explanation appears to be that, although there is appreciable water vapor near the Cytherean surface, there is no liquid water at 600°K and 4 atm.

The total abundance of carbon dioxide in the atmosphere of Venus is about 4×10^3 g cm^{-2}. The carbon dioxide equivalent of the total sedimentary carbon in the Earth, fossilized as carbonates or as reduced carbon (but of ultimate atmospheric origin due to plant photosynthesis) is about 1.8×10^4 g cm^{-2} (Ref. 72). Especially since some CO_2 must reside in the Cytherean crust, these figures indicate that the carbon dioxide abundances on the two planets are approximately equal.

If the Earth had been placed in the orbit of Venus shortly after its origin, the higher radiation temperature would have resulted in an increased vapor pressure of water over the primeval oceans. Since $T_r \propto a^{-1/2}$, the surface temperature would have been about 1.2 times greater, neglecting any possible difference in albedos. For example, if the mean temperature of the primitive Earth were 0°C, placing it in the orbit of Venus would raise the surface temperature to about 50°C. The saturation vapor pressure above liquid water then becomes roughly 150 g cm^{-2}. Even if the relative humidity is 10%, the integrated atmospheric absorptivity approaches unity (see Fig. 3). A very efficient greenhouse effect is thus established, the surface temperature rises well above 100°C, and the oceans boil. Thereafter, outgassed carbon dioxide would generally not be sedimented as carbonates, and the CO_2 abundance in the terrestrial atmosphere would become comparable to that in the Cytherean atmosphere.

However, similar considerations of the water abundances lead to different conclusions. The total water abundance in the terrestrial atmosphere and hydrosphere is about 2.7×10^5 g cm^{-2}. Were the surface temperature of the Earth above the boiling point of water, this amount of water vapor would be in the atmosphere. In the wavelength intervals of complete absorption, the increased water-vapor abundance would not affect the integrated absorptivity of the atmosphere. But 10^5 g cm^{-2} is more than sufficient to fill in the windows in the 8- to 9-μ region and the 1.4- to 3.5-μ region. Appreciable absorption would exist throughout the photographic infrared, and radiation emitted by the surface would escape to space only in the visible. From the discussion of Sec. V, it is apparent that the surface temperature would then be greatly in excess of 600° K. Thus, if the Earth had been placed in the orbit of Venus in early times, the present surface temperature and water-vapor abundance would be much larger than they are for Venus. There is no reason to believe that the gravity and exosphere temperatures of Venus have ever permitted escape of oxygen atoms during the last 4.5×10^9 years. The reaction of olivine with water, forming serpentine, might conceivably take out large quantities of water, but it is unlikely that this reaction would be more efficient on Venus than it is on the much cooler Earth. Thus, Venus must have been formed with a factor of 10^4 to 10^5 less water than was Earth. The relative depletion of water on primitive Venus has previously been suggested by Urey (Ref. 71). It should be noted that the absence of liquid water would greatly reduce solar tidal friction on Venus; synchronous rotation is thereby rendered more unlikely. That the period of rotation should be even as long as a few weeks remains to be explained.

Above the present Cytherean cloud layer, water is being photodissociated. The hydrogen atoms diffuse to the exosphere and escape, while the oxygen atoms remain behind to oxidize minor constituents of the atmosphere. Today, carbon monoxide is likely to be a principal incompletely oxidized molecule, and the low carbon monoxide abundance is probably due to this effect (Ref. 23). In early times, it is likely that CH_4, NH_3, and simple organic molecules abounded. Urey (Ref. 63) has computed the diffusion rate of atomic hydrogen from the cloud layer to the exosphere of Venus to be $J = 10^{-14}$ g cm^{-2} sec^{-1}, and believes that it is this diffusion rate which limits the rate of oxidation of the Cytherean atmosphere. In 4.5×10^9 years, this diffusion rate is enough to oxidize 10^3 g cm^{-2} of carbon from methane or carbon monoxide to carbon dioxide, or roughly, enough to account for the present CO_2 abundance.

However, the photodissociation of water cannot occur immediately above the cloud layer. If there are 2×10^{-3} g cm^{-2} of water vapor above the cloud layer (Ref. 24), at $\lambda < 1800$ Å the optical depth at the cloud layer will be in excess of 70. Thus, a critical datum is the diffusion rate of water vapor from the cloud layer to optical depth unity. If the atmosphere above the cloud layer is in diffusive equilibrium and approximately isothermal at 234°K, the scale height of water vapor is $H = 13.4$ km, and an optical depth of unity is reached at about four H_2O scale heights. The diffusion rate is then given by

$$J = D\rho l^{-1} (1 - e^{-4H/l})^{-1} \tag{35}$$

where l is the scale height corresponding to μ (atmosphere) $- \mu(H_2O)$, ρ is the mass density of water vapor immediately above the cloud layer, and D is the diffusion coefficient (Ref. 72). With $D = 0.22/p(\text{atm}) = 1.5$ cm^2 sec^{-1} (Ref. 74), $J = 2 \times 10^{-15}$ g cm^{-2} sec^{-1}, a factor of about five less than Urey's value for the diffusion rate of the hydrogen atoms resulting from water photodissociation (Ref. 63). If the atmosphere above the cloud layer is not in complete diffusive equilibrium—which, from terrestrial analogy and the evidence for convection, is more likely—then the coefficient of H/l in Eq. 35 is > 4, but the value of J remains unchanged. It is curious that if the amount of water vapor above the cloud layer were the saturation abundance (Table 3), and if the cloud layer were at the 8- to 13-μ brightness temperature, the two diffusion rates would be in agreement, and the present Cytherean carbon dioxide could be explained. If Strong's value for the water abundance (Ref. 24) is correct, then the present CO_2 abundance cannot be explained by the photodissociation of water vapor during geological time if the water vapor originated from a cloud layer at the present thermocouple temperature.

On the basis of the foregoing discussion, it appears that the 600°K surface temperature is well established, and is consistent with the spectroscopic and thermocouple observations. Instrumentation of probes attempting a

Venus landing will have to withstand such high temperatures. No known terrestrial micro-organisms can survive more than a few minutes' exposure to 600°K; proteins are immediately denatured, desoxyribonucleic acid is depolymerized, and even small organic molecules are dissociated in short periods of time. Consequently, there seems to be little danger of biological contamination of Venus (Ref. 75). However, because of the great scientific losses potentially involved in the biological contamination of a planet, it is nevertheless recommended that all Venus probes be decontaminated as protection against the (very remote) possibility that the observed microwave emission does not arise from the Cytherean surface; or, alternatively, that less severe conditions prevail underground, in the atmosphere, or in the polar regions. At these elevated temperatures, and in the absence of liquid water, it appears extremely unlikely that there are indigenous organisms on the surface. In the light of present evidence, Venus is a hot, dry, sandy, windy, cloudy, and probably lifeless planet.

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