TEMPERATURES IN THE UPPER ATMOSPHERE OF VENUS,

AS INDICATED BY THE INFRARED CO_2 BANDS

by

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ABSTRACT

The appearance of the infrared emission spectrum of Venus is considered with regard to its implications as to (1) the emissivity of the clouds of Venus, (2) the temperature of the atmosphere in the vicinity of the clouds, and (3) the temperature profiles in the atmosphere above the clouds. Computations are made of the emission and absorption in the 10.4 micron band of CO_2 under a variety of different assumptions of emissivity and temperature. The infrared emission spectrum requires the emissivity of the clouds to be at least as high as 0.65, and the temperature of the clouds to be less than 250°K. The atmospheric temperature most likely decreases with increasing altitude in the vicinity of the clouds. The spectrum also indicates an absence of temperature inversions and associated warm zones in the upper atmosphere, unless they are at extremely high altitudes.

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INTRODUCTION

The carbon dioxide in the atmosphere of Venus contains in its absorption spectrum much information on the atmospheric temperature and pressure. The CO_2 absorption bands appear prominently in the sunlight reflected from the clouds of Venus. They also are superimposed on the infrared radiation continuum emitted by the clouds.

Radiometric observations of Venus were made with the 200-inch telescope in 1953 and 1954 and were reported in 1960 by Sinton and Strong.[(1)] The intensity of the emitted infrared radiation yielded a quite uniform brightness temperature of about 230°Kelvin. There was some limb-darkening, but for approximate treatments of the radiative properties of the disk, a 230° temperature can be assumed overall.

The principal CO_2 absorption bands which would be expected to show in the emitted radiation are the 9.4, 10.4 and 12.7 micron bands. Of these three, the easiest to detect is the 10.4 micron band, because it falls near the peak of emission and in a region where there is very little interference from absorption by the earth's atmosphere.

The 10.4 micron band results from absorption by the CO_2 molecule when it is in the (1,0,0) excited vibrational state, 1388 wavenumbers above the ground level. The absorption strength of the band is therefore strongly dependent on the temperature of the gas. It is this property which makes the band particularly useful.

Sinton and Strong[1] remarked that the 10.4 micron band was weaker in their spectra than they anticipated, but they did not discuss the properties of the band in any detail. The purpose of the present paper is to explore the implications of the intensity of the 10.4 micron CO_2 band in the Venus spectrum. It will be shown that the observed infrared spectrum places some limitations on permissible assumptions as to temperatures and cloud emissivities.

CALCULATIONS

If the temperature of the atmosphere above the emitting layer were the same as the brightness temperature of the emitting layer, the emission by the CO_2 would compensate its absorption, and only a continuum would be seen. However, this required condition is not a likely one, and either an emission or absorption spectrum is expected, depending on the temperature distribution in the atmosphere. In order to predict the spectra for various temperature profiles, an approximate expression is derived below relating the number of absorbing molecules in a vertical path to the temperature distribution. The band strength will then be derived from the number of absorbers with the aid of the laboratory absorption measurements of Burch, Gryvnak and Williams.[2]

The number of CO_2 molecules in the (1,0,0) state which occur in a volume perpendicular to the surface with a unit cross sectional area and a height increment, Δh, is a product of the number density, the Boltzmann factor and the height increment:

$$N_{(1,0,0)} = \frac{\rho(h)\ g\ e^{-\frac{\epsilon}{kT(h)}}\ \Delta(h)}{Q} \text{ particles} \qquad (1)$$

$N_{(1,0,0)}$ = The number of CO_2 molecules in the (1,0,0) state in the altitude increment, Δh.

$\rho(h)$ = The number density of CO_2 as a function of height.

$T(h)$ = The atmospheric temperature as a function of height.

g = Statistical weight of vibrational level involved.

Q = Vibrational partition function.

ϵ = Energy of state involved.

k = Boltzmann's constant.

In the present case, the appropriate values of Q and g are both unity. The value of ϵ is 1388 cm^{-1}. When the density is related to pressure and temperature through the perfect gas law, and the CO_2 pressure at the base of the column of gas P_0, in millibars, is expressed in terms of the barometric formula, the following density expression is obtained.

$$\rho(h) = \frac{7.3\times10^{18} P_0 \exp(-mgh/kT(h))}{T(h)} \text{ particles/cc} \qquad (2)$$

The above expression applies strictly only to an isothermal atmosphere, but its use in the present calculation will not introduce much error if the temperature is not varied too widely. The average molecular weight, m, of the Venus atmosphere is assumed to be 30. For the purpose of the present calculation the CO_2 partial pressure at the base of the gas column, P_0, is assumed to be 20 millibars. The calculated values of absorption or emission in the 10.4 micron band can later be scaled up or down to account for other values of P_0.

Substituting the density expression into equation (1) gives the following equation

$$\Delta N_{(1,0,0)} = \frac{1.46\times10^{20} \exp - \left(\frac{1995 + 3.03\times10^{-4}h}{T(h)}\right) \Delta h}{T(h)} \text{ particles} \quad .(3)$$

When the density distribution of molecules is known, the absorption and emission of radiation can be calculated from a laboratory measurement of band strength. Burch, Gryvnak and Williams[2] have published band strength measurements which can be related to the number of absorbing molecules in the (1,0,0) state. They showed that at 299°K the integrated absorption intensity of the 10.4 micron CO_2 band follows the expression

$$\int A(v)\, dv = 0.016 \,(w\, P_e^{\,0.25})^{0.78} \quad (4)$$

where w is the number of centimeter-atmospheres of gas being studied and P_e is the effective total pressure (allowing for self-broadening) in millimeters of mercury. From the perfect gas law and the Boltzmann distribution equation, the total number of molecules in the (1,0,0) absorbing state has been calculated and substituted for w in formula (4). Then, assuming an average effective pressure of 100 mm Hg, a graph of absorption strength versus the number of absorbing molecules has been plotted and is shown in Figure 1. This pressure estimate is loosely derived from the discussions of Kellogg and Sagan.[3] The fourth-root dependence of the integrated absorption on total pressure allows a large margin of error in this estimate without affecting the qualitative nature of the conclusions of the present work.

From Figure 1 and equation (3) the absorptivities and emissivities averaged over the spectral region 10 to 11 microns have been calculated per kilometer of atmospheric thickness. It should be kept in mind that the calculations are based on the previously-mentioned assumption of 20 millibars pressure of CO_2 at the cloud level.

Figures 2 through 4 show results of the calculations. The symbols are defined as follows:

h = Altitude above the emitting layer, in kilometers

$N_{(1,0,0)}$ = Number density of CO_2 in the (1,0,0) absorbing state, in particles per cc

T = Temperature of atmosphere, in degrees Kelvin

Figure 1. Absorption Strength Curve for 10.4 Micron CO_2 Band.

$\int A(\nu)d\nu$ = Absorption Strength of 10.4 Micron Band (cm^{-1})

N_v = Total Number of Vibrationally Excited (1,0,0) CO_2 Molecules in Light Path per Square Centimeter Cross Section

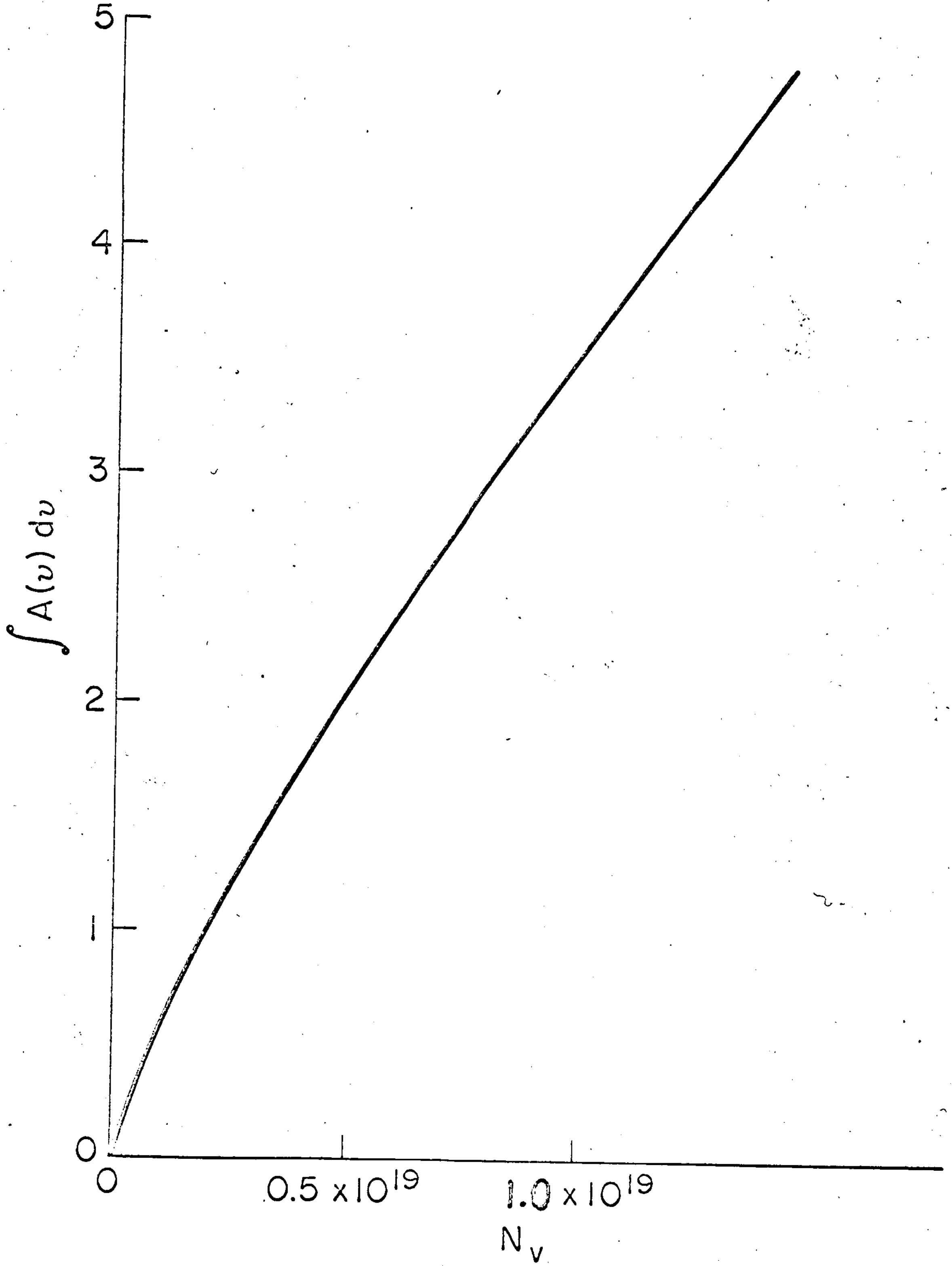


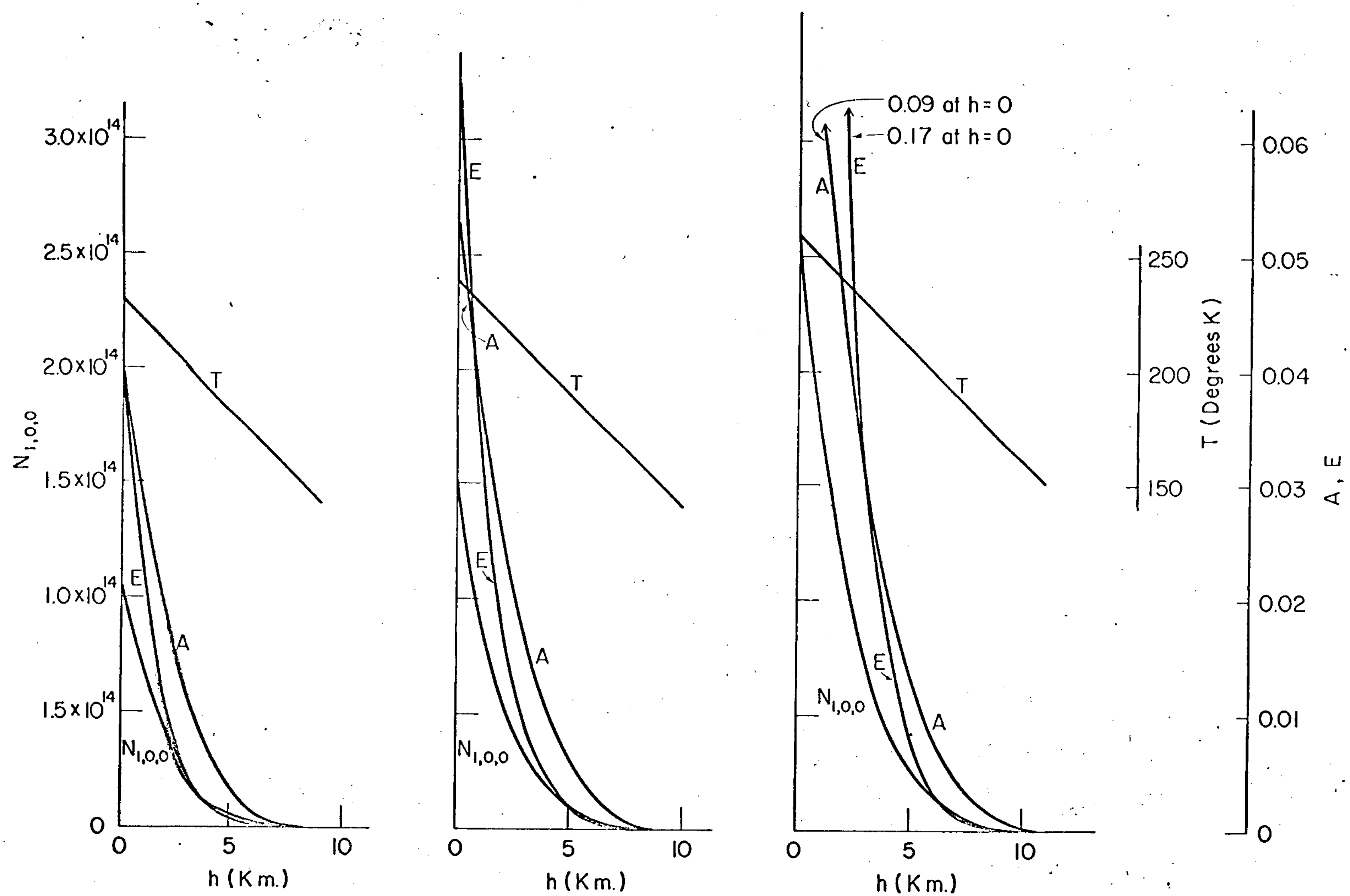
Figure 1

Figure 2. Left-Vertical Profiles When $\epsilon = 1.0$, and Lapse Rate is 10°K/Km. Predicted Absorption, 3.1%

Center-Vertical Profiles When $\epsilon = 0.8$, and Lapse Rate is 10°K/Km. Predicted Absorption, 2.4%

Right-Vertical Profiles When $\epsilon = 0.5$, and Lapse Rate is 10°K/Km. Predicts Emission 7.5% as Strong as Underlying Continuum.

See Text for Definition of Symbols.



$N_{1,0,0}$
3.0x10^14
2.5x10^14
2.0x10^14
1.5x10^14
1.0x10^14
1.5x10^14
0
T
A
E
$N_{1,0,0}$
h (Km.)
0 5 10
0.09 at h=0
0.17 at h=0
T (Degrees K)
250
200
150
A, E
0.06
0.05
0.04
0.03
0.02
0.01
0

Figure 2

Figure 3. Left-Vertical Profiles When $\epsilon = 1.0$,
and Lapse Rate is 2°K/Km
Predicts 5.2% Absorption

Right-Vertical Profiles When $\epsilon = 0.8$
and Lapse Rate is 2°K/Km
Predicts 0.5% Absorption

See Text for Definition of Symbols

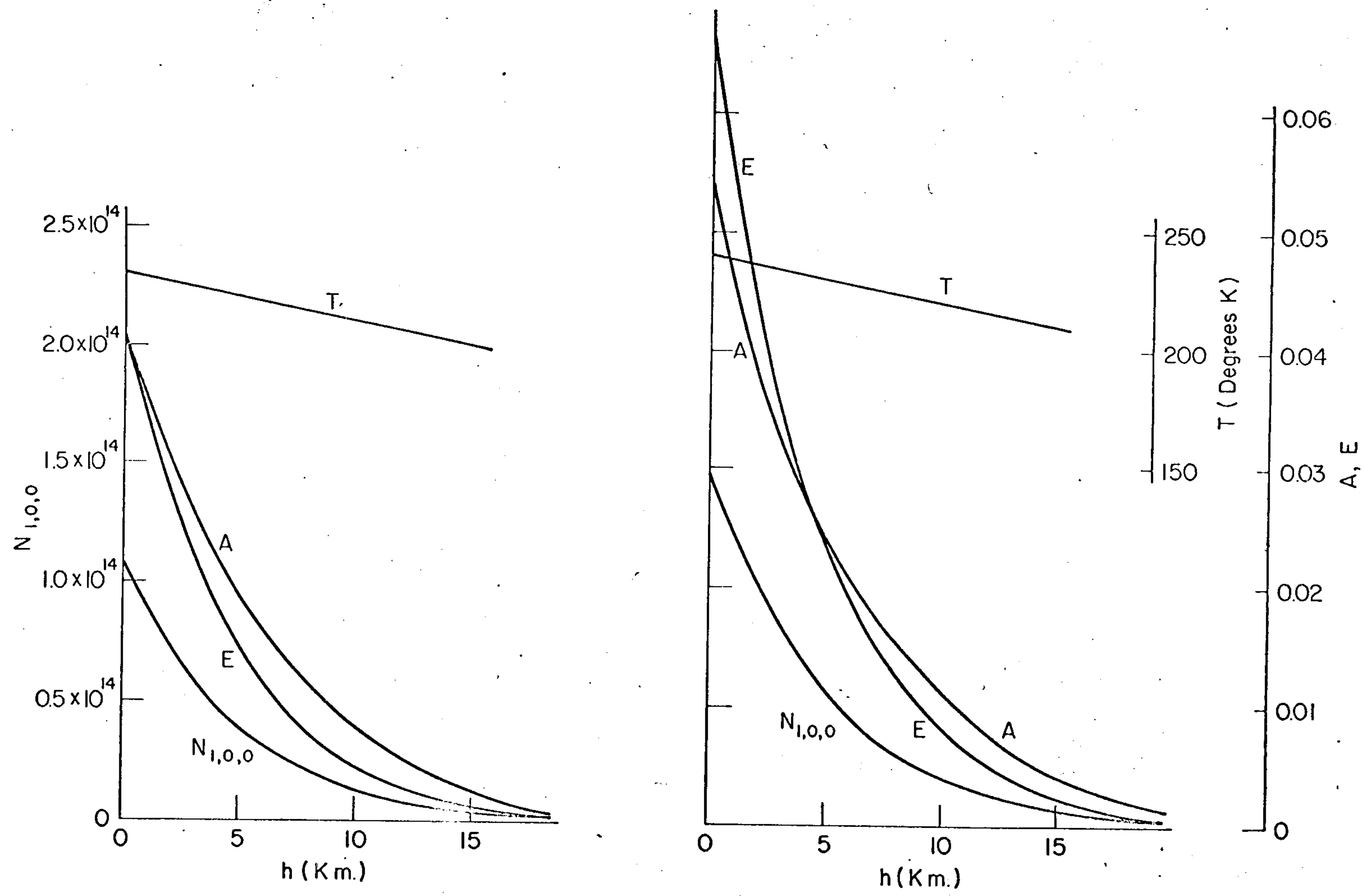

2.5x10^14
2.0x10^14
1.5x10^14
1.0x10^14
0.5x10^14
0
N 1,0,0
T
A
E
N 1,0,0
0
5
10
15
h (Km.)
E
A
T
N 1,0,0
E
A
0
5
10
15
h (Km.)
250
200
150
T (Degrees K)
0.06
0.05
0.04
0.03
0.02
0.01
0
A, E

Figure 3.

Figure 4. Left-Vertical Profiles When $\epsilon = 1.0$ and There is a Temperature Inversion. Predicts Substantial Emission

Right-Vertical Profiles When $\epsilon = 1.0$, the Temperature is 200°K at the Cloud, and the Lapse Rate is 2°K/Km. Predicts 1.5% Absorption

See Text for Definition of Symbols

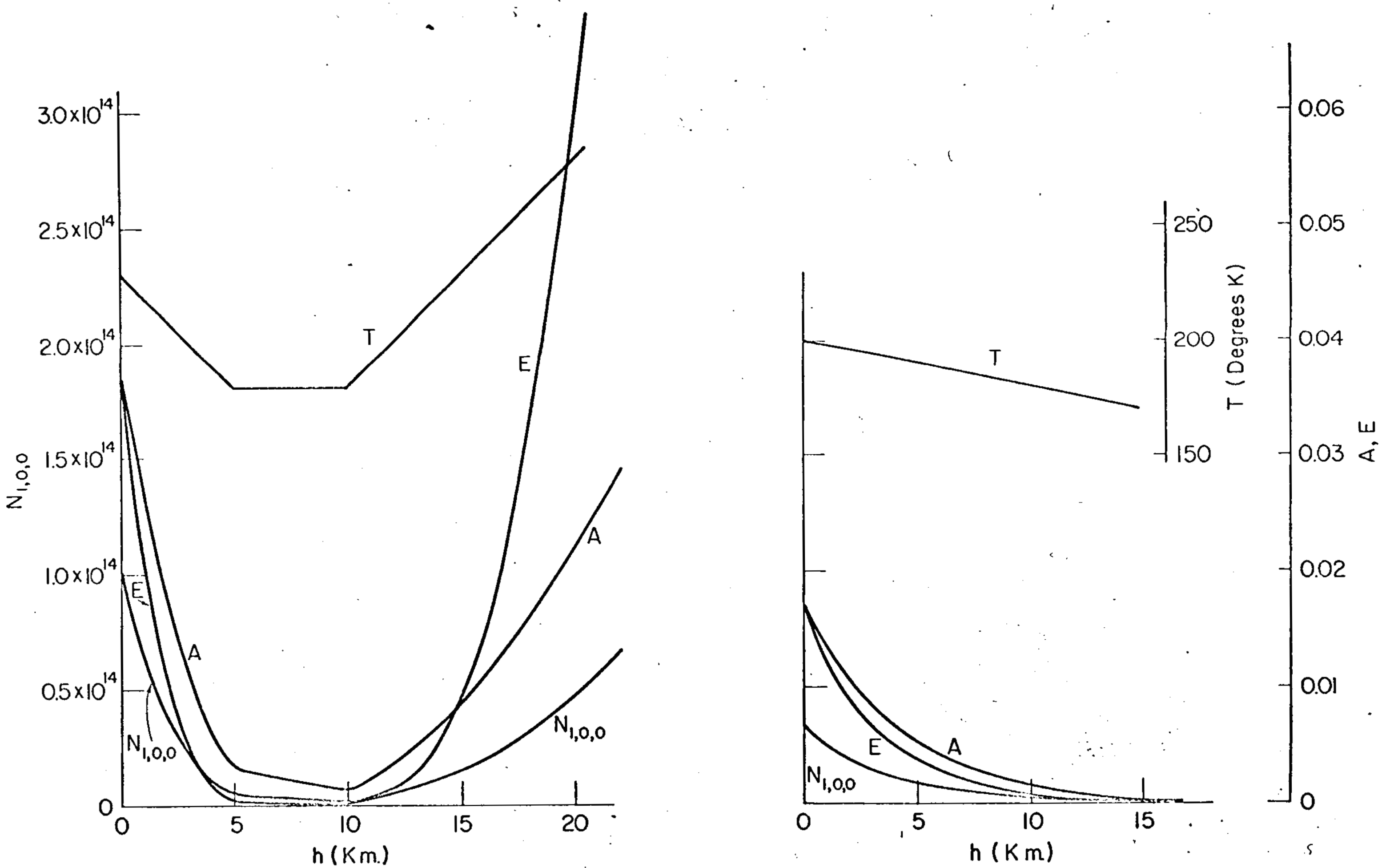

3.0x10^14
2.5x10^14
2.0x10^14
1.5x10^14
1.0x10^14
0.5x10^14
0
N1,0,0
T
E
A
N1,0,0
A
N1,0,0
5
10
15
20
h (Km.)
T
E
A
N1,0,0
0
5
10
15
h (Km)
250
200
150
T (Degrees K)
0.06
0.05
0.04
0.03
0.02
0.01
0
A, E

Figure 4

A = Absorptivity per kilometer, averaged over the spectral region 10 to 11 microns

E = Ratio of emitted intensity to incident intensity, per kilometer, averaged over the spectral region 10 to 11 microns.

The numerical calculations were made as follows. For each assumed temperature profile, at a number of different altitudes, values of h and $T(h)$ were inserted in equation (3) and the numbers of absorbing and emitting molecules per kilometer of vertical path were calculated. The average absorptivities per kilometer in the spectral region 10 to 11 microns were then calculated by referring to Figure 1 and dividing the indicated equivalent widths by 90 wavenumbers. The intensity of radiation emitted by the kilometer of atmosphere under consideration was then obtained by multiplying the calculated absorptivity (assumed equal to emissivity) by the Planck blackbody function for the temperature and wavelength region involved. The ratio of this emitted radiation intensity to the incident radiation intensity was then obtained. The incident intensity was assumed to be that emitted by a body whose brightness was similar to a 230°Kelvin blackbody. Various combinations of emissivity and temperature of the emitting body were chosen.

The difference between the areas under the absorption and emission curves gives the total absorptivity (or excess emission) expected when looking through the whole atmosphere. The calculated values of emission or absorption should be multiplied by the appropriate value of η, the effective path length in the Venus atmosphere, before they are compared with observations.

~~A~~ Spectra could be predicted for each of the cases analyzed ~~Figures 2 through 5.~~ However, it is not considered appropriate or necessary to draw spectra, since it is the qualitative nature of the results which is of principal interest.

Some general features of the results are the following: (1) The highest values of absorptivity are obtained when the emitting cloud is assigned an emissivity of unity. As the emissivity of the cloud is lowered, the cloud temperature must be increased, with the result that the gas above the cloud radiates more than it absorbs. (2) If the cloud and atmosphere are assumed to be colder than measured by Sinton and Strong[1] (for example, 200°K as reported by Murray, Wildey and Wesphal[4]), the predicted absorption or emission is smaller in magnitude because of the smaller population of the (1,0,0) state. (3) If the lapse rate is varied from 10°K/Km to zero for a cloud emissivity of unity, the predicted absorptivity will start at an intermediate value, rise somewhat, and then fall to zero. (4) If the lapse rate is varied from 10°K to zero for a cloud emissivity appreciably less than unity, the absorption (if any) will start at its maximum, fall rapidly and go over into a predicted emission before the zero is reached. (5) If the temperature of the atmosphere is assumed to first fall, and then at a somewhat higher altitude to rise and go above the cloud temperature, a net emission along a vertical path will almost always be predicted. Only if the temperature rise is assumed to take place at an extremely high altitude, such as 100 kilometers above the emitting layer, can a net absorption be predicted.

CONCLUSIONS AND DISCUSSION

Based on the observations of Sinton and Strong[1] that the Venus spectrum actually shows a few percent absorption in the 10 to 11 micron wavelength region, a number of conclusions are indicated. These are enumerated and discussed below.

(1) The emissivity of the emitting cloud must be high, and therefore its temperature cannot be much higher than the observed brightness temperature. If the emissivity is chosen low, the required cloud and gas temperature becomes high enough for total emission to

exceed total absorption. Figure 3 shows that if the lapse rate in the vicinity of the cloud is 2°K per kilometer, an emissivity of 0.8 with the required cloud temperature of 240°K would predict essentially no net absorption. If the lapse rate is 10 degrees Kelvin per kilometer, an emissivity of 0.8 is acceptable, as shown in Figure 2. However, an emissivity of 0.5 with its corresponding cloud temperature of 260°K is not acceptable with a 10 degree lapse rate, ~~as shown in Figure 4~~. Since 10°K/Km is the maximum possible lapse rate, an interpolation ~~between Figures 3 and 4~~ leads to the conclusion that about 0.65 is the lower limit of the emissivity of the cloud and about 250°K is the upper limit of its temperature.

(2) The emitting cloud most likely occurs in a region where the temperature decreases as the altitude increases. A temperature decrease is required to produce absorption. If the temperature increased with altitude in the vicinity of the cloud, but decreased at higher altitudes, the result would probably be that the total emission along a vertical path would exceed the total absorption, because the population of the (1,0,0) state would be so much higher in the warmer regions. One can devise temperature profiles which will predict a net absorption along a vertical path even though the temperature increases

with altitude in the vicinity of the cloud. However, all such profiles will require a downturn in temperature a short distance above the clouds.

(3) <u>The decreasing temperature cannot reverse itself except at extremely high altitudes.</u> If the temperature falls with increasing altitude in the vicinity of the clouds, but then starts up again at an altitude not too high above the clouds and goes above the cloud temperature, the fast increase in population of the (1,0,0) state will cause emission to exceed absorption. This is illustrated in Figure 4 where a temperature increase to only 300°K causes a significant excess of emission. At extremely high altitudes, such as 100 kilometers above the clouds, the atmosphere is so thin that emission will not exceed the lower altitude absorption even if the temperature goes as high as 600°K.

<u>FURTHER APPLICATION OF THE RESULTS</u>

If the temperature profile is known, then the results can be used to calculate the CO_2 partial pressure. If the CO_2 mixing ratio in the atmosphere is known, the total pressure can then be computed.

Obviously, a more accurate measure of the extent of absorption or emission is desired.

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