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A TITAN ATMOSPHERE WITH A SURFACE TEMPERATURE OF 200 K

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ABSTRACT

The brightness temperature of Titan at 3 mm wavelength is around 200 K, according to Ulich, Conklin, and Dickel (1978). Although an earlier measurement by Briggs is much colder, we adopt 200 K as the surface temperature and build an atmospheric model with a surface pressure of 21 bars. CH_4 clouds form between 100 and 120 km altitude. The visual limb is near 200 km. The methane mixing ratio is 0.25% above the clouds and 7% below; the dominant gas is assumed to be N_2. The thermal opacity is due to pressure-induced absorption in N_2 and a trace (0.5%) of H_2, with some help from cloud particles; unit opacity is reached at 600 mbar, 110 km from the surface. The radius of the solid body in this model is 2700 km, in reasonable agreement with 2600 km obtained if the density is the same as that of Ganymede and Callisto. Deeper atmospheres can be obtained if the temperature gradient is subadiabatic or greater CH_4 abundance is assumed.

INTRODUCTION

It has been clear for some years that a deep, cloudy atmosphere, with a surface pressure of many bars, was not ruled out for Titan by any existing data (Lewis and Prinn, 1973; Pollack, 1973). On the other hand, no data required it. Recently, however, Ulich *et al.* (1978) have obtained a 3-mm brightness temperature of 200 K. It is, therefore, worthwhile to explore the properties of a deep atmosphere in some detail. The model has quite a bit in common with the established picture of Venus, with a surface temperature 3–4 times the effective temperature, and a dense cloud layer tens of km deep. Because of the lower gravity, however, this depth is achieved with a lower surface pressure, only 21 bars.

Since the next three sections are devoted to a variety of detailed discussions, we refer ahead to the final model illustrated in Figure 3. There is a clear layer 100 km deep composed of N_2 with a few % of CH_4. Dense methane clouds form at 100 km and extend up another 10-20 km. Their top is diffuse enough to have an important effect on the formation of the observed absorption bands. We do not treat the question of how much solar radiation penetrates to the surface to drive the greenhouse, but we can appeal to the analogy with Venus to suggest that the mechanism is at least plausible.

The model presented here is far from unique, but we feel it to be conservative, in the sense that any plausible variant with a 200 K surface would have a still deeper atmosphere and greater surface pressure. An absorbing layer at the 200 K level is one possibility; another has more methane vapor, which increases the scale height and gives a deeper region of small (wet adiabatic) lapse rate. Or the lapse rate could be less than the adiabatic.

A summary of numerical data for Titan is given in the Appendix. Earlier reviews appear in the books edited by Hunten (1974) and Burns (1977). We make no attempt to summarize this material, but some of it is surveyed and updated in the preceding article by Caldwell.

THE RADIO DATA

The brightness temperature T_B deduced from a radio flux measurement is inversely proportional to the square of the assumed radius. Table 1 shows the data of Ulich *et al* (see also Conklin *et al.*, 1977) and Briggs (1974) as given and as converted to a radius of 2700 km, justified below.

Table 1. Radio Data

Source	Wavelength (mm)	T_B (K)	Radius (km)	T_B (2700) (K)
Ulich *et al.*	3	200	2900	231
Briggs	37	103	2550	115

Although each result has fairly large error bars, they do not overlap. Since we do not know how to resolve the discrepancy, we take a round value of 200 K for the present work, assuming it to be the surface temperature. The bias above the mean of the data is partly to account for an emissivity less than unity. The radiating layer could also be within the atmosphere if there is enough microwave opacity, due perhaps to NH_3. For convenience, however, we shall use the term "surface". A lower temperature, if required by later data, is readily accommodated by inserting a new "surface" at the appropriate height.

COMPOSITION OF THE VISIBLE ATMOSPHERE

Quantitative interpretation of the "red" bands of CH_4 (which extend from 4410 to 9000 Å) has only recently become possible through the laboratory work of Lutz, Owen, and Cess (1976) (hereafter, LOC), Fink, Benner, and Dick (1977), and Giver (1978). For practical purposes, the absorption at each wavelength is purely exponential and independent of pressure; an observation of Titan, therefore, gives a methane abundance, and LOC obtained 80 m-A (meter-Amagat). Lines of the $3\nu_3$ band are pressure-dependent in a known way; LOC used a result by Trafton (1975b), with their methane abundance, to obtain a total abundance of 21 km-A (if the major gas is N_2); the corresponding pressure is 300 mbar for a gravity of 117 cm s^{-2}, and the CH_4 mixing ratio 0.4%. There is no direct evidence that the gas is N_2, but we feel the indirect arguments for it are strong (Hunten, 1973, 1977).

This analysis assumes that the visible atmosphere is a clear gas above a discrete cloud top: the reflecting layer model or RLM. If, on the other hand, the cloud top is very fuzzy, the homogeneous scattering model or HSM is more appropriate. Indeed, Trafton (1975a) has already clearly demonstrated that the RLM does not fit the data; the analysis below merely substitutes laboratory data for the Saturn data he was forced to use. A crude HSM analysis has kindly been carried out by L. Wallace, as illustrated in Figure 1. The residual intensities, as a fraction of the nearby continuum, were estimated for several wavelengths from the spectra published by Trafton (1975a), and were plotted against the laboratory absorption coefficients of Giver (1978). It can hardly be claimed that the HSM, represented by the solid curves, is a good fit to the points, but at least it is much better than the RLM, which is simply an exponential. Some of the discrepancies may derive from the assumed location of the continuum at

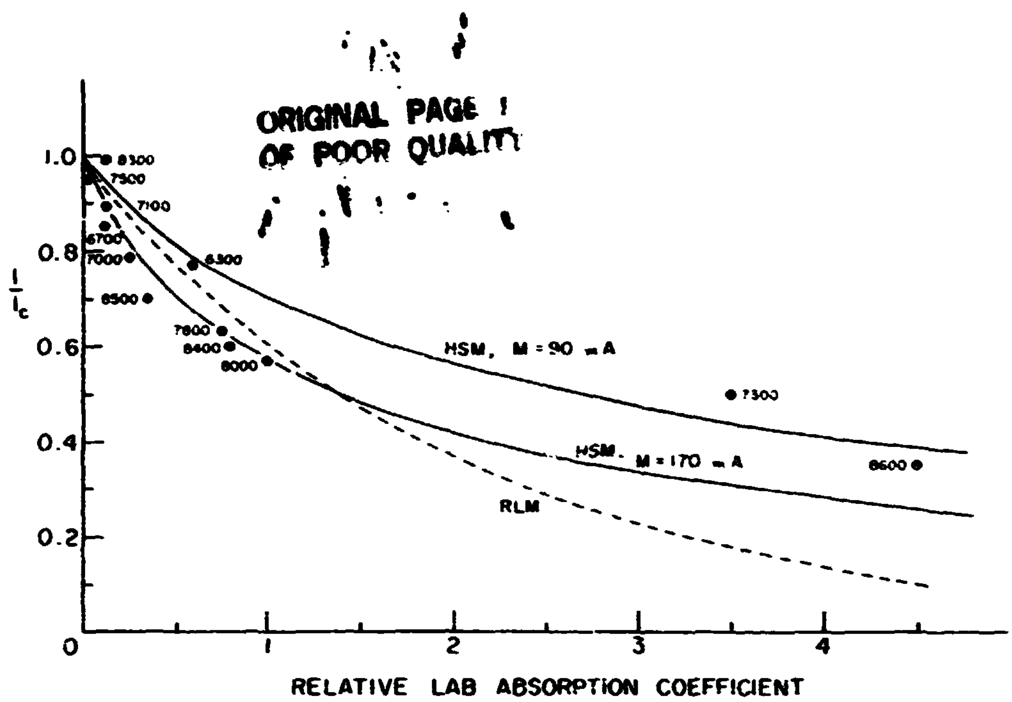

Figure 1. Rough analysis of Titan's "red" CH_4 bands. Points are estimates of intensity I divided by continuum intensity I_c. The solid curves are HSM models for two different specific amounts M, and the dashed line shows an RLM. (Wavelengths are ± 30 Å, except "6300" which should be 6165. The "8300" point should be at .012, not 0.12.)

longer wavelengths: it may be that the continuum is never reached. The best fit lies between the two curves of Figure 1; we adopt a specific methane abundance M of 150 m-A per mean free path.

To interpret the $3\nu_3$ line, we use the curve of growth (their Figure 12) derived by Wallace and Hunten (1978), which takes account of the varying pressure through the scattering atmosphere. With the specific abundance and equivalent width as input, we get a value for p_1, the pressure at unit scattering optical depth. For this first rough analysis, we divided Trafton's (1975b) equivalent width of 1.0 Å, and the laboratory strength, by 2, since the line can be approximated as a doublet with only slight overlap. The broadening coefficient at 1 bar is $\alpha^\circ = 0.169\ cm^{-1}$ for N_2 at 100 K (Darnton and Margolis, 1973). The result is p_1 = 900 mbar; the N_2 abundance corresponding is 63 km-A which, like the CH_4 specific abundance, is referred to unit mean free path. The ratio, 0.24%, is therefore, the CH_4 mixing ratio according to the HSM. It makes little difference whether we use the RLM or the HSM, but we shall adopt the latter value, which is clearly uncertain by at least a factor of 2.

Methane photolysis and escape of the resulting H_2 gives a predictable H_2 mixing ratio of 0.47% (Hunten, 1973, 1977). Our picture of the visible atmosphere is therefore:

- A gas, predominantly N_2 containing 0.25% CH_4 and 0.5% H_2;

- A cloud (argued below to be mainly liquid CH_4) with a very diffuse top, and unit optical depth at 900 mbar;

- A haze of "Axel dust" (Danielson *et al.*, 1973; Caldwell, 1977) extending well into the stratosphere. Since it is probably a mixture of methane photolysis products, it is likely to dissolve readily in the methane cloud droplets and give them also a dark color.

Elliot, Veverka, and Goguen (1975) have obtained a radius of 2900 km by analysis of a lunar occultation. It is known that a scattering atmosphere closely resembles a Lambert sphere, the model that was used (Harris, 1961). But what pressure level does the radius refer to? A ray grazing the limb encounters unit optical depth due to molecular scattering alone at a pressure of 50 mbar. In Titan's impure atmosphere, the level might be higher by 1 or 2 scale heights, or the pressure as low as 10 mbar. About 4 scale heights, or 100 km, separate this level from the 900 mbar level; the latter is, therefore, close to 2800 km radius, a value we henceforth adopt.

FAR-INFRARED OPACITIES

It is now necessary to tie the optical structure to the thermal structure. As on Venus, a high surface temperature can be sustained only by a large opacity, probably greater than 100, through the whole thermal infrared. Pollack (1973) has laid much of the groundwork for study of a Titan greenhouse. We have simply adopted his illustrative result for pressure-induced absorption in H_2, scaling by the factor 2.67 (Kiss, Gush, and Welsh, 1959) appropriate for collisions with N_2 instead of H_2. Nitrogen opacity (Bosomworth and Gush, 1965) dominates at the lower frequencies below 350 cm^{-1}, and totally swamps the CH_4 absorption which has a similar shape. Bosomworth and Gush give N_2 data only at 298 K; we have omitted the temperature correction to both width and strength of the absorption, discussed by them and also by Pollack (1973). The adopted curve is shown in Figure 2.

As found below, the gases alone have plenty of opacity to blanket the warm surface. But it is known that the structure due to the H_2 S(0) and S(1) lines does not appear

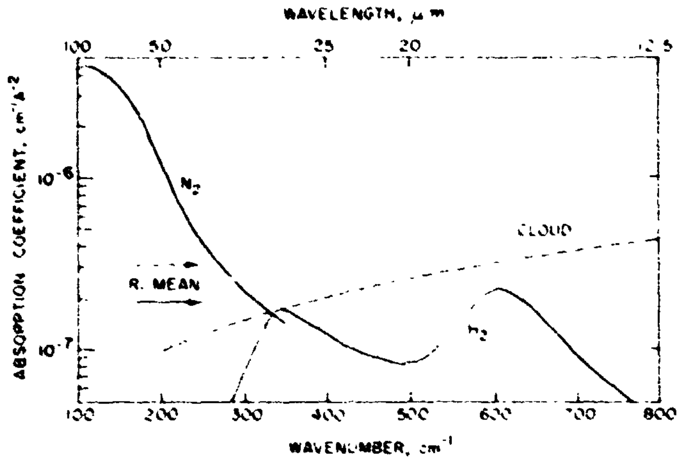

Figure 2. Pressure induced opacities for N_2 with 0.5% H_2, and an assumed cloud opacity. The latter is referred to the N_2 abundance. Rosseland means are shown for the cases with and without cloud.

in Titan's thermal emission spectrum (Pollack, 1973; Low and Rieke, 1974; Hunten, 1977). It is reasonable to suppose that the cloud particles provide enough opacity above 350 cm^{-1} to smooth out the structure. Liquid methane alone would not be adequate, but the dissolved hydrocarbons already referred to might give enough absorption at all frequencies. Following Danielson *et al.* (1973), we have adopted the curve shown in Figure 2, with opacity proportional to frequency. Use of the HSM implies uniform mixing of particles and gas; if, however, the particle mixing ratio increases downwards, the corresponding absorption can be crudely represented in the same terms as the N_2 absorption.

We now form the Rosseland mean of the data in Figure 2 (e.g., Schwarzschild, 1958):

$$\frac{1}{\overline{A}} = \frac{15}{4\pi^4}\int_0^\infty \frac{x^4 e^{-x}}{A_x} \frac{dx}{(1-e^{-x})^2} \qquad (1)$$

where $x = h\nu/kT$ and A is the absorption coefficient. Without cloud opacity, the result is

$$\overline{A} = 1.87 \times 10^{-7}\ cm^{-1}\ A^{-2};$$

with clouds included, we have

$$\bar{A}_c = 3.10 \times 10^{-7}\ \text{cm}^{-1}\ \text{A}^{-2}.$$

The level having temperature T_e, the effective temperature, is taken at the depth where the optical depth τ is unity. For pressure-induced absorption,

$$\tau = \frac{\bar{A}}{2H} w^2(N_2), \tag{2}$$

where H is the scale height and $w(N_2)$ is the abundance. Solving for the latter, and converting to pressure, we find

$$\begin{aligned} p &= 790 \text{ mbar (no cloud)} \\ &= 610 \text{ mbar (with cloud)} \end{aligned}$$

We adopt the latter estimate and give it the equilibrium temperature 77 K. It is slightly above the 900 mb level that has unit cloud optical depth in the red. For the stratosphere we simply accept the thermal-inversion model of Caldwell (1977 and preceding chapter of this volume).

THE DEEPER ATMOSPHERE

We shall, somewhat loosely, use the name "tropopause" for the point (610 mbar, 77 K) just derived. For the deeper structure we assume an adiabat, making allowance for the latent heat of condensation of the methane that forms the cloud.

Sagan (1969) has given a conveniently parameterized discussion of radiative and convective temperature gradients, and finds them so nearly the same that the tropopause location is often very sensitive to small changes. Conversely, the profile is insensitive to just where the tropopause occurs.

As a first approximation we neglect latent heat and find the pressure that corresponds to 200 K. The adiabatic lapse rate for N_2 is $\Gamma = \mu g/C_p = 1.16$ K/km and the scale-height gradient is $\beta = -1/3.5$. With the standard expression (e.g., Hunten, 1971) for the barometric law,

$$\frac{p}{p_o} = \left(1 + \frac{\beta z}{H_o}\right)^{-1/\beta} = \left(\frac{H}{H_o}\right)^{-1/\beta}, \tag{3}$$

we can substitute the ratio of temperatures (200/77) for H/H_o and obtain a pressure ratio of 28.2. This estimate of the surface pressure is therefore, $0.61 \times 28.2 = 17.2$ bars. After allowance for condensation as described below, a better estimate is 19.7 bars of N_2. A possible surface material is methane clathrate hydrate, whose vapor pressure is 1.38 bars at 200 K (see Appendix). The atmospheric composition at the surface would thus be about 6.6% CH_4, 93% N_2, which gives a total pressure

$p_s = 21.1$ bars, as well as plenty of material to condense into the clouds. Since the vapor pressure of CH_4 is about 2 orders of magnitude greater than that of clathrate, there will be an extended clear region above the surface. Once the cloud is reached, the dry adiabat used for the preliminary estimate is not satisfactory. Various expressions for the wet lapse rate appear in the literature (Brunt, 1933, 1939; Danielson *et al.*, 1977), but the best seems to be that of Lasker (1963). In practice the differences are minor, especially since the fate of the condensate is uncertain. If it falls out or remains at the height where it condenses, its specific heat should be omitted, and the curve is called a "pseudoadiabat". If the condensate moves with the gas, the situation is truly adiabatic. Lasker's expression for the pseudo-adiabat is

$$-\beta = \frac{d \ln T}{d \ln p} = \frac{1 + \gamma(1+\alpha)}{(C_p/R) + \gamma\alpha(1+\alpha)}. \qquad (4)$$

Here β is the same quantity used in (3), which, however, is valid only over a region where β is constant. The specific heat C_p pertains to the mixture of gas and vapor; γ is the mixing ratio $[CH_4]/[N_2]$; and $-\alpha$ is the exponent in the vapor-pressure relation. For CH_4, $\alpha = 1024/T$ (see Appendix). As suggested by Lasker, a suitable method is to find the (T, p) relation from (4) and then obtain the height scale from the hydrostatic equation. Where β is independent of height, (3) may be used, and it gives useful accuracy even where β is slowly varying. In the present case, γ varies from 0.070 to essentially zero and $\alpha \simeq 12.5$; $-\beta$ is 0.282 below the cloud, and drops to 0.127 at the cloud base, back to 0.286 above the cloud.

Figure 3 shows the model. The vertical scale is linear in the logarithm of pressure, with an auxiliary (nonlinear) height scale. The Danielson-Caldwell stratospheric model does not specify a pressure scale; the one adopted is by analogy with the Jupiter model of Orton (1977).

The cloud base is at 103 km and has a methane partial pressure of 70 mbar at a total pressure of 1080 mbar. The potential cloud mass is the amount contained in a scale height, or 600 g cm^{-2}. In the form of 10 μm diameter droplets, this amount would have a scattering optical thickness of over 10^6. Thus, most of it could precipitate out and still leave a very respectable cloud. The temperature is 87 K, somewhat below the freezing point (89 K); the form may therefore be either crystals or supercooled droplets. The level found in Section 3 for unit optical depth in the "red" is a few km above the base, a reasonable location.

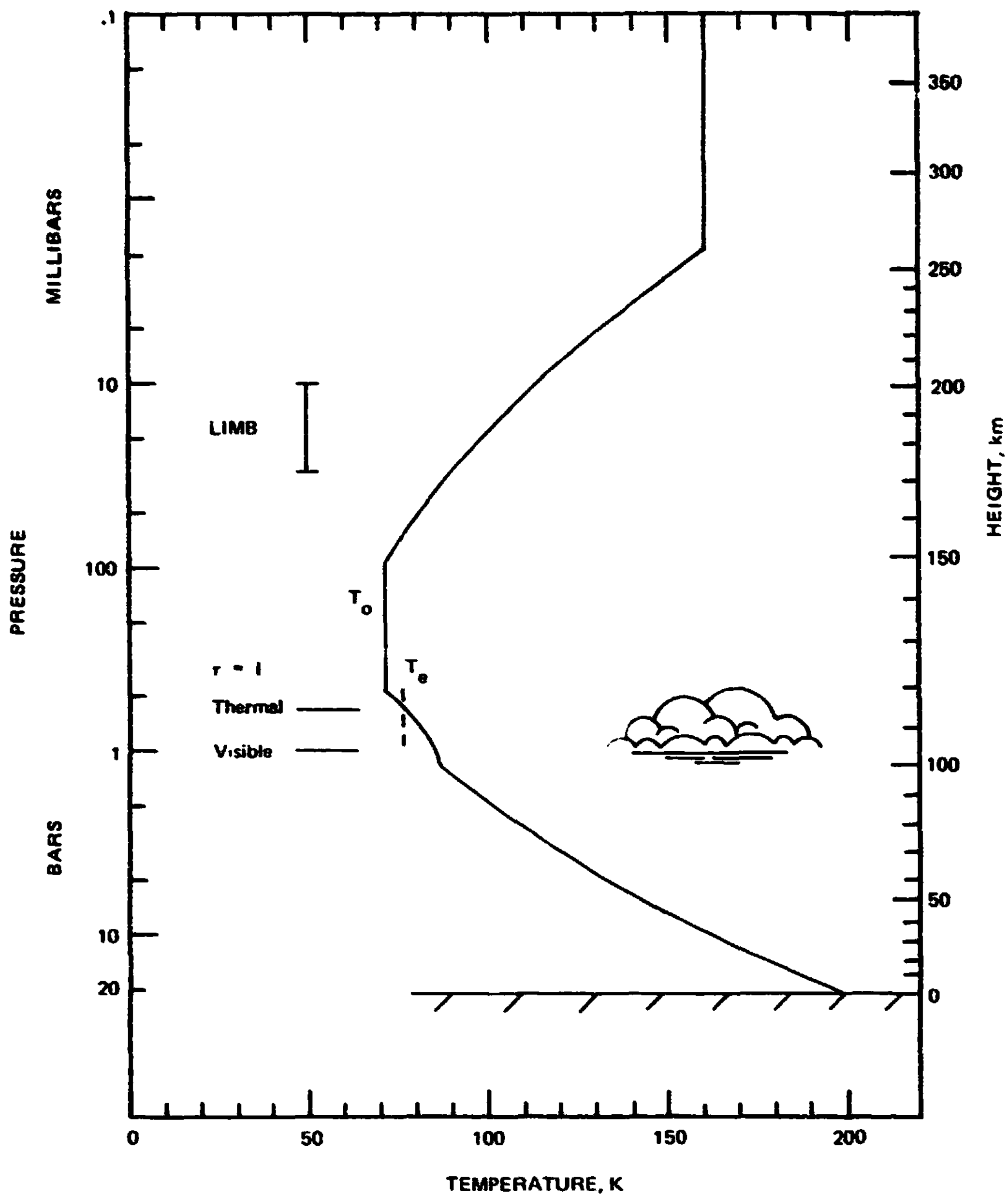

Figure 3. Temperature as a function of log pressure, along with a height scale. The position of the cloud layer is sketched, and the levels of unit thermal and visible opacity are indicated. If the surface is at a radius of 2700 km, the limb position shown is in agreement with the observed radius of 2[illegible]00 km.

DISCUSSION

As pointed out in the Introduction, the present model is conservative in the sense that any other that gives a "surface" temperature of 200 K requires an even deeper atmosphere. A totally different argument is to estimate the radius of solid Titan from its known mass and a reasonable mean density. For the latter, we take Callisto and Ganymede as analogs, weighting the densities of Morrison *et al.* (1977) inversely by the stated errors. The result (1.89 g cm^{-3}) combines with a mass of 1.40×10^{26} g to give a radius of 2605 km. A 10% change of density reflects into a radius change of 80 km. Titan is likely to be less dense, if anything, than any Galilean satellite; if so, a reasonable range for the radius is 2600-2700 km, which just includes the value from the atmospheric model.

The vapor pressure of NH_3 dissolved in ice is roughly 1 mbar at 200 K. The mixing ratio could thus be around 5×10^{-5}. The optical depth of this amount is about 8 at 3 mm wavelength, according to the approximate treatment of Field (1959). Perhaps the ammonia is kept out of the atmosphere by a layer of hydrocarbons on the surface.

Much of this paper is built on the assumption that the surface temperature is 200 K, as suggested by the microwave observations. The issue of ammonia opacity only serves to point up the crucial nature of such data, and the importance of data at other wavelengths. The disagreement shown in Table 1 is particularly disturbing, and a resolution is badly needed. The measurements are, however, so difficult that progress is sure to be slow. Ammonia opacity cannot be called on, because it is nearly the same at the two wavelengths. The preliminary VLA results reported by Caldwell at the end of the preceding chapter support a lower temperature, although they would still permit it to be above 150 K. However, a temperature of, say, 100 K can be accommodated by placing the surface at 2 bars or 85 km in Figure 1. The model is unchanged at greater heights.

Added after the Workshop:

Shortly after the Workshop, a preprint by Podolak and Giver (1978) became available. This work, an extension of Podolak and Danielson (1977), adopts as its model an atmosphere of pure CH_4, 2 km-A deep, with a layer of Axel dust occupying the top

50 m-A. This dust is nearly opaque in the blue, grading rather suddenly in the red to essentially transparent in the infrared. The surface (or cloud top) has an albedo of 50-60%. An excellent fit is obtained to the observed CH_4 bands from 5000 to 10,000 Å. Although the $3\nu_3$ band is not discussed, the model is consistent with Trafton's analysis for a reflecting-layer model, which requires 1.5 km-A if the atmosphere is pure CH_4. At this and longer wavelengths, the Podolak-Giver model reduces to a reflecting layer.

How might a choice be made between this model and the one described here? They were both fitted to the same data; thus we require some additional information. Two recent lines of evidence can in fact be brought forward: (1) the work of Rages and Pollack reported in Chapter 11 of this volume; (2) spectra of the 1-3 μm region.

Rages and Pollack find the mean particle radius to be 0.2-0.4 μm, and strongly exclude the value (slightly under 0.1 μm) required by Giver and Podolak to obtain the necessary optical properties.

The infrared spectra, shown in Figure 4, were obtained by U. Fink and H. Larson in 1975, and are reproduced here by their kind permission.

A detailed analysis has not yet been done, but two facts stand out clearly:

(1) The Titan spectrum is utterly unlike the laboratory spectrum of 1.5 km-A of methane.

(2) The closest analog to Titan in this spectral region is Neptune.

The laboratory spectrum is the analog of a clear atmosphere of pure methane (the Podolak-Giver model at these wavelengths). Neptune is an analog of a deep scattering atmosphere with a small fraction of methane. Although the major gas is assumed to be H_2-He on Neptune and N_2 on Titan, the important thing is the scale height, not the composition, and the scale heights are rather similar. These arguments strongly suggest that the deep, N_2-CH_4, atmosphere is preferred over the pure-CH_4 one. A detailed analysis is highly desirable, but in this spectral region it is very difficult because of the fine structure of the bands.

A direct comparison of a laboratory spectrum with Titan may be misleading because of the gross differences in the temperatures and pressures at which the CH_4 is observed. It has been shown by Ramaprasad *et al.* (1978) in a study of liquid CH_4 that band shapes are somewhat different at 90 K than they are at a room temperature. For example, a band may be seen at 9170 Å in the spectra of the cold liquid and of Titan which is completely masked by the wing of the strong band at 8890 Å. The sensitivity of the populations of high J levels to temperature must be accounted for before a truly meaningful comparison can be made.

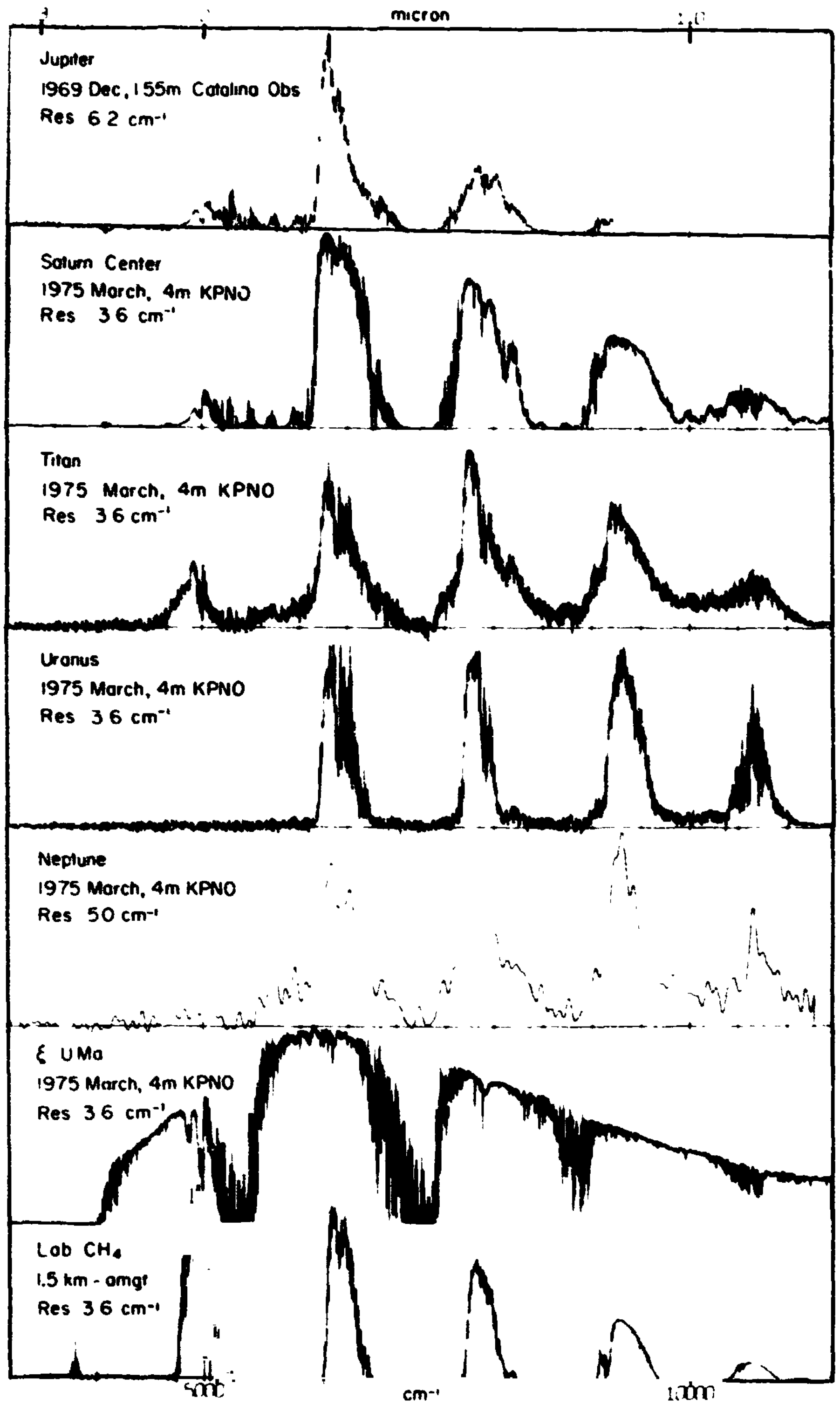

Figure 4. 1-2.5 μm spectra obtained in 1975 by U. Fink and H. Larson, reproduced by their kind permission. A solar-type star shows the atmospheric transmission.

Clearly, all this evidence refers only to the region that can be probed optically, and bears only on the composition of this region. The issue of the surface temperature and pressure is totally independent.

Atreya *et al.* (1978) have discussed in detail the production of N_2 by photolysis of NH_3, and have found that a surface partial pressure of 14-19 bars could reasonably be generated over the age of the solar system.

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APPENDIX

Table 2 gives various quantities for three radial distances r corresponding to heights of 0, 100, and 200 km in the model. They are the acceleration of gravity g, the scale height for pure N_2 at a reference temperature of 100 K, the base pressure for an N_2 abundance of 1 km-Amagat, and the dry adiabatic lapse rate for N_2.

Table 2. Quantities for Three Radial Distances

r (km)	2700	2800	2900
g (cm s^{-2})	125	117	109
H (km)	23.8	25.5	27.2
p/N (mb/km-A)	15.6	14.6	13.6
r (dry) (K/km)	1.20	1.13	1.05

Table 3 gives constants in the vapor-pressure equation, $p = A \exp(-B/T)$, from Delsemme and Wenger (1970) and the Handbook of Chemistry and Physics. The melting point of methane is 89 K.

Table 3. Constants in the Vapor-Pressure Equation

Form	A(bar)	$B = \alpha T$
Clathrate	75,300	2182
Liquid	9,714	1024
Solid	59,662	1190

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