2.6 MODELS OF TEMPERATURE STRUCTURE AND GENERAL CIRCULATION

J. B. Pollack

Rival Models of Titan's Atmosphere

Most of this paper will deal with greenhouse models of Titan's atmosphere. Towards the end, I will summarize some work done by Leovy and myself, in which elementary, general circulation models of its atmosphere are considered. This latter subject has significance both for providing estimates of horizontal temperature variations and in illuminating another unique characteristic of Titan's atmosphere.

Up until recently, infrared brightness-temperature measurements of Titan have been interpreted within the context of greenhouse models. Such models imagine that the atmospheric pressure is sufficiently high so that the lower atmosphere is opaque over almost all wavelengths containing large amounts of thermal radiation. Accordingly, the surface temperature is much higher than the effective temperature at which the satellite radiates to space and the lower atmosphere is characterized by a decrease of temperature with an increase in altitude. High infrared brightness temperatures are interpreted as occurring at wavelengths of reduced atmospheric opacity, which permit penetration to warmer temperature levels.

An alternative model has been proposed by Danielson, et al. (1973). According to this view, the upper atmosphere is heated to a high temperature through the absorption of much of the solar energy reaching the satellite and the surface has a temperature close to the effective temperature. In this case, high infrared brightness temperatures are understood as occurring at wavelengths that are fairly opaque, permitting a view of the warm upper atmosphere. Danielson's model considers almost all of the atmosphere to be at a high temperature, with only a narrow region next to the surface serving as a transition region between the two temperature extremes.

Danielson's model is partially supported by recent narrow-band measurements made in the 8 to 13 micron region by Gillett et al. (1973). As detailed below, at least part of these observations do refer to a warm upper atmosphere. It therefore seems appropriate to reconsider my greenhouse models, (Pollack, 1973), which were based on broad-band infrared measurements.

There are two questions that need to be addressed and these are quite separate from one another. The first concerns itself with the origin of the high brightness temperatures found in the 8 to 13 micron region. There is a continuum of possible answers to the first question: At some wavelengths the radiation may arise from a hot upper atmosphere and, at the remaining wavelengths, from a hot lower atmosphere. The ends of this continuum are the pure Danielson model and the pure greenhouse model.

The second question concerns itself with whether or not the surface has a temperature significantly above the effective temperature. In principle, one could imagine a situation in which all the 8 to 13 micron radiation came from a hot upper atmosphere and yet there was a significant greenhouse effect in the lower atmosphere. For example, clouds could prevent our viewing the lower atmosphere at wavelengths shortward of 13 μm. The answer to this second question may be crucial in assessing the feasibility of a Titan Entry Probe mission. If there is a significant greenhouse effect, the surface pressure would be high enough, so that measurements from an Entry Probe could commence well above the surface. This situation would not necessarily hold if Danielson's model is correct.

Greenhouse Model Revisited

Let us now review my prior greenhouse calculations. Because of Titan's low effective temperature, the only way to achieve a large greenhouse effect is by means of pressure-induced absorptions. Figure 2-24 illustrates the absorption coefficient of the pressure-induced transitions of hydrogen and methane as a function of wavenumber. The notation $X \rightarrow Y$ indicates that molecule X is absorbing in the presence of molecule Y. To cause a significant greenhouse effect the wavenumber region from about 50 cm^{-1} to 700 cm^{-1} should be opaque. We see from Figure 2-24 that in an atmosphere containing comparable amounts of methane and hydrogen, as is perhaps suggested by the spectroscopic observation, the methane and hydrogen opacity complement one another quite nicely. Where the hydrogen absorption is weak, the methane absorption is strong and vice versa.

Figure 2-25 shows a determination of the pressure-temperature structure of an atmosphere containing equal amounts of hydrogen and methane and having a surface temperature of 150°K. We see that the atmospheric temperature begins to rapidly increase with pressure above a pressure level of 0.1 atm. Put another way, in an atmosphere of this composition, if the surface pressure is above 0.1 atm, there will be a significant greenhouse effect. The spectroscopically determined gas amounts of methane and hydrogen indicate pressures of several hundredths of an atmosphere. The amounts of methane and hydrogen are comparable, as long as there is no other major component to the atmosphere, such as nitrogen. Trafton has shown that much of the line formation takes place in the vicinity of a cloud layer. Therefore, the surface pressure is significantly greater than several hundredths of an atmosphere and is close to or above the critical value of 0.1 atm needed for a greenhouse effect to become important.

Using model atmospheres of the type shown in Figure 2-25, I calculated the dependence of brightness temperature on wavelength. Figure 2-26 illustrates this dependence for atmospheres containing only methane and hydrogen. The curves are labeled according to the value of the hydrogen mixing ratio assumed. Also shown as circles are the four broad-band observations, available at the time the calculation was performed. The horizontal bar through the circle represents the band pass of the instrument used, while the vertical bar indicates the estimated error in the brightness temperature value.

The 20-micron observation provides a good discriminant of the hydrogen mixing ratio for this set of model atmospheres. This point is further illustrated in Figure 2-27, where the theoretical spectra have been convoluted over the instrument band pass at 20 μm. We see that approximately even proportions of hydrogen and methane are implied by the observed brightness temperature.

Table 2-5 summarizes the broad-band observations that have currently been made, as well as the recent narrow-band results of Gillett, et al. (1973). The broad-band values used for Figure 2-26 are marked with a star. The narrow-band observations force us to reconsider our interpretation of the 8-13 micron spectra.

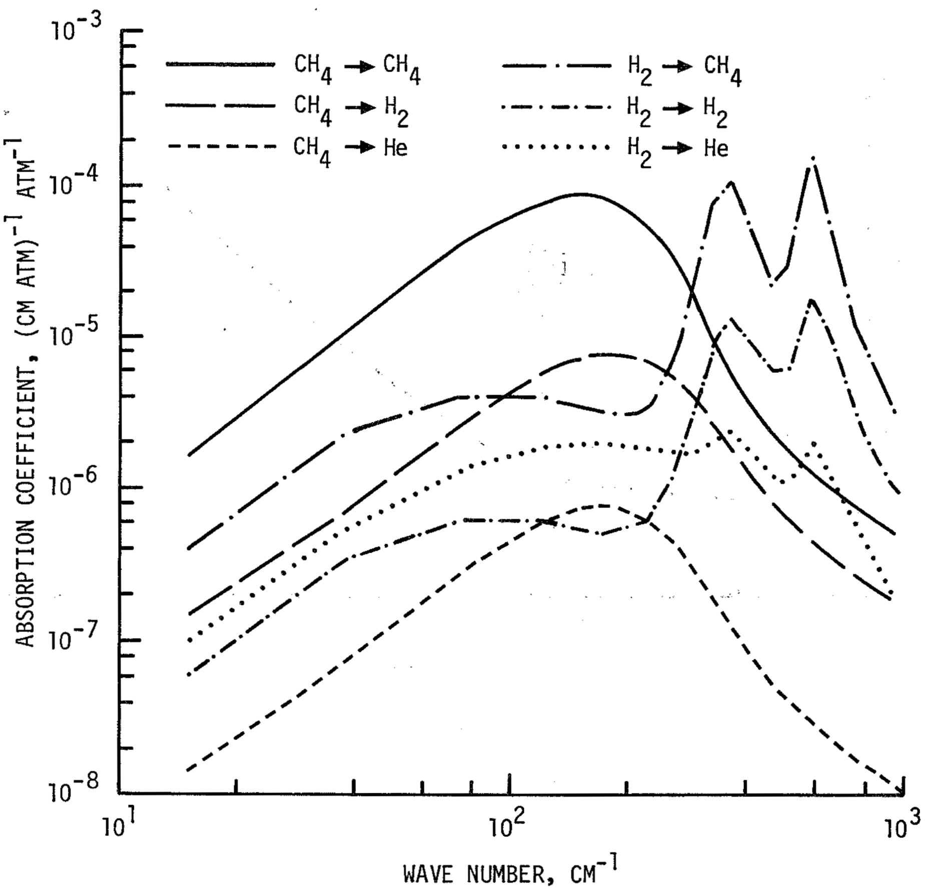

Figure 2-24. The absorption coefficients of the pressure-induced transitions of methane and hydrogen as a function of wavenumber. The notation X → Y indicates that molecule X is absorbing in the presence of molecule Y. After Pollack (1973). Reprinted from Icarus, 19:48, with permission of Academic Press, Inc. Copyright © 1973 by Academic Press, Inc. All rights of reproduction in any form reserved.

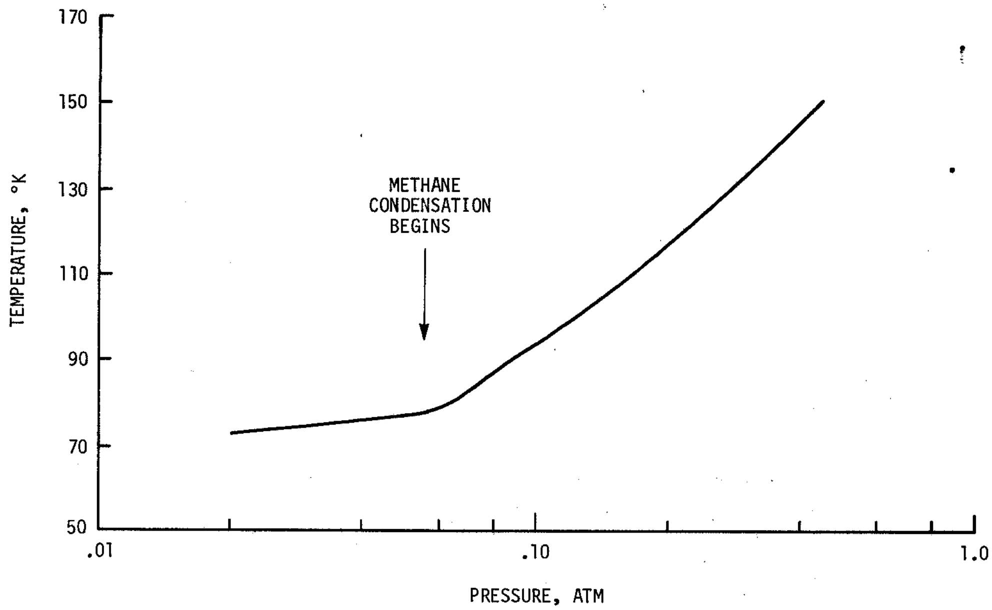

Figure 2-25. Temperature as a function of pressure for a model atmosphere of Titan containing equal amounts of hydrogen and methane and no helium. The mean surface temperature is 150°K. After Pollack (1973). Reprinted from Icarus, 19:49, with permission of Academic Press, Inc.

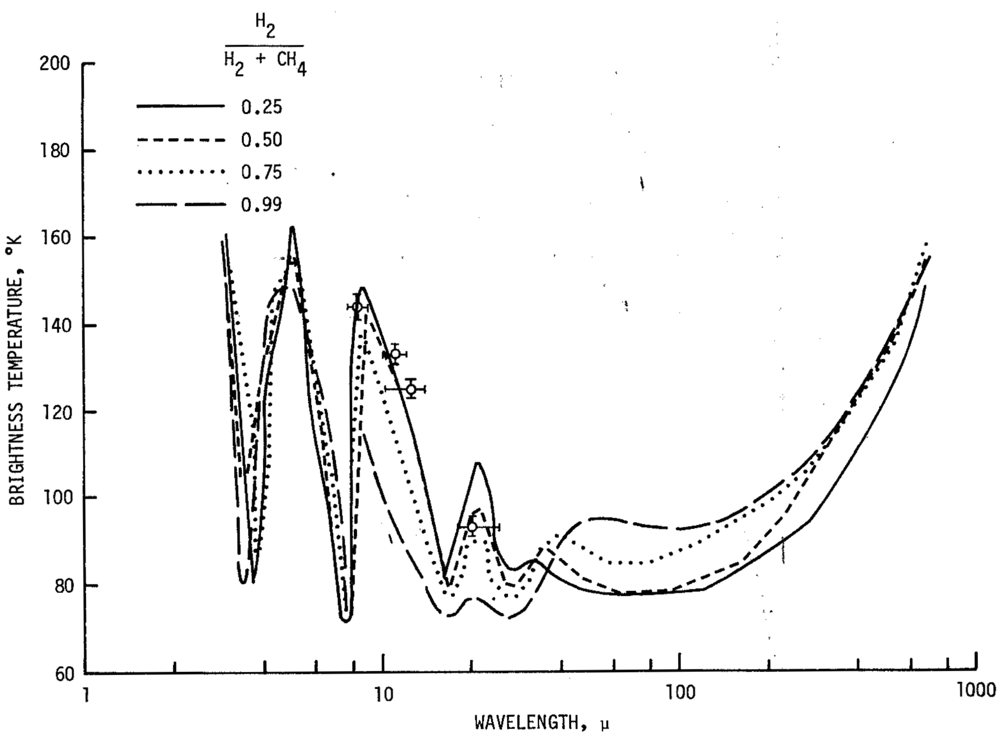

Figure 2-26. Brightness temperature as a function of wavelength for model atmospheres containing no helium and ammonia and varying proportions of methane and hydrogen. Observed temperatures are indicated by a circle, with vertical bars indicating the bandpass of the instrument. After Pollack (1973). Reprinted from Icarus, 19:50, with permission of Academic Press, Inc.

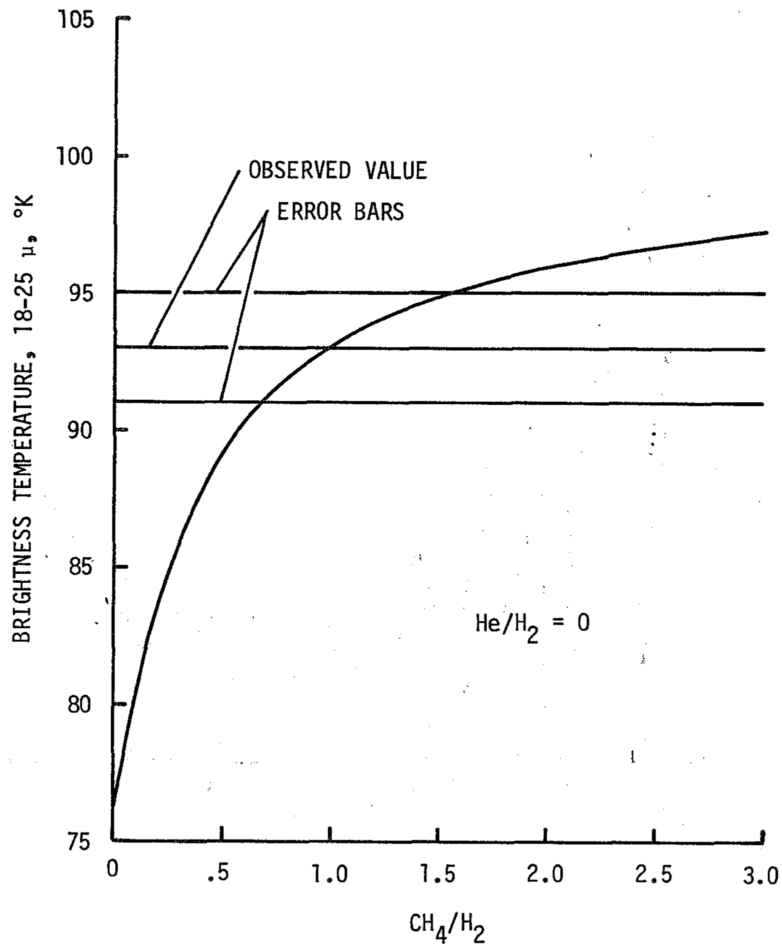

Figure 2-27. Theoretical brightness temperatures applicable to the 20 μm observation as a function of the methane-to-hydrogen ratio. The observed value with its mean and extreme values, permitted by the quoted error bars, is indicated by the horizontal lines. No helium is present in the model atmospheres. After Pollack (1973). Reprinted from Icarus, 19:50, with permission of Academic Press, Inc.

Table 2-5. Observed Brightness Temperatures of Titan

Narrow-Band Measurements (Gillett, et al. 1973)

λ	T_b (°K)
8.0	158 ± 4
9.0	130 ± 6
10.0	124 ± 3
11.0	123 ± 3
12.0	139 ± 1
12.5	129 ± 2
13.0	128 ± 2

Broad-Band Measurements

λ	Δλ	T_b (°K)	AUTHORS
4.9	0.8	<190	Joyce, et al. (1973)
8.4	0.8	146 ± 5	*Gillett, et al. (1973)
10.0	5.0	132 ± 5	Low (1965)
11.0	2.0	134 ± 2	*Gillett, et al. (1973)
12.0	2.0	132 ± 1	Gillett, et al. (1973)
12.4	4.0	125 ± 2	*Allen & Murdock (1971)
20.0	7.0	93 ± 2	*Morrison, et al. (1972)

* Used in prior calculations.

The measurement at 8.0 μm lies well within a very strong methane band centered at 7.7 μm. For the type of atmosphere discussed above, containing approximately equal proportions of hydrogen and methane, optical depth unity at 8.0 μm is reached at about the 10^{-3} atm level. This inference was based on laboratory measurements of the 7.7 μm methane fundamental. Thus we are led to conclude that the upper atmosphere is quite warm and that at least some of the radiation in the 8 to 13 micron region comes from the upper atmosphere. In addition, the apparent local peak in brightness temperature near 12 μm may be due to radiation within a strong band of ethane, as suggested by Danielson, et al. (1973).

According to Danielson's model, the remainder of the high brightness temperature radiation in the 8 to 13 micron region should be attributed to a warm upper atmosphere, with the opacity being supplied by a diffuse haze layer located throughout the atmosphere, which has been photochemically generated. The haze is not optically thick at these wavelengths and its opacity is declining with increasing wavelength. Thus, in this model there is some contribution from the cool surface.

However, the remaining portions of the 8 to 13 micron region can equally well be understood within the context of a greenhouse model. According to Figure 2-26, the brightness temperature near 12.5 μm should be about 115°K; this prediction is consistent with the observations if we allow for the rather sizeable uncertainties in the shape of the far wings of the hydrogen rotational lines, which are responsible for the 12.5-micron opacity. These wings have been measured only for $H_2 \rightarrow H_2$, not for $H_2 \rightarrow CH_4$. The latter is by far the more important for Titan. Gillett's 13-micron observation is inconsistent with Danielson's model. However, it may not be inconsistent with some variant of this model.

Figure 2-28 shows the brightness temperature spectra for atmospheres containing no ammonia in the lower atmosphere and amounts of ammonia dictated by its vapor pressure curve. The latter situation corresponds to the maximum amount of ammonia that could be present. We see that the observed narrow-band brightness temperatures, as given in Table 2-5, are close to the values expected for the saturated ammonia model. Thus these data points may indicate the presence of small amounts of ammonia in the lower atmosphere.

The dependence of brightness temperature on wavelength for a variety of surface temperatures is illustrated in Figure 2-29. These calculations once again refer to greenhouse models containing equal proportions of hydrogen and methane. They illustrate that there is some residual opacity at 12.5 μm and hence surface temperatures in excess of the observed brightness temperature of 129°K would be required, within the context of this model.

Finally, in Figure 2-30, we show how the surface pressure varies when we introduce helium into the model atmosphere. The surface temperature has been fixed to a value of 155°K and the atmosphere contains equal proportions of hydrogen and methane. As the helium content is increased, the surface pressure increases. For the case of zero helium, perhaps the most likely a priori case, a surface pressure of 0.45 atm is required.

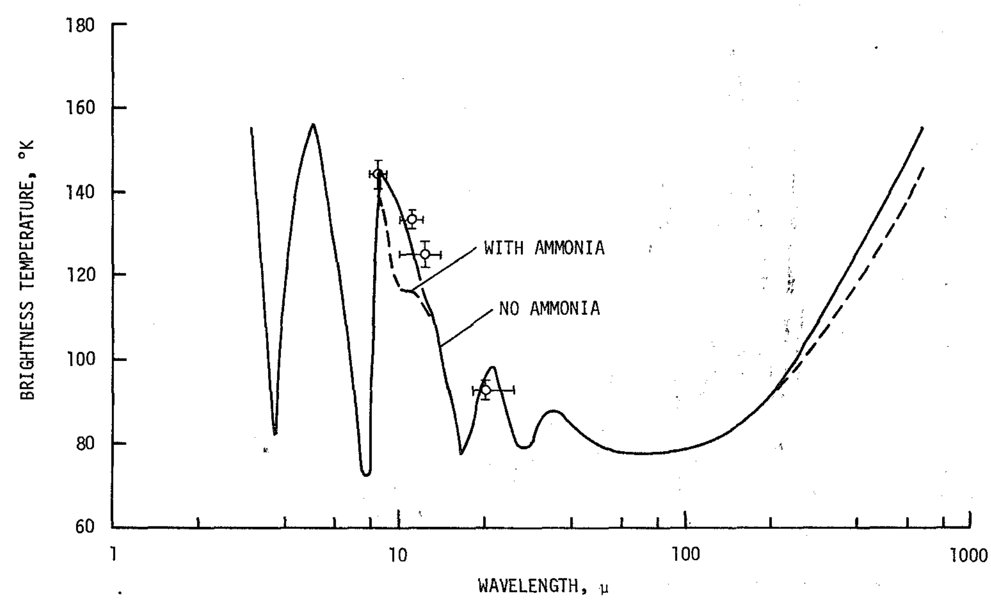

Figure 2-28. Brightness temperature as a function of wavelength for model atmospheres with and without ammonia. Both model atmospheres have equal proportions of hydrogen and methane, no helium, and a daytime surface temperature of 155°K. Observed temperatures are indicated by a circle, with vertical bars indicating the estimated error and horizontal bars the band-pass of the instrument. After Pollack (1973). Reprinted from Icarus, 19:51, with permission of Academic Press, Inc.

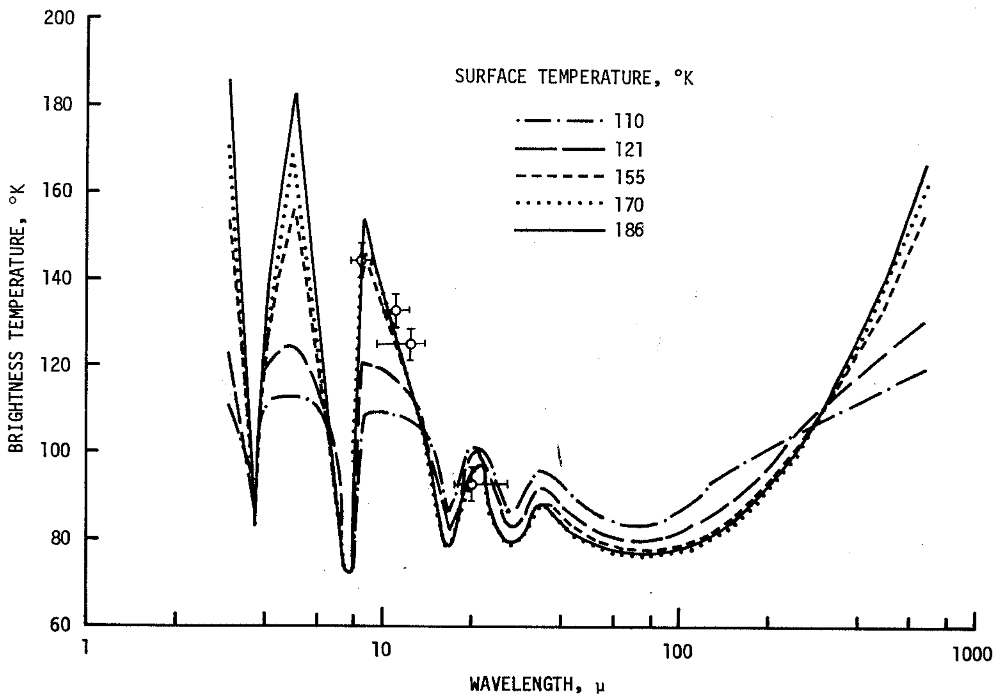

Figure 2-29. Brightness temperature as a function of wavelength for model atmospheres having no helium or ammonia and equal proportions of methane and hydrogen. The surface temperature is varied between models. The observed temperatures are indicated by a circle, with vertical bars indicating the estimated error and horizontal bars the band-pass of the instrument. After Pollack (1973). Reprinted from Icarus, 19:53, with permission of Academic Press, Inc.

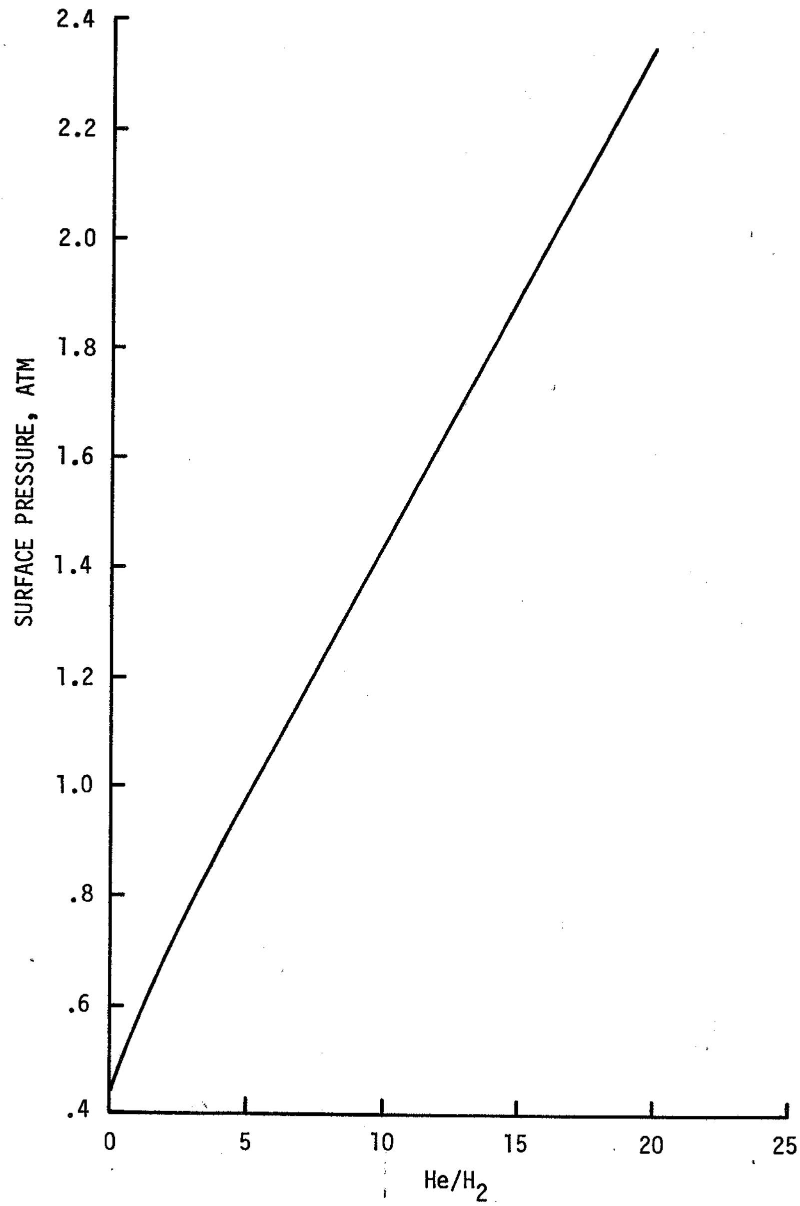

Figure 2-30. Surface pressure as a function of the helium-to-hydrogen ratio for model atmospheres having equal proportions of methane and hydrogen and a surface temperature of 155°K. After Pollack (1973). Reprinted from Icarus, 19:53, with permission of Academic Press, Inc.

Future Observations

Above we have seen that it is not possible to deduce a unique model of the atmosphere of Titan from the presently existing data. At some of the wavelengths in the 8 to 13 micron region, e.g., 8.0 μm, the radiation undoubtedly originates from a warm upper atmosphere; however at other wavelengths, e.g., 10, 11, 12.5, and 13 μm, the radiation may originate either from a warm upper atmosphere or a warm lower atmosphere. The distinction between lower and upper atmosphere as used here is that the lower atmosphere is envisioned as optically thick at all important thermal wavelengths, i.e., 15 μm < λ < 200 μm, while the reverse is true of the upper atmosphere. Even should future observations in the 8 to 13 micron region show that all the radiation in this region comes from a hot upper atmosphere, the possibility of a hot lower atmosphere could not be dismissed.

Future spectral observations of Titan at wavelengths longward of 15 μm can determine whether the lower atmosphere and surface have significantly higher temperatures than the effective temperatures. Radio observations permit a direct determination of the surface temperature and are discussed elsewhere in this report. Here we consider the significance of future spectral infrared observations beyond 15 μm. As can be seen from Figures 2-24 and 2-26, greenhouse models predict the presence of several spectral features in this wavelength region. In particular, there should be comparatively sharp features centered at 17 and 28 μm due to hydrogen pressure induced transitions and a broader feature centered close to 50 μm due to the sum of the methane pressure-induced transitions. Whether these features show up as absorption or emission features depends on the exact temperature structure of the atmosphere. In this regard, Figure 2-26 should not be taken literally. However, if the greenhouse model is correct, these features should be present. Groundbased measurements within the 20-micron region will permit a search for part of the structure expected from the hydrogen transitions, while observations from the C-141 aircraft will permit a view of the entire spectral region of interest.

Clouds

According to Danielson's model, aerosols produced photochemically should be present throughout the entire atmosphere. In addition, several types of condensation clouds may also be present. The model atmosphere shown in Figure 2-25 becomes cold enough in the upper part of the troposphere for methane to condense out. This occurs near the 5 x 10^{-3} atm pressure level. However, whether such clouds will indeed exist in the atmosphere of Titan depends on the details of the solar energy deposition profile. The model atmosphere calculated in Figure 2-25 was based upon the assumption that all the solar energy is deposited at the surface. The existence of a warm upper atmosphere, as discussed above, may mean that the tropopause is too warm to permit methane condensation anywhere in the atmosphere. However, it is worth noting that several independent pieces of evidence, discussed elsewhere in this report, suggest the presence of clouds with a definite bottom, located near the pressure levels expected for the methane clouds.

We have also seen in this discussion that the new 10 and 11 micron narrowband temperatures may imply the presence of ammonia in the lower atmosphere. At the temperatures appropriate to Titan ammonia is severely limited by its saturation vapor pressure curve and, hence, ammonia clouds may be present in the lower atmosphere. The possible presence of ammonia in the lower atmosphere needs to be factored into considerations of potential constraints on the communication link between a Titan Probe and its Relay Bus.

Solar Energy Deposition

The above greenhouse calculations have been performed assuming that all the solar energy deposition takes place at the surface. It is quite legitimate to inquire whether these results will significantly be modified if one allows for large amounts of solar energy deposition within the atmosphere, because of absorption by both the near infrared vibration bands of methane and those of the cloud aerosols. A somewhat analogous situation exists for Venus, where a bright cloud layer in the upper troposphere absorbs some of the incident sunlight and the atmosphere absorbs a significant fraction of the sunlight penetrating beneath the clouds. Yet the recent Venera-8 Probe has shown that some sunlight does reach the surface and is probably responsible for the high surface temperature in the sense of a classical greenhouse effect. This situation is also consistent with greenhouse calculations I have performed for Venus, which indicate that even large amounts of solar energy absorption within the atmosphere do not significantly change the greenhouse effect. We conclude that if Titan has a massive enough atmosphere (say, a surface pressure greater than 0.1 atm), it will have a significant greenhouse effect.

Atmospheric Dynamics

Scaling the equations of motion, Leovy and Pollack (1973) have made a first estimate of the atmospheric dynamics of Titan. They considered both baroclinic and axially symmetric general circulation models and concluded that the latter was much more probable. Titan's circulation may represent an important intermediate case between the baroclinic circulation typical of mid-latitude regions on the Earth and Mars on the one hand and the symmetric circulation of Venus on the other hand. Titan is rotating slowly enough to have a symmetric circulation. Yet in contrast to Venus, which rotates much slower, coriolis effects are probably quite important for Titan. Conceivably by studying Titan's circulation, as might be possible with a multiprobe, second generation mission to Titan, we might obtain important insights into the circulation of the Earth's equatorial regions.

A second important aspect of Leovy and Pollack's study is their estimates of horizontal temperature gradients within Titan's atmosphere and along its surface. Let us first consider the atmosphere. The diurnal variation is severely restricted by simple considerations of thermal inertia. Assuming that the atmosphere is optically thick at all thermal wavelengths, that the surface pressure is 1/3 of a bar, and that the period of rotation equals the orbital period, they find a diurnal temperature amplitude of 0.03°K. To first order this result will scale inversely as the surface pressure and so will remain quite small, even for the smallest surface pressure considered likely ($\sim 2 \times 10^{-2}$ atm). Equator to pole temperature variations are limited by the atmospheric meridional circulation. For the same conditions given above, Leovy and Pollack estimate a latitudinal temperature variation on the order of 0.1°K. This variation scales approximately as the surface pressure to the (-5/3) power. As a result, this variation could be important at the lowest possible values of surface pressure ($\sim$10 mb).

We next turn to Leovy and Pollack's estimates of surface temperature variations. In the case of a strong greenhouse effect, the atmospheric radiation will severely restrict these temperature variations. For example, with a mean surface temperature of 150°K, the surface temperature amplitude is less than 15°K. In the case of Danielson's model, radiation from the atmosphere also serves to prevent extremely large temperature variations. However, the atmosphere, which in this model radiates effectively only on the Wien tail of the blackbody function, may be less effective near the poles than near the equator as a result of the meridional cooling discussed above. Danielson assumed that there was no meridional cooling.

It is not clear that Danielson's model is entirely consistent, even within the context of his calculations. According to this model, the amount of methane in the atmosphere is controlled by the temperature of the summer pole, which he finds to be 80°K. The corresponding abundance of methane is 2 km-A. However, as discussed above, the observed abundance of 2 km-A may be significantly less than the total atmospheric content of methane, since most of the line formation takes place near a discrete cloud layer. Furthermore, Danielson assumes the dominant methane surface ice is pure methane, while Lewis suggests that methane clathrate is more likely. The vapor pressure curve of methane clathrate is orders of magnitude below that of solid methane. Danielson's model would be inconsistent with a surface containing methane clathrate.

Conclusions

Titan has a warm upper atmosphere. Whether it has a warm lower atmosphere and hot surface is an open question at present, which future radio and infrared observations from the ground and from aircraft can help answer. This question is important not only from a purely scientific point of view, but also for assessing the viability of a Titan Entry Probe. As current entry probes would begin to make measurements at about the 7 mb level, the value of Titan's surface pressure or at least a lower bound is of extreme importance.

Sagan: The ammonia curve in Figure 2-28 is far below an observed broad-band point. Is this consistent with your suggestion of ammonia in the lower atmosphere?

Pollack: The new narrow-band points are far below this broad-band point. This perhaps indicates the presence of another emission line, as suggested by Danielson and Caldwell.

Veverka: From the measured infrared spectra, can you exclude the presence of large amounts of helium?

Pollack: Unfortunately, no.

Danielson: Your greenhouse models require large amounts of methane, on the order of 40 km-A. With such gas amounts, there will be a significant amount of Rayleigh scattering at short wavelengths and a lot of absorption at longer wavelengths by gaseous methane. In this sense, is your model consistent, that is, will enough sunlight reach the surface to cause a greenhouse effect?

Pollack: As I discussed above, it is even more difficult to have a greenhouse work in the case of Venus. Yet, the Venera-8 results imply that it is operative for Venus. A greenhouse can work as long as a minimal amount of sunlight reaches the surface. The most serious constraint on a greenhouse of Titan is the requirement that the atmosphere is massive enough, that is, that the surface pressure exceeds 0.1 atm.

Danielson: The situation for Titan may be even worse than for Venus in view of the low albedo of the clouds.

Pollack: Not really. If the clouds have a low albedo because they have an optical depth not much above unity, then more light will be transmitted through the clouds on Titan. Furthermore, the surface pressures I consider for Titan are orders of magnitude lower than for Venus. When Boese finishes his important laboratory study of methane at low temperatures, I hope to construct some greenhouse models for Titan that allow for solar energy deposition in the atmosphere.

Veverka: In performing the circulation calculations, you made two assumptions that are reasonable, but we are not sure they are true. One is that Titan has a synchronous rotation period and the other is that its rotation pole lies perpendicular to the orbital plane.

Pollack: I would be very surprised if Titan did not have a synchronous period, since we know that other less massive satellites of Saturn do.

Hunten: Also, the Lewis models of the interior of Titan imply that it is highly dissipative.

Danielson: In the case of a transparent atmosphere, can frictional heating by winds at the surface boundary help equalize the surface temperatures?

Pollack: Based on my experience with Mars, I am very skeptical that this would be important. I believe the key factor is radiative exchange between the atmosphere and surface, which is important for your model as well as the greenhouse model.

Trafton: If there is a high altitude cloud, then its bottom would have to be located in a zone of changing temperature.

Pollack: As you mentioned in your talk, your observations appear to imply a discrete cloud layer. My methane cloud would fit that requirement, and it is located in a region where the temperature is still noticeably decreasing in my model atmospheres. I might mention that it is not at all clear how one would get such a discrete cloud within the context of Danielson's model.

Hunten: Sagan's photochemically produced aerosols will eventually collect as a deposit of brown polymer on the surface. It might be as much as a few kilometers deep. This layer could prevent contact between gaseous methane in the atmosphere and solid methane clathrate and hence vitiate some of the above vapor pressure arguments.