2.8 AN INVERSION IN THE ATMOSPHERE OF TITAN*

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Introduction

Measurements of unexpectedly high infrared brightness temperatures on Titan in the 8-14 micron window (Low 1965, Allen and Murdock 1971, Gillett, Forrest, and Merrill 1973) and a lower temperature in the 20-micron window (Morrison, Cruikshank, and Murphy 1972) have been widely interpreted in terms of greenhouse models (Pollack 1973, Sagan 1973) where the 8-14 micron radiation originates at or near the surface while the 20-micron flux is emitted high in the atmosphere. A very detailed greenhouse model due to Pollack (1973) derives a methane (CH_4) to hydrogen (H_2) ratio of unity (within a factor of 3) and a minimum surface pressure of 0.4 atm. Based on a surface gravity g = 140 cm sec^{-2}, the minimum CH_4 abundance is 30-40 km-A and the minimum H_2 abundance varies from 15 to 85 km-A.

It is the purpose of this paper to propose an alternate model of the atmosphere of Titan which seems to be consistent with observations and requires a much smaller CH_4 abundance (of the order of 2 km-atm). Although no H_2 is required, the presence of some H_2 as reported by Trafton (1972a) is readily accommodated. In this model, a temperature inversion exists in the atmosphere due to absorption of blue and ultraviolet solar radiation by small particles. The absorbed radiation is re-radiated by the dust and by molecules having long wavelength bands such as CH_4 at 7.7 μm and ethane (C_2H_6) at 12.2 μm. The brightness temperature at 20 μm is primarily due to re-radiation by the dust.

The Origin of the Inversion

The continuum geometric albedo of Titan, shown in Figure 2-32, is unusually low in the blue and ultraviolet for an object with an extensive atmosphere. The presence of a large abundance of CH_4 (of the order of 2 km-A) is strongly indicated by the observations of Trafton (1973) which show near-infrared bands of CH_4 having widths comparable with those in Uranus. The observed geometric albedo $p = 0.05 \pm 0.02$ at 2600 Å (Caldwell 1973) can be produced by the Rayleigh scattering of about 0.15 km-A CH_4 overlying a black surface. Under the same conditions, 1 km-A CH_4 will produce p = 0.22 and 10 km-A will yield p = 0.60. One must therefore conclude that some substance is strongly absorbing in the blue and ultraviolet. We propose that this absorption is due to small particles (hereafter called dust) produced as a result of photolysis in the uppermost portions of the atmosphere. A dark reddish-brown polymer with properties qualitatively similar to those required of the dust has been produced in the laboratory by Khare and Sagan (1973).

If these dust particles were very large, they would radiate like black bodies with emissivity, $\varepsilon \approx 1$, and their temperature would approach 90°K, the black sphere temperature at the distance of Titan from the Sun. On the other

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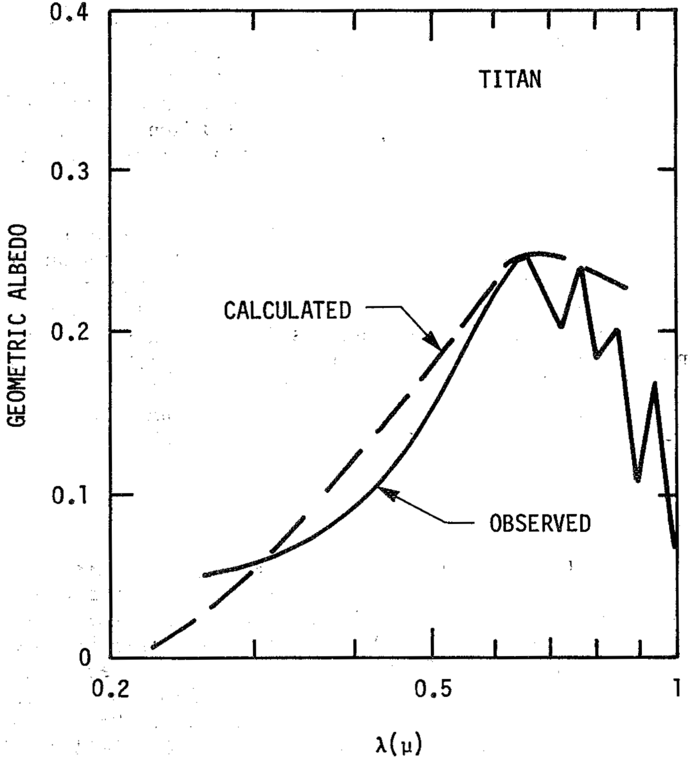

Figure 2-32. The observed geometric albedo is based on the observations of McCord, Johnson, and Elias (1971) normalized to p = 0.20 at λ = 0.555 μm and on the OAO observations of Caldwell (1973). The calculated curve is from the simplified model in Section 4.

hand, if the particles are small compared with the wavelengths characteristic of a 90°K Planck spectrum, they will be poor emitters and will rise to temperatures higher than 90°K. The gaseous atmosphere will be heated to nearly the same temperature as the dust due to collisions of gas molecules with the dust particles. The final temperature will be determined by the emissivity of the dust and the available molecular bands. Methane has no allowed bands longward of 7.7 μm and hydrogen, which has no allowed dipole bands, has negligible opacity due to collision induced transitions at the atmospheric pressures characteristic of our model (of the order of 0.01 atmosphere). Among likely additional constituents, the longest allowed bands are 10.5 μm (ethylene, C_2H_4), 12.2 μm (ethane, C_2H_6) and 13.7 μm (acetylene, C_2H_2). No plausible molecule has any appreciable emission longward of 15 μm. If such a molecule were present, no large inversion could be sustained.

The Emission of the Titan Atmosphere

To estimate the emission of the Titan atmosphere, we assume (for simplicity) it is isothermal except in the boundary layer near to the surface. Some justification for this assumption is given in Section 6. We fix the atmospheric temperature at 160°K by noting that the brightness temperature measured by Gillett, Forrest, and Merrill (1973) at 8.0 μm, which is near the center of the very strong CH_4 band at 7.7 μm, is nearly 160°K. (See Figure 2-33.)

The emission of the dust is calculated to be that of an optically thin medium radiating at 160°K. The emissivity of the atmosphere is assumed to vary as λ^{-1}, which would be characteristic of particles which are small compared with the wavelength and which are composed of a substance whose complex index of refraction is independent of wavelength. The curve of dust emission shown in Figures 2-33 and 2-34 is calculated by adjusting the emissivity to agree with observations at 9 and 10 μm.

We propose that the large peak near 12 μm is due to the 12.2-micron band of C_2H_6. Based on a band strength of 24 cm^{-1}/cm-A (Thorndike 1947), we estimate that the amount of C_2H_6 required to produce a mean emissivity of $\sim$0.1 at the 12.2-micron peak is of the order of 1 cm-A. The width of the 12-micron feature as shown in Figure 2-34 was taken to be the same as a similar feature at 12 μm observed in Saturn (Gillett 1973, private communication). Laboratory measurements and detailed calculations on the 12.2-micron C_2H_6 band will be required to establish its width under the conditions in the Titan atmosphere.

The Energy Balance of Titan's Atmosphere

The energy balance of this model of Titan will be illustrated by an idealized calculation in which Rayleigh scattering is ignored for simplicity. Adopting a radius of 2550 km, as did Morrison, Cruikshank, and Murphy (1972) based on a correction to the measurements of Dollfus (1970), the visual geometric albedo (p) equals 0.20 if the visual magnitude of Titan at mean opposition is taken to be 8.39 (Harris 1961) and if the absolute visual magnitude of the Sun equals -26.78 (Allen 1963). Using the observations of spectral reflectivity given by McCord, Johnson, and Elias (1971), one obtains the curve of observed geometric albedo shown in Figure 2-32. The maximum geometric albedo ($p \approx 0.25$) occurs at $\lambda \approx 0.65$ μm, or approximately the same wavelength as the minimum absorption of the brown polymer (dust) shown in Figure 2-35.

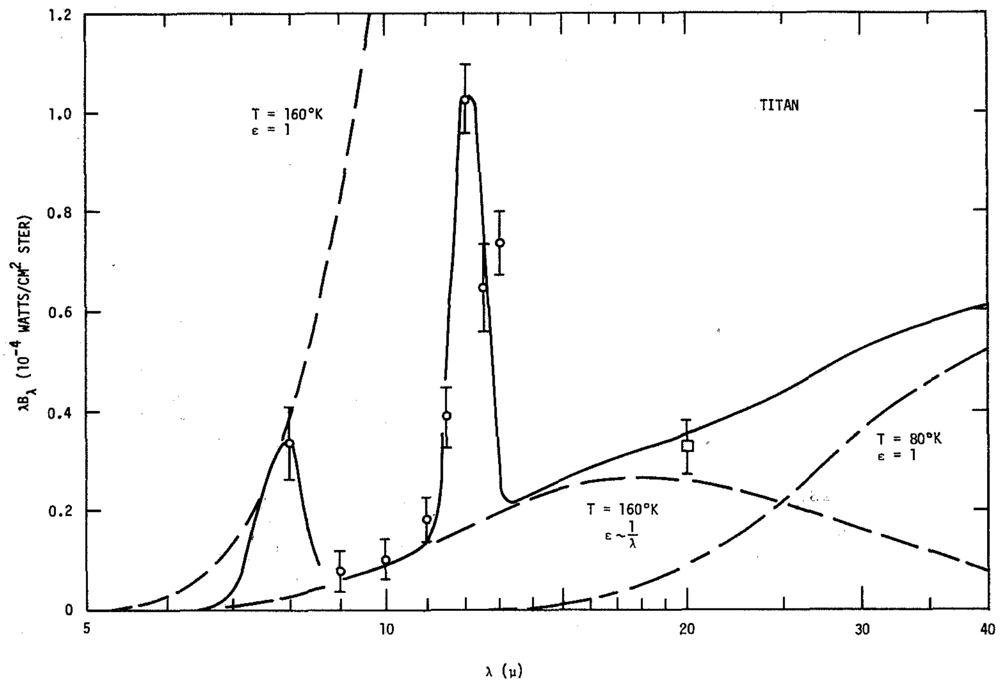

Figure 2-33. The solid curve shows the predicted emission spectrum based on a highly simplified inversion model of Titan. The peaks at 7.7 μm and 12.2 μm are due to emission by CH_4 and C_2H_6 bands. The emission by the dust is shown as a 160°K black body having an emissivity which is inversely proportional to the wavelength. The radiation from the surface is shown as an 80°K black body. This graph is constructed in such a way that the area under the curves is proportional to the energy radiated. In both this figure and in Figure 2-34, the filled circles are data by Gillett et al. (1973), and the filled square is a measurement by Morrison et al. (1972).

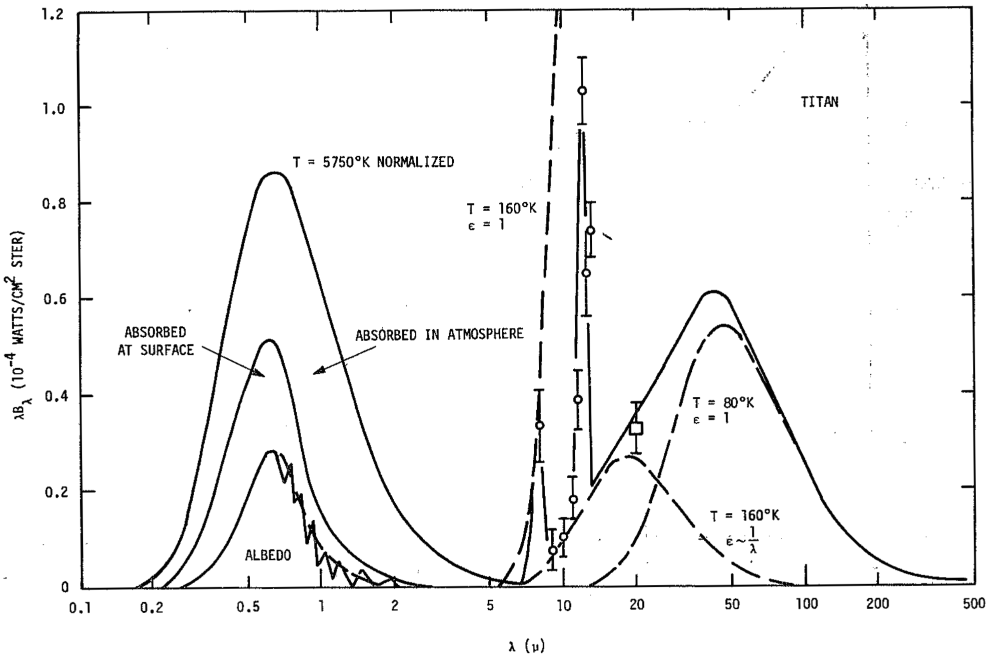

Figure 2-34. The energy balance of the inversion model of Titan is illustrated in this figure where area is proportional to energy. The area under the curve representing the incident solar radiation (T = 5750°K) is equal to the area under a 90°K black body curve. Most of the solar radiation is absorbed by the dust in the atmosphere and re-radiated in the far infrared.

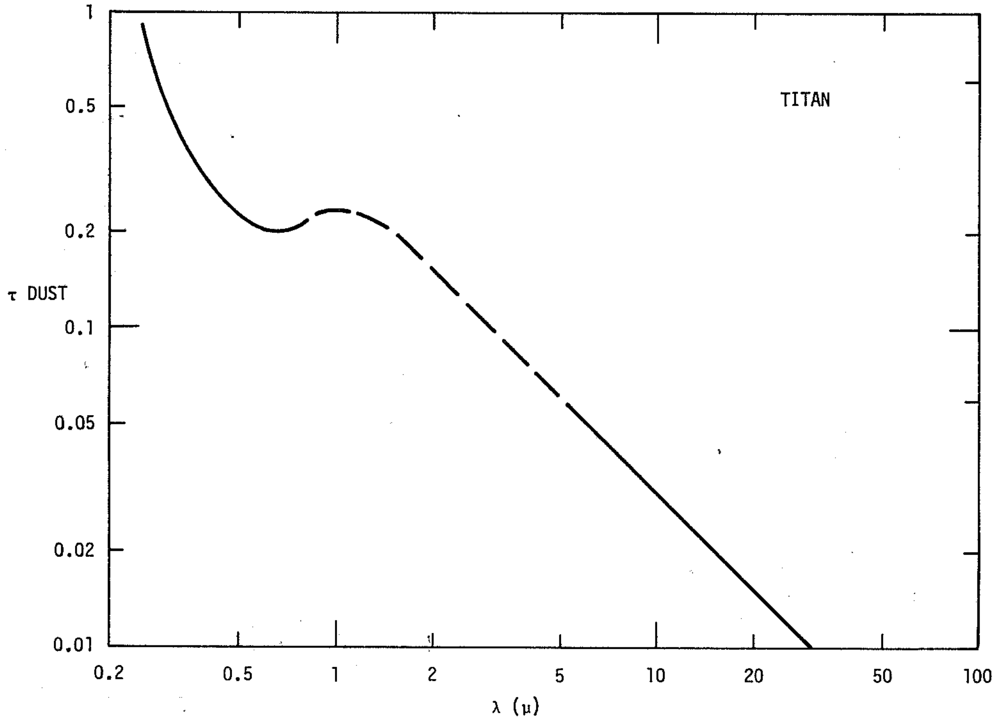

Figure 2-35. The optical thickness of the dust suspended in the Titan atmosphere. The solid curve shortward of 0.8 μm is based on the measurements of Khare and Sagan (1973) normalized to agree with the observed geometric albedo. The curve longward of 5 μm is based on an assumed λ^{-1} dependence normalized to agree with the observed flux at 9 and 10 μm.

In order to have a definite exploratory model, the surface albedo of Titan is taken to be proportional to wavelength up to $\lambda = 0.65$ µm, above which it is assumed to be 0.65. The rationale behind this arbitrary choice of surface albedo comes from the working hypothesis that the surface of Titan is covered by snow whose reflectivity is governed by the dust which has settled out of the atmosphere.

The geometric albedo, p, and Bond albedo, A, of a purely absorbing atmosphere (obeying Beer's law) which has an optical depth, τ, overlying a Lambert surface having a reflectivity R can be shown to be:

$$p = \frac{2}{3} Re^{-2\tau} [1 - \tau + 2\tau^2 - 4\tau^3 e^{2\tau} E(2\tau)], \qquad (1)$$

and

$$A = Re^{-2\tau} [1 - \tau + \tau^2 e^{\tau} E(\tau)]^2, \qquad (2)$$

where:

$$E(y) = \int_y^\infty \frac{e^{-x}}{x} dx. \qquad (3)$$

From Equation 2, $p = 0.25$ yields $\tau = 0.20$ which establishes the normalization of the visible and ultraviolet portions of the curve of τ_D, the optical depth of the dust in the atmosphere, shown in Figure 2-35. Figure 2-35 is based on the measurements of the transmission of a thin layer (thickness of the order of 0.03 mm) of brown polymer by Khare and Sagan (1973). It can be shown that the optical depth of a layer containing particles (small compared with the wavelength) is approximately equal to that of a slab having the same mass per unit area if $k << 1$, where k is the imaginary part of the index of refraction. This condition is satisfied for the brown polymer, for which k is the order of 3×10^{-3}.

The adopted variations of τ_D and R lead to the calculated curve of p shown in Figure 2-32. For the purposes of this paper, the predicted geometric albedo is in satisfactory agreement with that observed shortward of 0.65 µm. The Bond albedo shown in Figure 2-34 is based on the crude assumption that Beer's law holds for the CH_4 absorption longward of 0.65 µm. The albedo for the incident solar radiation is 16%; the corresponding black sphere temperature is 86°K.

Under the same assumptions governing equations 1-3, the fraction of the intercepted solar radiation which is absorbed at the surface is given by:

$$f_s = (1 - R)e^{-\tau} [1 - \tau + \tau^2 e^{\tau} E(\tau)] \qquad (4)$$

Based on Equation 4, 23% of the solar radiation is absorbed at the surface. The remaining 61% is absorbed in the atmosphere. Since the atmosphere is optically thin in the far infrared (except near 7.7 µm), approximately half of the absorbed radiation is reemitted downward and is absorbed by the surface. This absorbed radiation would, by itself, keep the surface at a temperature of 67°K.

Absorbed radiation: $1.13 \times 10^{-4} \frac{\text{watts}}{\text{cm}^2}$

From Figure 2-34, the radiation emitted (upward) by the atmosphere equals 1.38×10^{-4} watts/cm^2 which is 22% larger than half of the radiation absorbed in the atmosphere. In a fully self-consistent model, these numbers would be equal. (They would be equal if the far infrared emissivity of the dust decreased a little faster than λ^{-1}, for example.) The important conclusion to be drawn from the above discussion is that the solar radiation absorbed by the dust is sufficient to maintain a large inversion (temperature approximately 160°K) in the entire atmosphere of Titan.

From the emitted flux and the heat capacity of the atmosphere, one may compute its rate of cooling when it is not illuminated by the Sun. The result is about 0.1°K/day if the atmosphere contains 2 km-A of CH_4. Thus the change in atmospheric temperature is insignificant during Titan's solar day (16 days if its rotation is synchronous with its orbital period). Furthermore, the cooling rate is sufficiently slow to allow the atmospheric temperature over the winter pole to be maintained near 160°K (except near the surface) by lateral transport (winds).

The Surface Temperature of Titan

If the atmospheric radiation were the only source of heating the winter poles (which are inclined 27° if the axis of Titan is parallel to the axis of Saturn), the surface temperature would only be 67°K. The vapor pressure of solid methane at this temperature is about 10^{-3} atm corresponding to a methane abundance of about 0.1 km-A. This abundance is too small to explain the width of the Titan methane bands observed by Trafton (1973). If the minimum surface temperature is 80°K, the corresponding CH_4 abundance is 2 km-A and the C_2H_6 abundance is of the order of 5 cm-A. Extending the calculations in Section 4, we find that the surface temperature at the sub-solar point would rise to nearly 100°K assuming the surface has negligible thermal inertia. Under the same assumptions, Figure 2-36 shows the variation in surface temperature on the illuminated portion of the surface.

Undoubtedly some heating of the unilluminated portion occurs as a result of surface winds driven by surface temperature differences. In our model, however, the main source of heating (in addition to the atmospheric radiation) is by means of the latent heat released as a result of the condensation of solid methane. We propose that the winter polar regions are kept near 80°K as a result of the condensation of CH_4 gas. Reduction of the albedo of the polar caps by the dust which has settled out is the vital factor which enables the condensed snows to be resublimed in the polar summer. In the absence of the dust, the summer pole would be much too cold.

During the 30-year long Titan year, the surface pressure may vary somewhat with time because the sublimation and condensation would not always be equal. We can estimate the magnitude of this variation by computing the decrease in CH_4 abundance required to keep a polar cap (down to a latitude of 63°) at a temperature of 80°K for 15 years. The result is 0.08 km-A of CH_4 which is small compared with the abundance of 2 km-A adopted in our exploratory model.

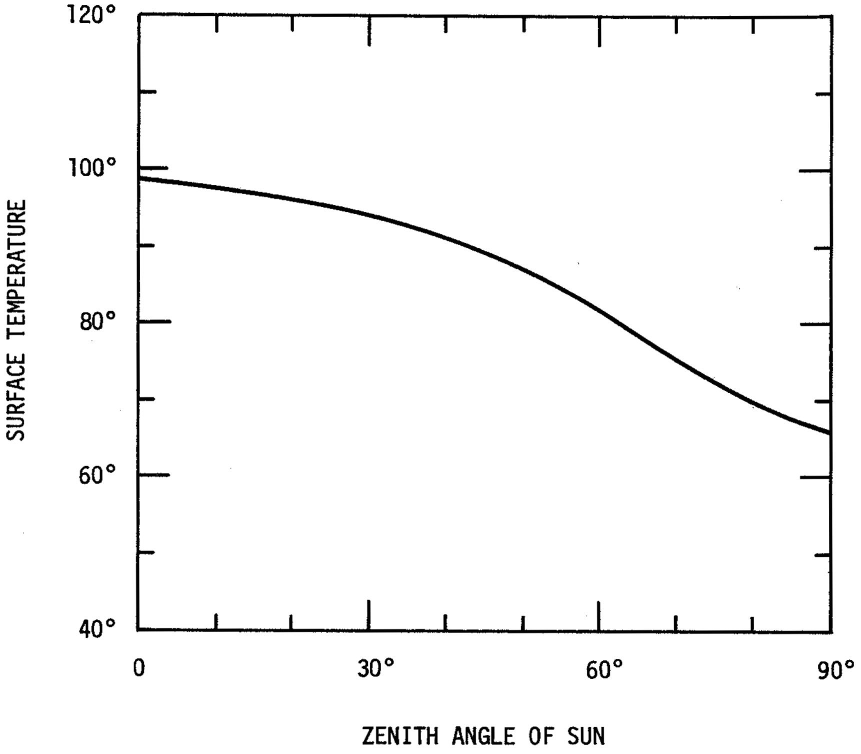

Figure 2-36. The surface temperature of Titan predicted by ignoring the thermal inertia of the surface, the energy transfer by surface winds, and the latent heat of CH_4. Inclusion of the latent heat is expected to make the surface temperature more uniform than shown.

Similarly, methane condensation will supply heat to the equatorial regions at night and sublimation will occur during the daytime. Much, if not all, of the surface of Titan should be covered with frozen CH_4 and other ices. If this be the case, the surface temperature will be more uniform than indicated in Figure 2-36 due to the thermostatic effect of the solid CH_4. In Figures 2-33 and 2-34, the predicted radiation from the surface is indicated as an 80°K black body.

Summary Discussions of the Model

With the aim of introducing the basic ideas as clearly as possible, the inversion model of Titan presented in this paper is highly simplified, thereby avoiding prematurely complex calculations. If the model continues to be viable after further scrutiny, many of its features should be studied in more realistic detail.

A more detailed analysis must include the effects of Rayleigh scattering. We have made some calculations including scattering which indicate that the visible and ultraviolet optical depth of the dust must increase more rapidly than shown in Figure 2-35 in order to explain the observed geometric albedo. Macy (1973) finds the same to be true for Saturn. It therefore seems that the dust produced in planetary atmospheres exhibits a more rapid increase in absorption toward the ultraviolet than does the substance produced by Khare and Sagan (1973). Further laboratory investigations in which mixtures of only CH_4 and H_2 are irradiated with hard ultraviolet photons may be required. The full index of refraction (real and imaginary parts) of the substances produced should be measured.

We believe that detailed knowledge of the properties of the dust will be important in understanding other planets as well as Titan. Both Jupiter and Saturn exhibit absorption features which begin in the red and increase toward the blue. Preliminary attempts to explain these features in terms of absorption by dust particles similar to those postulated for Titan have been made for Jupiter (Axel 1972) and for Saturn (Macy 1973). Uranus may also have some absorbing particles in its atmosphere (Light and Danielson 1973). Hence the major planets should have substantial inversions in the upper portions of their atmospheres where the density is $\approx 10^{18}$ cm^{-3} or less. Such an inversion has been observed on Jupiter (Gillett, Low, and Stein 1969, Gillett and Westphal 1973). Indeed, if Titan should have a massive atmosphere of the type proposed by Pollack (1973), an inversion would occur in the upper portion of its atmosphere.

We are of the opinion that the dust particles are composed mainly of higher hydrocarbons from the by-products of the photolysis of CH_4 by solar ultraviolet photons having wavelengths shorter than 1600 Å. Strobel (1973, see also Strobel and Smith 1973) has performed detailed studies of the photochemistry of hydrocarbons in the Jovian atmosphere. He finds that approximately 20% of the dissociated methane is irreversibly converted to higher hydrocarbons. If a similar percentage is valid for Titan, of the order of 10 km-A of CH_4 should have been converted over the lifetime of the satellite. Strobel's (1973) calculations suggest that C_2H_6 may be the main substance formed. In our inversion model, almost all of the C_2H_6 will freeze out on the surface leaving only a few cm-A of gaseous C_2H_6 in the atmosphere.

Our most recent attempt to model the emission peak at 12.2 μm is shown in Figure 2-37. Using the formulae for a symmetric top molecule given by Herzberg (1950) and random band transmission formulae from Goody (1964), the disk-integrated thermal emission from an isothermal (160°K) atmosphere of 2 km-atm of CH_4 and 0.5 cm-atm C_2H_6 has been calculated. Also shown are some of the data of Gillett et al. (1973). The agreement is fair near the center of the band, but breaks down away from the center. This may indicate that the molecular model used is not correct, or there may be additional trace materials present. The discrepancy between the 0.5 cm-atm of C_2H_6 in this calculation, and the 5.0 cm-atm quoted earlier, could result from the uncertain extrapolation of measured vapor pressure data points to low temperature, or perhaps partly from the Titan inversion not extending down to the surface.

Based on a surface temperature of 80°K, the corresponding abundance for C_2H_2 is $\sim 10^{-2}$ cm-A and ~ 40 cm-A for C_2H_4. The latter abundance is sufficiently large that the atmosphere should be optically thick at 10.5 μm (the band strength is about 500 cm^{-1}/cm-A) yielding a brightness temperature of about 160°K. Although no narrow-band measurement has been made at 10.5 μm, the measured flux from 10-12 μm is consistent with a substantial emission peak at 10.5 μm (Gillett, Forrest, and Merrill 1973). In addition, the observed brightness temperature at 13 μm suggests the possibility of some atmospheric emission at 13.7 μm due to C_2H_2. These two possible emission peaks were not included in our exploratory model.

A more detailed analysis of this model should also include a calculation of the vertical temperature distribution. Since the grains reradiate most of the radiation they absorb, the atmospheric temperature is mainly determined by the solar radiation at each elevation above the surface. The decrease of incident solar radiation with depth in the atmosphere is somewhat compensated by the increased amount of outgoing solar radiation (reflected by the surface) in the lower atmosphere. Hence the assumption of an isothermal atmosphere may not be too unrealistic.

Acknowledgement

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Morrison: I would like to raise a question that perhaps several people would want to address. A number of you talk about models in which all, or a significant fraction, of the radiation has to reach the surface. You've said this about the poles and Pollack's models, as I recall, assume that all radiation is deposited at the surface. But Veverka has talked about optically thick clouds. I wonder what both of those things mean. In an optically thick cloud, what fraction of the total radiation can get through to the surface? When you say you assume that large fractions, or all, of the radiation reaches the surface, what really do you mean are the limitations?

Danielson: Well, we had a luncheon discussion on that very subject, and if I may, let me summarize it for you. What Veverka says is that a dense cloud is needed. An alternate version of that would be a snow field with the absorbing dust in the atmosphere. Veverka agrees that a snow field will give him the

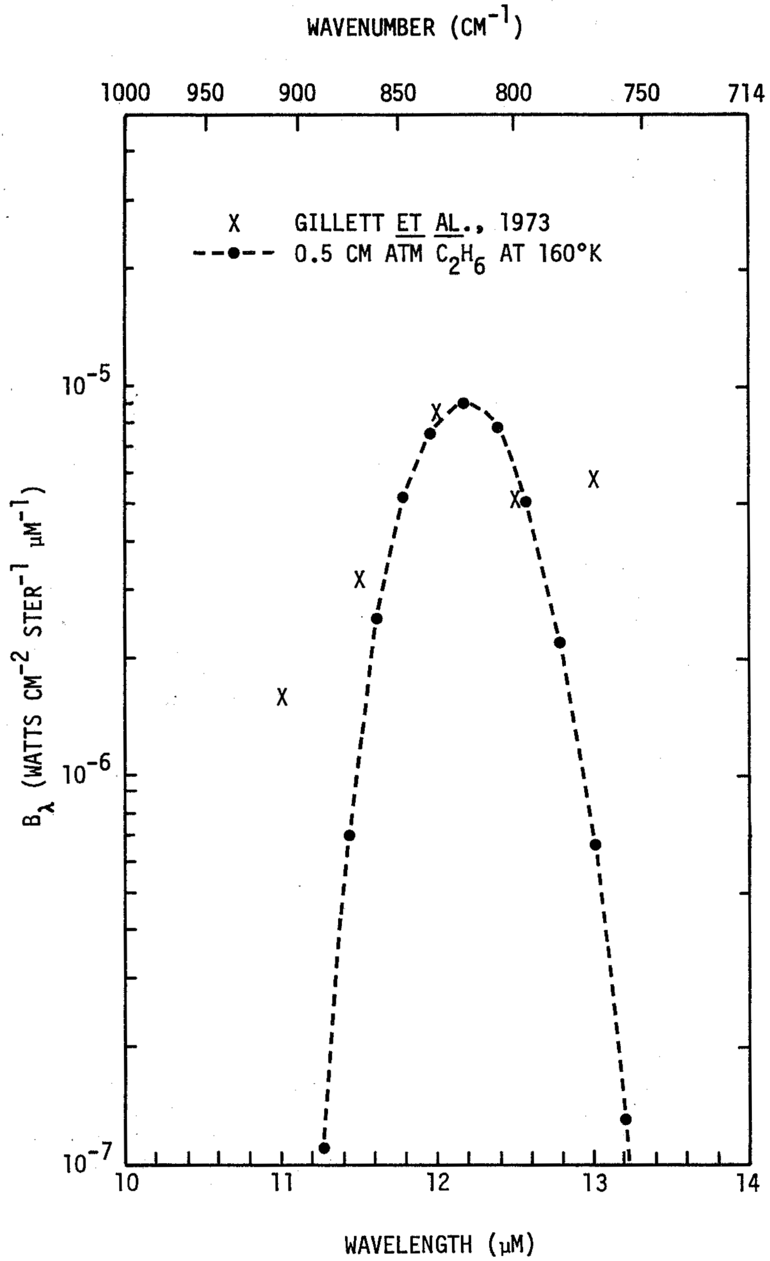

Figure 2-37. The thermal emission from an atmospheric inversion consisting of a 160°K atmosphere (2 km-atm CH_4, 0.5 cm-atm C_2H_6) above an 80°K surface. The emission is averaged over a hemisphere.

variations of polarization with phase that he needs, but it has to be bright, and we know that Titan is not bright. However, if we put in these nonscattering particles which are purely absorbing, it is like putting a neutral density filter in front of the snow. Then it might have the same polarimetric properties for all we know at the moment; isn't that right, Joe (Veverka)?

Veverka: In principle, yes. It is certainly true that, out of hand, one cannot reject your model on the basis of the phase coefficients or the polarization measurements. What has to be done, of course, is to perform the calculations and see if that kind of model fits. But, I would also like to address the question of getting energy through clouds to the surface. This is the problem with Venus, right? You have optically thick clouds and you have no problem getting energy to the surface, or at least quite deep anyway.

Danielson: Well, Venus' clouds are optically thick but the albedo is high, so you have τ^{-1} reaching the surface in conservative isotropic scattering.

Morrison: Could Pollack or Sagan make an elucidating comment as to how this affects their models? I'm not sure I understood what was just said about Venus.

Pollack: Well, let me explain the Venus story in a somewhat different way. That is, that a greenhouse model, in order to work, really doesn't need very much solar energy reaching the surface. It needs some nonzero amount to reach the surface, but that nonzero amount, as in the case of Venus, could be very small. Now, in the case of Titan, I think the real question is how optically thick are the clouds. To satisfy observational measurements, like the polarization, I'm sure doesn't require huge optical thickness as the lower bounds. To just throw a number out, I would rather suspect that optical depths on the order of unity would satisfy all the observational constraints, like the polarization. Certainly under those conditions a significant amount of radiation will reach the surface. Now, obviously if it's a lot higher it's a whole new ball game.

Danielson: I would like to emphasize that, in our model, the atmosphere has no clouds, and I am worried about Trafton's contention that you must have clouds to fill in these methane bands. Frankly I don't see how clouds in the upper portion of the atmosphere can form in the presence of our proposed inversion. An action item I am going to take for myself is to try and see if there isn't some way to get around Trafton's argument on the clouds. It is the most difficult one that I am aware of, at the moment, for this atmosphere which has no clouds unless you want to call the dust a cloud. Veverka's cloud is a snow covered surface, but there's no way that that would satisfy Trafton.

Trafton: But my cloud need not be at the same altitude as your inversion. What do you mean by high? You mean optical depth unity in your emission bands, don't you? What do I mean by high? I mean a level above which the methane absorption is negligible compared to the observed methane absorption.

Pollack: I think we're really dealing with methane bands of very different strengths. For example, the 8 μm observation refers to the fundamental of methane where optical depth unity is something like 10^{-3} atm. In the case of Trafton's observations, they are overtone or combination bands that are a lot weaker. So presumably his clouds could be a lot higher and at a pressure level a lot higher than 10^{-3} atm. I think you have to be careful as to where different things are in the atmosphere.

Morrison: Is this also true of the polarization measurement? Could Trafton's clouds be the clouds that one sees photometrically and polarimetrically and all of this exist below your dust layer?

Veverka: Sure. I think I can reverse your argument, Bob (Danielson). I was probably very generous in saying that my observations can be consistent with what you're saying. But I don't see why I can't turn it around. You keep talking about your Lambert surface. Why can't it be a white cloud?

Danielson: Yes, that's quite true. If you wanted a greenhouse model in addition to the inversion, you could replace the snow-covered surface with a cloud. I don't think the cloud would be white though, because of the dust which must be there acting as nucleating particles for it.

Trafton: What about the emissivity of this dust? It seems as if your whole model is predicated on this emissivity being so low that the temperature of the dust is disproportionately high, and this in turn results in the mechanism for your model of a temperature inversion. Basically, it's the non-unit emissivity of the dust which allows you to construct your model. What is the observational evidence that dust particles, small compared to the wavelength of light, are higher in temperature than their surroundings?

Danielson: There is no observational evidence. It is purely a theoretical argument but I think it is a pretty strong one. Think of the particle as an antenna. Just try to radiate at one meter with such a small antenna and you find that it's a very inefficient antenna. That's the origin of this λ^{-1} dependence for small particles.

Trafton: You mentioned this is observed in interstellar dust?

Danielson: Yes, isn't it true that the interstellar dust, if it were simply in equilibrium with starlight and such, it would be 3°K, whereas typical temperatures are believed to be around 100°K.

Trafton: Well, contrary to the situation with the interstellar medium, in Titan's atmosphere the dust particles are going to be colliding with a lot of methane molecules and stuff like that. How do you know that the collisional interactions here won't be enough to cool down the dust?

Danielson: The dust and the molecules go to the same temperature. The molecules have limited ability to radiate it away since they can only radiate in the 12-micron and 7.7-micron bands. If you could invent another molecule that was a good strong radiator at 30 μm, then the dust would cool down and there would be no inversion. But as long as you don't have any emissions longward of 15 μm, I believe my argument is correct, as long as the particles are small. That is, small compared to the 40-micron wavelengths, so 1 μm or half a micron particles would be quite adequate for that.

Sagan: In other words, things that radiate at 30 μm, which is the pure rotation spectrum, like CH_4 and H_2, aren't awfully good for that, but what about any molecule that's not symmetric?

Danielson: Well, name one. That's the problem.

Sagan: Asphalt.

Danielson: That becomes a solid, forming my little particles. The vapor pressure very quickly eliminates almost all molecules. That's the trouble we found at first when we were trying to fill up this 8-14 micron region with emitters. Everything solidifies very quickly, and ethane and ethylene are really the only two effective constituents I'm aware of. Caldwell's question on silane was motivated by this as a substance whose vapor pressure is substantial. We wondered if that might play a role because it has an emission somewhere in this region of 9-12 μm. However, unless we can short-circuit some of Lewis' comments, it's also hard to get.

Trafton: There's one other point about the dust I'm concerned about. You might expect the dust to have a distribution rather than coming out something like all the same size, and, therefore, a certain fraction would be larger than the average. Since a lot more flux from the exponential side of the emission function occurs at longer wavelengths, maybe this could compensate, or more than compensate, to the point where you could have significant long wavelength radiation from the particles.

Danielson: Well, you've got to have something like a 15 μm diameter particle, and that's going to drop out of the atmosphere awfully quick.

Sagan: Let me just say a word on that. We have measured the particle sizes of our polymers that you are using here. Now I'm sure that the particle sizes are dependent on some conditions which may not be the same as on Titan, but, to whatever extent you want to use our models, the average particle size is 100 μm.

Danielson: They won't stay in the atmosphere. They'll go plop.

Sagan: They will go plop, but there will be others that'll be made. The question is: might the cloud be a steady-state concentration between (1) formation, (2) growth to 100 μm, and (3) Stokes-Cunningham fallout? The answer to that might be yes. If the answer is yes, and you have particles much larger than the infrared emission wavelengths, then, is it true that you are in trouble trying to stay hotter than the equilibrium temperature?

Danielson: I think so. That would do the trick.

Hunten: How many solar constants of UV do you have in your experiments, Carl (Sagan)? Grossly, you'd expect the growth rate of the particles to be proportional to the UV flux, other things being equal.

Sagan: But surely, the particle size depends on the fall-out rate as well as the UV flux.

Hunten: Yes, radiation, the flux, the time, the rate of fallout; and obviously fallout is a lot slower on Titan than in your flask. It seems to me very difficult to estimate particle sizes in Titan's atmosphere on the basis of these lab experiments.

Sagan: Yes, I agree.

Veverka: Do you have a feeling, Bob (Danielson), for how dependent your conclusions are on this λ^{-1} dependence. For example, if the dependence is $\lambda^{-1.5}$ does everything fall apart?

Danielson: Well, actually, it would have been more comfortable in this model to have it $\lambda^{-1.2}$, I believe, because then we would have exact balance between the absorbed and emitted radiation. If it turns out that the complex index varies rapidly with wavelength in a way that is very different than that, then at some point the model is no longer viable. How much it is, I don't know.

Sagan: There's one other thing I wanted to ask about. The C_2 molecules are a central part of the Inversion Model story. They have transitions in the near IR and, particularly, in the near UV. So I wonder what observational limits have been set on these. For example, is there some critical UV observation that could be made, say with the International Ultraviolet Explorer, or from Skylab?

Strobel: The problem with ethane is that it's masked by methane. The onset of absorption for ethane is 100 Å longward of the onset of methane absorption; they almost parallel each other. Since methane is so much more abundant than ethane there's no way you're going to unravel one from the other.

Sagan: Okay, so that's ethane. What about ethylene and acetylene?

Strobel: They absorb at longer wavelengths, out to 2000 Å.

Sagan: So you might have a measurement there.

Hunten: As long as the dust doesn't ruin everything.

Strobel: Yes. There the problem is that as you approach 2000 Å, I think the dust is getting toward an optical depth of one, and all of these constituents absorb below 2000 Å.

Sagan: So the dust does mask the UV.

Danielson: The products formed by the radiation you want mask it. I think the best test I've heard yet is the radio interferometry observations that you mentioned, Carl (Sagan), of the surface temperature. I think that's a crucial thing, and another thing to do is to make really detailed calculations in the 8-14 micron region with the models and just see what fits and what doesn't.

Pollack: I think, though, that you have to be very careful here because there are two questions to be considered which are very distinct from one another. One question is: Is there a significant greenhouse so that the surface temperature is high? Almost independent of the answer to that is the question: What's mainly responsible for the radiation in the 8-14 micron region? It may turn out, for example, that in the whole 8-14 micron region you're just seeing gases and radiation from clouds, and yet have a high surface temperature. That's a plausible model. So, I think we have to be very careful here in separating these two questions.

Sagan: That's a good point. So, determining the surface temperature is not a way of deciding this question on the inversion.

Danielson: That's right. I think, then, that the best way to proceed here is to simply get the best measurements and apply the best theories in the 8-14 μm region.

Hunten: Clearly, a detailed Gillett-type spectrum with points every 0.1 μm would be tremendous. That's possible right now.

Pollack: I think in another half year, Gillett will give us absolute information; so I think in another half year we will be a lot further along.

Morrison: Jim (Pollack), is it really true for the greenhouse models, that you could think up a source of opacity through the 10-micron band such that very little radiation would get out and therefore one could explain the whole 10-micron spectrum by the Danielson approach and still have that compatible with a large greenhouse?

Danielson: Ammonia ... wouldn't that do it?

Pollack: Yes. That is, that the dip at 10 μm is perfectly consistent with the saturated atmosphere, i.e., the lower portion of the atmosphere having ammonia. So I don't think there is any problem there. Even if I didn't want to say that, I could just say, well ... I would have to go away from Danielson's small particles ... but I could say the clouds are optically thick. Thick enough, that is, in the 8-13 micron region that that's all we're seeing there.

Sagan: When I get to my presentation tomorrow, I'll show some substances which are quite opaque at this wavelength. So it's perfectly plausible that the clouds might not let the radiation through.

Hunten: Bob (Danielson), this is really an optical model, not a physical model you put together. You have a medium with dust and gas in it. You don't really have an explicit model for Titan's atmosphere, do you?

Danielson: Well, the temperature is basically determined, at least so far, by the amount of flux that falls on a particle at a given level. I think one could go through this and iterate it once more. If you did, I think you would find that it is not all that variable in temperature until you get right near the surface, where boundary temperature questions cloud the issue.