2.3 TITAN'S SPECTRUM AND ATMOSPHERIC COMPOSITION

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Morphology of Titan's Near-Infrared Spectrum

Titan's spectrum is remarkable both for its similarity and its dissimilarity with the spectrum of Saturn. The similarity shows up in the low resolution spectra of the two objects and also at very high resolution where there is a parallel microstructure in the spectral features of both objects. At intermediate resolution, however, there are gross differences in the sense that Titan's bands appear relatively washed out. The center of the strongest bands are filled in and the wings are enhanced in strength. The first three figures illustrate these characteristics.

Figure 2-1 shows the red and near-infrared spectra of Titan, Saturn, and the Rings. The Ring spectrum shows the telluric and solar absorption features. The resolution element is about 17 Å. Titan's 7250 Å methane band is weaker than Saturn's band as is Titan's 6000 Å methane band, but less so. On the other hand, the weak 7000 Å methane band may be stronger in Titan's spectrum. There is also a noticeable widening of Titan's bands compared to Saturn's. This widening is relatively small in this spectral region. Spectra of Titan and Saturn in the 8900 Å methane complex, ratioed to the spectrum of Saturn's Rings to remove solar and telluric features, are shown in Figure 2-2. The center of Titan's 8900 Å band is markedly filled, the 8600 Å band is filled to a lesser degree, but the 8400 Å band actually is stronger in Titan's spectrum than in Saturn's spectrum. This figure also shows the parallel microstructure clearly. Many small-scale features in Titan's spectrum also appear in Saturn's. Figure 2-3 shows the spectra of Titan's and Saturn's one-micron methane complex ratioed to Saturn's Rings. The wavelength range is about 9500 Å to 1.1 micron. Again, there is a partial washing out of Titan's spectrum with respect to Saturn's as well as a parallel microstructure. The long wavelength wing is enhanced in Titan's spectrum more than the wing at shorter wavelength. The $3\nu_3$ methane band is visible on the right.

Figure 2-4 shows a better representation of the 1.1 micron spectrum for Saturn, Titan, and Uranus ratioed to the Rings. The $3\nu_3$ band clearly is absorbing much more strongly in Titan's spectrum than in Saturn's spectrum. The Q branch is visible in each of these spectra as well as the R and P branches. There is a progressive increase of absorption in this sequence. The loss of contrast presumably results from the filling in of the continuum by overlapping lines. The Q branch is shown at higher resolution (6.6 Å) in Figure 2-5. On the left, the whole feature appears with the R(0) manifold for Saturn. On the right, the central region of this feature is depicted for Saturn's South central meridian, Titan, and Saturn's equator, respectively. Note the increased absorption going toward the limb of Saturn. According to the local continuum, the equivalent width of Titan's Q branch is about 2/3 the equivalent width of that feature in Saturn's spectrum.

The Bulk of Titan's Visible Atmosphere

Observations of the R(5) manifold of the $3\nu_3$ band are shown in Figure 2-6. The first two spectra are of Saturn and the Ring. The latter reveals only a weak water absorption feature. There follow three independent observations of Titan

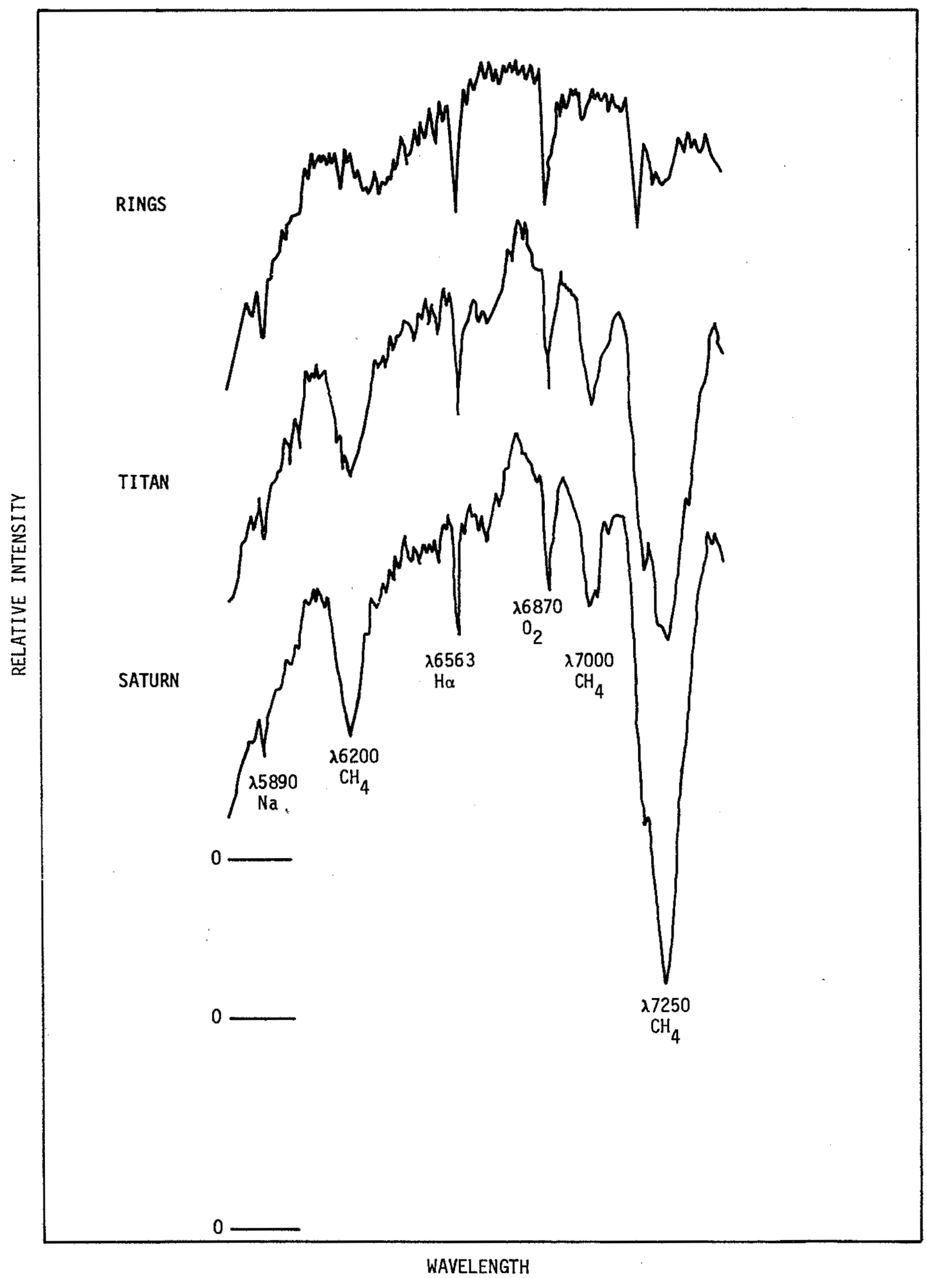

Figure 2-1. Comparative spectra of Saturn's Rings, Titan and the center of Saturn's disc in λ6200 - λ7250 Å CH_4 bands. After Trafton (1973a). Reprinted from Icarus, 21:in press, with permission of Academic Press, Inc. All rights reserved.

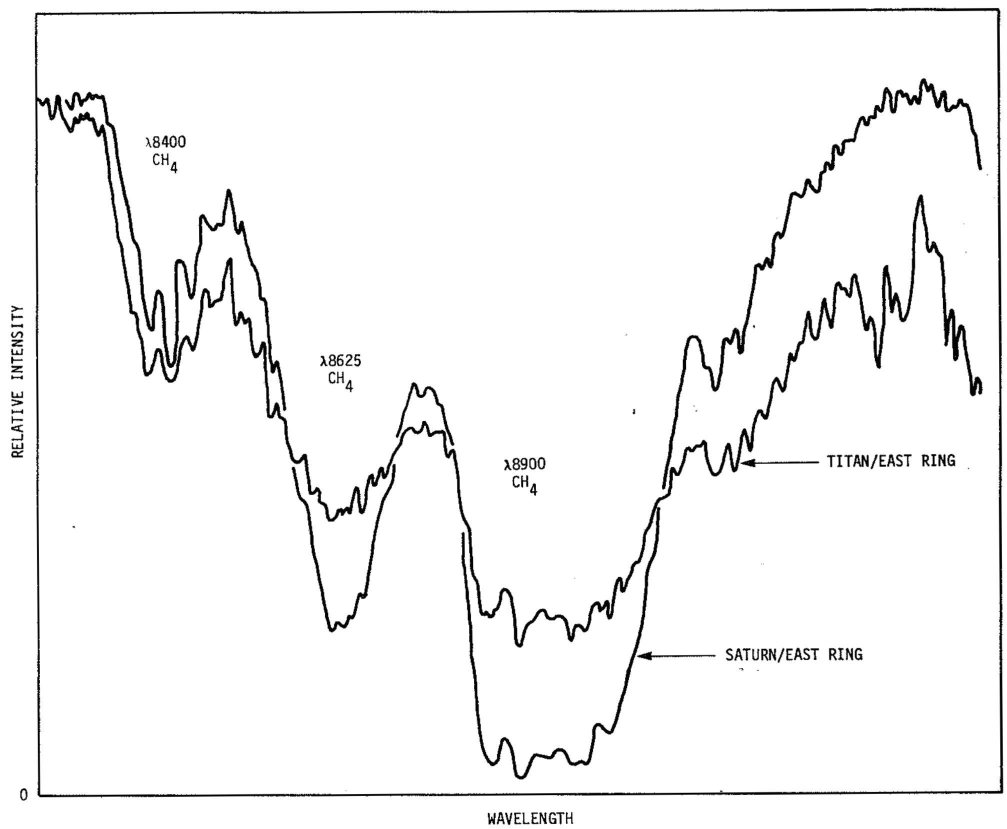

Figure 2-2. Comparative spectra of Saturn and Titan ratioed to the Rings for the 8900 Å CH_4 complex.

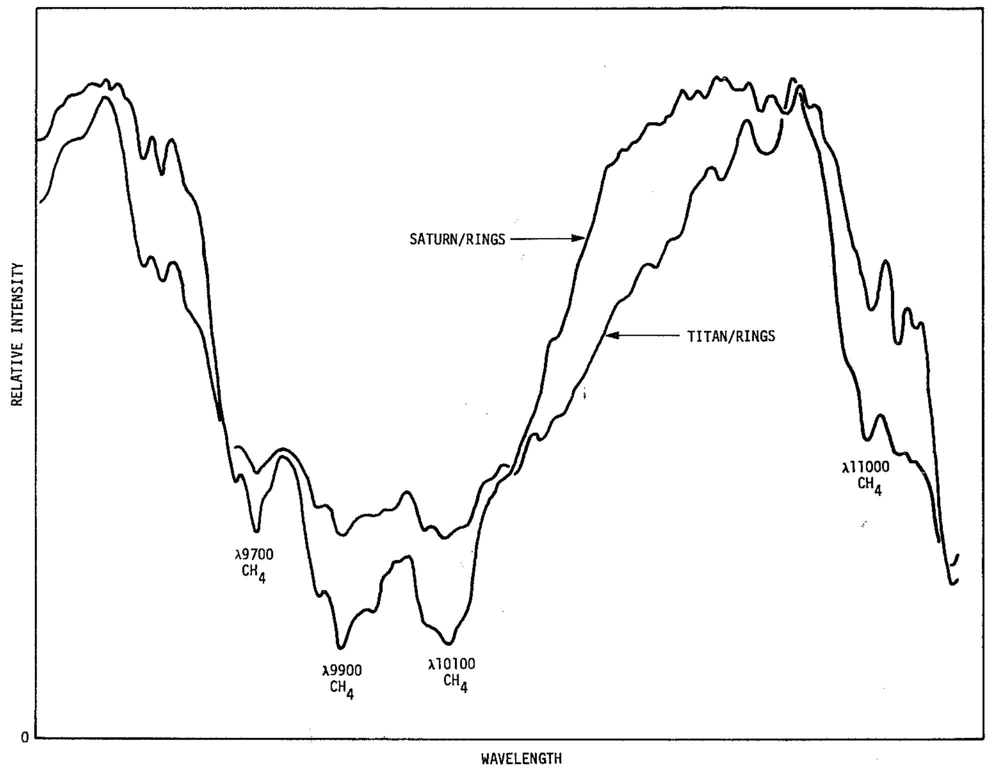

Figure 2-3. Comparative spectra of Titan and Saturn ratioed to the Rings at the 1-micron CH_4 complex.

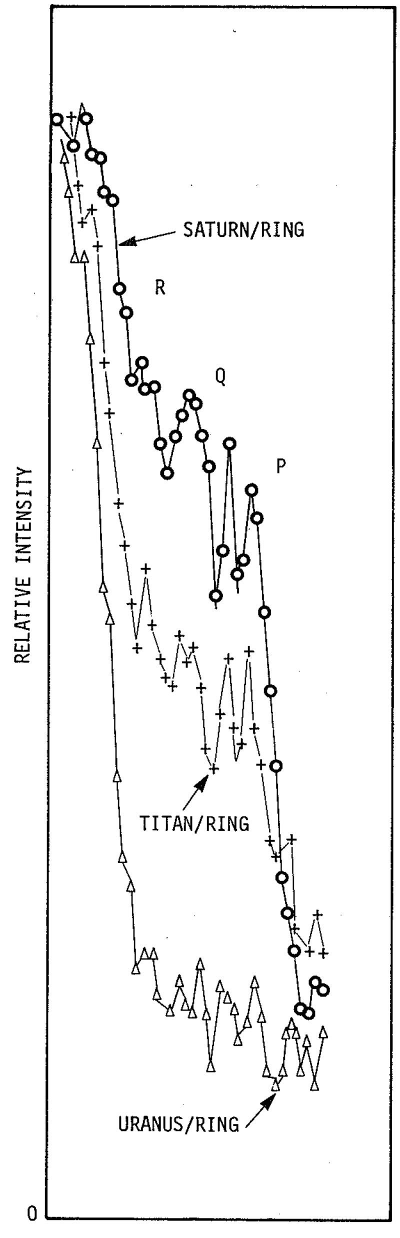

Figure 2-4. Comparative spectra of Titan, Saturn's south central meridian, and Uranus all ratioed to Saturn's Ring spectrum in the vicinity of the $3\nu_3$ CH_4 band at 1.1 μm. Note the strength of Titan's absorption. After Trafton (1973a). Reprinted from Icarus, 21:in press, with permission of Academic Press, Inc.

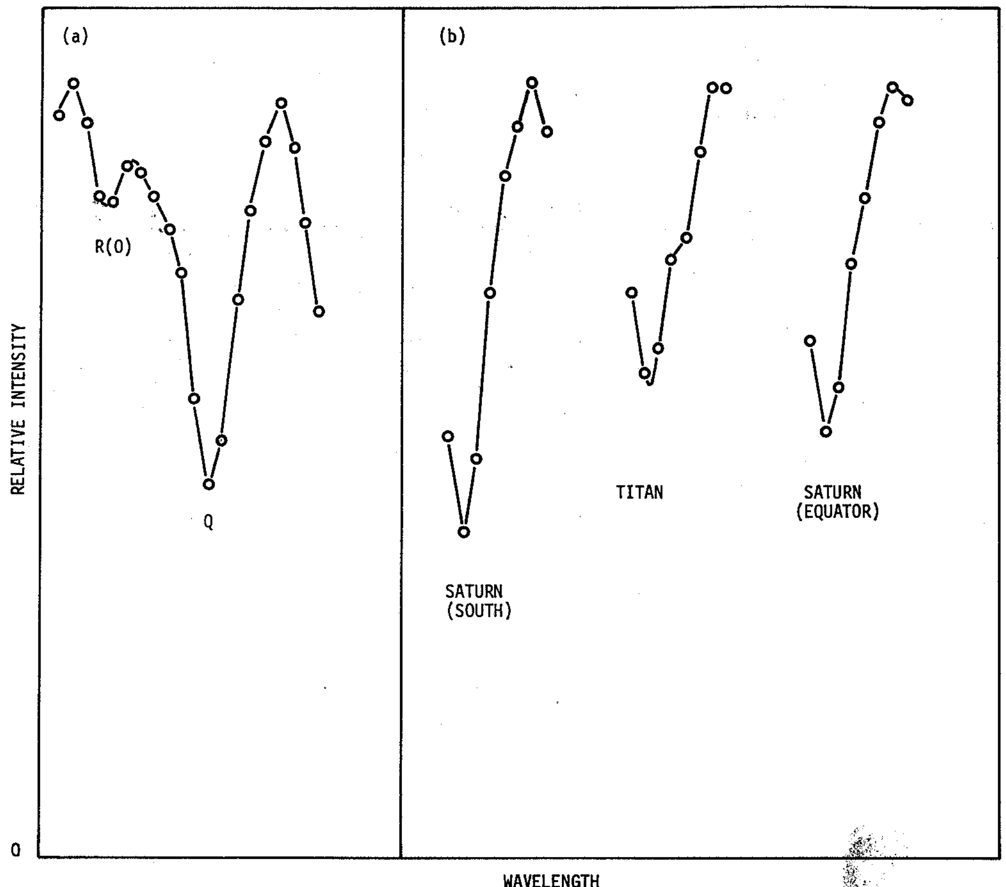

Figure 2-5. Comparative spectra of the Q branch (λ1105) of the $3\nu_3$ CH_4 band for Titan and Saturn. (a) Saturn at low latitudes. The R(0) manifold (λ11037) is visible here. (b) Narrow scans of the Q branch. The Saturn scans were taken with the slit set along the central meridian and excluded the Rings. After Trafton (1973a). Reprinted from Icarus, 21:in press, with permission of Academic Press, Inc. All rights reserved.

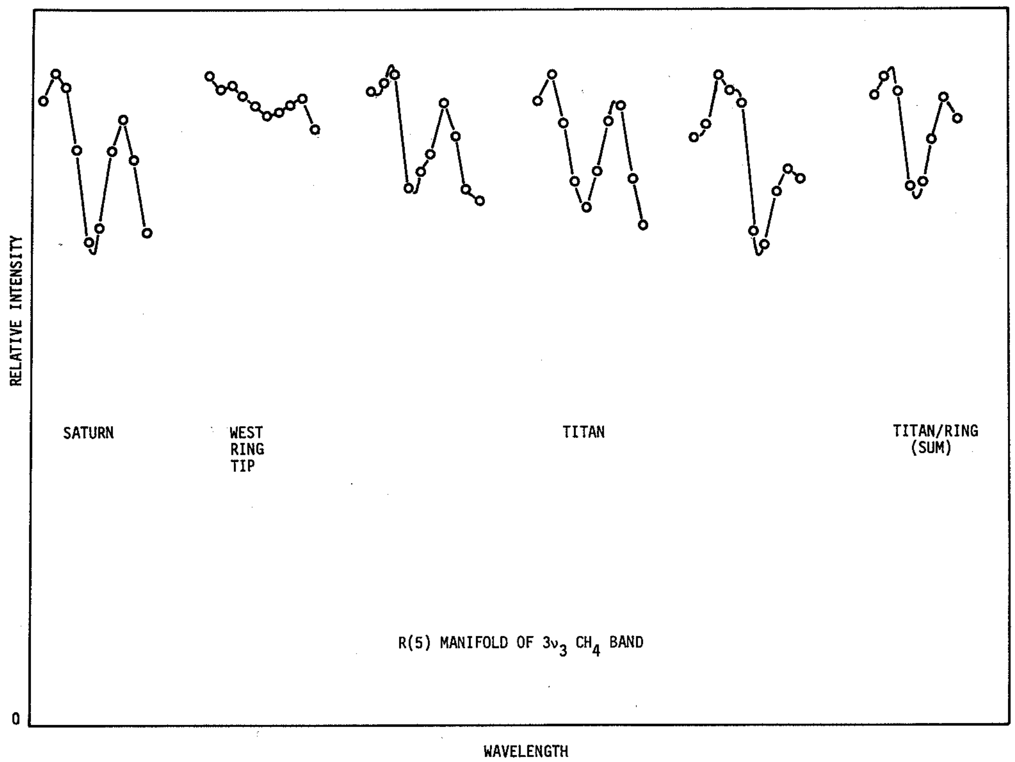

Figure 2-6. Comparative spectra of the R(5) manifold (λ10973) of the $3\nu_3$ CH_4 band. The first spectrum is taken along Saturn's south central meridian. The ring spectrum shows the strength and position of telluric H_2O absorption. The next three spectra are entirely independent observations of Titan's R(5) manifold. The last spectrum is the summation of these divided by the Ring spectrum to eliminate the telluric absorption. The first channel of the Ring spectrum corresponds precisely to the first channel of the following Titan spectrum. After Trafton (1973a). Reprinted from Icarus, 21:in press, with permission of Academic Press, Inc.

taken on different days; these agree fairly well. The sum of these observations ratioed to the Ring spectrum is shown on the right. The equivalent width of the manifold is just over one Ångstrom.

This result is a critical one because from it I conclude that a clear gas cannot explain the washing out of Titan's methane bands. There are four lines which make up this feature, so a lower limit for the equivalent width of one of them is 250 mÅ. Their Doppler width at this wavelength and at 90°K is about 11 mÅ. Figure 2-7 shows a curve of growth for a Lorentz line which is Doppler broadened. The ordinate is essentially the log of the equivalent width of a line in units of the Doppler width and the abscissa is essentially the line-strength abundance product in units of the Doppler width. A purely Doppler profile would qualitatively explain the washing out of the bands of Titan. Features in the square-root regime, however, would have too large a variation of the equivalent width with mean line strength to explain the washing out of Titan's bands. To establish Titan's regime, note that the lower limit for the equivalent width to Doppler width ratio for one of the lines of Titan's R(5) manifold is 23. This corresponds to 1.36 on the ordinate of Figure 2-7, well above the Doppler limit for any plausible range of conditions in Titan's atmosphere, so Doppler effects cannot wash out these spectral features. This should also be true for Titan's stronger bands since the line density appears not to exceed 7 times that for the ν_3 methane band. In this region of the diagram, the Lorentz domain, the absorption is given essentially by the pressure abundance product. Saturn's R(5) manifold is on the point of incipient saturation. Thus, throughout the entire range of physical conditions encompassing those of Saturn's and Titan's atmospheres, the line absorption is given essentially by the pressure-abundance product.

The fact that the absorption in Titan's spectrum is similar to the absorption in Saturn's spectrum indicates that Titan's smaller atmospheric pressure must be compensated by greater gaseous abundances. This is the fundamental reasoning for my upward revision by more than an order of magnitude of the amount of gas in Titan's visible atmosphere. The column abundance is at least 2 km-A of gas or 25 times that for Mars. A pure methane atmosphere corresponds to 2 km-A of gas at 10 millibars effective pressure (the "surface" pressure would be 20 millibars). Because the absorption fixes the pressure-abundance product, one could equally well explain the observation with less methane by adding another gas. For example, if there were only 100 meter-A of methane on Titan and the mean molecular weight of the atmosphere were 16, then there would have to be about 20,000 meter-A of some unknown gaseous constituent.

For 2 km-A of gas above Titan's clouds, the ratio of full width at half maximum to Doppler width (d) is 0.6. The curve of growth for this value has a slight inflection in it which could contribute to washing out spectral features only for a small range of line strengths. The value of the equivalent width at this inflection is still likely to be too low for the strong methane bands, but even for those bands which might be situated in this domain, the washing out from this slight inflection will be small. This picture of Titan's band absorption is thus self-consistent.

Danielson: On the question of the abundance, the total width of the band - never mind the washing out - does tell you something about abundances, does it not? Presumably the lines of methane that contribute to the outer wings of the band are weaker because it takes more methane to excite them. Have you ever tried to set any limits on that, or is that where you get your 2 km-A?

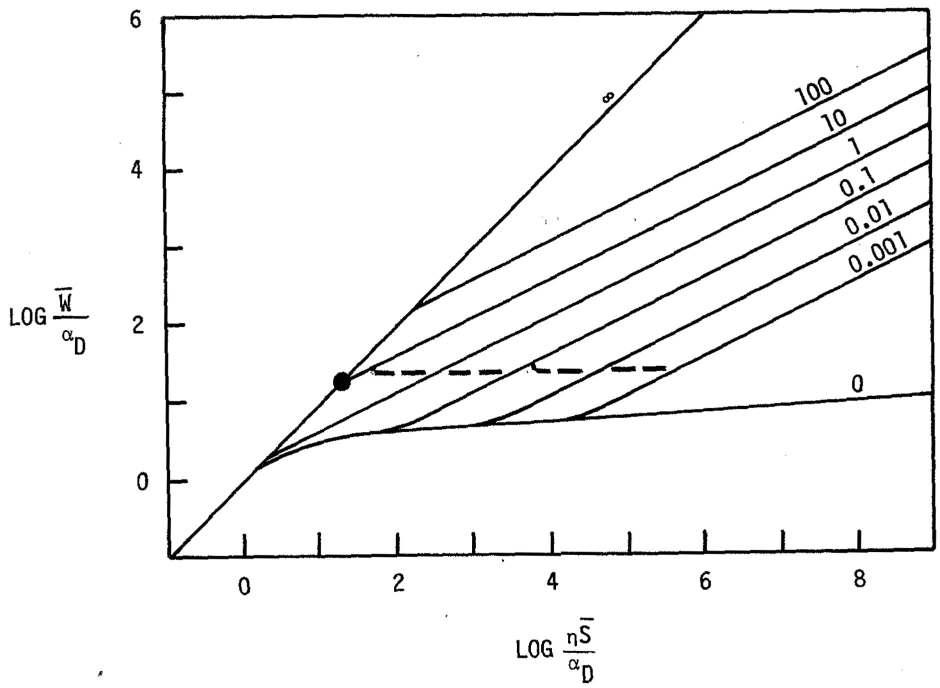

Figure 2-7. The curves of growth for a Lorentz line which is Doppler broadened. $\overline{W}$ is the equivalent width, α_D is the Doppler width, η is the air-mass factor and $\overline{S}$ is the mean line strength. The parameters represent the ratio of the full width of half maximum to the Doppler width (d). The dot denotes a typical line of Saturn's R(5) CH_4 manifold; the dashed line is the lower limit to the equivalent width of Titan's R(5) manifold.

Trafton: No. Temperature will also affect the band widths so that existing laboratory data, which are obtained at room temperature, would not be useful for abundance estimates. Comparison with Saturn's CH_4 bands is complicated by possibly different regimes in the curve of growth for the outer wings.

Pollack: Ames is now measuring the absorption of methane at different temperatures. What spectrum did you use to get your 2 km-A?

Trafton: In my original paper, I used the Q branch of the $3\nu_3$ band, but now I use the less ambiguous R(5) manifold. The results essentially agree.

Pollack: Do you mean to say you know the strength of the given line and then you go through the theoretical calculation to get its equivalent width? Is that how you do it?

Trafton: In essence, this is what I did.

Danielson: Have you not already emphasized that the continuum in all these planets is so poorly known that all kinds of things could happen just due to the continuum absorption?

Trafton: I think we do see the continuum in the vicinity of these bands I am talking about. The continuum geometric albedo is very flat in the range from 7500 Å to 10,000 Å and is about 0.36 to 0.40.

Spectroscopic Evidence for H_2

Spectroscopic evidence that H_2 is likely to be a major constituent of Titan's atmosphere is shown in Figures 2-8 through 2-11. They show spectra of Titan in the region of the (3-0) overtone of H_2. Figures 2-8 and 2-9 show the S(0) and S(1) features for the 1970 apparition, with a slit giving a resolution element of a third of an Ångstrom. On the left of Figure 2-8, a summation of 3 observations is shown and on the right a fourth observation of inferior quality owing to a larger air mass is added to these three. The arrows point to the predicted position of the hydrogen features on Titan. They differ from the position of Saturn because of the Doppler shift arising from the orbital motion of Titan. The disturbance in the continuum, which shows up in both these spectra, agrees with the predicted position within the resolution element of the slit.

Figures 2-10 and 2-11 show the S(0) and S(1) lines obtained during the 1972 apparition using a new experimental setup. We used a more sensitive photomultiplier tube having a GaAs photocathode and an echelle instead of the usual grating. The resolution element was reduced to a quarter of an Ångstrom. These data depict single observations rather than summations of a number of separate observations. Finally, the smoothing technique was a less subjective one, optimized from the modeling of the power spectra.

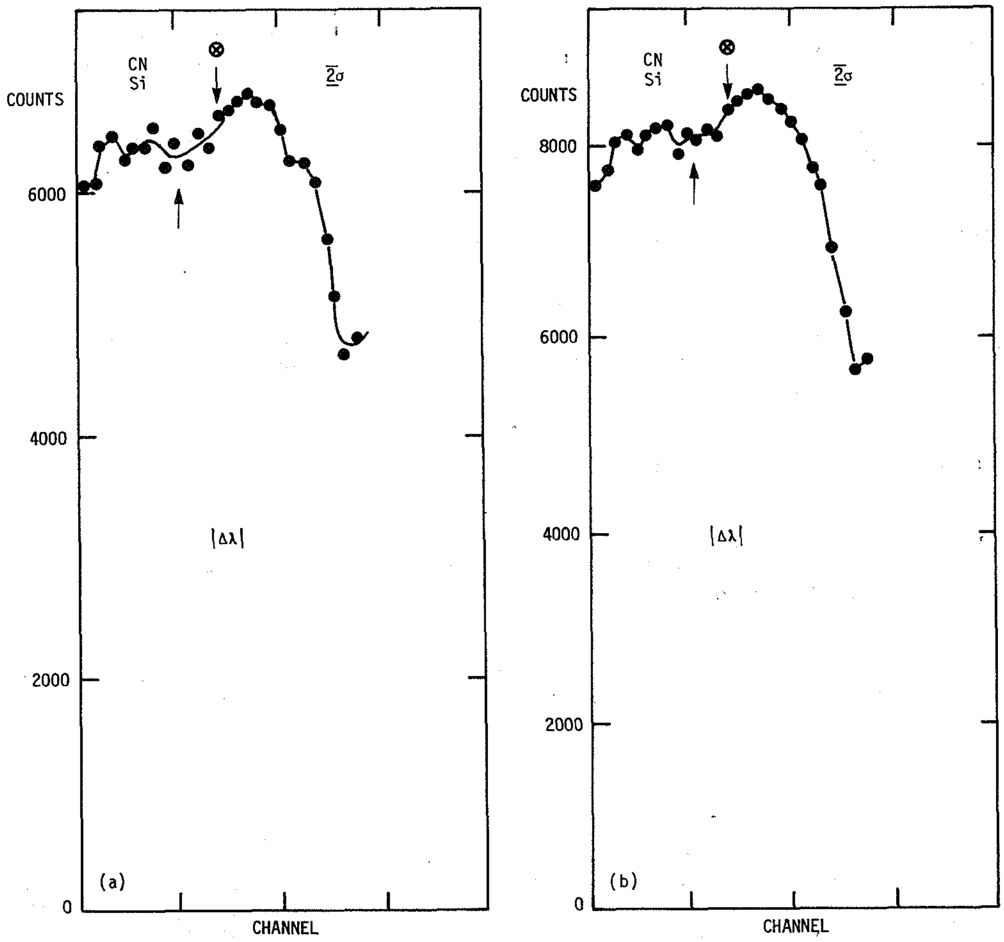

Figure 2-8. (a) Summation of the three Titan observations having the least air mass and covering the spectral neighborhood of the 3-0 S(1) H_2 line. The scans are superposed in Titan's reference frame, and the dispersed positions of weak solar CN and Si lines (4 mÅ) and a weak telluric H_2O line are indicated. The spectral resolution $\Delta\lambda$ and twice the expected standard deviation 2σ are marked. The lower arrow points to the wavelength where S(1) absorption would occur. (b) Similar to (a) except that all four observations are summed. After Trafton (1972b). Reprinted from The Astrophys. J., 175:288, with permission of The University of Chicago Press. © 1972. The American Astronomical Society. All rights reserved. Printed in U.S.A.

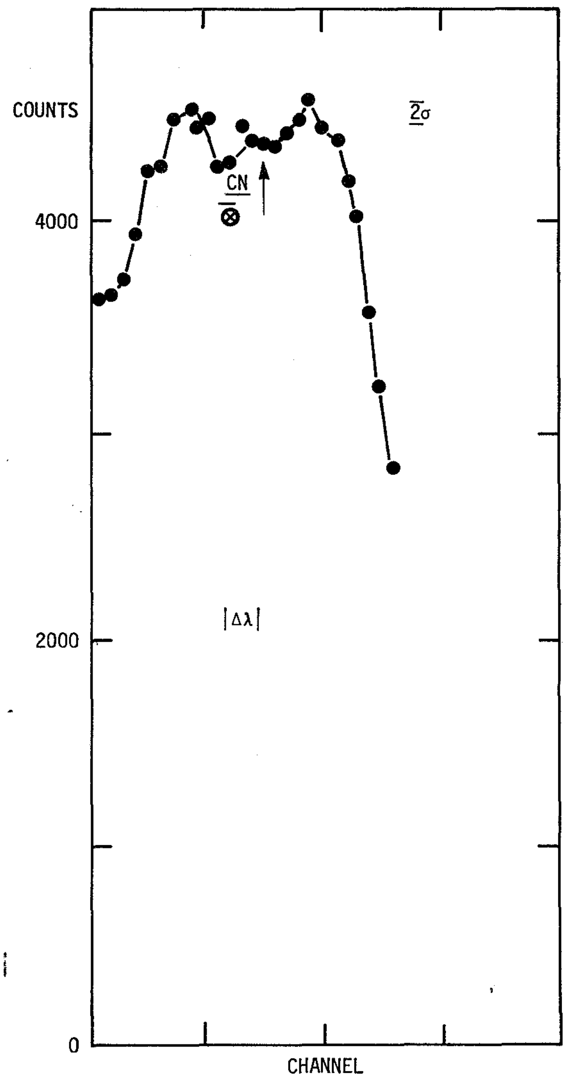

Figure 2-9. Summation of three Titan observations covering the spectral neighborhood of the 3-0 S(0) H_2 line. The scans are superposed in Titan's reference frame, and the dashes indicate the dispersed positions of the weak solar CN and telluric H_2O lines. The spectral resolution $\Delta\lambda$ and twice the expected standard deviation 2σ are marked. The arrow points to the wavelength where S(0) absorption would occur. The increased strength of the weak telluric H_2O feature results from the higher mean air mass and absolute humidity. After Trafton (1972b). Reprinted from The Astrophys. J., 175:288, with permission of The University of Chicago Press.

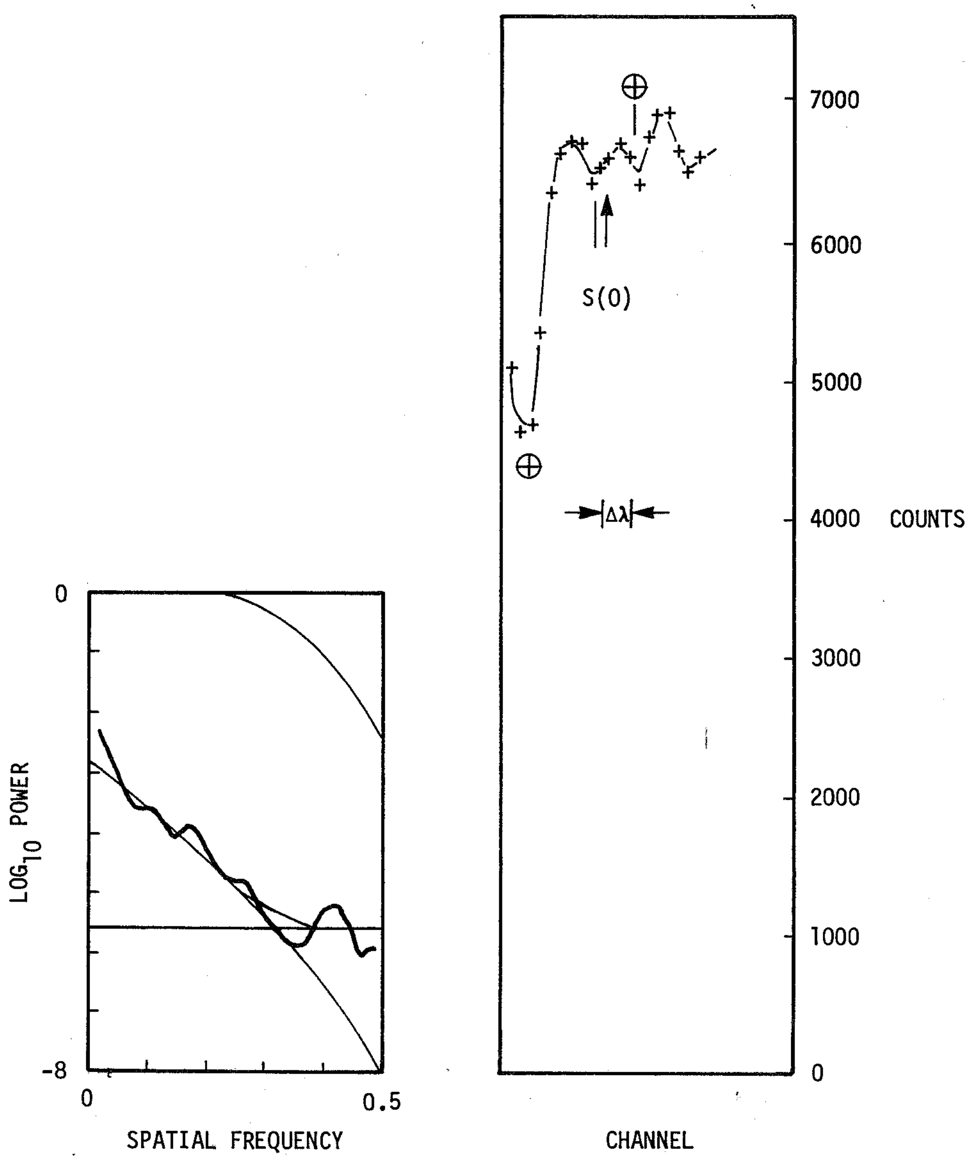

Figure 2-10. The 3-0 S(0) H_2 line for Titan during the 1972 apparition.

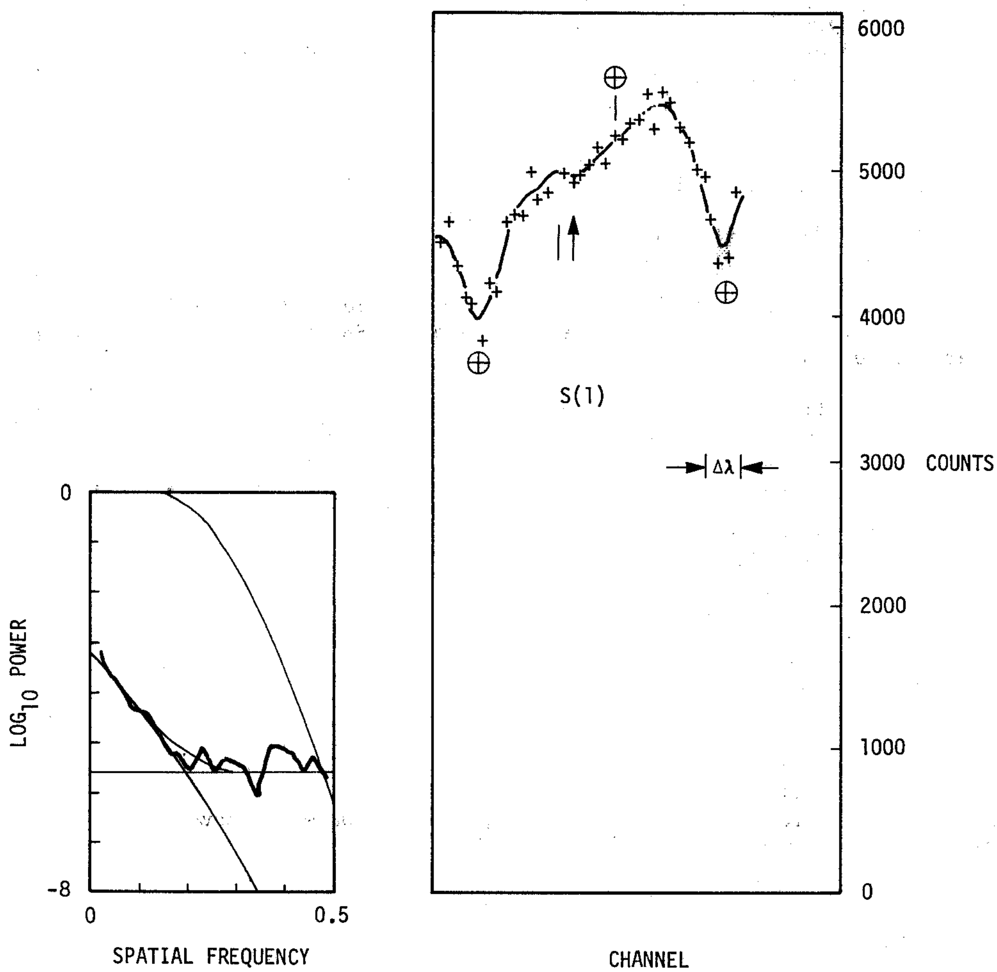

Figure 2-11. The 3-0 S(1) H_2 line for Titan during the 1972 apparition.

The arrows in Figures 2-10 and 2-11 show the predicted wavelengths and the lines show the positions of the H_2 absorption features in Saturn's spectrum. The S(1) line exhibits a noisier spectrum as one can also see from the white noise level in the power spectrum. Because of the increased noise, the smoothing is heavier than for the S(0) line. Nevertheless, there is an absorption feature at the position of the arrow. The location is in better agreement with the predicted position, which is more Doppler shifted than for the S(0) line. The absorptions appear to be quite real. These two line features suggest a hydrogen abundance of about 5 km-A, assuming that they indeed arise from hydrogen. Their tentative identification rests primarily on the coincidences in wavelength for the two features.

Spectroscopic Evidence for Another Gas

Additional spectroscopic evidence of Titan's atmospheric composition exists in the anomalous enhancement of the absorption in the long wavelength wing of the 1-micron methane band. Figure 2-12 shows distinct differences between Saturn's spectrum and Titan's spectrum at resolution 6.6 Å. The most prominent difference occurs for the feature at 1.053 μm. It shows up very clearly in Uranus' spectrum.

One can find other Titanian absorption features which also show up in Uranus' spectrum and which are either undetectable in Saturn's spectrum or are only marginally detectable. The 1.05 to 1.07 μm region of the spectra of these planets is shown with resolution element 4.4 Å in Figure 2-13. This figure shows quite a number of features in the spectrum of Titan which are confirmed in the spectrum of Uranus but which are not visible in the spectrum of Saturn. As far as such features in Titan's spectrum are concerned, Titan's atmosphere resembles Uranus' a lot more than it resembles Saturn's. It supports the concept of a deep atmosphere for the planet.

Acetylene can be excluded as the source of these features. Whether they arise from other light hydrocarbons such as ethylene or ethane remains unanswered because there is almost nothing in the literature on the spectra of these molecules between 1 and 2 μm. Isotopic methane is a very good candidate for this absorber because isotopic absorptions are shifted to the long wavelength parts of the CH_4 band. If these features arise from the photolysis of CH_4, I think there would be difficulties, because you would have to explain its absorption in the atmosphere of Uranus, where most of the methane should be frozen out in the upper layers. Also, I cannot rule out the possibility that these features arise from very weak methane transitions which do not show up as strongly in Saturn's spectrum because the amount of methane visible in Saturn's atmosphere is less. In this event, these features by themselves would imply more than an order of magnitude more methane in Titan's visible atmosphere.

Sagan: Regarding your isotopic explanation, are the isotopic ratios you need in order to give the observed line strengths consistent with, say, terrestrial planets?

Trafton: That's a good point. I haven't calculated it.

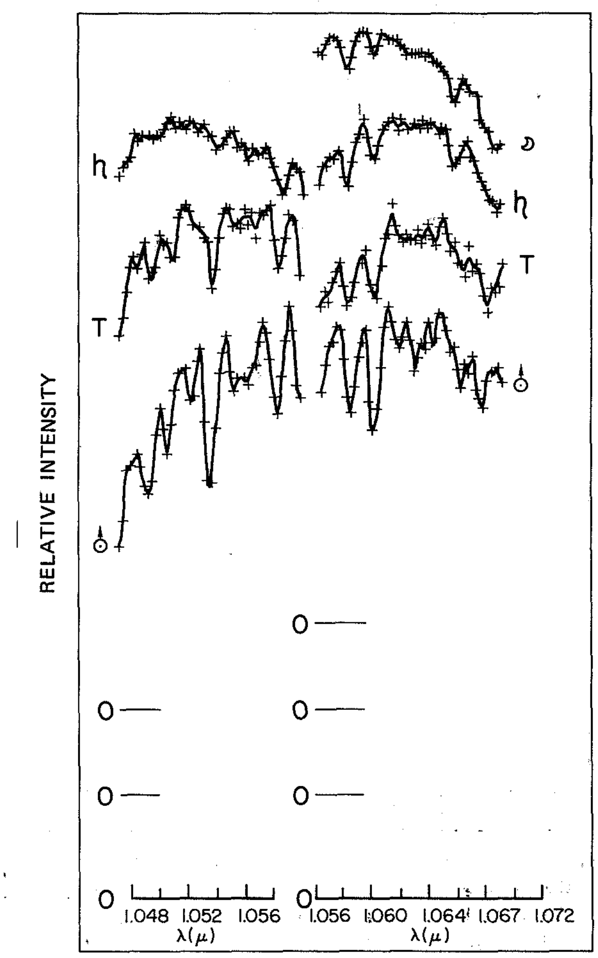

Figure 2-12. Comparative spectra of Titan, Uranus, Saturn's south central meridian, and the Moon from 1.05 μ to 1.07 μ, uncorrected for vignetting. The resolution element is 6.6 Å. The lines represent the optimally smoothed spectra and the pluses denote the data. Two observations per object were required to cover this range. Titan's spectrum includes a number of strong features which are marginally visible in Saturn's spectrum and quite pronounced in Uranus' spectrum. After Trafton (1973a). Reprinted from Icarus, 21:in press, with permission of Academic Press, Inc.

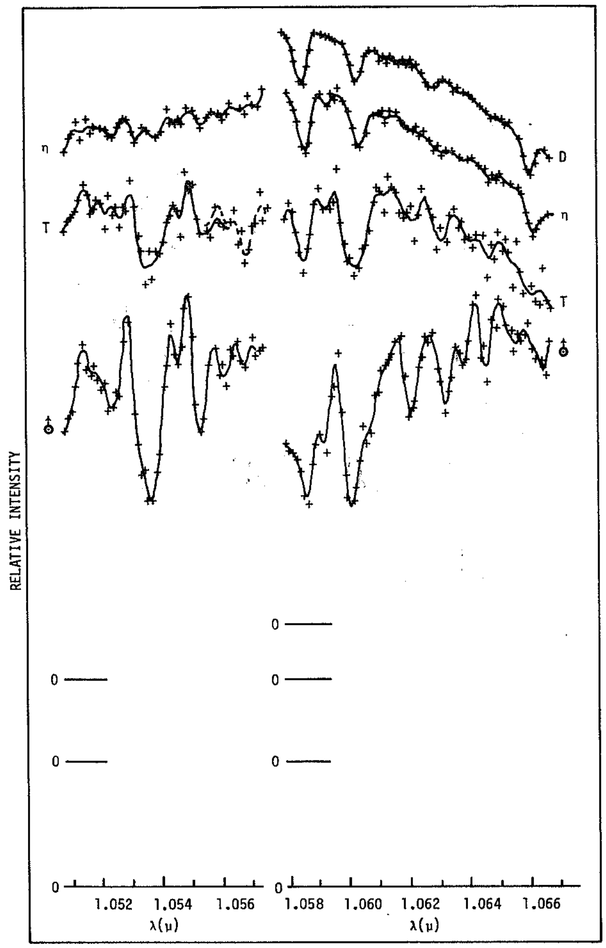

Figure 2-13. Comparative spectra for the 1.05 μm to 1.07 μm region for a 4.0 Å resolution element. These data were obtained during the latest apparition and have been normalized to the white light spectrum to remove vignetting effects. Titan's spectrum shows unequivocally the reality and strength of features hardly visible in Saturn's spectrum. The unidentified gaseous constituent responsible for these absorption features causes Titan's spectrum to approximate the spectrum of Uranus far better than the spectrum of Saturn. The visible abundance of this constituent may be much greater than that visible in Uranus' deep atmosphere owing to the probable saturation of the spectral features in Titan's spectrum and the low pressures. This points to a deep atmosphere for Titan. The unidentified feature at 1.057 μm must be of gaseous origin in order to produce this spectral variation. After Trafton (1973a). Reprinted from Icarus, 21:in press, with permission of Academic Press, Inc. All rights reserved.

Sagan: But you could at least see whether you're off by 2 orders of magnitude.

Hunten: The trouble with that is that very often the transition probabilities for vibration-rotation bands are grossly different for isotopic forms; again the real need is for lots of lab data.

Sagan: But surely, it would be astounding if, let's say, the C12/13 ratio of Titan were off by several orders of magnitude from what it is in comets and the Earth. I agree you have to use the right laboratory data.

Your point about it being unlikely that the absorber is a photolysis product is because it is in Uranus' atmosphere, where you have to go pretty deep in order to get optical depth unity, isn't it?

Trafton: Yes, deep in the H_2 to get optical depth unity in the CH_4.

Sagan: Have you calculated that? I mean, how does it work out quantitatively?

Trafton: No, I did not do a quantitative analysis. One really should do this accounting for the temperature profile including the effect of a temperature inversion in the upper layers of Uranus' atmosphere.

Sagan: Also, if it were a simple hydrocarbon other than methane, how would you understand that except by photolysis?

Trafton: Could there be other ways that hydrocarbons could be formed other than photolysis, perhaps in chemistry of the interior?

Spectroscopic Evidence for High-Altitude Dust

The remaining bit of spectroscopic evidence concerning Titan's atmospheric composition is the anomalous ultraviolet (UV) absorption. The relative reflectivity of Titan is very close to that of Saturn in the spectral range 3000 to 4500 Å, as is shown in Figure 2-14. This is an interesting result because the amount of gas in Titan's atmosphere should produce a marked brightening in the ultraviolet from Rayleigh scattering. Because the reflectivity is close to that of Saturn's Ring for all wavelengths in this region (the value at 3000 Å is uncertain because of strong telluric absorption), one concludes that there is no trace of Rayleigh scattering at all. This indicates that there is a strong amount of UV opacity high in Titan's atmosphere obscuring the deeper gases. The geometric albedo as a function of wavelength of Titan in this part of the spectrum is shown in Figure 2-15. The crosses depict McCord's data; he now disclaims the discrepant point at 3000 Å.

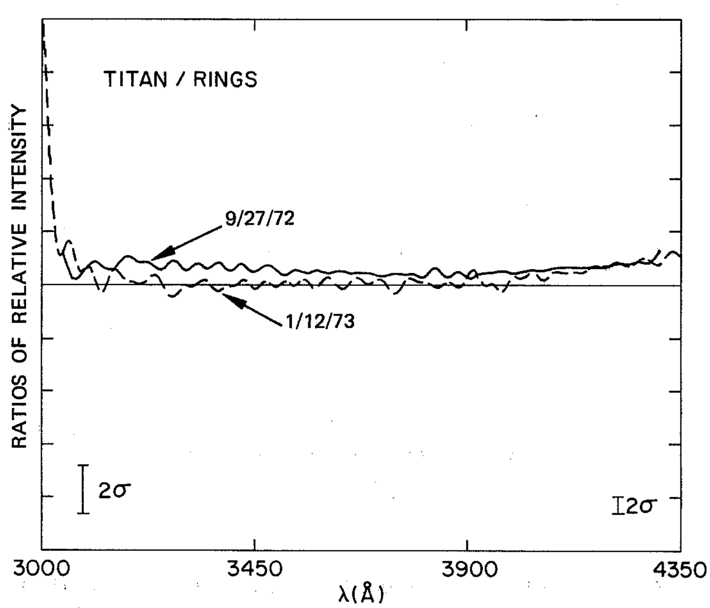

Figure 2-14. Ratio spectra of Titan vs. Rings, 9/27/72 and 1/12/73. After Barker and Trafton (1973). Reprinted from <u>Icarus</u>, 20:in press, with permission of Academic Press, Inc.

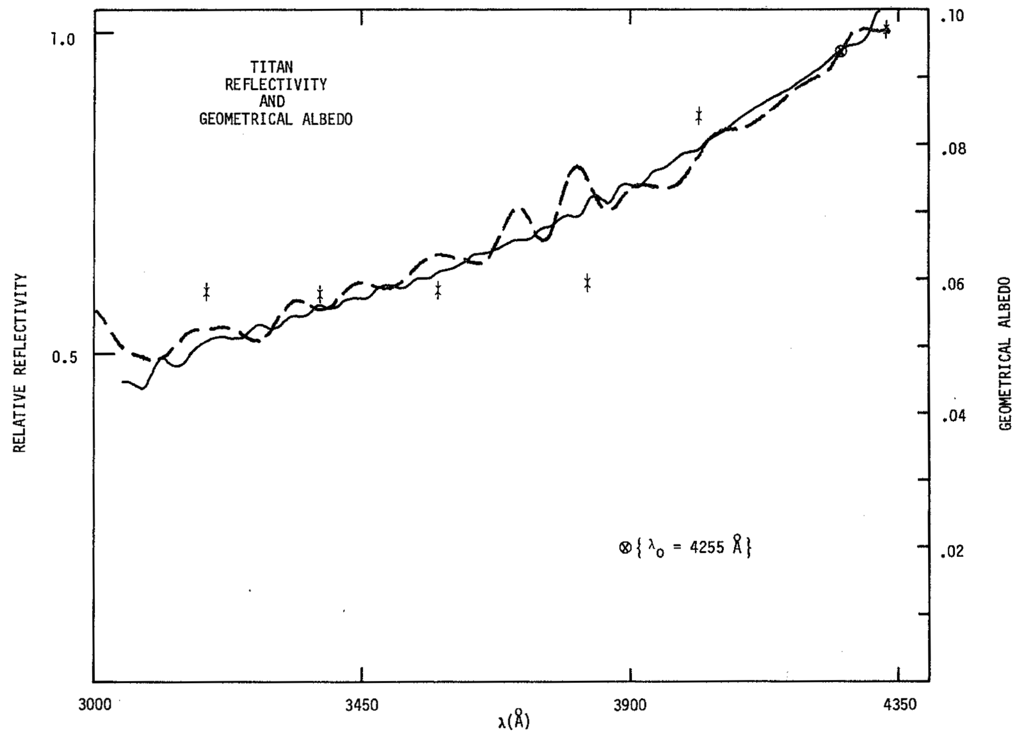

Figure 2-15. Relative reflectivity and geometrical albedo of Titan. Reflectivity normalized to 1.0 at 4330 Å. Symbols: solid curve, 9/27/72; dashed line, 1/12/73; ‡, McCord et al. (1971). Geometrical albedo of 0.094 ± 0.012 measured 4255 Å. After Barker and Trafton (1973). Reprinted from Icarus, 20:in press, with permission of Academic Press, Inc. All rights reserved.

Any homogeneous model atmosphere explaining Titan's ultraviolet albedo implies a UV absorber having a very large variation with wavelength, even more than that for Rayleigh scattering. Axel (1972) was able to explain Jupiter's anomalous UV absorption in terms of a fine dust; that is, an entity which he defines as nonscattering and varying inversely as the wavelength. This is the case for particles small compared to the wavelength of light when the complex index of refraction does not vary with wavelength. Because of the success of this model with Jupiter, an interesting question is whether one can also explain the phenomenon of Titan's UV absorption in terms of such a dust. This is possible only when there is an appropriately inhomogeneous distribution of the dust in Titan's atmosphere. If the gas density falls off more rapidly than the dust density with height, it is possible to explain the wavelength variation of the monochromatic UV albedo. I approximate this condition by a uniform dust layer overlying a layer which consists of a mixture of a fine dust and a Rayleigh scattering atmosphere. The calculations indicate that surface albedo versus wavelength is quite compatible with what one finds for the other satellites of the solar system. For a gray cloud underlying the dust layer, an opposite extreme for the underlying atmosphere, the calculations are also in fair agreement with the data. This UV opacity appears to be compatible with the observed albedo.

Veverka: What phase angles did you make these observations at?

Trafton: 4.5 degrees.

Veverka: In the ultraviolet the phase coefficient is quite appreciable and you could be off by as much as 7%.

Trafton: Then the data should be so corrected.

Morrison: And what radius did you use?

Trafton: I used the radius of 2550 kilometers.

Danielson: We have done some calculations with dust absorbing as λ^{-3} mixed uniformly in an atmosphere and, in addition, the surface albedo decreasing with wavelength and you can make the fit that way also. With that kind of model, you can fit one or two km-A of Rayleigh scattering methane.

Sagan: What is the optical depth of that model, say, at 5000 Å?

Danielson: The optical depth of the dust is about 0.2, and the Rayleigh scattering is somewhat less than that.

Sagan: Then you're seeing the surface very well.

Trafton: I used the constraint that the optical depth at 0.3 μm is at least 0.45 for Rayleigh scattering alone. In other words, I set a lower limit to the thickness of the atmosphere.

Danielson: If dust is defined as something that absorbs as $1/\lambda$, then it seems a very restricted definition. Its complex index must be independent of wavelength for that to happen; otherwise, you can get anything.

Veverka: The point is, you use dust to mean anything that scatters as $1/\lambda$ the way you want it, with no particular resemblance to anything real.

Trafton: Yes. My purpose is to see if one can explain Titan's phenomenon with the same dust theory that Axel used to explain Jupiter's.

Sagan: It seems to me the requirement for an absorbing particle high in the atmosphere is a very restrictive one in the sense that a lot of boundary conditions are being forced upon you. For example, it seems unlikely that the source would be below because of the transparent atmosphere underneath the dust. It looks as if your dust would have to be made up there at the top of the atmosphere and, if that is the case, it looks very much like a photochemical process.

Trafton: Yes, but it is interesting to note that the shape of Saturn's Ring spectrum in the ultraviolet is so close to that of Titan's that the same process may be operating on the particles of Saturn's Rings.

Sagan: Is it possible that all of this is solid state chemistry and doesn't involve the gas phase very much at all?

Trafton: Very possible.

Veverka: You should add Io to the list, because the spectrum of Io is very like that of Saturn's Rings.

Spectroscopic Evidence for an Elevated Cloud Layer

Turning now to an interpretation of the morphology of Titan's infrared spectrum, I indicate how these data imply a cloud layer above most of Titan's methane. Such a cloud would most likely be frozen methane particles, in which case a temperature near 90°K would appear near its base. Furthermore, there would be a temperature gradient at its lower boundary so that a greenhouse effect would be indicated in the lower atmosphere. This is not necessarily in contradiction with the temperature inversion observed at high altitudes since the levels of the atmosphere in question are very different. The level of the 12-micron emission applies to optical depth unity in this feature, while optical depth unity in the visual methane bands is probably much deeper because these bands are high overtones and, hence, considerably weaker than the fundamental. Some account must be made, however, of the relative band strength and abundance of of the gas causing the 12-micron emission before the separation in these levels can be determined.

Since laboratory data for methane are not available at low temperatures for these bands, I employed Saturn's spectrum along the central meridian at elevated latitudes to derive the necessary properties of the methane bands. The absorption in this region should be similar to the spectrum of the clear gas, as absorption dominates the scattering process here. Goody's random band model applied to the 8900 Å and 1 μm complexes provided the relative absorption strengths as a function of wavelength by assuming that these bands are saturated in the sense that they lie on the square root part of the curve of growth. I have already shown above that the clear gas model of Titan's atmosphere does not work. Similarly, my attempts to fit an isotropically scattering atmosphere to Titan's bands fail, both for a finite and a semi-infinite atmosphere, since the required degree of washing out is simply not obtained. Furthermore, adding an opacity within the confines of the band, such as might result from the increased absorption of methane particles, does not explain the enhanced strength of the weaker features in Titan's spectrum, even though it washes out the structure in the bands. In order to keep the band centers from becoming too dark from the added opacity, one has to increase the volumetric scattering coefficient to reduce the scattering mean free path. This reduces the specific abundance of the gas and weakens the features in the continuum, so this model must be rejected.

The only model which I have found which works is the inhomogeneous one consisting of a high cloud layer overlying most of the methane in the atmosphere. I assume the cloud to be gray and the scattering coefficient to be constant over each band. Intuitively, this model works because the particles high in Titan's atmosphere will reflect back a fraction of the solar flux before the methane can absorb it. This will fill in all bands uniformly, but the most apparent result will be to fill in the centers of the strong bands. If the optical depth of this haze layer is not too large, the absorption in the deeper layers will be visible. By making the clear layer below the cloud layer deep enough, one can enhance the strength of the weak features to an arbitrary fraction of the strong ones. Therefore, this model appears to be satisfactory.

Pollack: As I understand it, you're saying that the scattering model fits these bands and the continuum albedo varies across the band, is that right?

Trafton: I take the "continuum albedo" constant over the band but add a gray background opacity within the confines of the band. I do not let it vary across the band although, in reality, it probably would vary by some degree if it arose from, say, absorption in solid methane. The only way to get the semi-infinite scattering model to give the required washing out is to include this background opacity, but we arrive at a contradiction by doing that since the increase in scattering required to keep the band centers from becoming too dark causes other features to be too weak.

Rasool: Could the dust be in the form of ice? Can you have liquid particles in the cloud layer? What do you mean when you day "dust" -- liquid or solid?

Trafton: When I say "dust", I am talking about the ultraviolet opacity which occurs at wavelengths shorter than 4000 Å. In the infrared, the high cloud layer no longer looks like a dust layer, but like a scattering layer. I assume that its ultraviolet opacity varies as $1/\lambda$, to see if Titan can be explained with the model Axel used for Jupiter.

Pollack: Did I understand you to say that the 1 μm observation indicated scattering as well as absorption, is that correct?

Trafton: Yes. I believe the continuum albedo at 1 μm is about 0.36 to 0.39.

Danielson: Can you summarize the key reason or reasons why the washing out of the bands cannot be explained by the fact that lines on Titan must be quite narrow? It seems to me the washing out of the bands is a very important part of the argument that you need for a scattering layer. If that's true, your explanation will do it, but it may not be unique.

Trafton: I believe you do need it because the lines are so strong their Doppler cores are essentially black. Any further absorption depends on the absorption in the Lorentz wings.

Danielson: But there may be spaces between the lines.

Trafton: However, growth in absorption comes from the Lorentz wings; this will not wash out the structure of the bands.

Danielson: But doesn't that mean they make it black between the cores?

Trafton: No. The observed lower limit to the equivalent width of Titan's R(5) manifold, a relatively weak feature, implies that the absorption in the center of its lines is black; any further absorption must therefore occur in the Lorentz wings. The curve of growth in this regime will be the square root asymptote, which has a relatively steep slope. You can't explain washing out of the contrast with a slope that steep. You could explain it with the shallow Doppler curve of growth, but I attempted to show that Titan's physical regime lies above this curve so that this situation is excluded.

Danielson: Even in that regime with certain line spacings, you can get a washing out. Make little spaces big enough between the lines and you surely get it. So, it takes detailed modeling to really establish these facts, doesn't it?

Trafton: What we are measuring, and actually accounting for in the analysis, is an average of the rapidly varying monochromatic albedo over the 17 Å resolution element of the spectrograph. Random band models, as previously shown, establish the relationship between the albedo in the band and the behavior with wavelength of the mean line strength in terms of the equivalent width of a mean line and the curve of growth.

Danielson: That's correct, but one parameter in there is a mean line spacing. This spacing must depend on the total abundance you have, because if you had much more abundance in the line of sight on Titan, you would bring in far more lines and hence the mean line spacing would change, I suspect.

Trafton: There is that possibility.

Danielson: Your models are based on the fact that the mean line spacing is the same for Saturn and Titan, and then your calculations indicate that the clear spaces between the lines cannot explain the washing out and hence you need some scattering.

Trafton: That is right. I do assume that the line spacings are the same, going from Saturn to Titan at a given wavelength. To get a washing out, one must find that the ratio of the equivalent width of a mean line to the mean line spacing decreases with respect to the same ratio when no new lines are added as the abundance is increased. Adding weak lines reduces the mean line spacing; but it also reduces the mean equivalent width. It is not at all clear that the above ratio should become significantly less.

Note: This article is, in part, a summary of publications and preprints by Barker and Trafton (1973), and Trafton (1972a, 1972b, 1973a, 1973b).