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# TITAN'S ATMOSPHERE: COMMENTS ON HAZE CONTENT, METHANE ABUNDANCE, BAND SHAPES, AND HYDROGEN UPPER LIMIT

**Laurence Trafton**

*Department of Astronomy*
*University of Texas at Austin*
*Austin, Texas 78712*

**ABSTRACT**

This is a reply to the presentations of Caldwell and Hunten and was presented as part of the "discussion" following their papers.

I would like to reply to Caldwell's and to Hunten's presentations. First, I remind you that I have already demonstrated the existence of scatterers in Titan's atmosphere in a paper I published in the *Astrophysical Journal* three years ago (Trafton, 1975b). My conclusion is not affected by recent laboratory investigations showing that certain $CH_4$ bands are independent of pressure because I showed that the reflecting layer model fails to explain Titan's $CH_4$ absorptions *regardless* on which portion of the curve of growth Titan's $CH_4$ lines lie. In that paper, I used Saturn's atmosphere along the central meridian as my "laboratory" for studies of $CH_4$ absorption, arguing that my conclusion is insensitive to the moderate scattering there.

The quite pronounced role of scattering in Titan's atmosphere strongly suggests that Titan's surface is obscured. This is compatible with the lack of variation of Titan's brightness with orbital phase (Noland *et al.*, 1974), unless Titan has a featureless surface, because Titan almost certainly rotates synchronously about Saturn. Even if a smooth, featureless, or "tarry" surface exists (Hunten, 1973), the scattering probably veils it enough so that the ambiguity in interpreting Veverka's (1973) polarization measurements should be resolved in favor of atmospheric scattering rather than reflection from a smooth surface. So as the case for a significant haze is strengthened, the case for a smooth surface is weakened.

My second point is that the fact that certain $CH_4$ bands studied in the laboratory do not depend on pressure does not alter the $CH_4$ abundances I have derived in previous papers. While I concede that laboratory measurements have since shown that certain $CH_4$ bands behave like a linear opacity (following Beer's law), at least for the pressures and temperatures investigated, it is well known that the R branch of the $3\nu_3$ $CH_4$ band deviates from this behavior in the atmospheres of Jupiter and Saturn (Belton, 1969; Trafton, 1973b) and, consequently, at lower pressures. That is, the absorption of the $3\nu_3$ $CH_4$ band depends on the pressure as well as the $CH_4$ abundance throughout the physical regime spanning the conditions between the atmospheres of Titan and Saturn. In my original paper on Titan's bulk composition (Trafton, 1972), I argued qualitatively that the bulk of Titan's atmosphere is large because the strong $CH_4$ bands should depend on pressure but I derived the quantitative relation between $CH_4$ abundance and bulk composition on the basis of the Q branch of Titan's $3\nu_3$ $CH_4$ band, arguing that since the R branch is saturated, the Q branch is too. So the recent laboratory results refute my qualitative argument based on the strong $CH_4$ bands but not my quantitative result based on the Q branch of the $3\nu_3$ $CH_4$ band.

This analysis yielded 1600 m-A (meter-Amagat) $CH_4$ in the case of a pure $CH_4$ atmosphere and less $CH_4$ if another bulk constituent is present. In a following paper (Trafton, 1974), I revised this figure to 2 km-A based on a correction to the airmass factor for saturated bands pointed out to me by Hunten. I also reported three independent observations of the R(5) manifold of Titan's $3\nu_3$ $CH_4$ band and noted that the strength relative to Saturn's R(5) manifold was approximately the same as for the Q branches, supporting my analysis based on the Q branches. Figure 1 reviews my observations of the Q branches and R(5) manifolds. Since only part of the Q branch was observed on Titan, owing to the very low signal level, this confirmation was important.

The three independent observations of Titan's R(5) manifold shown are similar, giving confidence that their sum is accurate. The Ring spectrum shows the limited contribution of telluric $H_2O$. The equivalent width of the summed Titan spectrum divided by the Ring spectrum is proportional to the product of the effective pressure times the $CH_4$ abundance, in the reflecting layer approximation. For homogeneous scattering, it is proportional to the effective pressure times the $CH_4$ abundance along a scattering

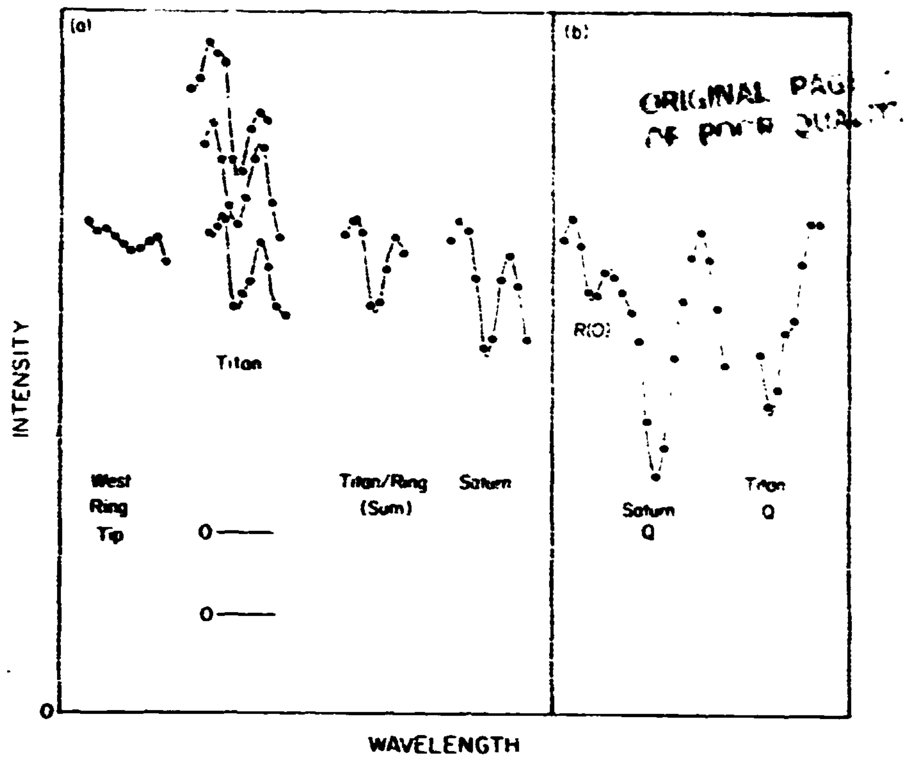


*Figure 1. (a) The R(5) manifold (10973Å) of Titan's $3\nu_3$ $CH_4$ band at a resolution of 4.0 Å. Three independent observations of this manifold are shown. The telluric $H_2O$ absorption is indicated by the scan of the west ring tip. The first channel corresponds to the first channel of the lowest Titan spectrum. The scale is 1.3Å/ch. (b) Comparison of a segment of Titan's Q branch of the $3\nu_3$ $CH_4$ band (11054Å) with Saturn's Q branch at a resolution of 6.6Å. As for the R(5) manifold the strength is about two thirds of that of Saturn's features, assuming a symmetrical profile. The scale is 2.0Å/Ch.*

mean free path (since in scattering models lines move over to the square root regime of the curve of growth for smaller values of the equivalent width [Chamberlain, 1970]). In a third paper, I analyzed the equivalent width of the R(5) manifold to obtain at least 1600 m-A for the pure $CH_4$ case in the reflecting layer approximation (Trafton, 1975a).

The figure 1600 m-A is a lower limit for the bulk atmosphere in this approximation. If there is less $CH_4$ than this, there is an even greater proportion of some other gas present. This figure can be greater if the local continuum in the center of the manifold is higher than in the wings (because of possible blending with neighboring features). The figure is not likely to be much less owing to superposition of some unidentified absorption at the same wavelength as the R(5) manifold because the absorption at this wavelength in Titan's spectrum relative to that in Saturn's spectrum is in essentially the same proportion as the Q branches. I have since discovered that telluric OH emission from the $P_1(3)$ doublet occurs in the blue wing of the R(5) manifold and may raise the local continuum and, hence, the derived equivalent width. The agreement, however, of the shapes of the R(5) manifold between Titan and Saturn indicates that the correction for this is small. Consequently, 1600 m-A remains essentially unchanged as the *lower limit* to Titan's *visible* (1.1 μm) *bulk atmosphere* or as a rough *upper limit* to Titan's spectroscopically *visible $CH_4$ abundance*, according to the reflecting layer approximation.

A more serious objection would be the invalidity of the reflecting layer model when the presence of significant scattering has been demonstrated. A scattering analysis has not yet been attempted which includes the $3\nu_3$ $CH_4$ band. I estimate on the basis of Titan's low albedo and whole-disk contribution to the spectrum that an analysis of the equivalent width of the R(5) manifold using a homogeneously scattering model atmosphere will yield a pressure-abundance product comparable with that using a reflecting layer model. But now abundance refers to the specific abundance and pressure to the effective level of line formation. [A crude analysis along these lines is given in Hunten's paper above].

My third point is that at sufficiently low pressures, or for sufficient haze, Titan's infrared $CH_4$ bands may show a pressure dependence after all. Chamberlain (1970) has shown that absorption lines depart from the linear portion of the curve of growth for smaller values of the equivalent width in a scattering atmosphere than in a clear one. This is a consequence of the "random walk" character of photon scattering, and the effect increases with the mean number of scatterings.

Figure 2 compares the 0.9 μm and 1 μm $CH_4$ bands of Titan and Saturn. It shows that the regions of high absorption are anomalously weak in Titan's spectrum. This point is reinforced in Figure 3 which plots the mean transmission over a small wavelength interval for Titan vs that for Saturn. The mean transmission is defined to be the residual intensity (relative to the apparent local continuum) averaged over a small wavelength interval. Since a given mean transmission may occur at several wavelengths within the band complex, it is surprising that a curve rather than an area results from such plots. I have interpreted this behavior both in terms of an elevated haze layer (Trafton, 1973a) and as differences in the region of the curve of growth on which Titan's and Saturn's bands lie (Trafton, 1975b). An argument that pressure does play some role is that in spite of the significant differences between Jupiter's and Saturn's haze distributions, their $CH_4$ spectra are remarkably similar compared to the difference between Titan and Jupiter, or Titan and Saturn. It is difficult to imagine an aerosol

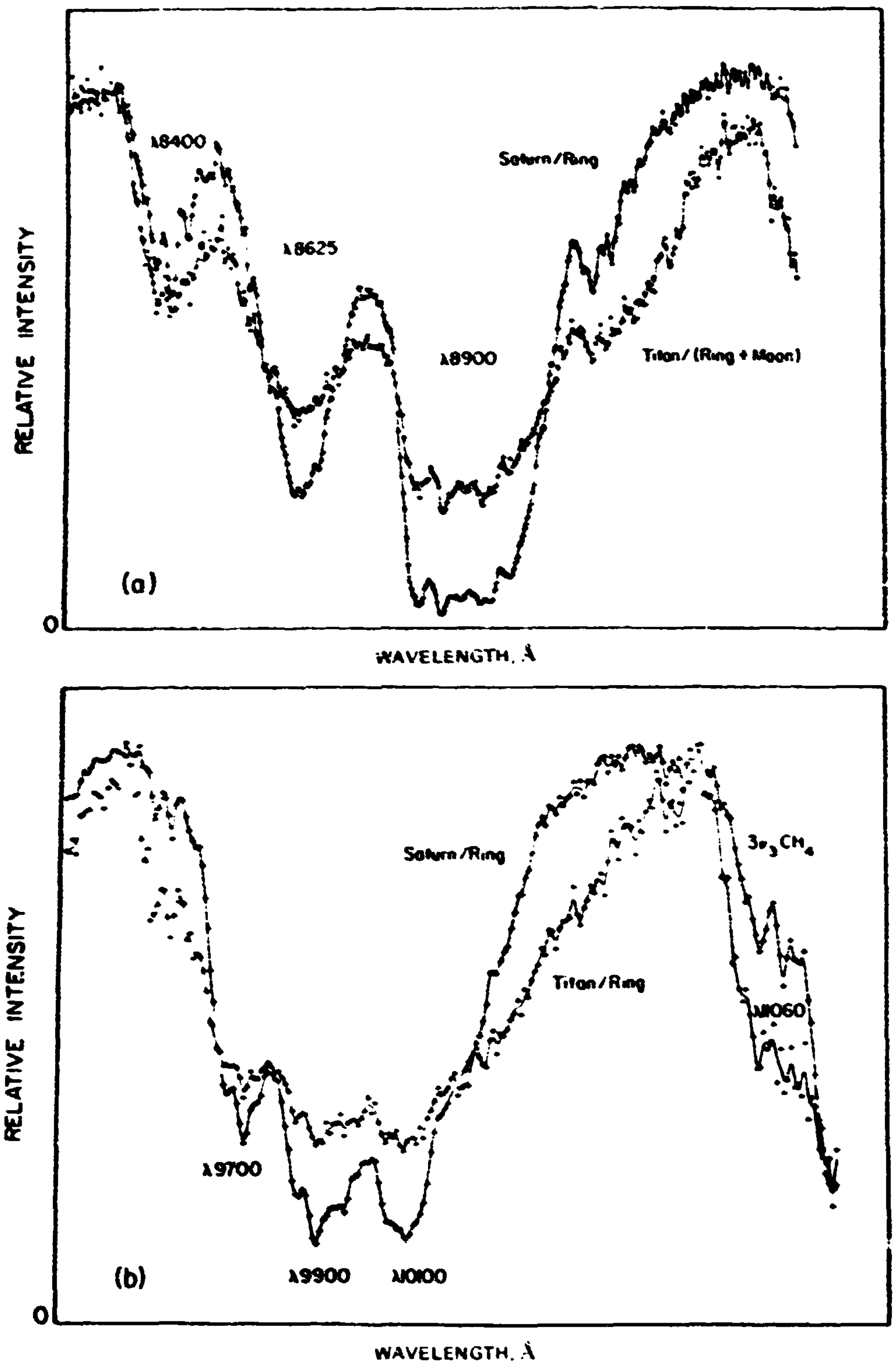


*Figure 2* Comparative spectra of Titan and Saturn. (a) The 0.9 μm band complex. The resolution element is 9 Å. (b) The 1 μm band complex. The resolution element is 35 Å.

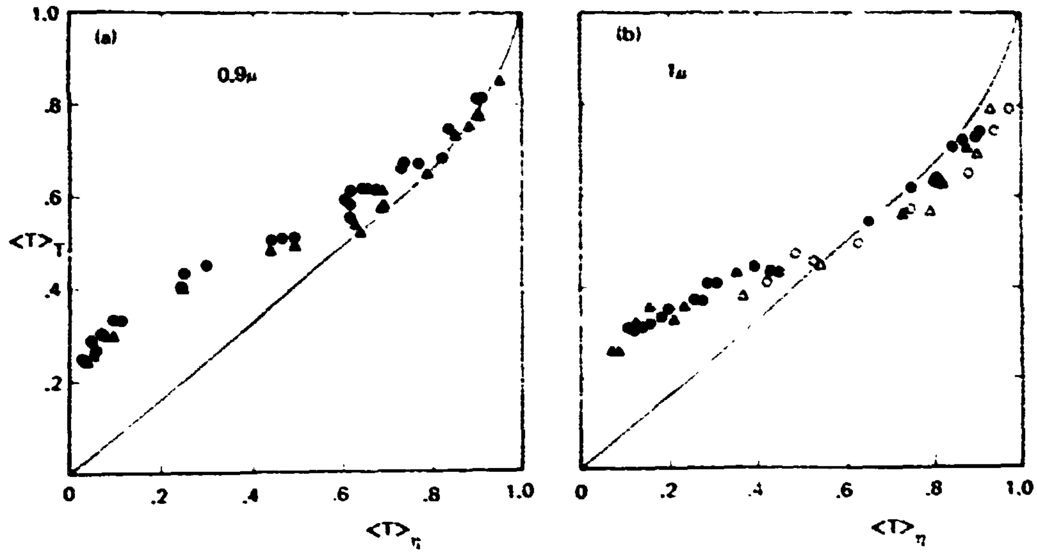


*Figure 5. Plots of Titan's band transmission vs Saturn's band transmission. Transmission is defined to be the residual intensity averaged over the resolution element. The circles and triangles correspond to different observations independently reduced (Trafton, 1975b). Each planetary spectrum was taken relative to a lunar or Ring spectrum to remove telluric features and vignetting effects. The solid line corresponds to the behavior of a reflecting layer model for band absorption illustrating the departure of Titan from this model. (a) The 0.9 μm $CH_4$ bands. (b) The 1 μm $CH_4$ bands. The open symbols denote points in the longer wavelength wing of the 1 μm band. The deviant behavior of the open symbols indicates that another gas is absorbing in the red wing of the 1 μm band complex.*

distribution on Saturn which might duplicate Titan's band morphology. Of course, now that $CH_4$ absorption coefficients are available, the sensitivity of $CH_4$ band shapes to aerosol distribution should be tested using model atmospheres to determine whether the haze distribution suffices to explain the band shapes.

My fourth point concerns the existence of the 8151 Å feature in Titan's spectrum. Although Münch *et al.* (1977) have used higher resolution than I have, their spectra are too noisy to reveal the weak telluric $H_2O$ line at 8151.3 Å which should be visible at their resolution and is visible in my lower-resolution spectra having higher signal to noise ratio (Trafton, 1975a). They may have therefore underestimated the upper limit on the $H_2$ abundance. I feel that an upper limit of about 2 km-A is more appropriate.

It is important to remember that the existence of a feature at this wavelength does not necessarily mean it arises from $H_2$. There are a number of unidentified lines in Titan's spectrum near 1.06 μm (Trafton, 1974) and the responsible gas might conceivably absorb at 8151 Å. Giver and Podolak (1977) have shown that long-path $CH_4$ spectra reveal many lines in this region so $CH_4$ cannot be ruled out as the source of the feature visible in my spectra of Titan. The same instrument has detected the slightly stronger (5mÅ vs Münch's *et al.* upper limit of 3 mÅ for $S_3(1)$ on Titan) S(1) line of the (5–0) band of $H_2$ in Uranus' spectrum (Trafton, 1978). I still believe there is an absorption feature at or close to this wavelength; the question is from what gas does it arise?

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