Titan's Upper Atmosphere: Structure and Ultraviolet Emissions

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The Voyager 1 ultraviolet spectrometer (UVS) solar occultation and airglow data obtained during the Titan flyby are analyzed for composition and thermal structure of the upper atmosphere and relative importance of airglow excitation processes. From optical depth profiles inferred by Smith *et al.* (1982, *J. Geophys. Res.* 87, 1351–1359) for the evening terminator, the entrance occultation, an asymptotic temperature of $T_{\infty} = 175$ K, and a CH_4 mixing ratio increasing from 0.06 ± 0.01 at 1000 km to 0.20 ± 0.02 at 1400 km are derived. The optical depth profiles are not of sufficient accuracy to extrapolate and accurately infer the tropopause CH_4 mixing ratio, but our preference is for high values ~ 0.026 – 0.034 . The homopause occurs high in the atmosphere (~ 1000 km) with an eddy diffusion coefficient $K_0 \sim (4\text{--}8) \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$ at this level and an approximate altitude dependence $K = K_0 \exp(\zeta/1.6)$, where ζ is the normalized geopotential height.

From the shape of the observed bright limb profile for N_2 emission (924–998 Å) the magnetospheric power dissipation is, at most, 10% of the solar EUV power input to Titan's extended atmosphere ($= 2 \times 10^9$ W for $\lambda < 800$ Å) and consistent with our estimates of magnetospheric power delivered to the ionopause by curvature drift of thermal and suprathermal electrons. This value of magnetospheric power input is a factor of 25 lower than the original estimate of Strobel and Shemansky (1982, *J. Geophys. Res.* 87, 1361–1368). Our calculated absolute intensities for the N^+ (1085 Å) multiplet are consistent with the UVS observed intensities after downward revision by the Holberg *et al.* (1982, *Astrophys. J.*, 257, 656–671) inflight calibration scheme, whereas the calculated N_2 c'_4 (0–0, 958 Å) plus (0–1, 981 Å) band intensities (the 970-Å feature) are only $\sim 50\%$ of the observed values. The nonthermal N atom escape rate is estimated to be $\leq 10^{25} \text{ sec}^{-1}$.

An upper limit on the tropopause Ar mixing ratio of 0.14 is derived from a comparison of the calculated relative intensities of

the Ar resonance lines at 1048 and 1067 Å with the N^+ (1085-Å) multiplet to the observationally inferred upper limit of 0.5. © 1992 Academic Press, Inc.

1. INTRODUCTION

The structure of Titan's thermosphere depends almost exclusively on the interpretation of data obtained by the Ultraviolet Spectrometer Experiment (UVS) on the Voyager 1 spacecraft during its Titan flyby in November 1980 (Broadfoot *et al.* 1981, Smith *et al.* 1982). In contrast, the thermal structure of the troposphere and stratosphere is derived from Voyager IRIS and radio occultation data (Lellouch *et al.* 1989). The connection between the upper stratosphere and the thermosphere is weakly constrained by groundbased observations of Titan's occultation of 28 Sagittarii (Hubbard *et al.* 1990, Sicardy *et al.* 1990) and must rely on the detailed, physically based radiative transfer model of Yelle (1991).

Broadfoot *et al.* (1981) and Strobel and Shemansky (1982) interpreted EUV emissions observed by the UVS as electron impact excitation of N_2 in the upper thermosphere due primarily to precipitation of magnetospheric electrons in Titan's sunlit hemisphere and estimated a power dissipation of $\sim 5 \times 10^9$ W. In a recent paper Strobel *et al.* (1991) calculated the disk center and bright limb intensities of N_2 and N^+ UV emission features due to solar and photoelectron excitation of N_2 . When they adopted the inflight calibration scheme developed by Holberg *et al.* (1982, 1991) which yielded a downward revision of the

originally reported intensities below 1100 Å by a factor of ~ 1.6 , they found that the N^+ (1085-Å) multiplet and the N_2 LBH intensities could be explained by solar and photoelectron excitation of N_2 . This would imply that magnetospheric electrons play only a minor role in Titan's UV airglow. However, if the bright 970-Å feature is mostly N_2 c'_4 -band emission, then the calculated photoelectron excitation rate is only 40% of the observed intensity and would suggest that magnetospheric electrons contribute significantly to the observed EUV emission.

In this paper we extend the study of Strobel *et al.* (1991) to explicitly estimate the power dissipation by magnetospheric electrons in Titan's upper atmosphere in a manner similar to the analysis of Strobel *et al.* (1990) for Triton's upper atmosphere. With this estimated power dissipation rate, magnetospheric electron excitation rates of N_2 are calculated for Titan by the same method used by Strobel *et al.* (1991) for Triton. The resulting disk center and bright limb intensities for the most important nitrogen airglow features are computed based on energetic magnetospheric electron fluxes observed during the Titan flyby (Hartle *et al.* 1982), MacLennan *et al.* 1982).

We discovered that the model thermosphere given in Smith *et al.* (1982) was not consistent with the observed optical depth profiles given in their Fig. 3. Thus the first task was to derive a new model thermosphere which smoothly joins the Yelle (1991) Model-A pressure and the temperature profiles at lower altitudes and has tangential optical depths in agreement with those inferred from the UVS solar occultation data by Smith *et al.* (1982).

2. MODEL ATMOSPHERE

Optical depths at six wavelengths, as a function of radial distance from the center of Titan ($r_T = 2575$ km is the surface) for the entrance occultation at the evening terminator, were digitized from Fig. 3 of Smith *et al.* (1982). Each profile represents the effective optical depth averaged over 9.26 Å whose central value is the indicated wavelength. The optical depth at 725 Å was assumed to be due solely to N_2 absorption by Smith *et al.* (1982), although as we shall show CH_4 contributes significantly. Methane absorption contributes also to the optical depths at 928, 1114, 1151, and 1373 Å, whereas the optical depth at 1540 Å must be due to other hydrocarbons and organic molecules, such as C_2H_x hydrocarbons and simple nitriles. In addition these molecules will contribute to the observed optical depths at shorter wavelengths. However, based on the photochemical model of Yung *et al.* (1984) and hydrocarbon absorption cross sections given in Table I, most of the opacity in the 928, 1114, 1151, and 1373-Å channels should be due to CH_4 . The cross sections in Table I are derived from the database used by the Voyager UVS team to analyze occultation data. It should be noted

that N_2 exhibits band structure in absorption at 725 Å and from low spectral resolution data one infers an average cross section over the 9.26-Å channel of 3.5×10^{-17} cm². If the individual rotational lines in these bands are extremely narrow, this average cross section is too large and the underlying continuum cross section will be more appropriate. Smith *et al.* (1982) used the continuum value to infer the reference N_2 density at $z = 1265$ km ($r = 3840$ km), and this value was used in our analysis.

Based on the authors' experience with UVS solar occultation data from other encounters, optical depths, τ , are most accurately inferred in the interval of 0.15–1.9. Thus the four channels, 725, 928, 1114, and 1151, yield the most reliable information on composition, density, and temperature in the range $z = 925$ –1325 km ($r = 3500$ –3900 km).

A background model atmosphere for N_2 density and temperature profiles was constructed based on the Lellouch *et al.* (1989) model atmosphere for the troposphere and stratosphere with the Yelle (1991) Model A pressure and temperature profiles imposed at $z = 293$ km to represent the mesosphere and lower thermosphere. The upper thermosphere is described by the Bates' (1959) temperature expression with the asymptotic temperature (T_∞) constrained by the UVS optical depth profiles. A model atmosphere with $T_\infty = 185.4$ K yields tangential N_2 column densities which with the N_2 continuum absorption cross section of 2.5×10^{-17} cm² accurately fits the inferred optical depth profile at 725 Å if the atmosphere were devoid of hydrocarbons.

To model the CH_4 mixing ratio the analytic expression of Steiner and Bauer (1990) was adopted,

$$f_{CH_4} = \frac{A}{[N_2]_0} \{1 + \exp(\zeta(1 - \kappa))\}^{(3/(7(1-\kappa)))} + \frac{7\phi N}{3K_0[N_2]_0}, \quad (1)$$

where $\zeta = 1.76 \times 10^5$ km $\cdot (z - z_0)/(r_0(r_T + z))$ is the normalized geopotential height measured relative to the homopause ($r_0 = r_T + z_0$), A is an integration constant, $[N_2]_0$ is the N_2 density at the homopause, ϕ is the upward flux of CH_4 referenced to Titan's surface, H is the scale height of the atmosphere, and $K = K_0 \exp(\kappa\zeta)$ is the vertical eddy diffusion coefficient with magnitude K_0 at the homopause.

Vertical mixing rates in Titan's upper atmosphere are inferred from boundary conditions on the CH_4 and the sum of the heavier hydrocarbons' mixing ratios at the tropopause and at $z = 1125$ km in the thermosphere. The basic approach and methodology were developed in Smith *et al.* (1982), who derived the homopause location at $z_0 = 925 \pm 70$ km, with $K_0 = 1^{+2.7}_{-0.7} \times 10^8$ cm² sec⁻¹. They suggested that the vertical eddy coefficient decreases with altitude as $\sim [N_2]^{-0.67}$. In a more detailed analysis with photochemistry using the same boundary conditions Yung

TABLE I
Absorption Cross Sections Used in Optical Depth Calculations

Channel wavelength (Å)	Absorption cross sections (10^{-17} cm ²)				
	$\sigma(\text{N}_2)$	$\sigma(\text{CH}_4)$	$\sigma(\text{C}_2\text{H}_2)$	$\sigma(\text{C}_2\text{H}_4)$	$\sigma(\text{Ar})$
725	2.1 ¹				
	3.5 ²	4.0	3.5	6.3	3.6
	~0				
928	0	5.4	4.0	5.2	0
1114	0	1.8	1.8	1.8	0
1151	0	1.7	1.5–11	1.5	0
1373	0	0.3	0.4	1.5	0

¹ Continuum cross section.

² Averaged cross section over 9.26-Å channel.

et al. (1984) found that the vertical eddy diffusion coefficient increased with height as $[\text{N}_2]^{-0.5}$, up to a homopause located at $z_0 = 680$ km with constant $K = 1 \times 10^6$ cm² sec⁻¹ above it. Steiner and Bauer (1990) repeated the analysis of Smith *et al.* (1982) and inferred an eddy diffusion coefficient proportional to $[\text{N}_2]^{-0.51}$ and equal to 1×10^6 cm² sec⁻¹ at an inferred homopause $z_0 = 660$ km.

With the homopause inferred by Smith *et al.* (1982) at $z_0 = 925$ km ($r_0 = 3500$ km), $K_0 = 2 \times 10^8$ cm² sec⁻¹ in our adopted model atmosphere. With $\kappa = 0$, a constant K profile, expression (1) becomes, for the CH_4 mixing ratio in the Smith *et al.* (1982) model,

$$f_{\text{CH}_4} = 0.020\{1 + \exp(\zeta)\}^{3/7} + 0.006, \quad (2)$$

and Fig. 1 illustrates how well the resulting model atmosphere fits the inferred optical depths. A close examination of Fig. 1 reveals that the only real agreement is in a small altitude region (near $z = 1125$ km, $r = 3700$ km) for the channels 928, 1114, 1151, and 1373 Å whose optical depths are dominated by CH_4 opacity. Based on the absorption cross sections in Table I and the inferred optical depths, one can conclude that the channels dominated by CH_4 are not internally consistent, in particular the channel 1114-Å optical depth appears to be 50% larger relative to what would be expected based on the other channels. Smith *et al.* (1982) preferred channel 928 Å where the CH_4 absorption cross section is three times larger than channels 1114 and 1151 Å to infer its density profile. The predicted optical depth profile at 725 Å exceeds significantly the observations due to the CH_4 contribution. The contribution by only N_2 would yield almost a perfect fit to the data, which was the assumption that Smith *et al.* (1982) used to infer the N_2 density and temperature at $z = 1165$ km ($r = 3840$ km).

The contributions of the higher hydrocarbons C_2H_x were included with the Steiner and Bauer expression,

$$f_{\text{C}_2\text{H}_x} = B\{[1 + \exp(\zeta(1 - \kappa))]^{-1/(14(1 - \kappa))} - 1\}, \quad (3)$$

with $B = -0.1$ and $\kappa = 0$. Whereas this expression yields heavier hydrocarbon mixing ratios greater than 1% above 3600 km, it clearly underestimates their observed mixing ratio in the lower stratosphere by a factor of 10^4 .

In Fig. 2 the optical depth profiles corresponding to the Steiner and Bauer (1990) model atmosphere are compared with the inferred UVS optical depths. (Note that for eddy diffusion to equal molecular diffusion at the homopause, $z_0 = 660$ km, in our adopted model atmosphere $K_0 = 2 \times 10^6$ cm² sec⁻¹, with $\kappa = 0.51$.) The fit to channels 928 and 1151 Å is significantly better than the Smith *et al.* (1982) model atmosphere in Fig. 1, but the calculated optical depth profile at 725 Å is still larger than the data, indicative of too large N_2 densities in the upper thermosphere. Also

FIG. 1. Comparison of calculated and observationally inferred optical depth profiles for indicated wavelength channels in angstroms at evening terminator, entrance occultation. Large symbols denote data and small symbols connected by lines denote calculations with the Smith *et al.* (1982) model atmosphere.

FIG. 2. Same as Fig. 1, but for the Steiner and Bauer (1990) model atmosphere.

the slope of the calculated optical depth profiles at 928, 1114, and 1151 Å is shallower than the data, which is also true for the Smith *et al.* (1982) profiles. While both models satisfy the observational constraint at $z = 1125$ km ($r = 3700$ km), neither captures the essentially constant mixing ratio implied by the data between $z = 925$ – 1125 km and the smaller CH_4 scale height implied above $z = 1125$ km than appropriate for CH_4 in diffusive equilibrium.

To obtain a substantially better fit to the inferred optical depths, there are three essential requirements: (1) CH_4 must be mixed to higher altitudes which implies a larger eddy diffusion coefficient at the homopause which is located at a higher altitude in the atmosphere than previously thought, (2) the CH_4 mixing ratio at the tropopause must be higher than 0.017 as adopted by Steiner and Bauer (1990) in order to obtain the quasi-mixed distribution below $z = 1125$ km, at which level the CH_4 mixing ratio is $\sim 8\%$, and (3) the asymptotic isothermal temperature, T_∞ , must be lower than 185.4 K to lower the N_2 density in the upper thermosphere.

Three additional model atmospheres were produced to illustrate these requirements. In addition, argon was introduced in the model atmospheres to satisfy the constraint on mean molecular mass ($27.8 < \bar{m} < 29.3$ amu) inferred by Lellouch *et al.* (1989). The first model atmosphere has a temperature profile with $T_\infty = 172$ K, homopause $z_0 = 985$ km with $K_0 = 4 \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$, $\kappa = 0.625$, tropopause CH_4 and Ar mixing ratios = 0.026 and 0.014, respectively, $\bar{m} = 27.8$ amu, CH_4 and Ar mixing ratios given by

$$f_{\text{CH}_4} = 0.02\{1 + \exp(0.325\zeta)\}^{3/7(1-\kappa)} + 0.006 \quad (4a)$$

$$f_{\text{Ar}} = 0.014\{1 + \exp(0.325\zeta)\}^{-0.3/(1-\kappa)}, \quad (4b)$$

and $B = -0.1$ in expression (3) for $f_{\text{C}_2\text{H}_2}$. As shown in Fig. 3, this model atmosphere yields optical depth profiles

with slopes that are a significant improvement over the previous two models in channels dominated by CH_4 absorption, but is slightly too opaque at 725 Å. The improvement in the fit to channel 1373 Å is primarily due to the adoption of the relative proportions of C_2H_2 and C_2H_4 from the Yung *et al.* (1984) photochemical model to obtain an average cross section of $1.1 \times 10^{-17} \text{ cm}^2$ for this channel rather than the assumption of pure C_2H_2 for the C_2H_x mixing ratio.

The second model atmosphere is constrained by the upper limit on the tropopause temperature, 74.5 K, which limits the stratospheric CH_4 mixing ratio to at most 0.034 (Samuelson *et al.* 1981, Lellouch *et al.* 1989). The inferred atmosphere has $T_\infty = 175$ K. The temperature difference from the previous model with $T_\infty = 172$ K is not significant, but the slightly larger T_∞ ensures that the derived thermosphere merges smoothly with the adopted lower model atmosphere at $z = 900$ km. The homopause is now at $z_0 = 1035$ km, $K_0 = 8.4 \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$, $\kappa = 0.625$, tropopause Ar mixing ratio = 0.136, and $\bar{m} = 28.7$ amu. Expressions (4) for CH_4 and Ar become

$$f_{\text{CH}_4} = 0.024\{1 + \exp(0.325\zeta)\}^{0.69} + 0.01 \quad (5a)$$

$$f_{\text{Ar}} = 0.136\{1 + \exp(0.325\zeta)\}^{-0.48}. \quad (5b)$$

The calculated optical depth profiles for this model atmosphere are shown in Fig. 4 and indicate an excellent fit to the 725-Å channel. The data point at $z = 1125$ km, where τ (725 Å) = 3.4 corresponds to weak transmission of sunlight through Titan's atmosphere ~ 0.03 , and actually may be scattered light in the spectrometer, which was a substantial problem as discussed by Smith *et al.* (1982), and accordingly not weighted heavily in this analysis. Likewise the data point for channel 1373 Å at 825 km

FIG. 3. Same as Fig. 1, but for the 2.6% CH_4 , 1.4% Ar model atmosphere.

FIG. 4. Same as Fig. 1, but for the 3.4% CH₄, 13.6% Ar model atmosphere.

suffers from the same problem. The CH₄ channels are fit slightly better with this model than with the 2.6% CH₄ model in Fig. 3.

The last model considered also has $T_\infty = 175$ K, the homopause at $z_0 = 1125$ km, $K_0 = 2.6 \times 10^9$ cm² sec⁻¹, $\kappa = 0.625$, tropopause CH₄ and Ar mixing ratios of 0.05 and 0.1, respectively, and $\bar{m} = 28.2$ amu. Expressions (4) for CH₄ and Ar become

$$f_{\text{CH}_4} = 0.03\{1 + \exp(0.325\zeta)\}^{0.69} + 0.02 \quad (6a)$$

$$f_{\text{Ar}} = 0.1\{1 + \exp(0.325\zeta)\}^{-0.48}. \quad (6b)$$

This model, which violates the cold trap tropopause temperature, provides an equally excellent fit to the 725-Å channel as shown in Fig. 5 and yields a somewhat better fit to channel 1151 Å at the expense of a slightly worse fit

FIG. 5. Same as Fig. 1, but for the 5.0% CH₄, 10% Ar model atmosphere.

FIG. 6. Our preferred model atmosphere with $T_\infty = 175$ K, number density, and temperature as a function of altitude and pressure.

to the 928-Å channel when compared to the 3.4% CH₄ model in Fig. 4. In our opinion, all three models with $T_\infty \sim 172$ –175 K and CH₄ ~ 0.026 –0.05 are as close to the optimal fit as is worth pursuing in this study, given the quality of the analyzed data. The 3.4% model is probably overall a slightly better fit to the data. In Fig. 6 our preferred $T_\infty = 175$ K model atmosphere, consistent with the inferred $T_\infty = 176 \pm 20$ K by Smith *et al.* (1982), is illustrated and was used for the models in Figs. 4–5. Note that the number density profile is the sum of the N₂, CH₄, and Ar concentrations. In Fig. 7 the various Ar and CH₄ mixing ratio profiles are shown.

The value of K at the homopause, $K_0 = (0.4$ – $2.6) \times 10^9$ cm² sec⁻¹, is so extremely large that one might be tempted to regard it as ridiculous. If we attribute vertical mixing to saturation of internal gravity waves and adopt the pa-

FIG. 7. The volume mixing ratios of CH₄ and Ar as function of altitude for the indicated tropopause boundary values.

parameterization developed by Lindzen (1981), who derived the gravity wave induced eddy diffusion coefficient for momentum stresses at saturation, D_M , to be

$$D_M = \frac{m(\bar{u} - c)^4}{2H\delta^3 N^3} \left\{ 1 - \frac{3H}{(\bar{u} - c)} \frac{\partial \bar{u}}{\partial z} \right\}, \quad (7)$$

where m is the zonal wavenumber; $\bar{u}$ is the zonally averaged wind; c is the phase speed of the gravity wave, $\delta = (1 + l^2/m^2)^{0.5}$, l is the meridional wavenumber; and N is the buoyancy frequency $= 1.5 \times 10^{-3} \text{ sec}^{-2}$. From the dispersion relation the vertical wavenumber γ is given by

$$\gamma = \left[\left(\frac{\delta N}{\bar{u} - c} \right)^2 - m^2 \delta^2 - \frac{1}{4H^2} \right]^{1/2}. \quad (8)$$

This yields numerically a vertical wavelength of $\lambda_z \sim 200 \text{ km}$ or $\sim 2H$ in the thermosphere, for $\bar{u} - c \sim 60 \text{ m sec}^{-1}$, (an estimate based on Flasar and Conrath, 1990), $H \sim 100 \text{ km}$, $m \sim l \sim 2\pi/(500 \text{ km})$, and $\partial \bar{u}/\partial z \sim 0$. For these values $D_M \sim 1 \times 10^9 \text{ cm}^2 \text{ sec}^{-1}$ and $K = D_M/P_r$, where P_r is the eddy Prandtl number (Strobel 1989). Thus with an eddy Prandtl number $\sim 2-3$ (cf. Fritts and Dunkerton 1985, Strobel *et al.* 1985) one obtains the inferred values of K at the homopause $\sim (3-5) \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$. Note that $\gamma H > 1$, so that the gravity waves are hydrostatic and the dispersion relation (8) is valid.

The $\lambda_z \sim 1 \text{ km}$ gravity waves derived by Hinson and Tyler (1983) from intensity and frequency fluctuations observed during the Voyager 1 radio occultation of Titan's equatorial troposphere are probably forced in the troposphere, e.g., by convection, in the presence of considerably weaker $\bar{u} - c$ near the surface, perhaps $\sim 1 \text{ m s}^{-1}$. These small scale gravity waves, however, cannot propagate upward into strong stratospheric zonal winds aloft (Flasar and Conrath (1990) because γ^2 becomes < 0 and these waves become evanescent; i.e., they are trapped in the troposphere. Only larger scale gravity waves can propagate to the homopause.

Based on the analytic expressions derived by Strobel *et al.* (1985) and Strobel (1989), the cooling/heating rate due to gravity wave saturation can be estimated by

$$H_{\text{gw}} = \frac{N^2 K_0}{2c_p} e^{\kappa \ell} (P_r - 6 + 7\kappa). \quad (9)$$

The heating rate depends very critically on the values of κ and P_r , for which the latter is poorly constrained by any data in Titan's atmosphere. For homopauses in the range $z = 925-1125 \text{ km}$ with $\kappa = 0.625$ and $P_r \sim 2$, gravity waves heat the thermosphere by an amount $H_{\text{gw}} \sim 1.5-9 \text{ K day}^{-1}$ (corresponding respectively to the altitude range 925-

1125 km), which is approximately 0.2 times the solar heating rate (Yelle 1991). Although not negligible, gravity wave saturation does not have to dominate the heat balance of the thermosphere even with an eddy coefficient as large as $10^9 \text{ cm}^2 \text{ sec}^{-1}$ at the homopause, if $P_r > 1$. To be more explicit $H_{\text{gw}} = 0$, when $\kappa = 0.5$ and $P_r = 2.5$ and when $\kappa = 0.625$ and $P_r = 1.5$.

3. ENERGY SOURCES

For the level of solar activity at the time of the Voyager 1 encounter with Titan, the appropriately scaled Hinteregger *et al.* (1981) reference solar EUV fluxes predict a total solar power input to Titan's thermosphere of $3 \times 10^9 \text{ W}$ for wavelengths below $1050 \text{ \AA}$ and $2 \times 10^9 \text{ W}$ for wavelengths below $800 \text{ \AA}$.

Our description of the interaction of magnetospheric plasma with Titan's upper atmosphere is based on the plasma properties summarized by Neubauer *et al.* (1984). In particular, the plasma consists of H^+ , with density $= 0.1 \text{ cm}^{-3}$, and N^+ , with density $= 0.2 \text{ cm}^{-3}$, for a total electron density of 0.3 cm^{-3} . The Maxwellian core of the electron distribution function has a characteristic temperature of 200 eV with a suprathermal tail represented by a temperature of 1 keV and a density of 0.01 cm^{-3} . For electron energies greater than 20 keV , the energy flux is negligible in comparison to the keV suprathermal tail (MacLennan *et al.* 1982) and would penetrate deep into the UV absorbing hydrocarbon region of Titan's upper atmosphere. The measured plasma flow speed was 120 km sec^{-1} , slower than the corotational velocity, 200 km sec^{-1} . Titan's orbital velocity is 5.57 km sec^{-1} . From these quantities an Alfvén Mach number of 1.8 and an Alfvén conductance of $\sim 4.5 \text{ mho}$ are derived. Based on models for Titan's upper ionosphere (e.g., Ip 1990) the ionospheric Pedersen conductivity was estimated to be $\sim 4500 \text{ mho}$ with a peak value of $\sim 0.01 \text{ mho m}^{-1}$ near the exobase, $z \sim 1500 \text{ km}$. With the ratio of Alfvén conductance to ionospheric conductivity only $\sim 10^{-3}$, direct convection of plasma into the ionosphere is improbable for reasons discussed by Hill *et al.* (1983). The principal mechanism for entry of energetic particles into Titan's extended atmosphere will be curvature drift toward lower altitudes as the curved magnetospheric flux tubes flow past Titan as argued by Hartle *et al.* (1982).

The curvature drift speed is $V_D = (cm_e v_{\parallel}^2)/(eR_{\text{Curv}}B)$, where m_e is the electron mass, $v_{\parallel}$ is the velocity parallel to the magnetic field $\mathbf{B}$, e is the electron charge, and R_{Curv} is the radius of curvature of the draped field lines. The radius of curvature is assumed equal to the radius of the ionopause, R_i . The inward drift per pass through the exosphere is $\delta = V_D(\pi R_{\text{Curv}}/v_{\parallel}) \sim (cm_e v_{\parallel} \pi)/(eB)$. The ionopause is defined for our purposes as the altitude where the drift time of flux tubes slowed down by mass loading is

comparable to the time constant for frictional drag $\tau_f \sim \nu_{in}^{-1}$, where ν_{in} is the ion-neutral collision frequency. From the inferred density profile in Titan's upper atmosphere, the ionopause is located at $R_i \sim 4400$ km, a result identical to Hartle *et al.* (1982). The total drift distance $d = 2\delta\tau_D/\tau_B$, where τ_D is the drift time of a flux tube through the atmosphere (~ 900 sec) and τ_B is the bounce period (~ 70 – 500 sec for electron energies in the 0.2–10 keV range). Curvature drift speeds vary from ~ 20 km sec $^{-1}$ at 0.2 keV to ~ 900 km sec $^{-1}$ at 10 keV. Over the same energy range the inward drift per pass varies from 30 to 200 km, whereas the total drift distance increases from 180 to 8700 km.

Based on derivations presented in Strobel *et al.* (1990) for Triton's magnetosphere-ionosphere interaction, the power, P_m , delivered to Titan's ionopause is given by the expression

$$P_M = 1.6 \times 10^{-6} \pi R_i \int_{0.1}^{10} 4\pi \Phi(E) E \delta(E) dE, \quad (10)$$

where $\Phi(E)$ is the measured electron flux in units of cm $^{-2}$ sec $^{-1}$ sr $^{-1}$ keV $^{-1}$, the energy E is in keV, $\delta(E)$ is in km, and R_i is in km. For the adopted plasma properties this expression yields an input magnetospheric power of 2.3×10^8 W to the hemisphere into which the electrons drift (the direction given by the vector $-\mathbf{R}_{curv} \times \mathbf{B}$). At the time of the Voyager 1 flyby of Titan this hemisphere essentially coincided with the sunlit hemisphere. The magnetospheric power is $\sim 7 \times 10^7$ W in the thermal range (< 0.7 keV) and $\sim 1.6 \times 10^8$ W in the suprathermal range (0.7–10 keV). To obtain a much larger magnetospheric power dissipation rate would require depletion of the energy content of all flux tubes which intersect Titan's extended atmosphere by direct convective flow. Then $P_M \sim 5 \times 10^9$ W could be achieved, but we consider this scenario extremely improbable.

4. CALCULATION OF ULTRAVIOLET EMISSIONS

Atmospheric excitation rate calculations by direct absorption of solar photons and indirectly by photoelectrons were performed with the photoelectron model of Strickland and Meier (1982) updated with more recent cross sections as described in Strickland *et al.* (1989). Magnetospheric electron transport and energy deposition on Titan were modeled with the auroral code developed by Strickland *et al.* (1989) for the Earth with the assumptions of a pure N $_2$ atmosphere and tangential penetration as discussed by Strobel *et al.* (1990) in the context of magnetospheric-ionospheric interaction on Triton. Updated cross sections for N $_2$ emission rates were adopted from Ajello *et al.* (1989) and James *et al.* (1990). The emission rates for the N $^+$ multiplets at 916 and 1085 Å by photodissociative ionization via the dissociative H state of N $_2^+$ were calcu-

lated with yields of 0.042 and 0.184 based on the laboratory and observational analyses of Meier *et al.* (1991). These calculations were performed as a function of N $_2$ column density and transformed to the model atmosphere shown in Fig. 6. Although the total inelastic energy loss for electrons and EUV photon flux attenuation ($\lambda < 800$ Å) were computed as if the atmosphere were pure N $_2$, the resulting atmospheric excitation rates calculated for a pure N $_2$ atmosphere were then multiplied by the tropopause N $_2$ mixing ratio ($= 1 - f_{CH_4} - f_{Ar}$ evaluated at the tropopause) to obtain the appropriate excitation rates in a three-constituent atmosphere. Solar radiation was assumed incident at 60° zenith angle to model airglow emission above the absorbing CH $_4$ region, whereas magnetospheric power was assumed to be dissipated uniformly over the hemisphere into which electrons were drifting which as discussed above coincided with the sunlit hemisphere.

Three model atmospheres were considered for the ultraviolet emission intensity calculations: (1) a pure N $_2$ atmosphere for reference purposes, (2) the 2.6% CH $_4$ model atmosphere representing the lower limit on CH $_4$ abundance to obtain a good fit to the Voyager UVS solar occultation data, and (3) the 3.4% CH $_4$ model atmosphere representing the upper limit on CH $_4$ abundance from IRIS data. The 5% CH $_4$ model atmosphere was not considered because it violated the IRIS constraint.

5. AIRGLOW RESULTS

From our calculations of a large number of N $_2$, N, and N $^+$ UV airglow excitation rates the intensities of the following emission features were selected for discussion: N $_2$ $c'_4 \Sigma_u^+$ Rydberg (0–0) and (0–1) bands, the N $^+$ multiplets at 916 and 1085 Å, and the N $_2$ LBH bands. The N $_2$ LBH bands are entirely due to electron impact and are essentially optically thin, with only weak absorption by CH $_4$. The N $^+$ multiplets are also optically thin and only the 916-Å multiplet is subject to significant absorption by N $_2$, because the 916.701- and 916.710-Å lines of the N $^+$ sextuplet (55% of the intensity) coincide with rotational lines of the N $_2$ $b^1\Pi_u$ (11–0) band [$J' - J'' = (4-5), (6-6), (8-7)$] and are absorbed with an effective cross section $\sim 2.9 \times 10^{-17}$ cm 2 at 180 K (Meier *et al.* 1991). The N $_2$ c'_4 (0–0) and (0–1) bands were chosen because they are the most prominent features of Titan's EUV emission. The strongest rotational line in the c'_4 (0–0) band reaches unit optical depth at line center when the N $_2$ column density is only $\sim 3 \times 10^{14}$ cm $^{-2}$ (Ajello *et al.* 1989). Also, the emission branching ratio for the (0–1) band is 0.14 from $c'_4 \Sigma_u^+$ ($v' = 0$) state. Thus a detailed interpretation of these c'_4 bands requires a radiative transfer analysis with optical thickness effects, predissociation, branching, etc., included, which is beyond the scope of this paper. An

TABLE II
Sources of Titan Nitrogen Airglow

Processes	Disk Center Emission Intensities ¹				
	N ⁺ (916Å) ^{2,3}	N ₂ (958Å) c ₄ '(0-0)	N ₂ (981Å) c ₄ '(0-1)	N ⁺ (1085Å) ³	N ₂ LBH
Observed(revised calibration)	0.6 R	8 R	6 R	8 R	96 R
Model 0% CH ₄					
• N ₂ + hν → N ₂ ⁺ (H)	2.0 R			8.4 R	
• photoelectrons + N ₂	0.2 R	9.0 R	1.5 R	2.2 R	94 R
• magnetospheric ⁴ e ⁻ + N ₂	<u>0.1 R⁵</u>	<u>2.0 R⁵</u>	<u>0.3 R⁵</u>	<u>0.8 R⁵</u>	<u>8.6 R</u>
Total	2.3 R	11 R	1.8 R	11 R	103 R
Model 2.6% CH ₄					
• N ₂ + hν → N ₂ ⁺ (H)	1.5 R			7.0 R	
• photoelectrons + N ₂	0.04 R	5.8 R	0.96 R	1.2 R	92 R
• magnetospheric ⁴ e ⁻ + N ₂	<u>0.09 R⁵</u>	<u>1.5 R⁵</u>	<u>0.3 R⁵</u>	<u>0.6 R⁵</u>	<u>8.2 R</u>
Total	1.6 R	7.3 R	1.3 R	8.8 R	100 R
Model 3.4% CH ₄					
• N ₂ + hν → N ₂ ⁺ (H)	1.3 R			6.0 R	
• photoelectrons + N ₂	0.02 R	5.0 R	0.8 R	1.0 R	78 R
• magnetospheric ⁴ e ⁻ + N ₂	<u>0.08 R⁵</u>	<u>1.4 R⁵</u>	<u>0.2 R⁵</u>	<u>0.5 R⁵</u>	<u>7.0 R</u>
Total	1.4 R	6.4 R	1.0 R	7.5 R	85 R

¹ Observations are slit-averaged intensities.

² Includes N₂ absorption.

³ Meier *et al.*(1991) with yields $\phi_{916} = 0.042$, $\phi_{1085} = 0.184$.

⁴ For power = 2.3×10^8 W.

⁵ Includes CH₄ absorption.

earlier, initial attempt by Conway (1983) indicated that strong mutual perturbations of the c₄' and b' states argued against detailed self-absorption calculations for band systems originating from these states.

5a. Disk Center Results

In Table II center-of-disk averaged calculations for the three model atmospheres are reported by specific process: solar excitation of the N₂⁺(H) state, photoelectron excitation, and excitation by precipitation of magnetospheric electrons and compared with the intensities given by Strobel *et al.* (1991) which are downward revisions of the original Strobel and Shemansky (1982) intensities. The absolute intensities from a reanalysis of the Voyager Titan EUV data by Hall *et al.* (1992) were not in final form to be used in this study. It should be kept in mind that

the "disk-averaged" intensities reported by Strobel and Shemansky (1982) were not really disk averaged but averaged over the UVS slit. The slit averaged intensities should be bounded by (0.67–1) times the calculated disk center intensities.

From Table II one concludes that a pure N₂ atmosphere yields intensities consistent with the observations in the limit of subsolar, center of the disk values. No formal error bars were put on the data by Strobel and Shemansky (1982) but in light of the revised calibration by Holberg *et al.* (1982, 1991), signal-to-noise, 30-Å spectral resolution, etc., error bars on bright spectral features of $\pm 50\%$ would not seem unreasonable. Given the low spectral resolution of the Voyager UVS, the inferred intensity of a weak narrow feature such as the N⁺(916 Å) multiplet is very uncertain and not much significance should be put on the differences between observations and calculations.

FIG. 8. Volume excitation rates in cubic centimeters per second as a function of altitude: (1) due to solar excitation via $N_2^+(H)$ state (s), (2) due to photoelectrons (p), and (3) due to magnetospheric electrons (m) for a pure N_2 atmosphere. (a) N^+ multiplets and (b) N_2 bands.

But the UVs solar occultation data requires $f_{CH_4} \sim 0.08$ at 1125 km and the impact of CH_4 on the emergent intensities is illustrated by the 2.6 and 3.4% model atmospheres in Table II. For emission features shortward of $Ly\ \alpha$ there is a 22–33% reduction in the calculated intensities for the 2.6% model and a 35–45% reduction for the 3.4% model. Even the LBH bands suffer a 17% decrease in intensity for the latter model. The intensity reductions result from the fractional decrease in the N_2 content of the atmosphere and absorption by CH_4 . The $N_2\ c'_4\ (0-0)$ and $(0-1)$ band intensities predicted for these models are too low when compared with observations, whereas the $N^+(1085\ \text{\AA})$ and N_2 LBH bands are consistent with observations. According to Hall *et al.* (1992) the N_2 LBH band intensities given by Strobel and Shemansky (1982) should be regarded as tentative and not given much weight.

5b. Volume Excitation Rates

To understand the contribution of CH_4 absorption to the disk center intensities the volume excitation rate profiles for the various emissions are instructive. The solar excitation of the $N_2^+(H)$ state peaks at ~ 975 km (Fig. 8a) and is the major source of $N^+(1085\text{- and }916\text{-}\text{\AA})$ multiplets as is evident from Table II. Photoelectron excitation of the LBH bands peaks at ~ 1000 km, but excitation of $N^+(916\text{-}\text{\AA})$ multiplet maximizes at ~ 725 km (Fig. 8). The latter excitation is dominated by soft X rays because dissociative ionization of N_2 and excitation of N^+ requires a threshold energy of 38 eV. Thus only the most energetic solar photons are capable of producing photoelectrons in excess of 38 eV and these photons are absorbed by N_2 with a significantly smaller cross section than the photons responsible for excitation of the $N_2^+(H)$ state and the photoelectrons that generate most of the LBH emission,

whose upper state has a threshold of only 8.5 eV. Electron impact excitation of the $N_2\ c'_4$ system and of $N^+(1085\ \text{\AA})$ from N_2 have respective thresholds of ~ 13 and 36 eV and thus are intermediate between the profiles for LBH and $N^+(1085\ \text{\AA})$. Excitation of these emission features by magnetospheric electrons is characterized by a peak at ~ 1350 km due to the Maxwellian core of the electron distribution function, with $T_e = 200$ eV and a lower peak at ~ 975 km due to the suprathermal tail of its distribution, with $T_e \sim 1$ keV as shown in Fig. 8. Photons emitted upward from the high altitude peak will not be absorbed by CH_4 , but photons emitted from the lower peak encounter a vertical CH_4 column density of $\sim 1 \times 10^{16}\ \text{cm}^{-2}$.

5c. Bright Limb Results

From the volume excitation rates presented in the previous section, it is straightforward to calculate bright limb profiles for three model atmospheres produced by the Sun at a 60° zenith angle and viewed by a spacecraft at a 90° angle to the Sun–Titan line. This geometry was selected to approximate the finite width of the UVS slit projected on Titan's atmosphere (~ 200 km) and the bias of preferential collection of photons emitted from the closer half of the sunlit hemisphere due to CH_4 absorption. Magnetospheric excitation was uniformly distributed over the sunlit hemisphere.

In Fig. 9 bright limb profiles are shown for direct solar plus photoelectron excitation in a pure N_2 atmosphere. Note that the limb profiles maximize at ~ 925 km, with the $N_2\ c'_4$ bands exhibiting a secondary maximum/ledge at ~ 750 km due to soft X rays. The equivalent limb profiles due to magnetospheric electron excitation are given in Fig. 9. The distinct signatures of thermal and suprathermal electrons are evident at 1300 and 900 km, respectively.

FIG. 9. Calculated bright-limb profiles as a function of altitude (1) due to solar/photoelectron excitation (*s*), (2) due to magnetospheric electron excitation (*m*), and (3) the sum of solar/photoelectron and magnetospheric electron excitation for a pure N_2 atmosphere (*s* + *m*).

The combined limb profiles from these two sources of excitation are presented in Fig. 9 and may be compared to the revised peak intensities based on Strobel and Shemansky (1982) of 2, 25, and 25 *R* for $N^+(916 \text{ \AA})$, $N_2 c'_4(0-0, 958\text{-}\text{\AA})$, plus $(0-1, 981\text{-}\text{\AA})$ bands, and $N^+(1085 \text{ \AA})$, respectively. It is evident from Fig. 9 that our calculations could easily account for the revised intensities and even the originally reported intensities, if predissociation can be neglected in the $N_2 c'_4$ system and Titan's atmosphere were pure N_2 .

The rather dramatic effect of CH_4 absorption can be seen by a comparison of Fig. 10a for the 2.6% CH_4 model atmosphere and Fig. 11 for the 3.4% CH_4 model atmosphere with Fig. 9. From Figs. 10 and 11 it is noted that CH_4 absorption eliminates the soft X-ray excitation signature evident in a pure N_2 atmosphere at ~ 750 km and reduces peak intensities by factors of 3–5. Also the peak intensities are produced ~ 50 – 100 km higher in altitude due to CH_4 absorption. An even more significant effect is evident in the limb profiles due to magnetospheric electron excitation where the dominant contribution of suprathermal electrons at 900 km (Fig. 9) is reduced to a weak ledge in the profiles of Figs. 10 and 11 at ~ 1150 km. Thermal electrons generate peaks at 1300 km (Figs. 10 and 11) which are comparable in intensity to those calculated for the pure N_2 atmosphere because the CH_4 model atmospheres are optically thin at this high altitude. The combined limb profiles from these two sources of excitation are presented in Figs. 10 and 11. When compared with Fig. 9, it is evident that CH_4 absorption reduces peak intensities by factors of 2–5 and displaces the predicted peaks upward by 75–100 km. If predissociation effects

were taken into consideration, the predicted $N_2 c'_4(0-0, 958 \text{ \AA})$ and $(0-1, 981 \text{ \AA})$ band intensities would be below the lower limits on the observed intensities, whereas the $N^+(1085\text{-}\text{\AA})$ intensities are within the observational error bars. Although the predicted $N^+(916\text{-}\text{\AA})$ intensities are in excellent agreement with observations, we don't regard this weak feature as a benchmark.

A further comparison of Figs. 9, 10a, and 11 indicates that the $N_2 c'_4(0-0, 958\text{-}\text{\AA})$ and $(0-1, 981\text{-}\text{\AA})$ band limb profiles contain two important signatures in their profile shapes. The ratio of peak intensity to the ledge intensity in the 700- to 800-km region (cf. Fig. 9) is indicative of the CH_4 absorption and hence its abundance in the upper atmosphere. Whereas the ratio of the peak intensity to the ledge intensity in the 1200- to 1300-km region is a measure of the ratio of excitation rates by photoelectrons to magnetospheric thermal electrons. To illustrate this latter point limb profile calculations were performed with the magnetospheric power dissipation increased by a factor of 3 for the 2.6% CH_4 model atmosphere. The profile is shown in Fig. 10b. Note that magnetospheric electrons produce a secondary maximum at 1300 km with intensity $\sim 90\%$ of the peak intensity at 1000 km. This shape is inconsistent with UVS observations and constrains the inferred magnetospheric power dissipation to be close to our estimates in Section 3.

Because this point is very important it is necessary to degrade the spatial resolution of the calculated limb profile by the finite UVS slit width (~ 200 km) projected on the limb with a computer program generously supplied by D. T. Hall and then to compare this with the observed limb profile illustrated in Fig. 2 of Hall *et al.* (1992). One ambiguity in this comparison is the actual location of peak bright limb emission to the apparent observed emission. Strobel and Shemansky (1982) reported the observed bright limb intensity peak for N_2 emission ($942\text{--}998 \text{ \AA}$) at $z \sim 1085$ km. Conway (1983) argued that the $N_2 c'_4$ bands should behave similarly to the N_2 BH bands that he modeled for Titan's upper atmosphere. According to Conway's calculations the limb brightening reported by Strobel and Shemansky (1982) for the $N_2 c'_4(0-0)$ band implies an excitation source at $z \geq 1400$ km in contradiction to the reported altitude peak of $z \sim 1085$ km. Another attempt to locate the peak limb emission indicated that it occurred at $z \sim 1325$ km (Hunten *et al.* 1984). This determination of the bright limb peak supported the conclusions of Conway (1983).

But the most recent JPL determination, at our request, yielded peak emission at $z = 765 \pm 50$ km based on Voyager optical navigation and NAIF (C. H. Acton and T.-C. M. Wang 1991, private communication). We clearly do not have an incontrovertible determination of the peak emission altitude. For the purposes of comparison we adjusted the UVS data upward by ~ 300 km to obtain peak

FIG. 10. Same as Fig. 9, but for the 2.6% CH_4 , 1.4% Ar model atmosphere. b is the same as a but with three times the magnetospheric electron excitation rates ($s + 3m$). c also illustrates bright-limb profiles for the N_2 LBH bands by solar/photoelectron excitation (s), magnetospheric electron excitation (m), the sum of $s + m$, and the sum of $s + 3m$.

emission at 1050 km which coincides with the calculated peaks (Fig. 12). The only calculated bright limb profile which would be consistent with the observed peak emission at $z = 765 \pm 50$ km would be our pure N_2 atmosphere result (Fig. 9) that has an apparent emission peak at ~ 800 km. But this model atmosphere is totally inconsistent with the UVS solar occultation data. In Fig. 12 actual and slit-averaged bright limb profiles for the 2.6% CH_4 model atmosphere with one [$s + m$] and three times [$s + 3m$] the magnetospheric excitation rate are compared with the adjusted data. It is evident that the topside [$s + 3m$] profiles are inconsistent with the observed rapid intensity falloff with altitude. It is apparent that the data exhibit altitude variations faster than the nominal 200-km slit smoothing can generate and for this reason unsmoothed profiles are also compared with data. The conclusion is the same: magnetospheric power dissipation is at most the value obtained from Eq. (10), 2.3×10^8 W.

At this point one might wonder whether the altitude scale on the UVS solar occultation data and consequently Figs. 1–5 could be in error by values comparable to the uncertainty in the location of the bright limb peak emission. The UVS occultation data distance scale is inherently much more accurate because of the near coincidence of earth occultation by the radio science experiment coupled with a highly accurate ephemeris for Titan and Voyager 1 spacecraft velocity during occultation to translate time into distance. This is demonstrated by the extremely smooth fits of the N_2 density and temperature profiles at 900 km in Fig. 6. Any atmosphere derived from the UVS solar occultation data must smoothly join the atmosphere below derived from IRIS and radio occultation data and extended upward from ~ 300 km by the Yelle (1991) radiative transfer model to 900 km.

To complete this section on limb profiles the calculated N_2 LBH bands' limb profiles are presented in Fig. 10c for

FIG. 11. Same as Fig. 10a, but for the 3.4% CH₄, 13.6% Ar model atmosphere.

the 2.6% CH₄ model atmosphere. Because the LBH bands are only weakly absorbed by CH₄, the peak LBH intensity at ~ 925 km of $430 R$ for photoelectron plus magnetospheric electron excitation differs by less than 10% from the pure N₂ atmosphere calculation. Note that there is only about a $30\text{-}R$ contribution from magnetospheric electrons. Thus the LBH limb profile intensity and also its shape is not diagnostic of magnetospheric power input to Titan's upper atmosphere.

6. UPPER LIMIT ON ARGON MIXING RATIO

The 2.6% and 3.4% CH₄ model atmospheres contain 1.4% and 13.6% Ar mixing ratios, respectively. The cross sections for electron impact excitation of the argon resonance lines at 1048 and 1067 Å are large, peaking at $(3\text{--}4) \times 10^{-17} \text{ cm}^2$ with thresholds ~ 12 eV (Ajello *et al.* 1990). The nominal spectral resolution of the Voyager UVS is 30 Å and these two resonance lines of Ar would be observed by the UVS as a single, extremely Doppler-broadened line rather than as two distinct lines. Given the concerns about absolute calibration of the Voyager UV spectrometers (cf. Holberg *et al.* 1982) and the underprediction of absolute intensities in comparison with observations in this study, the best method to infer upper limits on the Ar mixing ratio from the nondetection of its resonance lines is by comparison with a close spectral feature of nitrogen. The ideally suited spectral feature is the N⁺(1085-Å) multiplet which is within 40 Å of the Ar resonance lines and is almost entirely due to solar/photoelectron excitation of N₂.

In Table III the disk center emission rates of the argon resonance lines are compared with the N⁺(1085-Å) multiplet for the two model atmospheres. Although these Ar

lines are very optically thick, the emission rates corrected for CH₄ absorption are almost identically equal to the integrated excitation rates above the $\tau = 1$ level for CH₄ absorption. According to R. R. Meier (private communication, 1992), the latter rate should approximate the intensity obtained from a full radiative transfer calculation. Note that photoelectrons account for 85% of the total excitation of these Ar lines with only a 15% contribution from magnetospheric electrons. Thus an intensity ratio comparison (Ar lines/N⁺ 1085 Å) is to the first-order independent of the absolute solar fluxes and the magnetospheric power dissipation and is essentially a function only of the Ar/N₂ mixing ratio. From the first two models in Table III it appears that the disk center intensities of the Ar 1048- and 1067-Å lines are linearly proportional to the Ar mixing ratio, i.e., a factor of 10 increase in the mixing ratio yields a factor of 10 increase in intensity, although this is probably a result of the limited parameter space explored.

From the upper limit reported by Strobel and Shemansky (1982) ($<6 R$ revised to $4 R$) for the Ar 1048 Å, an upper limit intensity ratio of 0.5 for Ar 1048/N⁺ 1085 is derived. The predicted intensity ratio is 0.4 for the 13.6% Ar model atmosphere and when the Ar I 1067-Å line intensity is added to the 1048 line intensity this intensity ratio increases to 0.65. From the results in Table III an Ar mixing ratio in excess of 0.2 can be definitely excluded, because the Ar resonance lines would be as bright as the N⁺(1085-Å) multiplet which is not seen by visual inspection of Fig. 1 in Strobel and Shemansky (1982). We recommend a more stringent Ar upper limit of 0.14 based on our results for the 13.6% Ar model atmosphere

FIG. 12. Comparison of calculated bright limb profiles for the 2.6% CH₄ model atmosphere from Figs. 10a and 10b, cases: $s + m$ and $s + 3m$, unsmoothed and slit-averaged, with UVS observed limb data for N₂ emission (924–998 Å) from Fig. 2 of Hall *et al.* (1992).

TABLE III
Sources of Titan Argon Airglow

Processes	Disk Center Emission Intensities ¹		
	Ar(1048Å)	Ar(1048+1067Å)	N ⁺ (1085Å) ²
Observed(revised calibration)	< 4 R	< 4 R	8 R
Model 2.6% CH ₄ , 1.4% Ar			
- N ₂ + hν → N ₂ ⁺ (H)			7.0 R
- photoelectrons + N ₂	0.36 R	0.6 R	1.2 R
- magnetospheric ³ e ⁻ + N ₂	<u>0.06 R⁴</u>	<u>0.08 R⁴</u>	<u>0.6 R⁴</u>
Total	0.42 R	0.68 R	8.8 R
Model 3.4% CH ₄ , 13.6% Ar			
- N ₂ + hν → N ₂ ⁺ (H)			6.0 R
- photoelectrons + N ₂	3.4 R	5.7 R	1.0 R
- magnetospheric ³ e ⁻ + N ₂	<u>0.5 R⁴</u>	<u>0.84 R⁴</u>	<u>0.5 R⁴</u>
Total	3.9 R	6.5 R	7.5 R
Model 5% CH ₄ , 10% Ar			
- N ₂ + hν → N ₂ ⁺ (H)			6.0 R
- photoelectrons + N ₂	3.2 R	5.2 R	1.0 R
- magnetospheric ³ e ⁻ + N ₂	<u>0.5 R⁴</u>	<u>0.82 R⁴</u>	<u>0.7 R⁴</u>
Total	3.7 R	6.0 R	7.7 R

¹ Observations are slit-averaged intensities.

² Meier *et al.* [1991] with yield $\phi_{1085} = 0.184$.

³ For power = 2.3×10^8 W.

⁴ Includes CH₄ absorption.

and the fact that Strobel and Shemansky were able to fit the Voyager 1 dayside spectrum between 1000–1100 Å with nitrogen features only. The third model (5% CH₄, 10% Ar) in Table III illustrates that with an elevated vertical mixing rate the Ar mixing ratio at high altitudes can be comparable to a model with a higher tropopause mixing ratio (cf. Fig. 7) and can yield a comparable intensity ratio for Ar lines/N⁺ 1085 Å. Thus model atmospheres that are consistent with the UVS solar occultation data but with tropopause CH₄ mixing ratios that exceed the IRIS upper limit of 0.034 imply an upper limit on the Ar mixing ratio lower than 0.14. Calculations, not shown in this paper, for bright limb profiles of the Ar resonance lines in comparison with the N⁺(1085-Å) multiplet limb profile yield the same results and conclusions as the disk averaged results in Table III.

7. CONCLUDING REMARKS

From this study a firm, basic conclusion is that the slit-averaged absolute intensity of the N₂ c₄' (0–0, 958-Å) plus

(0–1, 981-Å) bands (~14 R) measured by the Voyager 1 UVS during the Titan flyby are inconsistent with model calculations (7–9 R center of disk) based on atmospheres consistent with UVS solar occultation data. The essential problem is that the occultation data require the CH₄ mixing ratio to exceed 0.05 above 1000 km, which results in reductions, by factors of 2–4 due to absorption, in the calculated absolute intensity of the 970-Å feature for a pure N₂ atmosphere. This inconsistency would be compounded if substantial predissociation occurred in the N₂ c₄' system, but would vanish in the limit of weak predissociation if generous error bars of ±50% are appropriate for the intensities inferred by Strobel and Shemansky (1982).

Another firm conclusion is that the magnetospheric power dissipation is, at most, 10% of the solar EUV power input to Titan's extended atmosphere (= 2×10^9 W for $\lambda < 800$ Å). This result is derived from the shape, rather than the absolute intensity, of the bright limb profile for N₂ emission (924–998 Å), and should be independent of calibration and more rigorous if predissociation in the N₂ c₄' system were important. It is consistent with our esti-

mates of magnetospheric power delivered to the ionopause by curvature drift of thermal and suprathermal electrons and with the downward revision of intensities based on the inflight calibration scheme of Holberg *et al.* (1982, 1991). Our estimate of magnetospheric power dissipation $\leq 2 \times 10^8$ W is a factor of 25 less than that inferred by Strobel and Shemansky (1982) and is a factor of 10 less than that inferred by Hunten *et al.* (1984). The one possible way to solve (1) the shape of the bright limb profile, (2) the absolute intensity problems for disk averaged spectra and bright limb profiles, and (3) the altitude location of the bright limb peak would be the enhancement in the suprathermal, keV electron energy flux relative to the thermal energy flux by more than an order of magnitude. But if this were the explanation, the distinction between the Maxwellian core and the suprathermal tail of the electron energy distribution would vanish.

Likewise our estimate of the nonthermal N atom escape rate is $\leq 10^{25}$ sec $^{-1}$ based on detailed N $_2$ dissociation rates by magnetospheric electron and photoelectron impact. Approximately 90% of the escape is driven by magnetospheric electrons for which we have inferred an upper bound on its magnitude. This estimate is comparable in magnitude to the Monte Carlo calculations of hot N atom concentrations and fluxes by Lammer and Bauer (1991). There is agreement on the magnitude of the photoelectron contribution, but we favor magnetospheric electrons as the dominant mechanism rather than N $_2^+$ dissociative recombination.

From the occultation data our preference is for model atmospheres with a tropopause CH $_4$ mixing ratio of ~ 0.026 – 0.034 . In order to test the robustness of this conclusion we construct a model atmosphere with a tropopause CH $_4$ mixing ratio of 0.017 and the homopause at $z = 875$ km. The fit to the optical depth data, not shown, is similar to but slightly worse than the 2.6% CH $_4$ model atmosphere fit in Fig. 3. The most significant difference between the 1.7% and 2.6% models and the 5% model is the fit to the optical depth profile for the 1151-Å channel. To the extent that this channel indicates the vertical distribution of CH $_4$ density over the altitude range 925–1325 km, the 5% model is decisively the better fit as it is also for channel 725 Å. However, the optical depths range from 0.04 to 4 and the height variations implied by optical depths for channels 928 and 1151 Å are different. The Smith *et al.* (1982) analysis of the solar occultation data and their derived optical depth profiles are not of sufficient accuracy to extrapolate to the tropopause and infer the CH $_4$ mixing ratio there. Clearly a reanalysis of the Titan UVS solar occultation data is needed to resolve the conflicting optical depth profiles near Ly- α which should be dominated by CH $_4$ absorption.

We conclude that the CH $_4$ mixing ratio from 1100 to 1300 km is accurately inferred from the solar occultation

data (cf. Fig. 7). Although we cannot accurately derive its tropopause value, our preference is for high CH $_4$ mixing ratios and we suggest that the homopause occurs high in the atmosphere, $z \sim 1000$ km, with a vertical eddy mixing rate $\sim (4\text{--}8) \times 10^8$ cm 2 sec $^{-1}$. An accurate, independent determination of the tropopause CH $_4$ mixing ratio in conjunction with the UVS occultation data could more precisely locate the homopause.

Comparison of the relative intensities of the Ar resonance lines at 1048 and 1067 Å with the N $^+$ (1085-Å) multiplet yields an upper limit on the Ar mixing ratio of 0.14. Detailed modeling of the UVS airglow spectra similar to the analysis of Strobel and Shemansky (1982) can probably reduce this upper limit to 0.1.

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