Nitrogen Emissions from Titan due to Energetic Electron Bombardment

Marykutty Michael and Robert E. Johnson

E-mail: mm2eq@virginia.edu

Astronomy Department and Engineering Physics,
University of Virginia, Charlottesville, VA – 22903, USA

Manuscript pages: 23
Tables: 2
Figures: 2

Proposed Running Head: Nitrogen Emissions from Titan

Editorial correspondence to:

Dr. Marykutty Michael

Engineering Physics

Thornton Hall B103

University of Virginia

Charlottesville

VA. 22904-4238

USA

Email : mm2eq@virginia.edu

ABSTRACT

Emissions from Titan's dayside atmosphere at ultraviolet wavelengths were observed by Voyager. The major source was shown to be photoelectron interactions with the neutral N_2 present in the atmosphere whether or not Titan was inside or outside Saturn's magnetosphere. Since discrepancies exist between observations and models, and photoelectrons do not contribute significantly to emissions from the night side, we use a Monte Carlo model to calculate the emission brightness due to the precipitation of energetic magnetospheric electrons. Titan is assumed to be inside the magnetosphere of Saturn, so that direct coupling of the magnetosphere with the atmosphere is possible. Using extrapolated electron fluxes based on Voyager measurements, the source rates are much smaller than the photoelectron source rates. Since the plasma flow onto Titan's exobase is highly variable and spatially non-uniform, we give night side emission intensities in a form that can be scaled to the expected Cassini electron flux measurements close to Titan.

Index Terms: Auroral phenomena (2704); Planetary atmospheres (0343); Saturnian Satellites (6280); Energetic particles precipitating (2716); Magnetosphere interaction with satellites and rings (2732); Modeling (3210)

INTRODUCTION

Titan's atmosphere was first observed by Kuiper (1944) when he detected absorption bands of CH_4. The IRIS instrument on Voyager 1 and 2 detected several hydrocarbons and nitrogen containing molecules (Hanel et al. 1981). A nitrogen-dominated atmosphere, predicted earlier by Hunten (1977) and Atreya et al. (1978), was recognized using the combined measurements of the extreme UV emissions of N_2 (Broadfoot et al. 1981), the radio occultation experiment (Tyler et al. 1981) and the infrared spectrometer (Hanel et al. 1981). The composition of this atmosphere near the surface is 97% molecular nitrogen. The remainder is made up of methane and other minor constituents. The atmosphere is highly extended with an exobase at about 1500 km. The atmosphere of Titan is of great interest, since it has a pressure like that at Earth but a much larger column density. Titan is at a distance of 20 Saturn radii from Saturn and, when the solar wind pressure is high enough, the satellite is outside the magnetosphere of Saturn. A review of Titan's ionosphere is provided in Nagy and Cravens (1998).

Voyager observations of Nitrogen emissions from the atmosphere of Titan have been reported by Broadfoot et al. (1981) and Strobel and Shemansky (1982). The originally reported intensities below 110 nm were reduced by a factor of 1.6 by Holberg et al. (1982, 1991). Initially the sources of emissions from Titan were believed to be photons, photoelectrons or electrons of Saturn's magnetospheric origin. The interaction of solar photons with the atmosphere of Titan was studied by Singhal and Haider (1986), Strobel et al. (1992), Gan et al. (1992), Galand et al. (1999), and Stevens (2001). Though the observed emissions are suggested to be primarily due to photo-electron excitation, the remaining uncertainties suggest that there could be other sources also. A brief review of the nitrogen emissions observed at Titan and the previous studies are presented in the next section.

Since Titan has a diurnal rotation period of 16 days, which is equal to its period of rotation around Saturn, each hemisphere is in shadow for a considerable time. Therefore it is important to study the sources of emissions from the atmosphere of Titan when solar radiation is not available. During this period particles originating in the magnetosphere of Saturn would be a major source of the emissions from the upper atmosphere of Titan.

At Io, which has a similar history, Voyager did not observe atmospheric emissions. However, Galileo instruments and the high resolution Imaging Spectrograph onboard Hubble Space Telescope observed emissions at ultraviolet and visible wavelengths. These were then correlated with the orientation of the Jovian magnetic field. Until the arrival of Galileo there was also little data on electron and ion fluxes close to Io. Using Galileo electron flux measurements, the interaction of Jovian magnetospheric electrons with the Io's atmosphere could explain to a considerable extent the relative emission intensities (Michael and Bhardwaj, 2000a; Saur et al. 2000).

Since the Cassini instruments may be able to observe emissions from Titan's night side atmosphere and the Cassini Plasma Spectrometer (CAPS) instrument will provide a wealth of charged particle data, the emission intensities expected due to magnetospheric electron precipitation are calculated. Most of Titan's emission features observed by Voyager are considered, as are certain other features that might be observable by Cassini. To be able to adjust the emission brightness to measurements of local flux, we also calculated intensities produced by electrons incident at specific energies in the range 0.02 to 10 keV. These can then be scaled when the electron fluxes close to Titan become available.

NITROGEN EMISSIONS FROM TITAN

The nitrogen emissions from the atmosphere of Titan were observed by the Voyager Ultraviolet Spectrometer (UVS) (Broadfoot et al. 1981). The UVS detected N_2 Rydberg band emissions, Lyman-Birge-Hopfield (LBH) band emissions, Birge-Hopfield (BH) emissions, emissions from the excited states of N_2^+, and other NI and NII emissions. Strobel and Shemansky (1982) calculated the emission intensities due to the interaction of electrons with Titan's atmosphere. But the electron flux used was much higher than that observed by Voyager plasma science experiments. Later the emission brightness was recalibrated and revised downward by a factor of about 1.6 (Holberg et al. 1982, 1991). Strobel et al. (1992) modeled these emissions and suggested that the magnetospheric power input is a factor of 25 lower than the original estimates by Strobel and Shemansky (1982) and some of the features could be explained by the photon and photoelectron interaction with the atmosphere of Titan. Strobel et al. (1992) adopted a simple model by Strickland et al. (1989) to simulate these emissions. Singhal and Haider (1986), Gan et al. (1992), and Galand et al. (1999) calculated the intensities of the observed emissions by the interaction of electrons with the atmosphere of Titan. Singhal and Haider (1986) used an analytical yield spectrum, and Galand et al. (1999) approached the problem by solving the Boltzman transport equation. Gan et al. (1992) used a two-stream simulation. Singhal and Haider (1986) and Gan et al. (1992) included photoelectrons and magnetospheric electrons while Galand et al. (1999) included only photoelectrons. The intensities of the LBH band calculated by Galand et al. (1999) and Gan et al. (1992) were close to each other but far from the observed intensities. Other N_2 band intensities calculated by

Galand et al. (1999) were almost in agreement with the observation, but those calculated by Gan et al. (1992) were much larger. The NI emissions calculated by Galand et al. (1999) were almost a factor of two less than the observations, while those of Gan et al. (1992) were almost a factor of 10 less than the observations. The Rydberg band intensity calculated by Galand et al. (1999) was in the error range of the observations. A recent paper by Stevens (2001) discussed the observations of N_2 Rydberg state emissions at 95.8 and 98.1 nm and suggested that the Voyager data in that wavelength region was wrongly interpreted. He suggested that 98.1 nm emission must be brighter than the 95.8 nm emission in contrast to the Voyager observation. Using the revised intensities and using a solar photon flux which is greater than that used in the previous studies, Stevens (2001) suggested that these Rydberg band emissions could also be explained by photoelectron interactions with Titan's atmosphere.

The Ultraviolet Imaging Spectrometer (UVIS) onboard Cassini will be observing emissions from Titan in the wavelength region of 55 – 190 nm and the Visible and Infrared Mapping Spectrometer (VIMS) in the wavelength region 200 – 1100 nm. The expected electron flux measurements by CAPS close to Titan will give the spatial distribution of the incident flux. This will be important, as it is known that the plasma flow onto the exobase is non-uniform (Bretch et al. 2000). As magnetospheric electrons are likely to be the only source of the night side emissions, the intensities of the most important expected emissions are calculated and presented below.

MODEL DESCRIPTION

A Monte Carlo model is constructed to simulate the degradation of electrons in an N_2 atmosphere. For simplicity the electrons are assumed to be incident in the vertical direction at the top of the atmosphere. The transport and degradation of electrons is simulated in a collision by collision manner. The physical processes included in the simulation are electron-neutral elastic collisions and inelastic processes like ionization, excitation, dissociative ionization, dissociative excitation, dissociative ionization excitation. Ionization produces secondary electrons and excitation leads to emission. All the secondary electrons are also treated in this model in the same manner as the primary electrons. When all the sampled electrons are degraded, the emission rate and subsequently the intensity of emission are calculated. The following assumptions, which are allowed in an auroral model, are made in the present simulation. All the collisions are binary, and collisions only reduce the energy of the incoming particles. A similar model was developed for the electron degradation in Io's atmosphere and the details are provided in Bhardwaj and Michael, (1999), Michael and Bhardwaj, (1997, 2000a, b) and references therein.

The most important input needed to study the electron collisions in an N_2 atmosphere is the data set for electron impact cross sections. Most of the emissions observed by Voyager and certain emissions that might be observed by Cassini are considered. The 98.1 nm and 95.8 nm emissions corrected by Stevens (2001) are not included, neither are emission features whose maximum cross section is less than 10^{-18} cm^2.

Emissions are produced from excited molecular nitrogen states, ionized excited molecular nitrogen states, excited atomic nitrogen states or from ionized excited atomic nitrogen states. A molecular band, the LBH (Lyman-Birge-Hopfield) band system, was the brightest emission feature observed by Voyager. It is mostly produced by the transition of $a^1\Pi_g - X^1\Sigma_g^+$ and in the wavelength region 130-200 nm. The BH band emission (95-170 nm) is mainly produced by the transition $b^1\Pi_u - X^1\Sigma_g^+$. The molecular transition $C^3\Pi_u - B^3\Pi_g$ gives rise to bands at 337.1, 315.8, and 380.4 nm. The 762.6 nm band is produced from the molecular transition $B^3\Pi_g - A^3\Sigma_u^+$. Dissociative excitation of N_2 produces lines in the wavelength range 110-180 nm. The 113.4 nm line was produced by the transition $2p^4\ ^4P - 2p^3\ ^4S$, while $3s\ ^4P - 2p^3$ 4S transition occurs at 120 nm. The transition $3s^1\ ^2D - 2p^3\ ^2D$ gives a line at 124.3 nm, $3s\ ^2P - 2p^3\ ^2D$ at 149.4 nm, and the transition $3s\ ^2P - 2p^3\ ^2P$ occurs at 174.3 nm. N_2 in the ionized excited state produces a feature at 391.4 nm and 427.8 nm that are due to the transition $B^2\Sigma_u^+ - X^2\Sigma_g^+$. Dissociative ionization excitation produces the 108.4 nm line associated with the atomic transition $2p^3\ ^3D - 2p^2\ ^3P$. The cross sections for these processes were taken from Majeed and Strickland (1997), Itikawa et al. (1986), Doering and Goembel (1992) and Shemansky et al. (1995).

The Voyager electron flux data are used to describe the energy distribution of the incoming electron flux. The plasma science instrument on Voyager measured the electron flux near Titan's orbit in the energy region 10 eV to 6 keV (Sittler et al. 1983). The low energy charged particle experiment onboard Voyager 1 made measurements from 20- 200 keV and the same experiment on Voyager 2 measured the electron flux in the energy region from 20 keV to 1 MeV (Krimigis et al. 1983). The data from 10 eV to 1 MeV data were extrapolated to 20 Rs by Maurice et al. (1996). Galand et al. (1999) described the electron flux using a Kappa distribution which is used in the present study. The model atmosphere of Titan was taken from Keller et al. (1998).

RESULTS AND DISCUSSION

Table 1 gives the intensities of emissions produced by the magnetospheric electrons. The intensities observed by Voyager and those calculated for the interaction of photoelectrons with the atmosphere of Titan by Gan et al. (1992), Strobel et al. (1992) and Galand et al. (1999) are also presented in Table 1. Although the Voyager observations can have an error of ± 50%, it is seen that some of the features do not have intensities within the combined errors of the observations and the calculations. However, the intensities produced by the magnetospheric electrons with the incident fluxes used here are seen to be much less than these differences.

The magnetospheric electron estimates reported by Gan et al. (1992) and Strobel et al. (1992) for the pure N_2 atmosphere are also presented in Table 1. Gan et al. (1992) used a Maxwellian distribution of electrons with a density of 0.1 cm^{-3} and a temperature of 200 eV. Strobel et al. (1992) used a Maxwellian distribution of electrons with electrons density 0.3 cm^{-3} and a characteristic temperature of 200 eV. The brightness of the LBH emission band is calculated by both Gan et al. (1992) and Strobel et al. (1992). As seen from Table 1 the intensity calculated in the present study is less than that reported by Strobel et al. (1992) and is greater than that of Gan et al. (1992). Similarly the intensity of NII (108.4 nm) obtained in the present study is less than that of Strobel et al. (1992) and greater than that of Gan et al. (1992). This discrepancy is attributed to the differences in the electron flux used. Gan et al. (1992) calculated intensities of the NI(113.4, 120.0, 124.3 nm) lines which are also less than that in the present study.

In this work we have used the precipitating electron flux as measured by Voyager and extrapolated to Titan. Though the intensities calculated here are much less than the observed intensities, this flux is expected to be highly variable and spatially non-uniform close to Titan. Therefore, there can be times or regions of Titan's night side atmosphere where the intensities will be significantly larger. As a check, the electron flux was doubled. The emission intensities were, of course, directly proportional to the incident particle flux. That is, if the electron flux is increased by a factor of two the intensities also will be increased by the same factor.

Since high-resolution spectral data and better electron fluxes close to Titan are expected from Cassini instruments, it would be useful to be able to easily apply the new electron flux data. To estimate the intensities, electrons of different energies (0.02, 0.03, 0.05, 0.1, 0.2, 0.5, 1, 5, 10 keV) were allowed to enter the atmosphere of Titan and lose their energy to the atmosphere. Emission rates and column intensities for each band are calculated for a unit flux (1 cm^{-2} s^{-1}). The results presented in Table 2 can be used to calculate the intensities of the various lines by multiplying by the electron flux.

Variations in the intensities of emissions presented in Table 2 are determined by the energy dependence of the cross sections. Therefore, observation of night side emissions can be diagnostic of the plasma interaction with Titan. It is seen from Table 2 that the LBH band has a maximum brightness when 30 eV electrons degrade in the atmosphere. Electrons of energies 20 – 30 eV contribute most to the production of all other emissions from the excited state of nitrogen molecule (762.6, 337.1, 315.8, 380.4 nm). NI(113.4 nm) intensity is largest for electrons of energy about 200 eV and NI(120 nm) intensity is largest for degradation of 500 eV electrons in the N_2 atmosphere. While the NI(124.3 nm) and BH band intensities are largest at 50 eV, NI(149.4 nm) and NI(174.3 nm) are largest at about 5 keV. Emission intensities at 391.4 nm and 427.8 nm, produced by the ionization excitation of the N_2 molecule, become maximum when electrons of energy about 5 keV interact with the atmosphere of Titan. Finally, the NII(108.4) emission is largest for 200 eV electrons. Ratios of these intensities compared with the observed data can suggest the electron energies principally responsible for the features that might be observable by Cassini.

The photoelectron flux in the ionosphere of Titan peaks below 30 eV (Singhal and Haider, 1986). Therefore, it is clear from Table 2 that certain features (LBH, 762.6, 337.1, 315.8, 380.4 nm) which are primarily produced by electrons of energy ≤ 30 eV will be dominated by photoelectrons in the dayside atmosphere. However, a few features (113.4, 120.0 and 108.4 nm) peak for energies 200 to 500 eV and the features at 149.4, 174.3, 391.4 and 427.8 nm are produced most efficiently by 5 keV electrons. This suggests that such features would be produced more efficiently by the energetic magnetospheric electrons than by the lower energy photo-electrons. However, to obtain the Voyager intensities for the 108.4, 120.0 and 113.4 would imply local magnetospheric electron fluxes at least two orders of magnitude greater than the extrapolated ambient Voyager fluxes used here.

Brecht et al. (2000) used a hybrid particle model to simulate the interaction of Saturn's magnetospheric plasma with Titan. Their study showed that the fields compress on the Saturn facing side of Titan while Voyager observations were made on the anti-Saturn side. The concentration of the electron flow on one side of Titan will produce emissions much more intense than those reported in Table I. But it is not clear that the large enhancement required above could be obtained. It is possible that incident protons also contribute. The energy distribution of protons in the vicinity of Titan is available only for a small energy region (80 keV – 8 MeV) and the energy flux of these protons are almost a factor of 3 less than that of magnetospheric electrons. We have published a study of the energy deposition of these protons in the atmosphere of Titan (Luna et al. 2003). This may become of interest when a more complete set of data becomes available from Cassini.

Figure 1a and b shows the emissions rate verses altitude for various lines. The figures show that most of the features peak at about 1100 km above the surface of Titan, which is consistent with the observations. The energy of the incident particles determines the altitude to which the bulk of the particles penetrate. Therefore, the emission rates at different altitudes were also calculated for the 8 various incident energies in Table 2. For 30 eV electrons the LBH emission rate peaks at 1200 km above the surface of Titan. 1 keV electrons produce an extended peak in the altitude region of 1000-1200 km, and 10 keV electrons produce a peak at about 1000 km. Electrons of higher energy would penetrate deep into the UV absorbing hydrocarbon region of Titan's upper atmosphere and would not contribute much to the auroral emissions.

CONCLUSIONS

Atmospheric emission intensities from Titan are estimated due to the precipitation of Saturn's magnetospheric electrons. Emissions in the ultraviolet and visible wavelength regions are simulated by a Monte Carlo model. Most of the emissions observed by Voyager and a few more emissions that might be observed by Cassini instruments are considered in the model. Although photoelectrons contribute more to the daytime emissions for most of the features examined in both models, magnetospheric electrons should be the major source of emissions from the night side. Based on the extrapolated Voyager electrons fluxes, the calculated intensities in Table I are far too low to account, for instance, for the discrepancy between Voyager dayside intensities for the NI lines and the intensities expected due to the photo-electrons. However, the flow of electrons on to the exobase is variable and spatially non-uniform (Bretch et al. 2000) so that larger intensities are expected locally. Therefore, magnetospheric electron-induced features may be observable at times, particularly on the night side. Even for the electron fluxes used here, certain of the visible features will be observable by Cassini when the spacecraft is ~ 2 Titan radii away. When the magnetospheric electron-induced effects can be seen, the observations can be diagnostic of the plasma-atmosphere interaction at Titan. With this in mind, and in anticipation of electron flux measurements close to Titan, electrons at a set of relevant energies were allowed to degrade in the atmosphere and the most probable incident energy associated with each feature was identified. The intensities versus incident electron energy given in Table 2 can now be scaled when Cassini electron flux data becomes available.

ACKNOWLEDGEMENTS

This work is supported by NASA's Planetary Atmospheres Program. We thank R.H. Brown for information on VIMS sensitivity.

REFERENCES

Atreya, S. K., T. M. Donahue, and W. R. Kuhn, Evolution of a nitrogen atmosphere on Titan, *Science*, **201**, 611-613, 1978.

Bhardwaj, A., and M. Michael, Monte Carlo model for electron degradation in SO_2 gas: Cross sections, yield spectra, and efficiencies, *J. Geophys. Res*., **104**, 24713-24728, 1999.

Brecht, S. H., J. G. Luhmann, and D. J. Larson, Simulation of the Saturnian magnetospheric interaction with Titan, *J. Geophys. Res.*, **105**, 13119-13130, 2000.

Broadfoot, A.L., B.R. Sandel, B.E. Shemansky, J.B. Holberg, and G.R. Smith, Extreme ultraviolet observations from Voyager 1 encounter with Saturn, *Science*, **212**, 206-211, 1981.

Doering, J.P., and L. Goembel, Absolute differential and integral electron excitation cross sections for atomic nitrogen. II - The $^4S^0$ - $^2p^4$ 4P(1135 Å) transition from 30 to 100 eV, *J. Geophys. Res.*, **97**, 4295-4298, 1992.

Galand, M.L., J. Lilensten, D. Toublanc, and S. Maurice, The Ionosphere of Titan: Ideal Diurnal and Nocturnal Cases, *Icarus*, **140**, 92-105, 1999.

Gan, L., C. N. Keller, and T. E. Cravens, Electrons in the ionosphere of Titan, *J. Geophys. Res.*, **97**, 12137-1215, 1992.

Hanel, R., and 15 colleagues, Infrared observations of the Saturnian system from Voyager 1, *Science*, **212**, 192-200, 1981.

Holberg, J. B., W. T. Forrester, D. E. Shemansky, and D. C. Barry, Voyager absolute far-ultraviolet spectrophotometry of hot stars, *Astrophys. J.*, **257**, 656-671, 1982.

Holberg, J. B., B. Ali, T. E. Carone, and R. S. Polidan, Absolute far-ultraviolet spectrophotometry of hot subluminous stars from Voyager, *Astrophys. J.*, **375**, 716-721, 1991.

Hunten, D.M., Titan's atmosphere and surface, in *Planetary Satellites,* edited byJ.A. Burns, pp. 420-437, University of Arizona Press, Tucson, 1977.

Itikawa, Y., M. Hayashi, A. Ichimura, K. Onda, K. Sakomoto, and K. Takayanagi, Cross sections for collisions of electrons and photons with nitrogen, *J. Phys. Chem. Ref. Data*, **15**, 985-1010, 1986.

Keller, C. N., V. G. Anicich, and T. E. Cravens, Model of Titans ionosphere with detailed hydrocarbon ion chemistry, *Planet. Space Sci*., **46**, 1157-1174, 1998.

Krimigis, S. M., J. F. Carbary, E. P. Keath, T. P. Armstrong, L. J. Lanzerotti, and G. Gloeckler, General characteristics of hot plasma and energetic particles in the Saturnian magnetosphere - Results from the Voyager spacecraft, *J. Geophys. Res.*, **88**, 8871-8892, 1983.

Kuiper, G.P., Titan: A satellite with an atmosphere, *Astrophys. J.*, **100**, 378-383, 1944.

Luna, H., M Michael, M. B Shah, R. E. Johnson, C. J. Latimer, and J. W. McConkey, Dissociation of N_2 in capture and ionization collisions with fast H^+ and N^+ ions and modeling of positive ion formation in the Titan atmosphere. *J. Geophys. Res.*, in press, 2003.

Majeed, T., and D.J. Strickland, New survey of electron impact cross sections for photoelectron and auroral electron energy loss calculations, *J. Phys. Chem. Ref. Data,* **26**, 335-349, 1997.

Maurice, S., E. C. Sittler, J. F. Cooper, B. H. Mauk, M. Blanc, and R. S. Selenick, Comprehensive analysis of electron observations at Saturn: Voyager 1 and 2, *J. Geophys. Res.*, **101**, 15211-15232, 1996.

Michael, M., and A. Bhardwaj, On the dissociative ionization of SO_2 in Io's atmosphere, *Geophys. Res. Lett.,* **24**, 1971-1974, 1997.

Michael, M., and A. Bhardwaj, FUV emissions on Io: Role of Galileo-observed field-aligned energetic electrons, *Geophys. Res. Lett*., **27**, 3137-3140, 2000a.

Michael, M., and A. Bhardwaj, Precipitation of energetic electrons in the atmosphere of Io: Production of UV emissions, *Adv. Space Res.*, **26(10**), 1519-1524, 2000b.

Nagy, A.F., and T.E. Cravens, Titan's ionosphere: A review, *Planet. Space Sci.*, **46**, 1149-1155, 1998.

Saur, J., F.M. Neubauer, D.F. Strobel, and M.E. Summers, Io's ultraviolet aurora: Remote sensing of Io's interaction, *Geophys. Res. Lett*., **27**, 2893-2896, 2000.

Shemansky, D. E., J. M. Ajello, and I. Kanik, Electron Excitation Function of the N_2 Second Positive System, *Astrophys. J.*, **452**, 472-479, 1995.

Singhal, R. P., and S. A. Haider, Some molecular nitrogen emissions from Titan-solar EUV and magnetospheric interaction, *Indian J. Radio Space Phys.*, **15**, 46-52, 1986.

Sittler, E. C. Jr., K. W. Ogilvie, and J. D. Scudder, Survey of low-energy plasma electrons in Saturn's magnetosphere - Voyagers 1 and 2, *J. Geophys. Res*., **88**, 8847-8870, 1983.

Stevens, M.H., The EUV airglow of Titan: Production and loss of N_2 $c'_4(0)$-X, *J. Geophys. Res.*, 1**06**, 3685-3689, 2001.

Strickland, D.J., R. R. Meier, J. H. Hecht, and A. B. Christensen, Deducing composition and incident electron spectra from ground-based auroral optical measurements: Theory and model results, *J. Geophys. Res.*, **94**, 13527-13539, 1989.

Strobel, D.F., M.E. Summers, and X. Zhu, Titan's upper atmosphere - Structure and ultraviolet emissions, *Icarus*, **100**, 512-526, 1992.

Strobel, D. F., and D. E. Shemansky, EUV emission from Titan's upper atmosphere - Voyager 1 encounter, *J.Geophys. Res.*, **87**, 1361-1368, 1982.

Tyler, G. L., V. R. Eshleman, J. D. Anderson, G. S. Levy, G. F. Lindal, G. E. Wood, and T. A. Croft, Radio science investigations of the Saturn system with Voyager 1 - Preliminary results, *Science*, **212**, 201-205, 1981.

Table 1.

Calculated and observed emission intensities in Rayleighs due to precipitating electrons

Transition	Emission feature (nm)	Magnetospheric electron excited	Observed by Voyager	Photoelectron excited
$a^1\Pi_g - X^1\Sigma_g^+$	LBH	1.85 (0.9[b]) (8.6[c])	96	70[a] (65[b]) (94[c])
$b^1\Pi_u - X^1\Sigma_g^+$	BH	1.64 (1.6[b])	25	
$2p^3\ {}^3D - 2p^2\ {}^3P$	108.4	0.17(0.08[b]) (0.8[c])	12	0.08[b]
$2p^4\ {}^4P - 2p^3\ {}^4S$	113.4	0.05 (0.03[b])	7.9	0.7[b]
$3s\ {}^4P - 2p^3\ 4S$	120.0	0.47 (0.15[b])	30	2.2[b]
$3s^1\ {}^2D - 2p^3\ {}^2D$	124.3	0.13(0.05[b])	8.0	1.1[b]
$3s\ {}^2P - 2p^3\ {}^2D$	149.4	0.37	15	
$3s\ {}^2P - 2p^3\ {}^2P$	174.3	0.08		
$C\ {}^3\Pi_u - B\ {}^3\Pi_g$	315.8	0.31		
	337.1	0.67		
	380.4	0.19		
$B^2\Sigma_u^+ - X^2\Sigma_g^+$	391.4	1.25		21.7[a]
	427.8	0.31		6.8[a]
$B\ {}^3\Pi_g - A\ {}^3\Sigma_u^+$	762.6	1.95		

[a]The intensities are reported by Galand et al. (1999)
[b]The intensities are reported by Gan et al. (1992)
[c]The intensities are reported by Stobel et al. (1992)
The intensities from Voyager observation are taken from Strobel and Shemansky (1982).

Table 2.

Column production rates of Nitrogen emissions in cm^{-2} s^{-1} for monoenergetic unit electron flux

Emission Features (nm)	20 eV	30 eV	50 eV	100 eV	200 eV	500 eV	1 keV	5 keV	10 keV
LBH	1.4E-1	1.8E-1	1.6E-1	1.2E-1	1.1E-1	9.8E-2	9.7E-2	9.2E-2	8.3E-2
BH	5.6E-2	1.1E-1	1.4E-1	1.0E-1	1.2E-1	1.1E-1	8.3E-2	1.2E-2	7.9E-2
108.4	-	-	7.6E-3	1.1E-2	1.6E-2	1.4E-2	8.2E-3	1.2E-2	6.5 E-3
113.4	-	-	0.2E-3	0.4E-3	0.5E-3	0.4E-3	0.2E-3	0.3E-3	0.2E-3
120.0	1.0E-3	0.8E-3	2.0E-2	2.3E-2	4.0E-2	5.4E-2	3.8E-2	1.3E-1	8.4E-2
124.3	5.0E-3	0.8E-3	1.1E-2	8.2E-3	9.2E-3	8.1E-3	6.2E-3	6.9E-3	5.0E-3
149.4	3.0E-3	1.0E-2	1.9E-2	1.9E-2	3.1E-2	4.0E-2	2.8E-2	9.2E-2	6.0E-2
174.3	2.0E-5	1.4E-3	4.6E-3	0.5E-3	7.2E-3	7.4E-3	4.7E-3	8.7E-3	5.0E-3
315.8	2.8E-2	2.6E-2	2.0E-2	1.8E-2	2.0E-2	1.8E-2	1.9E-2	1.9E-2	1.7E-2
337.1	5.8E-2	5.5E-2	4.5E-2	4.0E-2	4.2E-2	3.8E-2	4.0E-2	4.1E-2	3.6E-2
380.4	1.8E-2	1.8E-2	1.5E-2	1.2E-2	1.2E-2	1.0E-2	1.1E-2	1.0E-2	9.4E-3
391.4	4.0E-4	2.2E-2	6.9E-2	7.5E-2	1.1E-1	1.1E-1	7.0E-2	1.3E-1	7.4E-2
427.8	6.0E-5	3.9E-3	1.4E-2	1.6E-2	2.7E-2	3.3E-2	2.2E-2	5.9E-2	3.5E-2
762.6	1.5E-1	1.6E-1	1.3E-1	1.2E-1	1.3E-1	1.1E-1	1.2E-1	1.2E-1	1.1E-1

1.4E-1 should be read as 1.4×10^{-1}

FIGURE CAPTIONS

Figure 1(a). Emission rate vs. altitude for various emissions at wavelengths 120.0, 149.4, 315.8, and 337.1 nm. (b) Same as (1a) for LBH band emission, 391.4, 427.8, and 762.6 nm

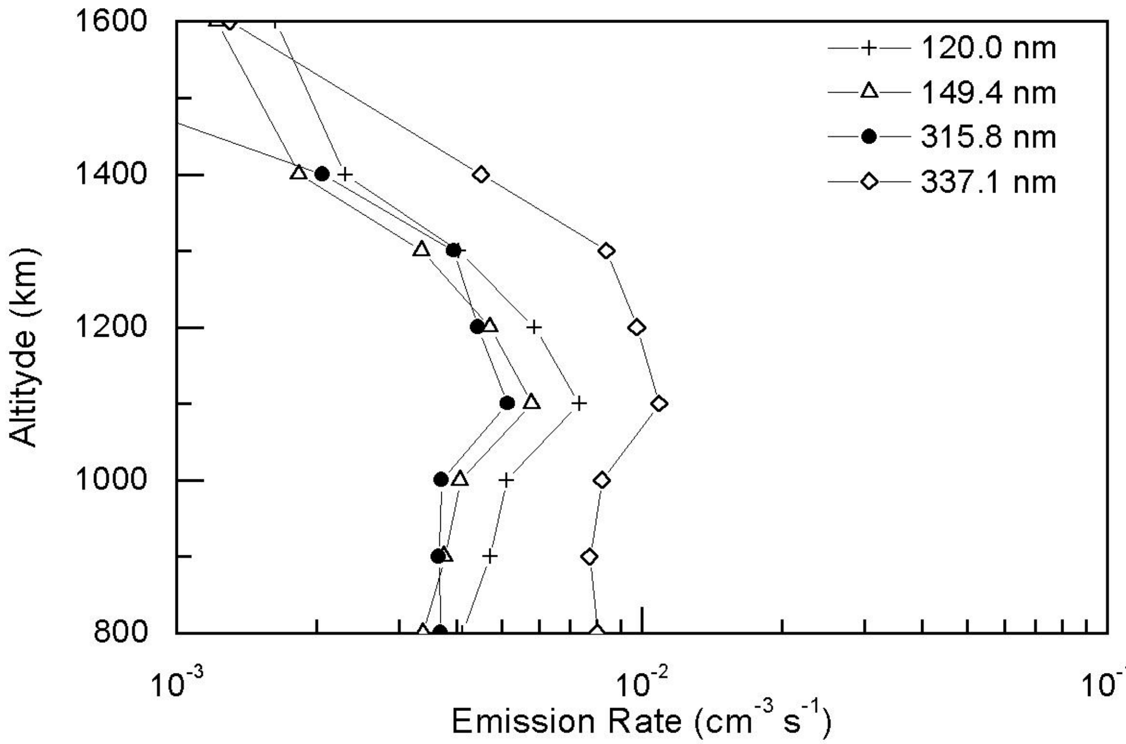

Figure 1(a). Emission rate vs. altitude for various emissions at wavelengths 120.0, 149.4, 315.8, and 337.1 nm.

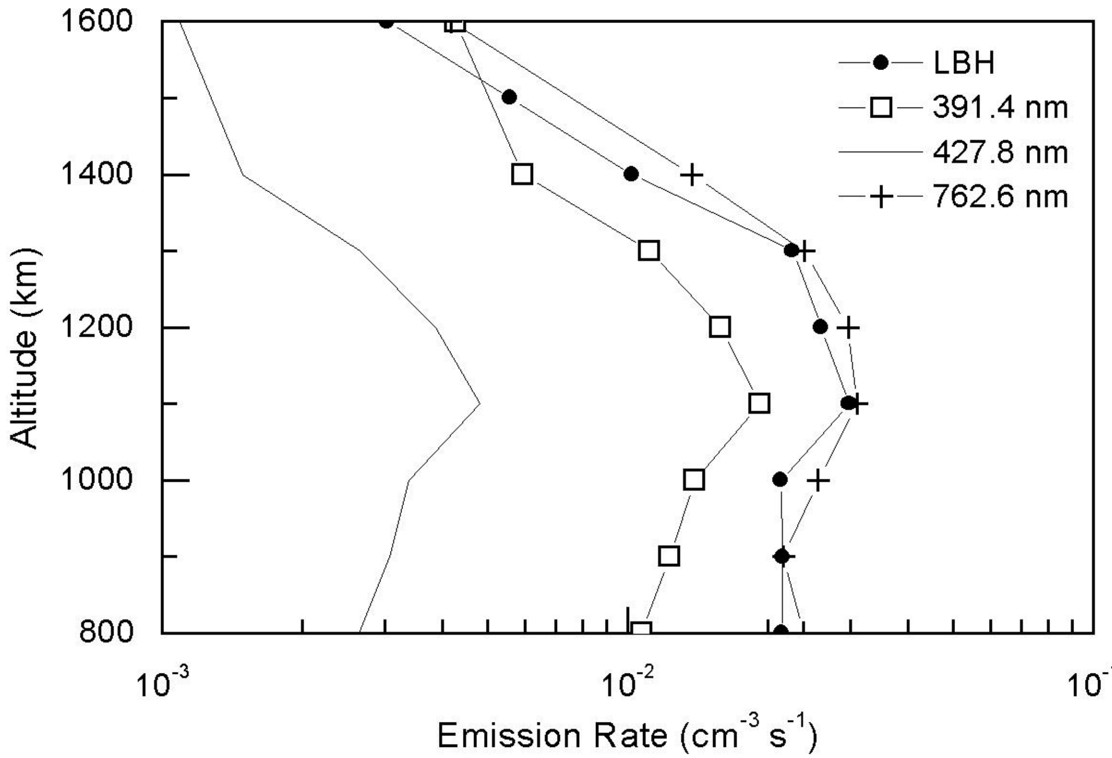

Figure 1 (b). Same as (1a) for LBH band emission, 391.4, 427.8, and 762.6 nm