2.11 ATOMIC HYDROGEN DISTRIBUTION

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Introduction

Molecular hydrogen (H_2) has been identified in Titan's atmosphere by its quadrupole absorption line, with an estimated total quantity of 5 km-A (Trafton 1972). There must then be some atomic hydrogen (H) in Titan's atmosphere, which may be accessible to observation in Lyman-α at 1216 Å.

In this study we have examined several possible H_2 vertical distributions with the constraint of 5 km-A as a total quantity, and have calculated, with approximations, the corresponding vertical distributions of atomic hydrogen. It was found that the H distribution is quite sensitive to two other parameters of Titan's atmosphere: the temperature and the presence of other constituents. The escape fluxes of H and H_2 were also estimated as well as the consequent distributions trapped in the Saturnian system.

Models of H_2 Distribution

The constraint of 5 km-A of H_2 makes impossible an atmosphere of pure H_2, since it would escape so fast that the total mass of Titan would vanish in less than 10^6 years. Additional constituents with molecular weight higher than H_2 have to be present to accommodate the 5 km-A of H_2. Two constituents were considered separately: (1) N_2 after a suggestion by Hunten (1972), with various mixing ratios ranging from 10^{-3} to 10^{-1} for H_2/N_2; and (2) CH_4, which was positively identified by Kuiper (1944), with a mixing ratio of 1.

For the sake of simplicity the atmosphere was considered to be spherically symmetrical and isothermal, with a temperature of either 80, 100, or 120°K. By analogy with the terrestrial atmosphere, three different zones were considered: The turbosphere where the mixing is constant, the diffusosphere where each constituent follows its own scale height, and the exosphere where collisions are not important. The turbopause level was defined as the altitude Z_a where the total number density is 10^{11} mols cm^{-3}. The exobase level was defined as the altitude Z_c where the density of H_2 is 10^7 mols cm^{-3}, except if it was found to be higher than the blow off level (kinetic energy equal to gravitational energy), in which case the exobase was located at the blow off level. These levels are indicated in Table 2-8, together with the escape fluxes of H_2 at the exobase estimated from the Jeans formula. The various calculated H_2 distributions are indicated in Figure 2-39. The main feature of these H_2 distributions is the existence of a very large diffusosphere when compared to the terrestrial case. This is due to the low gravity of Titan and to the high total quantity of H_2.

Models for H Vertical Distribution

Photodissociation of H_2 and CH_4 by the solar flux was considered as the only source of H, compensated by escape at the exobase and by three-body recombinations at lower altitudes. For each H_2 profile a corresponding H profile

Table 2-8a. H_2 Fluxes for Titan Atmospheric Models

TEMP.	MIXING RATIO	TURBO-PAUSE Za km	EXOBASE Zc km	DENSITY AT GROUND (H_2) mols cm^{-3}	DENSITY AT Zc (H_2) mols cm^{-3}	EFFUSION VELOCITY (H_2) cm sec^{-1}	ESCAPE FLUX (H_2) mols $cm^{-2}sec^{-1}$	TOTAL FLUX (H_2) mols sec^{-1}	FLUX AT GROUND (H_2) mols $cm^{-2}sec^{-1}$
80°K (H_2-N_2)	10^{-3}	520	1570	11.0×10^{18}	10^7	2.3×10^2	2.3×10^9	4.8×10^{27}	5.9×10^9
	10^{-2}	470	3420	10.5×10^{18}	10^7	1.3×10^3	1.3×10^{10}	5.9×10^{28}	7.0×10^{10}
	10^{-1}	460	8950	9.5×10^{18}	10^7	7.0×10^3	7.0×10^{10}	1.6×10^{30}	2.0×10^{12}
100°K (H_2-N_2)	10^{-3}	670	2410	8.0×10^{18}	10^7	1.5×10^3	1.5×10^{10}	4.6×10^{28}	5.6×10^{10}
	10^{-2}	610	6050	8.0×10^{18}	10^7	6.8×10^3	6.8×10^{10}	6.3×10^{29}	7.7×10^{11}
	10^{-1}	590	12060*	7.0×10^{18}	3.6×10^7	1.4×10^4	5.0×10^{11}	1.3×10^{31}	1.6×10^{13}
120°K (H_2-N_2)	10^{-3}	840	3470	6.4×10^{18}	10^7	5.5×10^3	5.5×10^{10}	2.4×10^{29}	3.0×10^{11}
	10^{-2}	750	9600*	6.3×10^{18}	1.7×10^7	1.6×10^4	2.6×10^{11}	4.8×10^{30}	5.8×10^{12}
	10^{-1}	730	9600*	5.6×10^{18}	1.5×10^8	1.6×10^4	2.3×10^{12}	4.2×10^{31}	5.1×10^{13}
80°K (H_2-CH_4)	1	1470	15710*	2.7×10^{18}	2.7×10^8	1.2×10^4	3.2×10^{12}	1.4×10^{32}	1.7×10^{14}
100°K (H_2-CH_4)	1	2070	12060*	2.1×10^{18}	2.3×10^9	1.6×10^4	3.2×10^{13}	8.6×10^{32}	10^{15}

* Exobase = Blow-off level in this case.

Table 2-8b. H Fluxes for Titan Atmospheric Models

TEMP.	MIXING RATIO	TURBO-PAUSE Za km	EXOBASE Zc km	DENSITY AT Zc (H) atoms cm^{-3}	ESCAPE FLUX (H) atoms $cm^{-2}sec^{-1}$	TOTAL FLUX (H) atoms sec^{-1}	FLUX RATIO H/H_2
80°K (H_2-N_2)	10^{-3}	520	1570	7.50×10^4	3.7×10^8	8.0×10^{26}	1.6×10^{-1}
	10^{-2}	470	3420	2.50×10^4	2.7×10^8	1.2×10^{27}	2.0×10^{-2}
	10^{-1}	460	8950	7.80×10^3	1.7×10^8	2.8×10^{27}	1.7×10^{-3}
100°K (H_2-N_2)	10^{-3}	670	2410	2.30×10^4	2.9×10^8	9.0×10^{26}	2.0×10^{-2}
	10^{-2}	610	6050	7.40×10^3	1.7×10^8	1.5×10^{27}	2.0×10^{-3}
	10^{-1}	590	12060*	10^4	3.0×10^8	8.0×10^{27}	6.0×10^{-4}
120°K (H_2-N_2)	10^{-3}	840	3470	1.10×10^4	2.5×10^8	1.1×10^{27}	6.5×10^{-3}
	10^{-2}	750	9600*	5.60×10^3	1.8×10^8	3.3×10^{27}	6.8×10^{-4}
	10^{-1}	730	9600*	1.60×10^4	5.5×10^8	1.0×10^{28}	2.0×10^{-4}
80°K (H_2-CH_4)	1	1470	15710*	3.00×10^4	8.0×10^8	3.3×10^{28}	2.0×10^{-4}
100°K (H_2-CH_4)	1	2070	12060*	1.25×10^3	3.7×10^7	10^{27}	10^{-6}

* Exobase = Blow-off level in this case.

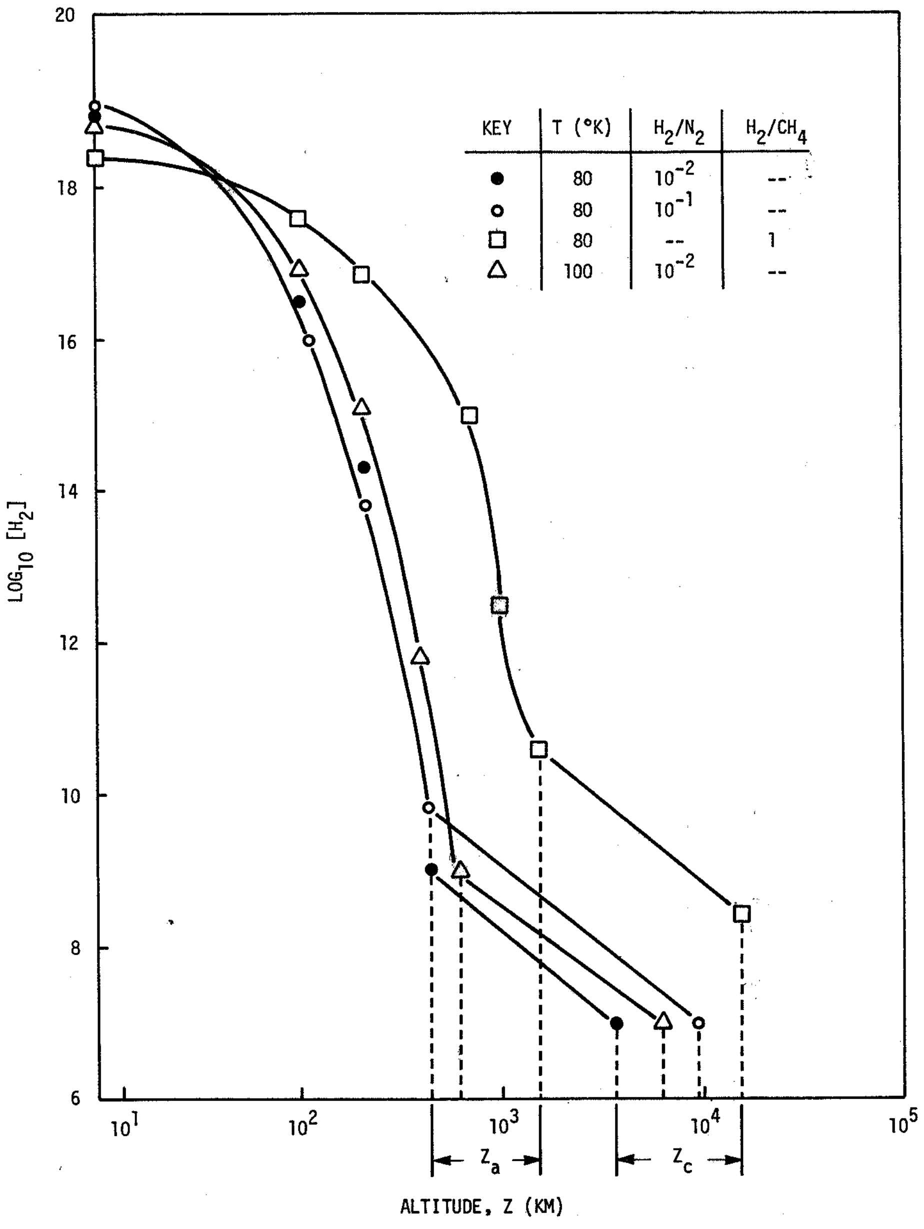

Figure 2-39. Profile of molecular hydrogen for H_2-N_2 and H_2-CH_4 model atmospheres at temperatures of 80°K and 100°K. Z_a is the turbopause level and Z_c is the exobase level.

was calculated along the vertical at the sub-solar point by solving simultaneously the diffusion equation and the continuity equation in the spherical case:

$$\phi_H(r) = -D(r) \left[\frac{dn_H}{dr} + \frac{n_H(r)}{H(r)}\right]$$

$$\frac{d\phi_H(r)}{dr} = P(r) - L(r) - \frac{2}{r}\phi_H(r)$$

where:
$H(r)$ = scale height of atomic hydrogen.
$H_e(r)$ = scale height of the atmosphere.
$\phi_H(r)$ = the diffusion flux of atomic hydrogen in ats cm^{-2} sec^{-1},
$P(r)$ = production rate of H through photodissociation of H_2,
$L(r)$ = loss rate of H by three-body recombinations with H_2 and N_2,
$D(r)$ = diffusive coefficient:

$D(r) = \frac{2 \times 10^{19}}{n_{H_2}(r)}$ in the case of diffusion of H in an atmosphere of H_2,

$D(r) = \frac{3.19 \times 10^{16}\, H_e(r)}{n_{N_2}(r)}$ in the case of diffusion of H, in an atmosphere essentially of N_2.

The exospheric distribution was calculated with no satellite particles from Chamberlain's theory.

For H_2-N_2 model atmospheres the effect of the mixing ratio (H_2/N_2) at ground level is illustrated in Figure 2-40 for T = 80°K. When this ratio increases the density maximum of H, located in the turbosphere, decreases, while the density of H in the diffusosphere increases substantially. Above 10^4 km altitude in the exosphere, the density is insensitive to the mixing ratio.

The effect of the isothermal temperature (T) on the H density is illustrated for an H_2-N_2 mixing ratio of 10^{-1} in Figure 2-41. The H density increases substantially with T in the diffusosphere. Again the density in the exosphere is not very sensitive to the temperature.

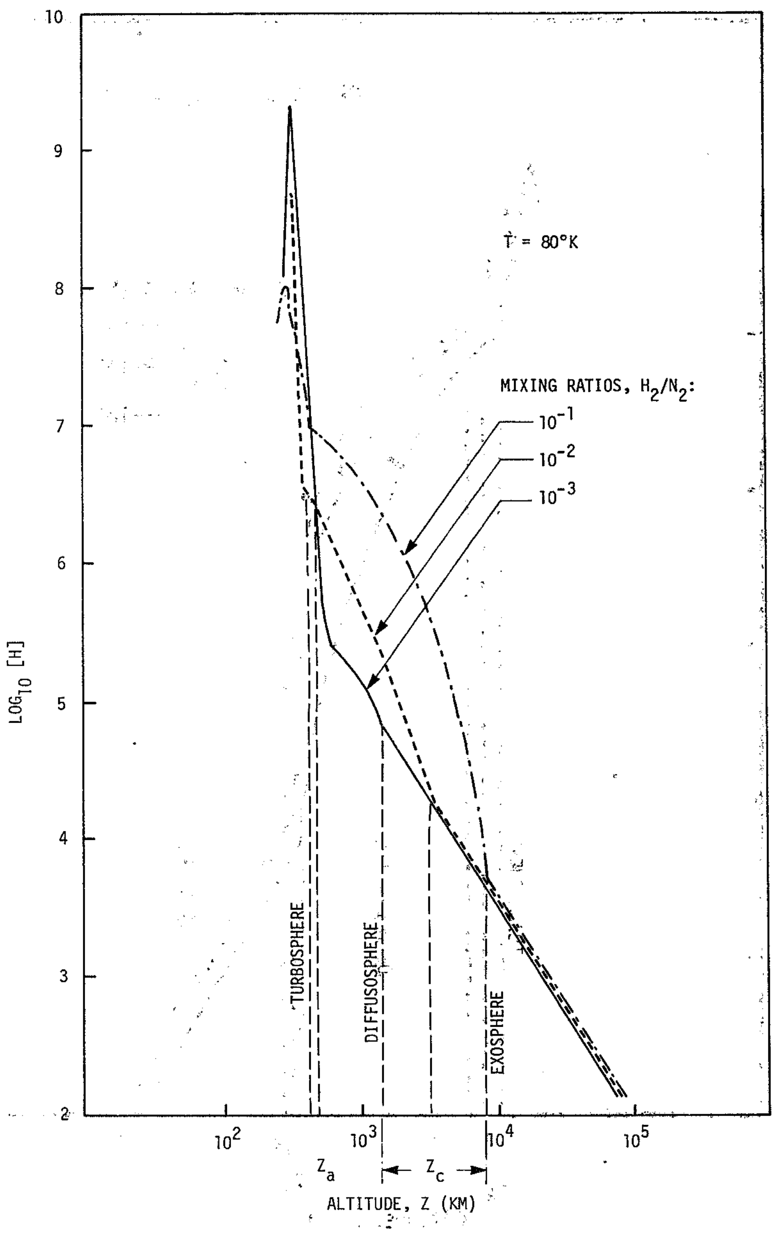

Figure 2-40. Profile of atomic hydrogen for H_2-N_2 model atmospheres at a temperature of 80°K. The effects of three different mixing ratios, H_2/N_2 equal to 10^{-3}, 10^{-2}, and 10^{-1}, are shown. Z_a is the turbopause level and Z_c is the exobase level.

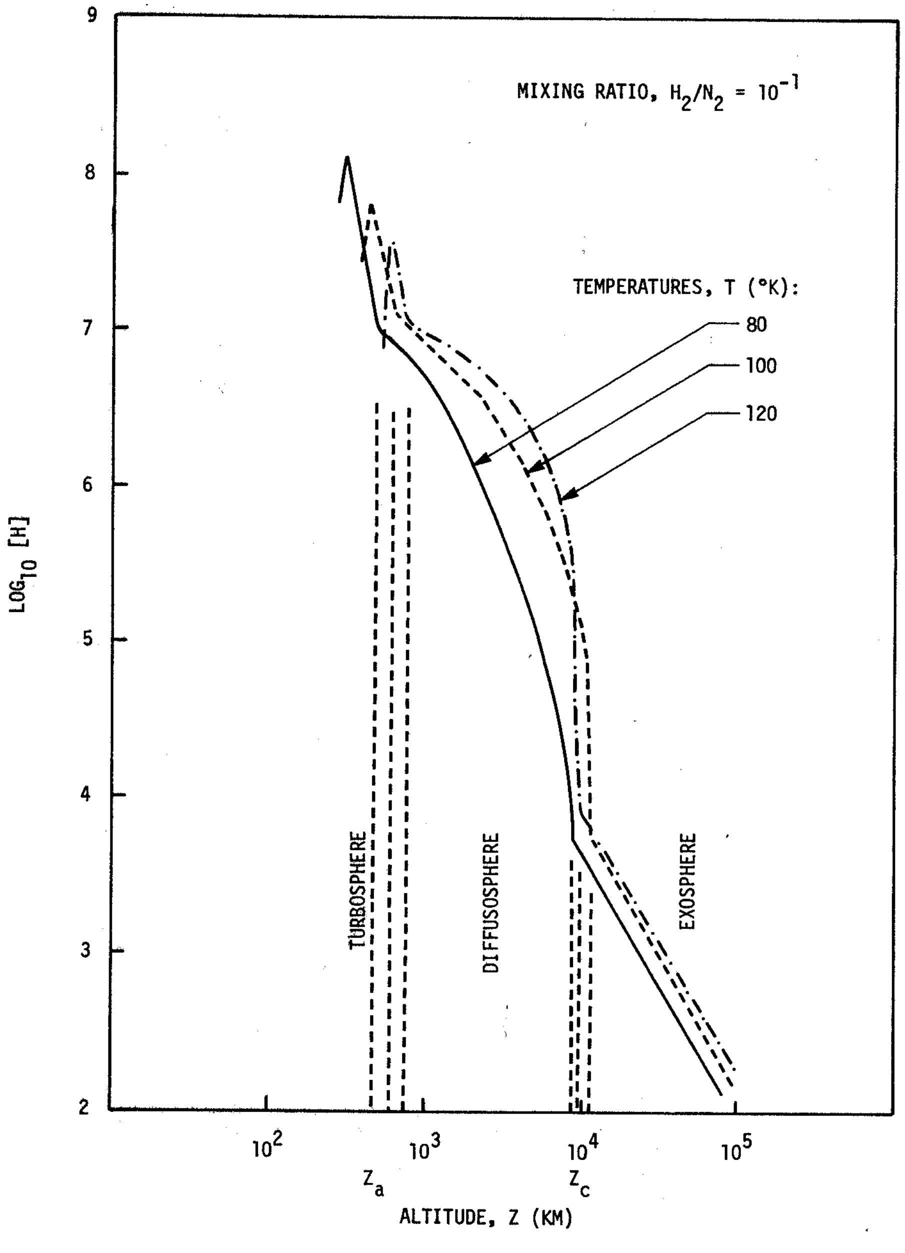

Figure 2-41. Profile of atomic hydrogen for H_2-N_2 model atmospheres for temperatures of 80°K, 100°K, and 120°K. A mixing ratio, H_2/N_2, of 10^{-1} is assumed. Z_a is the turbopause level and Z_c is the exobase level.

For H_2-CH_4 model atmospheres the effect of temperature is illustrated in Figure 2-42 for a mixing ratio of unity. The density profiles of H are quite different than for the H_2-N_2 models; the density at 5 x 10^3 km and on into the exosphere is much higher for the same temperature of 80°K. The effect of T is at variance with H_2-N_2 models in that an increase in T results in a decrease in the H density in an H_2-CH_4 model. This difference between the two types of models is due partly to the higher mixing ratio in the H_2-CH_4 model and partly to the increase of H production through photodissociation of CH_4. This later process is underestimated in our approach, since only photodissociation giving CH_3 + H was considered.

H and H_2 Escape Fluxes

The total fluxes of H and H_2 indicated in Table 2-8 were calculated by assuming spherical symmetry which might lead to an overestimation by a factor of 2 for H. In any case, the total flux of H is found to vary quite widely with the atmospheric parameters between 7.9 x 10^{26} atoms sec^{-1} for the H_2-N_2 model to 3.3 x 10^{28} atoms sec^{-1} for the H_2-CH_4 model at 80°K. The flux of H_2 is even larger than the flux of H for all models by a factor of between 6 and 10^6. For H_2-CH_4 models the H_2 flux is much larger than for H_2-N_2 models, and a hydrodynamic approach would be more appropriate than the assumption of hydrostatic equilibrium.

It has been suggested by Brice and McDonough (1973) that a large escape flux of H_2 from Titan would result in a toroid of hydrogen around Saturn. Dennefeld (private communication) has calculated the distribution of atomic H resulting from the escape of H and H_2. He found that a flux of 2 x 10^{28} atoms cm^{-3} sec^{-1} of H would result in a mean density of 22 ats cm^{-3} in the whole volume indicated in Figure 2-43 around the orbit of Titan. With a density of 22 ats cm^{-3}, such a toroid of H should be easily detected by its resonant Lyman-α emission, with an intensity of several hundred Rayleighs. In addition, since 10% of escaping H_2 molecules will be photodissociated into 2 H atoms when they are around Saturn, a flux of 10^{31} H_2 molecules (corresponding roughly to all encountered blow off conditions) would result in a much larger mean density of 22 x 100 = 2200 ats cm^{-3}, greatly increasing detectability of the toroid.

Summary

The distributions which we have obtained show that a determination of the vertical distribution of atomic hydrogen could easily be fitted to a model and that the two significant parameters, temperature and mixing ratio, could then be determined. However, since the differences between H_2-N_2 and H_2-CH_4 models are not very large, a high spatial resolution in the measurements would be necessary.

Hunten: Going back to my discussions of the limiting escape flux, the distributions of H and H_2 are independent of K (the eddy diffusion coefficient) until it reaches a value even larger than was assumed here (2 x 10^8 cm^2 sec^{-1}). For very large values, the densities are decreased. (K is related to the number density at the turbopause, n_a, by K = 2 x $10^{19}/n_a$.) What is the storage time in the toroid for hydrogen atoms and molecules?

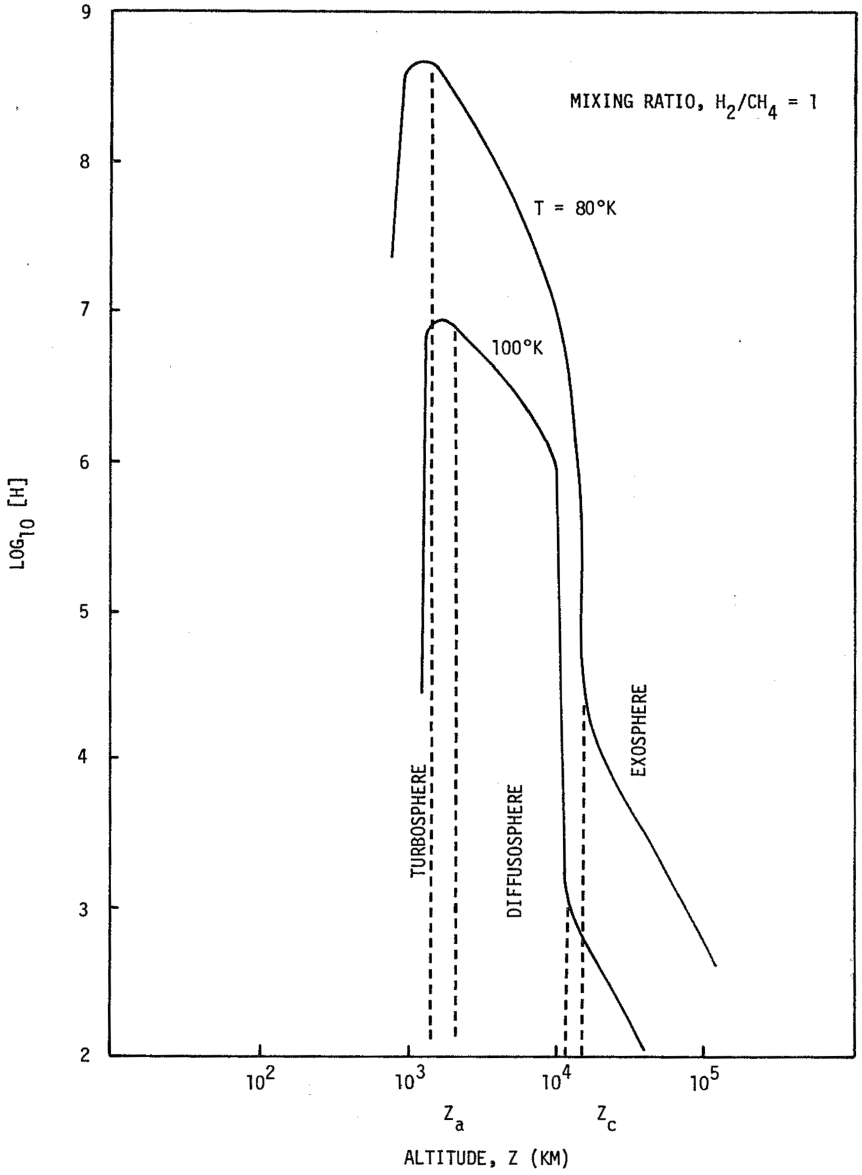

Figure 2-42. Profile of atomic hydrogen for H_2-CH_4 model atmospheres for temperatures of 80°K and 100°K. A mixing ratio, H_2/CH_4, of unity is assumed. Z_a is the turbopause level and Z_c is the exobase level.

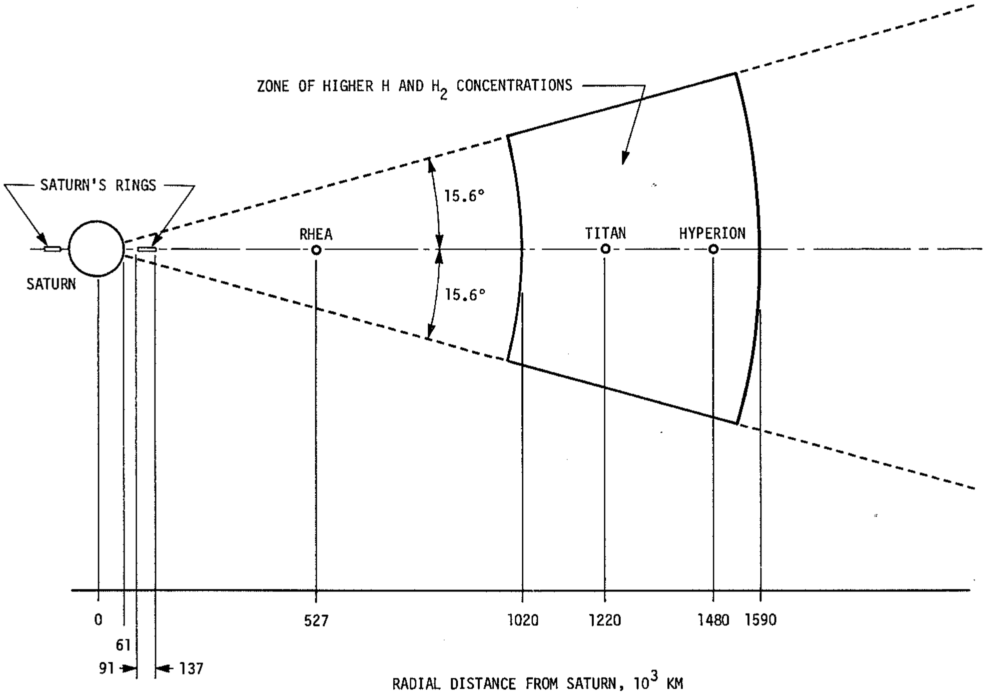

Figure 2-43. Cross-section of toroidal zone H and H_2 concentrations in the Saturnian system.

Tabarié: About 2 x 10^8 sec which is determined by charge exchange and photoionization of the atoms.

McDonough: You will be able to see Lyman-α both from resonance scattering by H and photodissociation of H_2. Do you have any idea what the ratio is?

Hunten: This was an issue after the Mariner 5 flyby of Venus. Equal intensities from the two sources required an H_2/H ratio of about 10^5;

Blamont: ...which may be what we will have on Titan and in the toroid, but the line from H_2 fluorescence will be much wider and a good measurement of the line shape will allow you to discriminate.

Rasool: What will the Mariner Jupiter/Saturn (MJS) mission be able to do near Titan?

Broadfoot: MJS will have two spectrometers, one observing airglow, with a 6 arc-minute field, and one observing solar occultation (if it goes through Titan's shadow) with a 1-minute field. Occultation will give H, H_2, and CH_4. Airglow will give H, but with poorer vertical resolution.

Blamont: It seems doubtful that MJS can detect H by occultation, because the solar Lyman-α line is so much wider than the planetary absorption.

Hunten: The height resolution is not too bad if you can get close enough to Titan. One arc-minute at 30,000 km is 10 km, which isn't bad at all.

Sagan: If your instrument can measure as faint as 100 Rayleighs, it would be exciting to map the glow from the toroid or tail or whatever is there.

Broadfoot: We will be able to do that as we approach the planet; we can take days to scan over the whole Saturnian system.