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-$\alpha$ 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\textsubscript{2} Fluxes for Titan Atmospheric Models

<table>
<thead>
<tr>
<th>TEMP.</th>
<th>MIXING RATIO</th>
<th>TURBO-PAUSE Z \textsubscript{a} km</th>
<th>EXOBASE Zc km</th>
<th>DENSITY AT GROUND (H\textsubscript{2}) mols cm\textsuperscript{-3}</th>
<th>DENSITY AT Zc (H\textsubscript{2}) mols cm\textsuperscript{-3}</th>
<th>EFFUSION VELOCITY (H\textsubscript{2}) cm sec\textsuperscript{-1}</th>
<th>ESCAPE FLUX (H\textsubscript{2}) mols cm\textsuperscript{2}sec\textsuperscript{-1}</th>
<th>TOTAL FLUX (H\textsubscript{2}) mols sec\textsuperscript{-1}</th>
<th>FLUX AT GROUND (H\textsubscript{2}) mols cm\textsuperscript{2}sec\textsuperscript{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>80\textdegree K (H\textsubscript{2}-N\textsubscript{2})</td>
<td>10\textsuperscript{-3}</td>
<td>520</td>
<td>1570</td>
<td>11.0 x 10\textsuperscript{18}</td>
<td>10\textsuperscript{7}</td>
<td>2.3 x 10\textsuperscript{5}</td>
<td>2.3 x 10\textsuperscript{5}</td>
<td>4.8 x 10\textsuperscript{27}</td>
<td>5.9 x 10\textsuperscript{9}</td>
</tr>
<tr>
<td></td>
<td>10\textsuperscript{-2}</td>
<td>470</td>
<td>3420</td>
<td>10.5 x 10\textsuperscript{18}</td>
<td>10\textsuperscript{7}</td>
<td>1.3 x 10\textsuperscript{3}</td>
<td>1.3 x 10\textsuperscript{12}</td>
<td>5.9 x 10\textsuperscript{28}</td>
<td>7.0 x 10\textsuperscript{9}</td>
</tr>
<tr>
<td></td>
<td>10\textsuperscript{-1}</td>
<td>460</td>
<td>8950</td>
<td>9.5 x 10\textsuperscript{18}</td>
<td>10\textsuperscript{7}</td>
<td>7.0 x 10\textsuperscript{2}</td>
<td>7.0 x 10\textsuperscript{12}</td>
<td>1.6 x 10\textsuperscript{30}</td>
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<td>670</td>
<td>2410</td>
<td>8.0 x 10\textsuperscript{18}</td>
<td>10\textsuperscript{7}</td>
<td>1.5 x 10\textsuperscript{5}</td>
<td>1.5 x 10\textsuperscript{12}</td>
<td>4.6 x 10\textsuperscript{28}</td>
<td>5.6 x 10\textsuperscript{10}</td>
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<td>1.4 x 10\textsuperscript{4}</td>
<td>5.0 x 10\textsuperscript{11}</td>
<td>1.3 x 10\textsuperscript{31}</td>
<td>1.6 x 10\textsuperscript{13}</td>
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<tr>
<td>120\textdegree K (H\textsubscript{2}-N\textsubscript{2})</td>
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<td>1.5 x 10\textsuperscript{8}</td>
<td>1.6 x 10\textsuperscript{4}</td>
<td>2.3 x 10\textsuperscript{12}</td>
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<tr>
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<td>1470</td>
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<td>2.7 x 10\textsuperscript{18}</td>
<td>2.7 x 10\textsuperscript{8}</td>
<td>1.2 x 10\textsuperscript{9}</td>
<td>3.2 x 10\textsuperscript{12}</td>
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<tr>
<td>100\textdegree K (H\textsubscript{2}-CH\textsubscript{4})</td>
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<td>12060*</td>
<td>2.1 x 10\textsuperscript{18}</td>
<td>2.3 x 10\textsuperscript{9}</td>
<td>1.6 x 10\textsuperscript{9}</td>
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<td>10\textsuperscript{15}</td>
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* Exobase = Blow-off level in this case.
Table 2-8b. \( ^{3}H \) Fluxes for Titan Atmospheric Models.

<table>
<thead>
<tr>
<th>TEMP.</th>
<th>MIXING RATIO</th>
<th>TURBOPAUSE ( Za ) km</th>
<th>EXOBASE ( Zc ) km</th>
<th>DENSITY at ( Zc ) ( (\text{H}) ) atoms ( \text{cm}^{-3} )</th>
<th>ESCAPE FLUX ( \text{H} ) atoms ( \text{cm}^{-2} \text{sec}^{-1} )</th>
<th>TOTAL FLUX ( \text{H} ) atoms ( \text{sec}^{-1} )</th>
<th>FLUX RATIO ( \text{H/H}_2 )</th>
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<tbody>
<tr>
<td>80(^{\circ})K ( (\text{H}_2-\text{N}_2) )</td>
<td>( 10^{-3} )</td>
<td>520</td>
<td>1570</td>
<td>( 7.50 \times 10^6 )</td>
<td>( 3.7 \times 10^8 )</td>
<td>( 8.0 \times 10^{26} )</td>
<td>( 1.6 \times 10^{-1} )</td>
</tr>
<tr>
<td></td>
<td>( 10^{-2} )</td>
<td>470</td>
<td>3420</td>
<td>( 2.50 \times 10^6 )</td>
<td>( 2.7 \times 10^8 )</td>
<td>( 1.2 \times 10^{27} )</td>
<td>( 2.0 \times 10^{-2} )</td>
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<td>( 10^{-1} )</td>
<td>460</td>
<td>8950</td>
<td>( 7.80 \times 10^3 )</td>
<td>( 1.7 \times 10^8 )</td>
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<td>100(^{\circ})K ( (\text{H}_2-\text{N}_2) )</td>
<td>( 10^{-3} )</td>
<td>670</td>
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<td>( 2.30 \times 10^6 )</td>
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<td>( 6.0 \times 10^{-4} )</td>
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<tr>
<td>120(^{\circ})K ( (\text{H}_2-\text{N}_2) )</td>
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<td>3470</td>
<td>( 1.10 \times 10^6 )</td>
<td>( 2.5 \times 10^8 )</td>
<td>( 1.1 \times 10^{27} )</td>
<td>( 6.5 \times 10^{-3} )</td>
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<td>( 10^{-2} )</td>
<td>750</td>
<td>9600*</td>
<td>( 5.60 \times 10^3 )</td>
<td>( 1.8 \times 10^8 )</td>
<td>( 3.3 \times 10^{27} )</td>
<td>( 6.8 \times 10^{-4} )</td>
</tr>
<tr>
<td></td>
<td>( 10^{-1} )</td>
<td>730</td>
<td>9600*</td>
<td>( 1.60 \times 10^6 )</td>
<td>( 5.5 \times 10^8 )</td>
<td>( 1.0 \times 10^{27} )</td>
<td>( 2.0 \times 10^{-5} )</td>
</tr>
<tr>
<td>80(^{\circ})K ( (\text{H}_2-\text{CH}_4) )</td>
<td>1</td>
<td>1470</td>
<td>15710*</td>
<td>( 3.00 \times 10^6 )</td>
<td>( 8.0 \times 10^8 )</td>
<td>( 3.3 \times 10^{28} )</td>
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<tr>
<td>100(^{\circ})K ( (\text{H}_2-\text{CH}_4) )</td>
<td>1</td>
<td>2070</td>
<td>12060*</td>
<td>( 1.25 \times 10^3 )</td>
<td>( 3.7 \times 10^7 )</td>
<td>( 10^{27} )</td>
<td>( 10^{-6} )</td>
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</table>

* Exobase = Blow-off level in this case.
Figure 2-39. Profile of molecular hydrogen for H₂-N₂ and H₂-CH₄ model atmospheres at temperatures of 80°K and 100°K. Zₐ is the turbopause level and Zₑ is the exobase level.
was calculated along the vertical at the sub-solar point by solving simultane-
ously 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.
- \( H_o(r) \) = scale height of the atmosphere.
- \( \phi_H(r) \) = the diffusion flux of atomic hydrogen in \( \text{cm}^{-2} \text{sec}^{-1} \),
- \( P(r) \) = production rate of H through photodissociation of \( \text{H}_2 \),
- \( L(r) \) = loss rate of H by three-body recombinations with \( \text{H}_2 \) and \( \text{N}_2 \),
- \( D(r) \) = diffusive coefficient:

\[ D(r) = 2 \times 10^{19} \text{ in the case of diffusion of H in an } \]
\[ \frac{n_{\text{H}_2}(r)}{n_{\text{N}_2}(r)} \text{ atmosphere of } \text{H}_2, \]
\[ D(r) = \frac{3.19 \times 10^{16} H(r)}{n_{\text{N}_2}(r)} \text{ in the case of diffusion of H,} \]
\[ \text{in an atmosphere essentially of } \text{N}_2. \]

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

For \( \text{H}_2-\text{N}_2 \) model atmospheres the effect of the mixing ratio \( (\text{H}_2/\text{N}_2) \) at
ground level is illustrated in Figure 2-40 for \( T = 80^\circ \text{K} \). When this ratio in-
creases 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 illus-
trated for an \( \text{H}_2-\text{N}_2 \) 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 H₂-N₂ model atmospheres at a temperature of 80°K. The effects of three different mixing ratios, H₂/N₂ equal to 10⁻³, 10⁻², and 10⁻¹, are shown. Zₐ is the turbopause level and Zₑ is the exobase level.
Figure 2-41. Profile of atomic hydrogen for H₂-N₂ model atmospheres for temperatures of 80°K, 100°K, and 120°K. A mixing ratio, H₂/N₂, of 10⁻¹ is assumed. Zₐ is the turbopause level and Z_c is the exobase level.
For H₂-CH₄ 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 H₂-N₂ models; the density at 5 x 10⁵ km and on into the exosphere is much higher for the same temperature of 80°K. The effect of T is at variance with H₂-N₂ models in that an increase in T results in a decrease in the H density in an H₂-CH₄ model. This difference between the two types of models is due partly to the higher mixing ratio in the H₂-CH₄ model and partly to the increase of H production through photodissociation of CH₄. This later process is underestimated in our approach, since only photodissociation giving CH₃ + H was considered.

**H and H₂ Escape Fluxes**

The total fluxes of H and H₂ 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 10²⁶ atoms sec⁻¹ for the H₂-N₂ model to 3.3 x 10²⁹ atoms sec⁻¹ for the H₂-CH₄ model at 80°K. The flux of H₂ is even larger than the flux of H for all models by a factor of between 6 and 10⁶. For H₂-CH₄ models the H₂ flux is much larger than for H₂-N₂ 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 H₂ 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 H₂. He found that a flux of 2 x 10²⁸ 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 H₂ molecules will be photodissociated into 2 H atoms when they are around Saturn, a flux of 10³¹ H₂ molecules (corresponding roughly to all encountered blow off conditions) would result in a much larger mean density of 22 x 10⁶ = 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 H₂-N₂ and H₂-CH₄ 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 H₂ are independent of K (the eddy diffusion coefficient) until it reaches a value even larger than was assumed here (2 x 10⁸ cm² sec⁻¹). For very large values, the densities are decreased. (K is related to the number density at the turbopause, nₐ, by K = 2 x 10¹⁹/nₐ.) What is the storage time in the toroid for hydrogen atoms and molecules?
Figure 2-42. Profile of atomic hydrogen for H₂-CH₄ model atmospheres for temperatures of 80⁰K and 100⁰K. A mixing ratio, H₂/CH₄, of unity is assumed. Zₐ is the turbopause level and Zₑ is the exobase level.
Figure 2-43. Cross-section of toroidal zone H and H₂ concentrations in the Saturnian system.
Tabarie: About $2 \times 10^8$ sec which is determined by charge exchange and photodissociation of the atoms.

McDonough: You will be able to see Lyman-$\alpha$ 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-$\alpha$ 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.