

THE ORTHO-PARA HYDROGEN EQUILIBRIUM

IN THE URANUS ATMOSPHERE

by

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S.B., Massachusetts Institute of Technology

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ABSTRACT

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ABSTRACT

Ortho-para conversion may be an important heating mechanism in the Jovian planets. In order to calculate the o-p equilibrium, an atmospheric model must be developed. Temperature, pressure, scale height, eddy diffusion coefficient, and number density of H_2 , the dominant gas in the atmosphere, are all defined as a function of altitude above the 450°K level. Ortho-para conversion mechanisms are considered, with the conclusion that the ion-molecule recombination $H^+ + o-H_2 = p-H_2 + H^+$ is important in the upper atmosphere, while $H + o-H_2 = p-H_2 + H$ is dominant in the lower atmosphere. Consideration of the differing loss mechanisms in the atmosphere leads to conclusions that, although cosmic rays are an important source of ionization, the source occurs at a level where the ion loss is fast due to interactions with methane. UV ionization very high in the atmosphere above the methane level leads to high proton densities and subsequent o-p conversion of H_2 . The lower atmosphere mechanism, on the other hand, is too slow compared to loss mechanisms for H.

In order for the above conclusions to fit with observations, there must be essentially no H_2 transport across the tropopause. An argument is made for the feasibility of this condition. The percentage of para-hydrogen is graphed as a function of altitude in the Uranus atmosphere.

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TITLE: Associate Professor

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1. Introduction

1.1 The Uranus atmosphere

Uranus is unique in the solar system in that the axis of its rotation is inclined 98° to the normal of its orbital plane. The planet has five satellites and a system of rings, all of whose axes of rotation are also inclined 98° . The internal pressures on Uranus are much less than on Jupiter or Saturn, but its density is large in comparison with solar composition material. Uranus is estimated to be 50% by mass heavy elements. Therefore, it is thought likely that Uranus possesses a differentiated core containing higher mass elements. Most models of the planet (Hubbard, 1975; Podolak & Cameron, 1974) suppose a rocky core surrounded by an extensive ice layer.

Brown (1976) detected non-thermal radio emission from the direction of Uranus with IMP-6. He estimated a polar field intensity of 0.6 - 0.9 gauss. The dipole axis of any Uranian magnetic field would probably be aligned with its spin axis. A magnetic field oriented 98° would have unique properties as outlined by Siscoe (1975).

The effective temperature of Uranus has been observed to be $58 \pm 3^\circ\text{K}$ (Fazio, Traub, and Wright, 1976). Since the calculated temperature of a gray body at Uranus' distance is $58 \pm 2^\circ\text{K}$, this leads some to conclude that Uranus has no internal heat source, while the other Jovian planets do.

However, the effects of the planet's unique orbital inclination must be taken into account when measuring effective temperature and determining a value for the internal heat source. Fazio, Traub, and Wright (1976) have considered this problem and have concluded that the internal heat source should have a maximum value of $\sim 10^3$ ergs $\text{cm}^{-2} \text{sec}^{-1}$.

Uranus is the first planet which is far enough from the Earth so that dynamical activity manifested by clouds cannot be observed with ground-based observations. Consequently there is no direct information concerning motions in the atmosphere, although motions must be present because of differential solar heating. There is visual evidence for broad bands in the atmosphere, and discrete features exist. The planet appears greenish-blue with faint dusky belts.

Tables 1 and 2 summarize the orbital and atmospheric parameters for Uranus.

Two molecules have been identified in the Uranus atmosphere: H_2 and CH_4 (Newburn and Gulkis, 1973). The C/H ratio has been estimated to be between 1 and 300 times the solar value (Trafton, 1976). The high mean density indicates that other, heavier molecules may be found in the atmosphere. Prinn and Lewis (1973) and others have suggested other other gases which are likely to be present. These include He, NH_3 , H_2O , H_2S , C_2H_2 , and C_2H_6 . Prinn and Lewis (1973) have concluded that cloud layers of CH_4 , NH_3 , NH_4SH , and H_2O are possible. H_2S , H_2O , and NH_4SH would primarily be confined

to the deeper layers ($P \gtrsim 10$ bars). Trafton (1976) suggests that there exists a thin CH_4 haze at $P \sim 0.2 - 0.7$ bars and a thick NH_3 cloud at $P \sim 4 - 10$ bars

1.2 A model of the Uranus atmosphere

Any derivation of the ortho-para hydrogen equilibrium in the Uranus atmosphere must have as a basis an atmospheric model. The model atmosphere used here is a compilation of the models of Trafton (1976), Wallace (1975), and Weidenschilling & Lewis (1973). In addition, an adiabat was assumed ($P = 2.3 \times 10^{-7} T^{3.4}$) above $T = 400^\circ\text{K}$ and $P = 158$ bars. The P-T diagram for the Uranus model atmosphere is shown in Figure 1.

Graphs of pressure and temperature, $P(z)$ and $T(z)$, are derived from models of Trafton (1967) and Weidenschilling & Lewis (1973), and are shown in Figures 2 and 3.

Scale height $H(z)$ was calculated using the equation

$$H(z) = \frac{RT(z)}{ug},$$

R = gas constant

u = molecular weight of atmosphere

g = acceleration of gravity

Values were supplied by Table 2 and Figure 3. The $H(z)$ profile is shown in Figure 4.

The eddy diffusion coefficient $K(z)$ is shown in Figure 5. $K(z)$ was calculated using the equation

$$K(z) = H(z) \left[\frac{R\phi T(z)}{3uP(z)} \right]^{1/3},$$

which applies in the case of free convection ($P \gtrsim$ few bars). Values of $P(z)$, $T(z)$, and $H(z)$ were supplied from Figures 2 - 4. The internal heat source ϕ was calculated using the conservative estimate that the long-lived radionuclides U, K and Th are the only internal heat sources. This provides a value for ϕ of $\sim 10^2$ ergs $\text{cm}^{-2} \text{sec}^{-1}$.

High in the atmosphere ($P \lesssim 0.1$ bars),

$$K(z) \propto \rho^{-1/2} = \left[\frac{RT(z)}{uP(z)} \right]^{1/2}.$$

While the proportionality constant is unknown, it is known that $K \sim 10^4$ in the stratosphere. Thus for higher altitudes, the values for $K(z)$ derived from the above equation were adjusted accordingly.

The number density of H_2 was derived from the equation

$$n_{\text{H}_2}(z) = \frac{P(z)}{kT(z)},$$

$$k = \text{Boltzmann's constant} = 1.38 \times 10^{-16} \text{ erg}^\circ\text{K}^{-1}.$$

$n_{\text{H}_2}(z)$ is shown in Figure 6. Trafton (1976) notes that observations of the hydrogen spectrum indicate that H_2 dominates all other gases in the atmosphere.

Now that the Uranus atmosphere has been quantitatively modeled, the next step is to consider the ortho-para hydrogen question. Section 1.3 deals with the distinctions between ortho- and para- hydrogen, and section 1.4 looks at the different ortho-para conversion mechanisms.

1.3 Ortho- and para- hydrogen

The two protons in an H_2 molecule can possess either parallel or anti-parallel spins. An H_2 molecule with parallel nuclear spin is called ortho-hydrogen and has odd rotational quantum numbers. Para-hydrogen has anti-parallel nuclear spin and even quantum numbers. Spontaneous conversion of the two types of molecules practically does not take place, either by radiative or collisional processes. The lifetime of a radiative transition from the $j=1$ rotational state of ortho-hydrogen ($o-H_2$) to the $j=0$ state of para-hydrogen ($p-H_2$) is 1.3×10^{10} sec (Raich and Good, 1964). Thus ortho- and para- hydrogen can be considered as molecules of two different gases, which differ in certain optical and thermal properties.

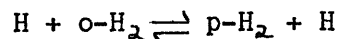
The thermodynamic equilibrium between ortho- and para-hydrogen is governed by Boltzmann's distribution law. At temperatures near $0^\circ K$, all molecules pass into their lowest energy states. Thus, at low temperatures, all H_2 will be para-hydrogen. At high temperatures ($kT \gg B$), the equilibrium will correspond to the statistical weights due to nuclear spin. This equilibrium is practically attained at room temperatures, and thus "normal" hydrogen is composed of $3/4$ para-hydrogen and $1/4$ ortho-hydrogen (Farkas, 1935). A graph of para-hydrogen percentage vs. temperature is shown in Figure 7.

It would be useful to know the ortho-para ratio in the

atmospheres of the Jovian planets. The transition from para- to ortho- hydrogen is a heating mechanism, since ortho-hydrogen is in a higher energy state. Even though ortho- and para- hydrogen are coupled neither by radiative nor collisional mechanisms, interconversion between the two species can occur. Conversion can be accomplished by atom-atom or ion-atom interchanges, and these can be catalyzed by grains or paramagnetic substances. Section 1.4 looks at each of these interconversion mechanisms and estimates their importance in the atmosphere of Uranus.

1.4 Ortho-para conversion mechanisms

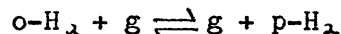
The atom-atom interchange conversion



has a rate constant k of $6.3 \times 10^{-13} \text{ cm}^3\text{sec}^{-1}$ at a temperature of 1000°K and $3.5 \times 10^{-17} \text{ cm}^3\text{sec}^{-1}$ at 283°K (Hirschfelder et al., 1936). Thus, at temperatures corresponding to the effective temperature of Uranus (58°K) and the upper troposphere of the atmosphere ($100^\circ - 300^\circ\text{K}$), the reaction rate will be less than or on the order of $10^{-17} \text{ cm}^3\text{sec}^{-1}$. Thus, this reaction is very slow in the upper atmosphere. Furthermore, the temperatures at which the reaction becomes fast enough to be an important factor in o-p conversion are temperatures so high that the o-p equilibrium is 3/4 para and 1/4 ortho hydrogen.

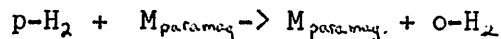
Ortho-para conversion can also be catalyzed on the

surface of grains:



The "grains" present in the Uranus atmosphere would be solid CH₄ particles, which are present at pressures of 0.2 to 0.7 bars. This corresponds to temperatures of 90° - 160°K and H₂ number densities of ~ 10²⁰ cm⁻³. At such temperatures, the collision of H₂ molecules with grains is likely to lead to the loss of kinetic energy of the gas particles. The efficiency of the catalysis is unlikely to be high at such low temperatures. It cannot exceed the collision rate of 10⁻¹⁷ n_{H₂} sec⁻¹ or 10³ sec⁻¹ (Dalgarno et. al., 1973), and is probably much less than that. Since there is no knowledge of grain surface conditions, no definite conclusions can be reached about the efficiency of the process.

Paramagnetic gases provide another way in which o-p conversion can be catalyzed. Ortho-hydrogen has a very small magnetic moment, while para-hydrogen has none. Conversion is caused by the non-homogeneous magnetic field of the paramagnetic molecules involved in the collision. Thus, paramagnetic gases will catalyze the para- to ortho-hydrogen conversion (Farkas, 1935). The reaction



has a rate constant of 5 x 10⁻²³ cm³sec⁻¹ (Farkas 1935).

Paramagnetic gases which may be present in the Uranus atmosphere include include free radicals such as PH₂, H, HS,

CH₃, and NH₃. The abundance of each species present can be calculated by assuming an atmospheric steady state, i.e. rate of production equals rate of destruction. For instance, The abundance of H can be roughly determined by using the major loss mechanism



which has a rate of reaction $k = 9.8 \times 10^{-33} \text{ cm}^6 \text{ sec}^{-1}$ at $T = 700^\circ \text{K}$ (Kondratiev, 1972). By scaling Jovian data from Strobel (1969) appropriately to account for Uranus' greater distance from the Sun, the production rate of H, as determined by

production rate = flux / scale height,

can be found to be approximately $10^3 \text{ cm}^{-3} \text{ sec}^{-1}$ at the 700°K level. Thus, the equation

$$d[H]/dt = k[H]^2[H_2] = \text{production rate}$$

can be solved for [H]. The number density of H from the above calculations is $n_H = 3 \times 10^6 \text{ cm}^{-3}$.

The number densities of the other free radicals involved are acquired in the same fashion, using as their major loss mechanisms interactions with H. At 700°K , the number densities of the free radicals range from 10^6 to 10^4 cm^{-3} . At 1000°K , their number densities are higher, from 10^{11} to 10^8 cm^{-3} . Any recombinations of these free radicals have comparable or lower number densities. At these levels in the atmosphere, the dynamical lifetime, as calculated by

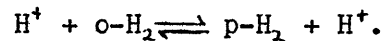
$$\tau_{dyn} = \frac{H^2}{K}$$

is approximately 2.5×10^6 sec. Even using the largest number density calculated for the paramagnetic gases, the chemical lifetime, as determined using

$$\tau_{chem} = \frac{1}{kn_{H_2}}$$

is approximately 2×10^{11} sec, much longer than the dynamical lifetime. Thus the paramagnetic substances will not be able to produce ortho-para conversion.

The single remaining method for o-p conversion is the ion-molecule interchange,



The rate constant for this reaction is given by Dalgarno et. al. (1973) as $k = 10^{-10} \text{ cm}^3\text{sec}^{-1}$ at a temperature of $\sim 50^\circ\text{K}$, which they calculated from quantal statistics. According to Dalgarno, the energy defect corresponds to a temperature of 170.5°K . Thus, at temperatures much less than 170°K , the reaction forms p- H_2 and destroys o- H_2 . By looking at reaction rates alone, it seems that the ionic mechanism is the fastest in the upper atmosphere. However, an assessment of the amount of ions present is required before a calculation of the chemical lifetime can be made.

2. The Ortho-Para Equilibrium

2.1 Sources of ions in the Uranus atmosphere

Atmospheric ions can derive from three possible sources. At high altitudes, photolysis produces ions. At great depths, ions can be a result of thermal equilibrium. And finally, lightning can be a source of ions, assuming that such a phenomenon occurs in the Uranus atmosphere.

Molecules in the Uranus atmosphere can be ionized by two sources of radiation: solar extreme ultra-violet (EUV) radiation and cosmic rays. Since the intensity of solar EUV radiation decreases with the square of the distance from the Sun, at Uranus' distance cosmic ray ionization is actually more important than EUV ionization (Capone, et. al., 1977). According to McElroy (1973), the most important source of H⁺ comes from the dissociative ionization of H₂. In addition, protons recombine very slowly in the atmosphere, so that most atmospheric models assume that protons are removed only by radiative recombination. The maximum proton density is about 10^5 cm^{-3} and occurs high in the atmosphere, at a hydrogen density of $\sim 10^{11} \text{ cm}^{-3}$ (Capone, et. al., 1977).

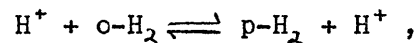
Lightning is unlikely to be a major factor in ion production. On Earth, approximately 10^{-5} of the incident energy is converted to energy in lightning (as electrical currents and acoustic waves). On Uranus, assuming similar conversion factors, 10^{-5} of the solar flux is converted to

electrical and acoustical energy. However a fraction of 10^{-2} of the incident solar flux is in the form of ultra-violet radiation. Therefore, there is 10^3 times more energy available from UV radiation to be used in breaking chemical bonds. In addition, a large part of the energy in lightning is involved in heating the atmosphere without causing dissociation. Thus, lightning is a minor factor in the bulk chemistry of a planet (Prinn and Owen, 1976).

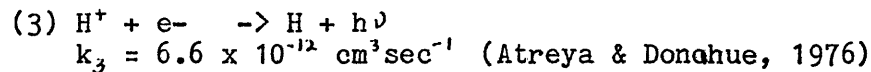
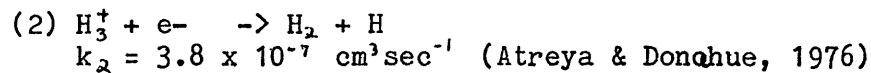
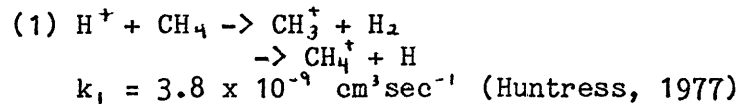
Thermochemical equilibrium, the last process involved in ion production, is difficult to quantify in the Uranus atmosphere since so little is known about the lower atmosphere. Any estimates of ion density would be pure guesswork. In the lower atmosphere of Earth, ion number densities range from 10^2 to 10^5 cm^{-3} (Wallace and Hobbs, 1977). So, for lack of any other data, the abundance of ions in the Uranus atmosphere will be taken to be approximately $10^{3 \pm 1}$ cm^{-3} .

2.2 Assessment of ion reactions

To calculate the chemical lifetime of the reaction



the abundance of H^+ is needed. H^+ abundance will depend on the ion production rate and on the various loss mechanisms for H^+ and H_3^+ :



H⁺, H₃⁺, etc. are not considered to be losses of H⁺, since these species can also produce o-p conversion. H⁺ abundance also depends on the ion production rate. As discussed in section 2.1, ions can be produced by two major sources: solar EUV radiation and cosmic rays. According to the model of Capone et. al. (1977) for the Uranus model atmosphere, UV production of H⁺ reaches a peak at n_{H₂} = 10¹¹ cm⁻³. Cosmic rays have a flux of 0.8 cm⁻²sec⁻¹ in interstellar space (Ginzburg, 1969). Typical cosmic rays have energies of 100 MeV. Therefore they will penetrate to greater depths in the atmosphere than UV radiation. In the ionospheric model of Capone et. al., the peak ion production from cosmic rays occurs at n_{H₂} = 10¹³ cm⁻³.

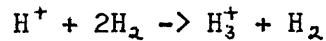
In the Uranus ionosphere, diffusive unmixing creates an upper region in which there exists no methane. This region can be divided into two layers: an upper layer (layer I) in which H⁺ is the dominant H ion, and a lower layer (layer II) in which H₃⁺ dominates. In the Capone model, layer I occurs at n_{H₂} ≤ 4x10¹¹ cm⁻³. Layer II is very thin, existing at 4x10¹¹ cm⁻³ < n_{H₂} < 3x10¹² cm⁻³. Layer III is the layer where the methane abundances become significant, and occurs at n_{H₂} ≥ 3x10¹² cm⁻³. The turbopause occurs at n_{H₂} = 10¹³

cm⁻³. The three layers are characterized by their rates of catalysis, their dominant loss mechanisms for H⁺ and H₃⁺, and their rates of ion loss.

The dominant loss mechanism in layer III is the H⁺ interaction with CH₄, reaction (1) as given above. The lifetime for neutralization of H⁺ for a typical point in this region ($n_{H_2} = 10^{16}$ cm⁻³) is

$$\tau_{chem}(H^+) = 1 / k_1 n_{CH_4} = 4 \times 10^{-6} \text{ sec.}$$

(Note that CH₄ is calculated using a value of CH₄ / H₂ enriched 10 times over solar proportions: $n_{CH_4} = 7 \times 10^{-3} n_{H_2}$.) H⁺ is the dominant H_x⁺ ion, since the conversion to H₃⁺ via the reaction



has a rate constant $k = 3.2 \times 10^{-27}$ cm³ sec⁻¹ (Atreya & Donohue, 1976) so that the lifetime of H⁺ until conversion into H₃⁺ is 3×10^{-4} sec, longer than neutralization time. The collision lifetime at this point is calculated from

$$\begin{aligned} \tau_{coll.} &= \text{mean free path} / \text{speed} \\ &= 10^{-2} \text{ cm} / 10^4 \text{ cm sec}^{-1} = 10^{-6} \text{ sec.} \end{aligned}$$

The number of collisions per H⁺ lifetime is equal to

$$\tau_{chem}(H^+) / \tau_{coll.} = 4 \text{ collisions/H}^+.$$

Assuming that each collision produces an o-p conversion, this means that every H⁺ will convert 4 H₂ molecules before becoming neutralized. The total number of H⁺ ions present will be due to cosmic ray ionization at this level. Assum-

ing 100 MeV cosmic ray energies and an ionization potential of 14 eV for H₂ (Huntress, 1977), then there exists 7x10⁶ cm⁻² sec⁻¹ H+. Thus, the total number of conversions possible is 4 x 7x10⁶ = 3x10⁷ cm⁻² sec⁻¹ conversions. The upper limit of the o-p conversion lifetime is the dynamical lifetime, since chemical lifetimes must be less than dynamical lifetimes for chemical reactions to occur. At this level in the atmosphere the dynamical lifetime is 8x10⁷ sec.

$$\hat{c}_{\text{conversion}} \times \text{total number of conversions} = \\ (8 \times 10^7 \text{ sec})(3 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}) = \\ 2 \times 10^{15} \text{ conversions/cm}^2.$$

This means that total conversion of H₂ will occur down to number densities of H₂ calculated from

$$n_{\text{H}_2} = 2 \times 10^{15} \text{ cm}^{-3} / \text{scale height}.$$

$n_{\text{H}_2} = 5 \times 10^8 \text{ cm}^{-3}$, a number density much lower than that present in layer III. The conclusion drawn from this is that little ortho-para conversion occurs where methane is present, because of the fast rate of loss of H+ ions due to methane interactions.

In layer II H₃⁺ is the dominant species. From the model of Capone et. al. (1977), the peak abundance of H₃⁺ is 10³ cm⁻³ at $n_{\text{H}_2} = 10^{12} \text{ cm}^{-3}$. The major loss mechanism is reaction (2) above, the electron- H₃⁺ recombination. The lifetime of H₃⁺ due to neutralization is 3x10³ sec, where the electron abundance is equal to the H₃⁺ abundance. The collisional lifetime is 10⁻² sec, taking the mean free path to be 10² cm. Therefore, there are 3x10⁵ collisions/H₃⁺

lifetime, and the total number of collisions is $3 \times 10^8 \text{ cm}^{-3}$. Since $n_{\text{H}_2} = 10^{12} \text{ cm}^{-3}$ in this region, total o-p conversion does not occur in layer II. This is due to the electron-ion recombination mechanism which removes many H_3^+ ions before they can effect o-p conversion. Note however, that the ratio of conversions/total H_2 density is higher than in layer III.

In layer I, H^+ is the dominant ion and its major loss mechanism is given by reaction (3). H^+ density is at a maximum of 10^5 cm^{-3} at an H_2 density of 10^{11} cm^{-3} (Capone et. al., 1977). Taking a UV flux of $3.8 \times 10^{-3} \text{ erg cm}^{-2} \text{ sec}^{-1}$, the flux of H^+ becomes $2 \times 10^9 \text{ cm}^{-2} \text{ sec}^{-1}$. The lifetime of H^+ due to neutralization by electrons is $2 \times 10^6 \text{ sec}$, taking n_{e^-} equals n_{H^+} . The mean free path at this level is 10^3 cm , and the collisional lifetime is 10^{-1} sec . This produces 2×10^7 collisions/ H^+ lifetime. Therefore, the total number of conversions is $4 \times 10^{16} \text{ cm}^{-2} \text{ sec}^{-1}$. The conversion lifetime must be less than or equal to the dynamical lifetime $\tau_{\text{dyn}} = H^2 / D$ (D =molecular diffusion coefficient).

$$\tau_{\text{conv}} \times \text{total number of conversions} = 8 \times 10^{19} \text{ conv./cm}^2$$

Thus, total conversion of H_2 will occur down to 8×10^9 /scale height = $2 \times 10^{13} \text{ cm}^{-3}$. Note that this is greater than the number density of H_2 present in the region. Therefore total conversion of H_2 occurs in layer I.

2.3 Conditions for observation of o-p conversion

Many observations have been made (ex. Trafton, 1976) that indicate the presence of an ortho-para conversion above the tropopause. According to calculations made in section 2.2, the o-p conversion occurs at levels much higher than the tropopause. In order to fit with observations, the converted H_2 must be rapidly mixed down below the turbopause, but must not be mixed into the lower atmosphere below the tropopause. In order for this to occur, the transport rate across the turbopause must be relatively large, while the transport rate across the tropopause must be relatively small. The transport rate can be calculated from

$$\begin{aligned} \Phi_{H_2} &\approx w n_{H_2} \\ \Phi_{H_2} &= \text{transport rate of } H_2 \\ w &= \text{vertical speed} \\ w &= K / H. \end{aligned}$$

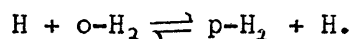
The turbopause in this atmospheric model occurs at $n_{H_2} = 10^{13} \text{ cm}^{-3}$. At this level, $K = 10^7 \text{ cm}^2 \text{ sec}^{-1}$ and $H = 5 \times 10^6 \text{ cm}$. Therefore, $\Phi_{H_2} = 2 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$. At the tropopause, $n_{H_2} = 10^{15} \text{ cm}^{-3}$, $K = 10^4 \text{ cm}^2 \text{ sec}^{-1}$, and $H = 2 \times 10^6 \text{ cm}$. Thus, $\Phi_{H_2} = 5 \times 10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$. Since the values of K , H , and n_{H_2} may be off by an order of magnitude, the transport rates can be said to be essentially equal. In particular, the minimum value of the eddy diffusion coefficient is uncertain. The minimum value calculated in this model is $10^4 \text{ cm}^2 \text{ sec}^{-1}$, but K could conceivably have a lower value still. Jupiter, a planet whose atmosphere is much more energetic, has a minimum value of $K = 10^4 \text{ cm}^2 \text{ sec}^{-1}$. Uranus, which is much

further from the Sun, will have a more stable atmosphere. It is therefore not unreasonable to expect that K will have a minimum value of $10^{-1} \text{ cm}^2 \text{ sec}^{-1}$.

The high flux of conversions calculated in section 2.2 produces total o-p conversion throughout the upper atmosphere, down to the tropopause. If, at that point, K has a low value as described above, a "bottleneck" will occur at the tropopause, such that mixing will be minimal across the boundary. Converted H_2 will then be seen in the upper atmosphere as described by observations.

2.4 Assessment of lower atmosphere conversion mechanism

Lower atmosphere conversion of hydrogen, if it takes place at all, will be caused by the reaction



The dominant loss mechanisms for H are

- (1) $\text{CH}_3 + \text{H} + \text{M} \rightarrow \text{CH}_4 + \text{M}$
 $k_1 = 8.5 \times 10^{-21} [\text{M}] \text{ cm}^3 \text{ sec}^{-1}$ (Strobel, 1973)
- (2) $\text{H} + \text{H} + \text{M} \rightarrow \text{H}_2 + \text{M}$
 $k_2 = 3 \times 10^{-32} \text{ cm}^6 \text{ sec}^{-1}$ (Kondratiev, 1972)

In addition, since CH_3 is an important species, loss of CH_3 must be included:

- (3) $\text{CH}_3 + \text{CH}_3 + \text{M} \rightarrow \text{C}_2\text{H}_6 + \text{M}$
 $k_3 = 6 \times 10^{-21} [\text{M}] \text{ cm}^3 \text{ sec}^{-1}$ (Strobel, 1973)

The loss mechanism $\text{H} + \text{H} \rightarrow \text{H}_2$ is not considered to be an important reaction due to the problems of energy dissipation.

A steady state is assumed: rate of production equals rate of destruction. Thus, two simultaneous equations may be set up:

$$\begin{aligned}d[\text{CH}_3]/dt &= J[\text{CH}_4] = k_1[\text{CH}_3][\text{H}][\text{M}] + k_3[\text{CH}_3]^2[\text{M}]. \\d[\text{H}]/dt &= J[\text{CH}_4] = k_1[\text{CH}_3][\text{H}][\text{M}] + k_2[\text{H}]^2[\text{M}].\end{aligned}$$

The CH_4 photolysis rate, $J[\text{CH}_4]$, is equal to the flux at the Uranus distance / scale height. $J[\text{CH}_4] = 500 \text{ cm}^{-3} \text{ sec}^{-1}$. Upon solving for the abundance of H, it is found that $n_{\text{H}} = 1.0 - 8 \times 10^5 \text{ cm}^{-3}$. This gives chemical lifetimes of $3 \times 10^{16} - 4 \times 10^{10} \text{ sec}$, which are much longer than the corresponding dynamical lifetimes. Thus, o-p conversion from this process will not occur.

3. Conclusions

3.1 Ortho-para equilibrium in the Uranus atmosphere

From the calculations done in section 2.2, and assumptions of minimal transport of H_2 across the tropopause due to a low eddy diffusion coefficient, a picture emerges of the o-p ratio as a function of altitude. The ortho to para conversion occurring at an ionospheric temperature of $135^\circ K$ will give a percentage p- H_2 of 30%, from Figure 7. This ratio will be mixed down to the tropopause, causing the observed o:p ratio to differ from that expected at upper atmospheric temperatures if o-p conversion did not occur. In the lower atmosphere below the tropopause no o-p conversion is able to take place, as determined in section 2.4. Therefore, lower atmospheric o:p ratios will be those produced by local temperature equilibrium, and will be identical to the ratios in Figure 7. The percentage of para-hydrogen vs. altitude in the Uranus atmosphere is shown in Figure 8.

3.2 Future work

The atmospheric model described here is a crude, one-dimensional calculation of the various atmospheric parameters. An improved model, since it is the basis for the ortho-para conversion calculations, would greatly improve understanding of o-p conversion in the atmosphere. Of

course, the atmospheric model must have for its basis observational evidence of different orbital and atmospheric parameters for Uranus. Improvement of these figures would greatly enhance not only comprehension of the ortho-para equilibrium, but also understanding of other aspects of the planet Uranus.

Uranus' distance from the Sun makes cosmic rays an important source of energy. Observations of the planet's magnetic field are essential in determining the effect of cosmic rays. Infrared observations are necessary to determine the value of Uranus' internal heat source. Uranus' radius and rate of rotation have yet to be measured with accuracy. All these quantities have some part in the determination of the o-p conversion. Hopefully, Voyager II in 1986 will shed light on these and other questions about the planet Uranus. Truly accurate calculations of the ortho-para equilibrium cannot be made until that time.

TABLE 1

Uranus' orbital parameters:

<u>Parameter:</u>	<u>Value:</u>	<u>Ref:</u>
orbital period:	$T = 84.01$ yrs	1
inclination of equator to orbit:	$i = 97.93^\circ$	1
rotation period:	$t = 15.57 \pm 0.80$ hr	2
radius:	$R_{eq} = 25,400$ km	3
mass:	$M = 14.6 M_\oplus$	3
equatorial surface gravity:	$g = 830$ cm sec ⁻²	3
solar constant:	$F = 3.8 \times 10^3$ erg cm ⁻² sec ⁻¹	4
bond albedo:	$A = 0.35$	3
effective temperature, measured:	$T_e = 58 \pm 3^\circ K$	5
effective temperature, predicted:	$T_e = 58.3 \pm 2.2^\circ K$	5
mean density:	$\rho = 1.31$ g cm ⁻³	3

References:

1. Levine, Kraemer, & Kuhn (1977)
2. Brown & Goody (1977)
3. Newburn & Gulbis (1973)
4. Stone (1975)
5. Fazio, Traub, & Wright (1976)

TABLE 2

Uranus' atmospheric parameters:

<u>Parameter:</u>	<u>Value:</u>
mean molecular weight:	$u = 3$
ratio of specific heats:	$\delta = 1.6$
gas constant:	$R = 3.0 \times 10^7 \text{ ergs } ^\circ\text{K}^{-1} \text{ g}^{-1}$
specific heat:	$C_p = 8 \times 10^7 \text{ ergs } ^\circ\text{K}^{-1} \text{ g}^{-1}$
adiabatic lapse rate:	$\Gamma = 1.0 \text{ } ^\circ\text{K km}^{-1}$
radiative time constant:	$\hat{c}_{\text{rad}} = 2 \times 10^{10} \text{ sec}$

(Values are approximate.)

All values taken from Stone (1975).

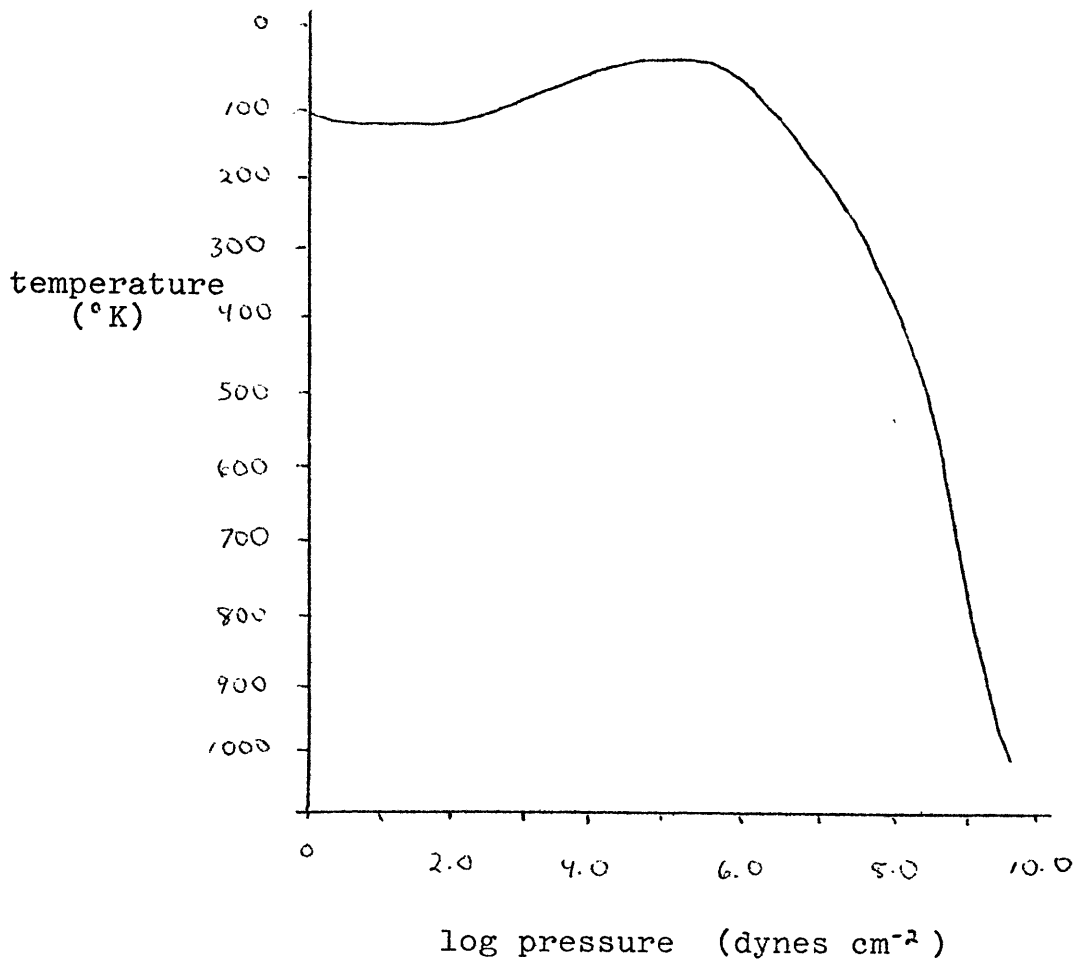


Figure 1.

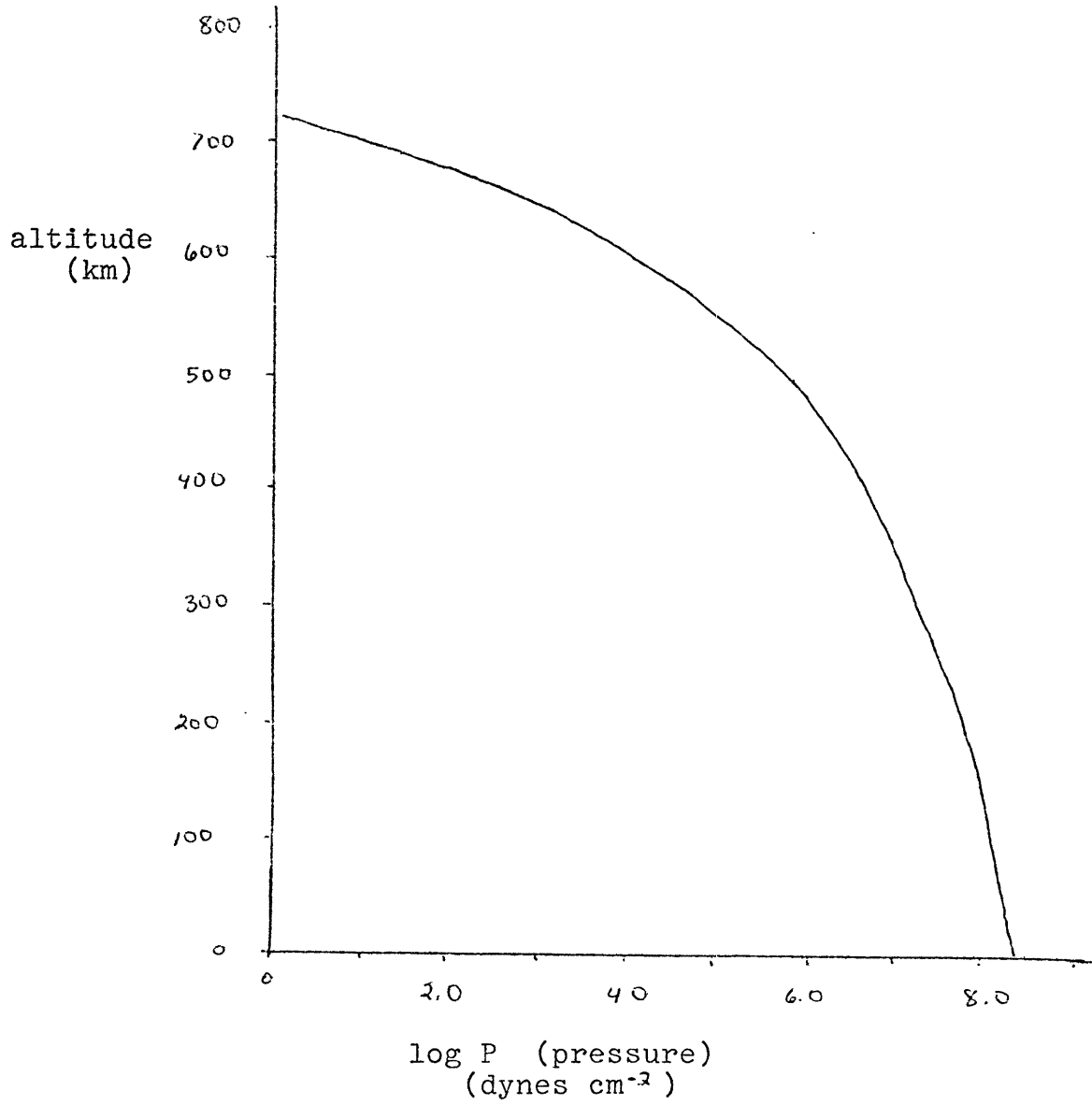


Figure 2.

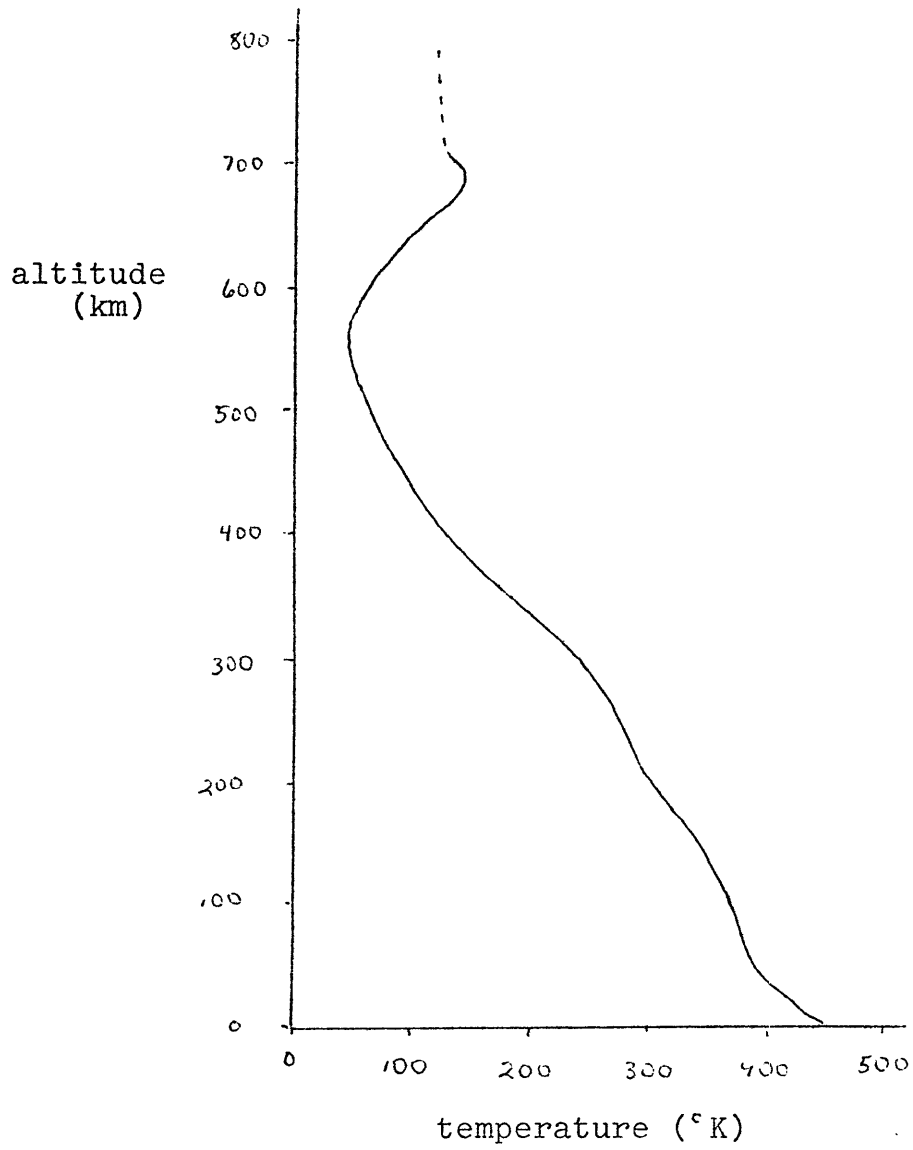


Figure 3.

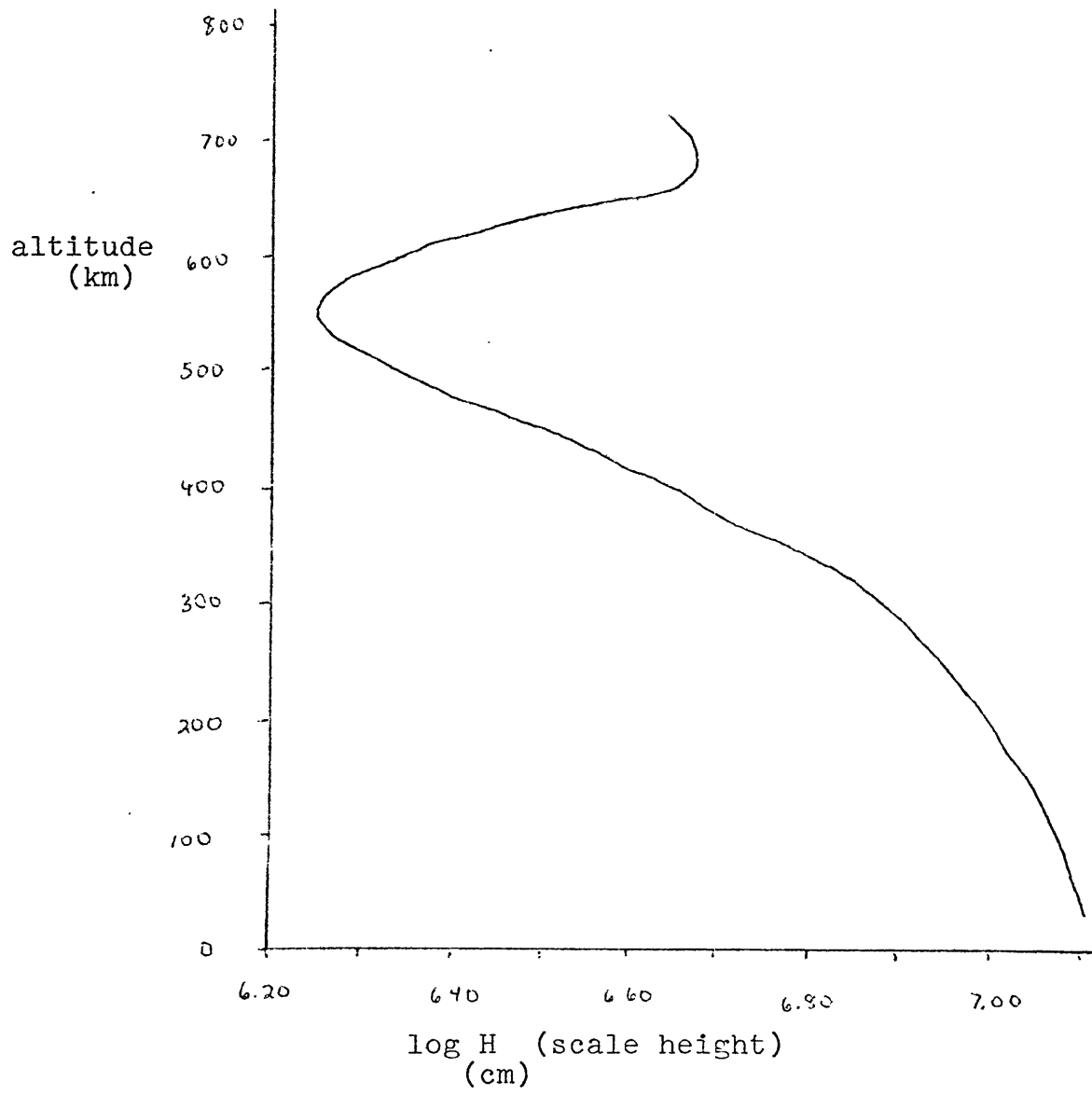


Figure 4.

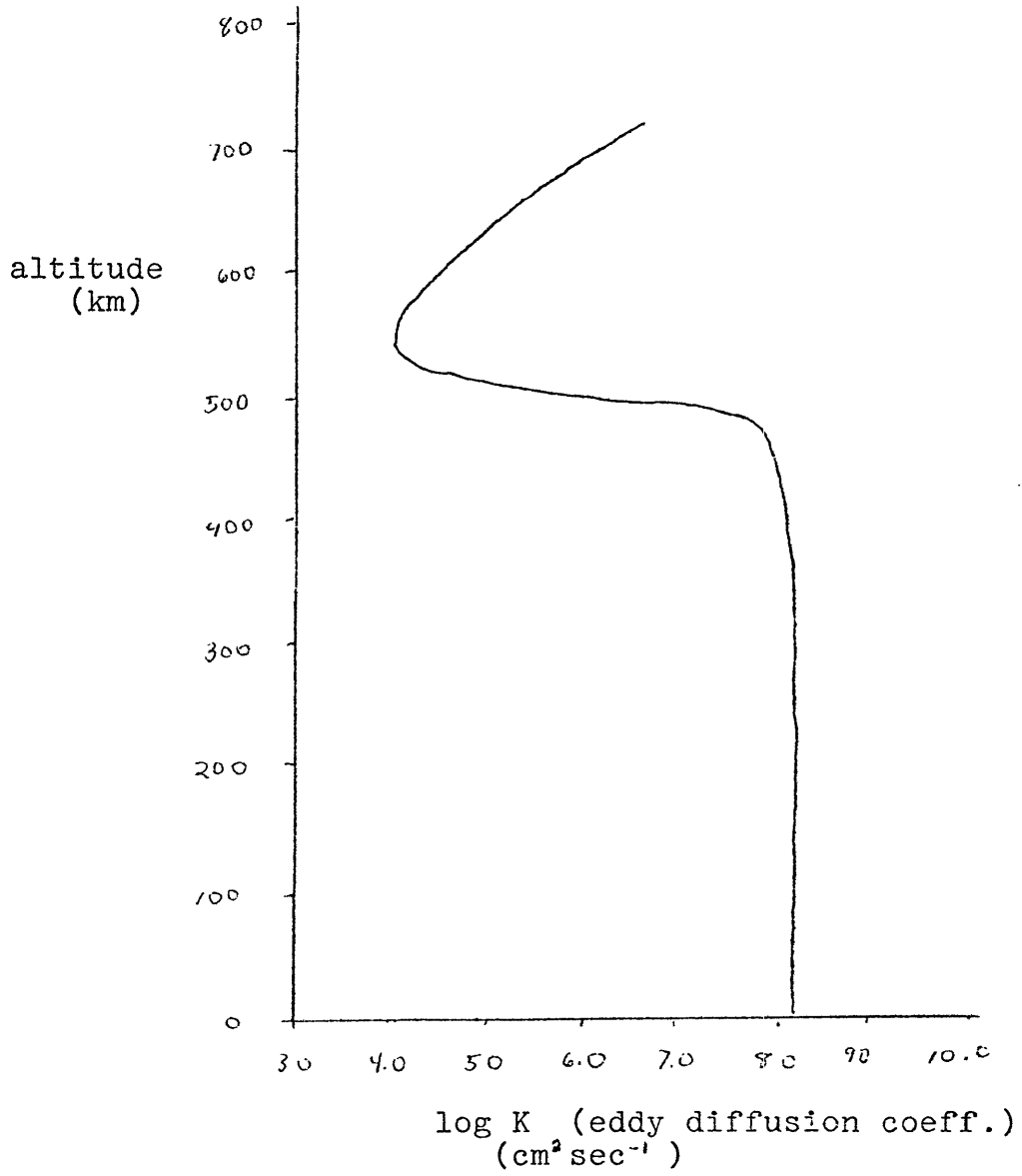


Figure 5.

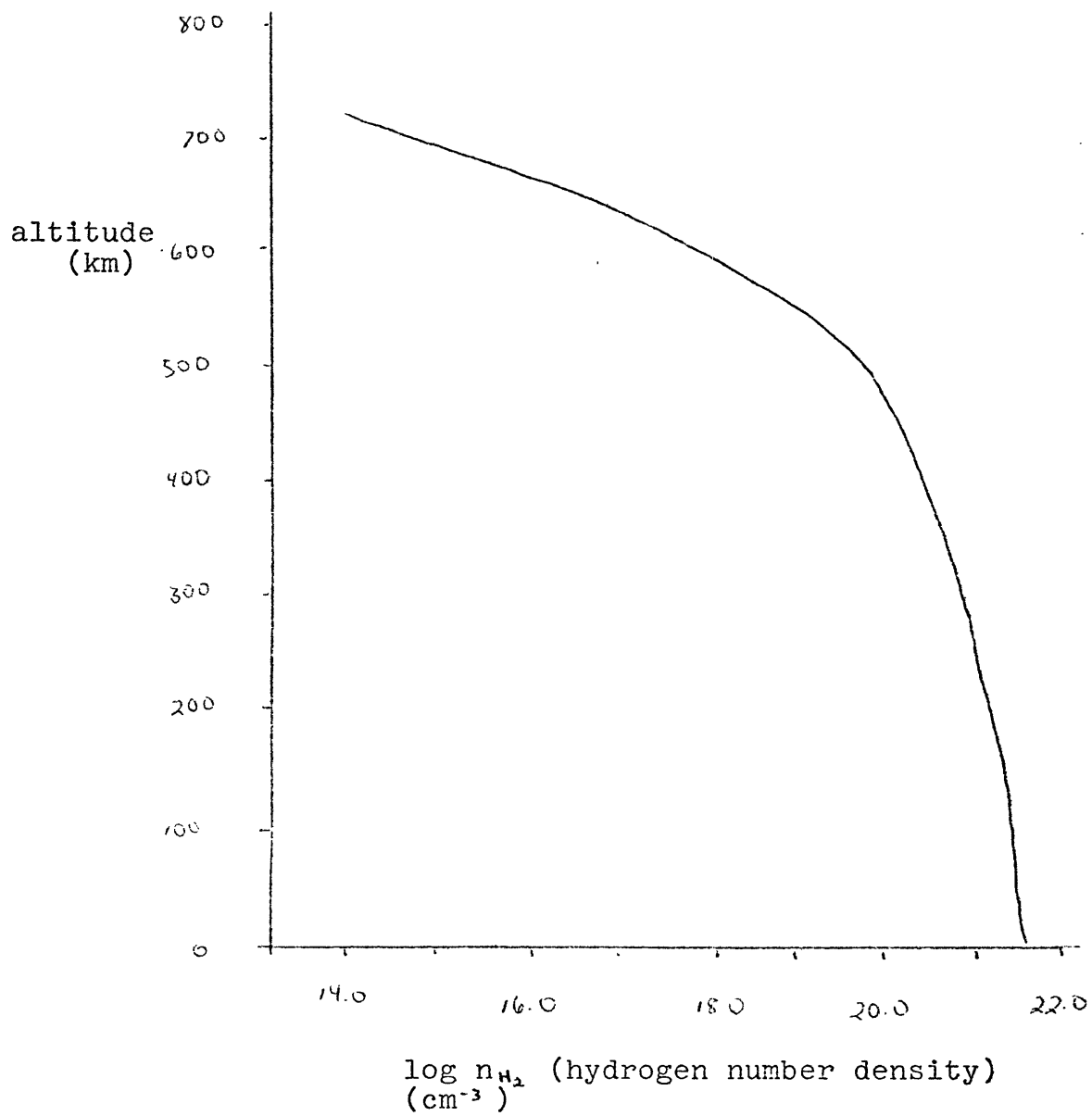


Figure 6.

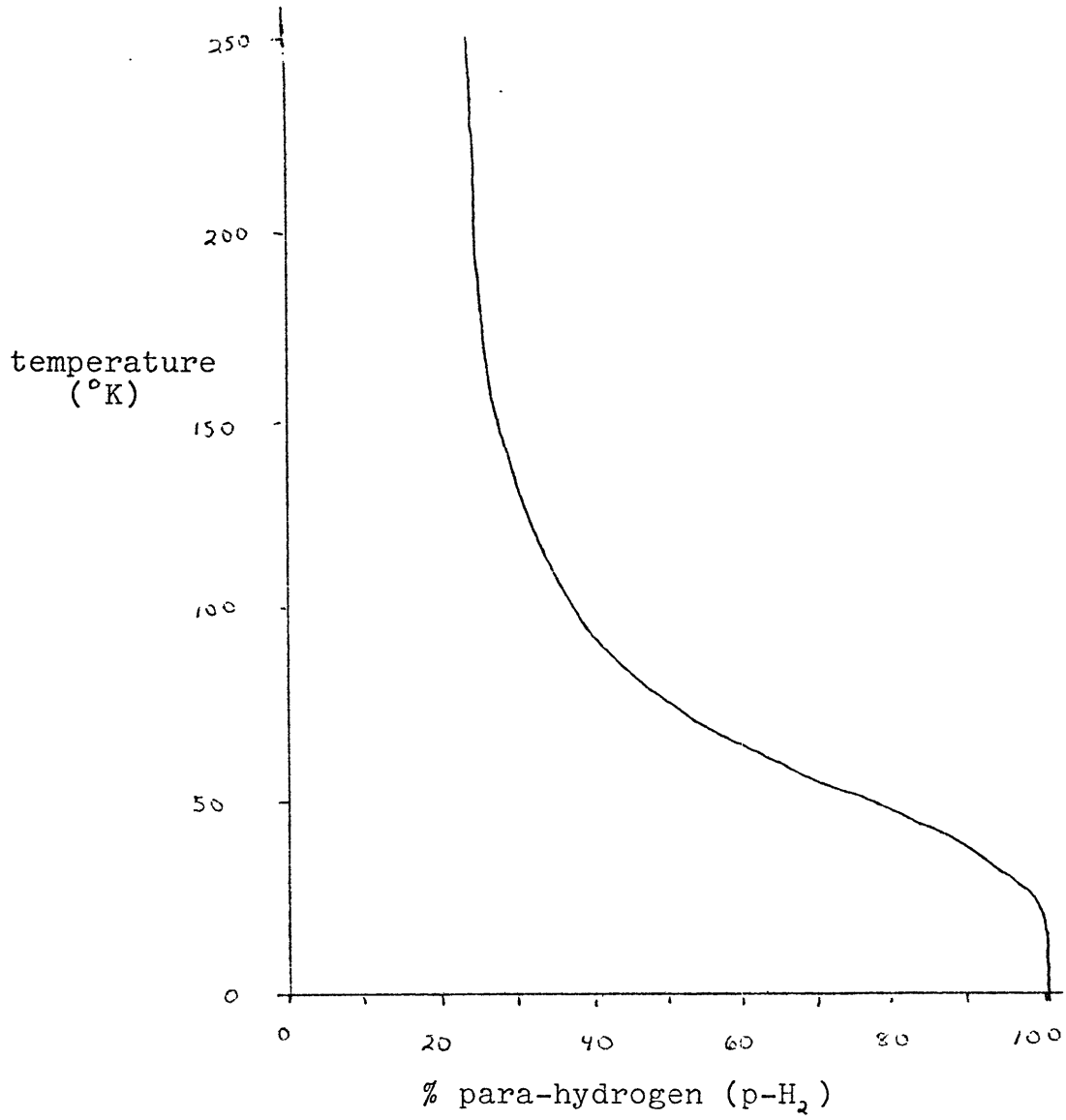


Figure 7.

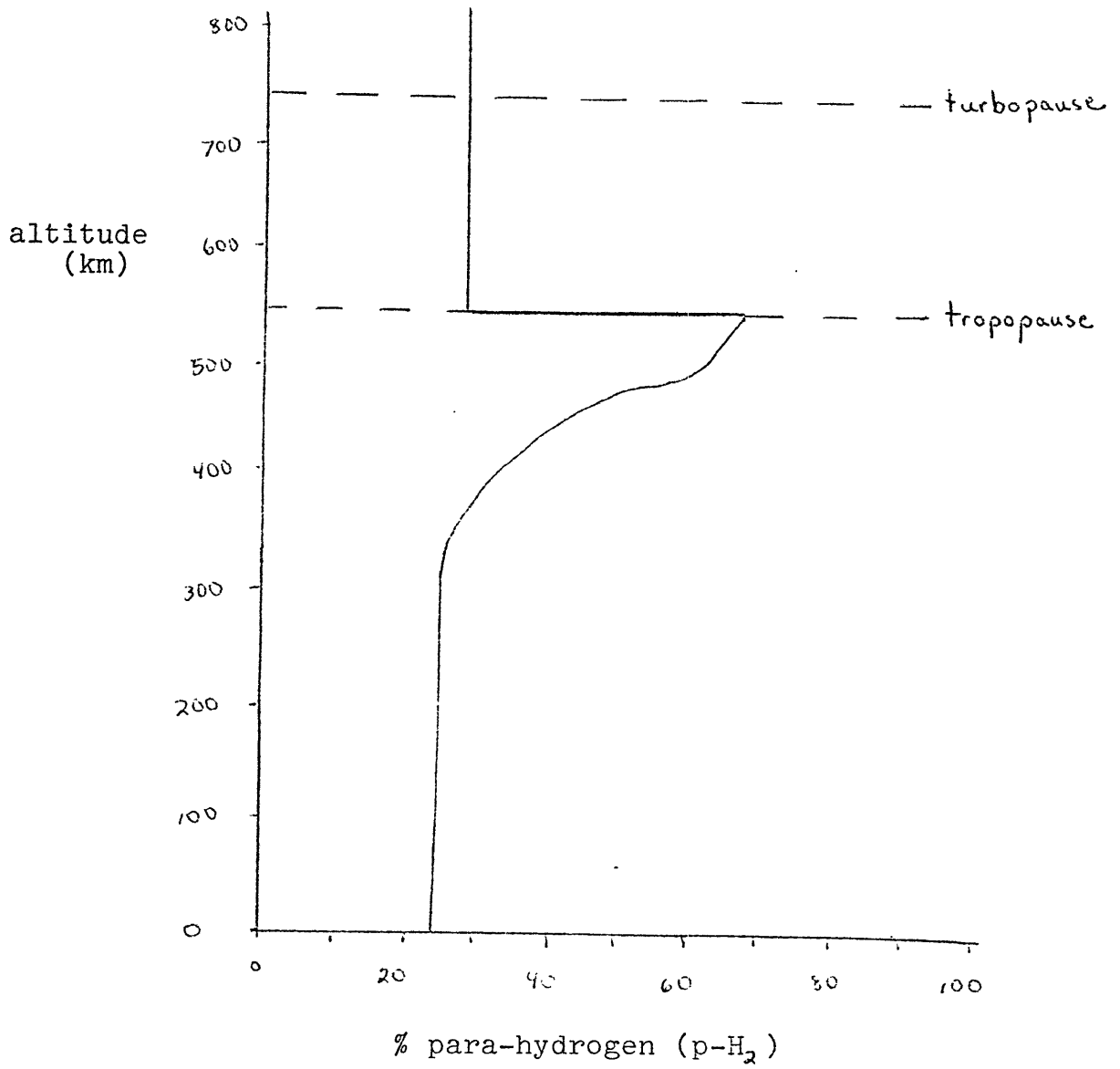


Figure 8.

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