Saturn Atmospheric Structure and Composition

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This abstract provides a brief overview of the composition, thermal structure, photochemistry and ionospheric aeronomy of Saturn. A comprehensive discussion appears elsewhere (Atreya, et al., 1984). The atmosphere is primarily composed of H_2 and He. For the bulk of the atmosphere, these gases represent the stable background atmosphere. The chemistry of the atmosphere, however, is driven by minor constituents, such as NH_3, PH_3 and CH_4, while H_2 plays the major role in topside ionosphere. Absorption of solar ultraviolet radiation not only triggers photochemical processes, it also provides a source of thermospheric heating in the equatorial and midlatitude regions. It is however found from the Voyager data that the exospheric temperatures are on the order of 600K, requiring substantial additional heat sources. The auroral electrons deposit $\sim 10^{11}$ Watts in a narrow latitude range of 78-81°. If an efficient thermospheric wind system exists on Saturn, the auroral energy would rapidly spread over the entire planet giving, in the best case, a globally averaged energy input of ~ 0.01 erg cm^{-2} s^{-1}. This energy is close to the value needed for explaining thermospheric temperatures. In this respect, Jupiter and Saturn seem to

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West Germany, April, 1984.

behave similarly. The solar EUV absorption also results in photochemically produced species, such as C_2H_2, C_2H_4, C_2H_6 and other organics, all of which have been detected on Saturn. Allene ($CH_2=C=CH_2$), on the other hand, poses a dilemma. The principal photolysis product of CH_4 is $^1CH_2$, which unlike on Titan, is not readily quenched to $^3CH_2$. The latter can react with C_2H_2 to yield either allene or methylacetylene. Table 1 lists all the species detected so far in Saturn's atmosphere. In the upper atmosphere at least, it is found that the vertical eddy mixing coefficient, K, is about 100 times greater than at Jupiter. If similar thermal structure in the middle atmosphere existed both on Jupiter and Saturn, the above discrepancy in K would descend to the tropopause. The electron concentration on Saturn has been measured on both Pioneer and Voyager spacecrafts. The latter measurements, done at S and X band frequencies are far more reliable. The ionosphere is driven primarily by the dissociative ionization of H_2. Subsequent chemistry can produce molecular ions, particularly in the denser part of the atmosphere. Serious discrepancies between the model and the measurements exist, particularly in regard to the magnitude and location of the electron concentration maximum. If the observed maximum is indeed the main peak, not simply a secondary peak, then several mechanisms can be invoked to reconcile theory with data. Possible candidates are vertical (up and/or down) drifts, coupled with high vibrational population of H_2, large methane abundance, large vertical mixing, and perhaps even presence of oxygen bearing molecules. Despite some major breakthroughs in our understanding of the atmosphere of Saturn, many new measurements are needed to answer some very fundamental questions about the atmospheric composition, structure, aeronomy and evolution of this intriguing planet. A list of unresolved major issues and candidate measurements to answer them follows. Several Figures and Tables to illustrate many of the issues raised here are appended to this abstract.

References

1. Atreya, S. K., *et al*. Theory Measurements, and Models of the Upper Atmosphere and Ionosphere of Saturn. A chapter in *Saturn* (editor, T. Gehrels), University of Arizona Press, 1984 (in press). Reprints available upon request.

2. Atreya, S. K. *Atmospheres and Ionospheres of the Outer Planets and Satellites*, in preparation. To be published by *Springer Verlag*, Heidelberg and New York.

SHOPPING LIST

(Outstanding Fundamental Questions of Saturn Composition and Structure)

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* Convective nature of deep trop

---- Thermal structure ($P > 1$ bar)

---- Ortho-para H_2 ratio

---- GeH_4, SiH_4, CO detection

---- $PH_3(z)$ with lat, long

* Trop/strat energy balance and vertical mixing

---- Aerosols (Identity, size, density, global maps)

---- Disequilibration: photochemical (H_2S, NH_3, N_2, PH_3); lightning (HCN)

---- Middle atmospheric temperature and constituent profiles

* Thermo/iono energy balance

---- Ionospheric conductivities

---- Global, diurnal, temporal ionospheric profiles

---- Electric fields, thermospheric winds

---- Auroral charged particle energy spectrum

---- Ring shadow effect

* Atmospheric interaction with extraplanetary material

---- H_2O (OH, HCHO, HCO, CO, H_2O^+, H_3O^+)

---- Metallic ions

---- Micrometeoritic dust

---- Isotopic ratios

Appendix

Figures and Tables Relevant
to S. K. Atreya's Paper

PHYSICAL CHARACTERISTICS

	SATURN	JUPITER	EARTH
R_{S-P} (AU)	9.554	5.202	1.000
M (10^{24} KGM)	569	1900	5.975
R_E (KM)	60,330	71,398	6,378
ρ (GM CM^{-3})	0.69	1.314	5.52
g_E (CM S^{-2})	904	2288	978
τ_0 (YRS)	29.458	11.8623	1.000
H (HRS)	10.233	9.841	23.9345
I	29°	3.°08	23.°44
MDM (G CM^{-3})	4.3×10^{28}	1.5×10^{30}	8.06×10^{25}
F_T/F_S	1.78	1.668	10^{-6}

Table 1a

Pre-Voyager Composition Measurements of the Saturn Atmosphere

Species	Spectral Region	References
H_2	S(0) & S(1) quadrupole lines of the (4,0) & (3,0) rotational-vibrational system	Münch and Spinrad (1963); Giver and Spinrad (1966); Owen (1969); Encrenaz and Owen (1973).
CH_4	$3\nu_3$ band in the 1.1 μm region	Trafton (1973); Trafton and Macy (1975); Lecacheux et al. (1976); Combes et al. (1977).
$^{13}CH_4$	1.1 μm	Combes et al. (1977).
C_2H_6	ν_9 at 12.2 μm	Gillett and Forrest (1974); Tokunaga et al. (1975).
PH_3	10–11 μm 5 μm	Encrenaz et al. (1975). Fink and Larson (1977).
CH_3D	5 μm	Fink and Larson (1977).
HD	$P_4(1)$ at 0.7467 μm $R_5(0)$	Trauger et al. (1977). Smith and Macy (1977).
NH_3	0.6450 μm 1.56 μm Radio	Woodman et al. (1977). Owen et al. (1977). Gulkis et al. (1969); Gulkis and Poynter (1972).
H_2S	1.59 μm 0.21–0.25 μm	Owen et al. (1977): upper limit. Caldwell (1977*b*): upper limit.
H	0.1216 μm	Weiser et al. (1977); Barker et al. (1980); Clarke et al. (1981).

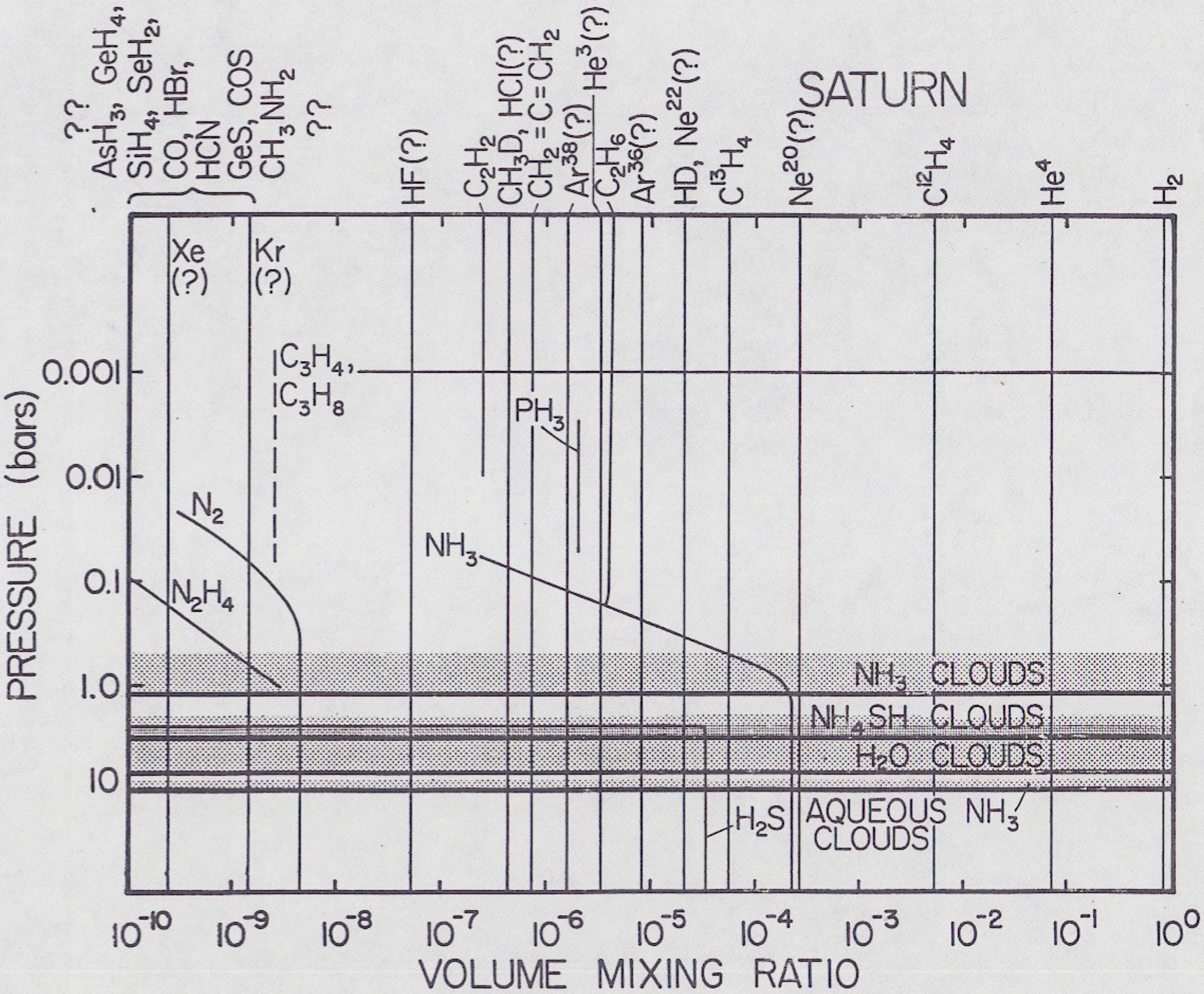
References in Atreya, et al. (1984)

Table 1b

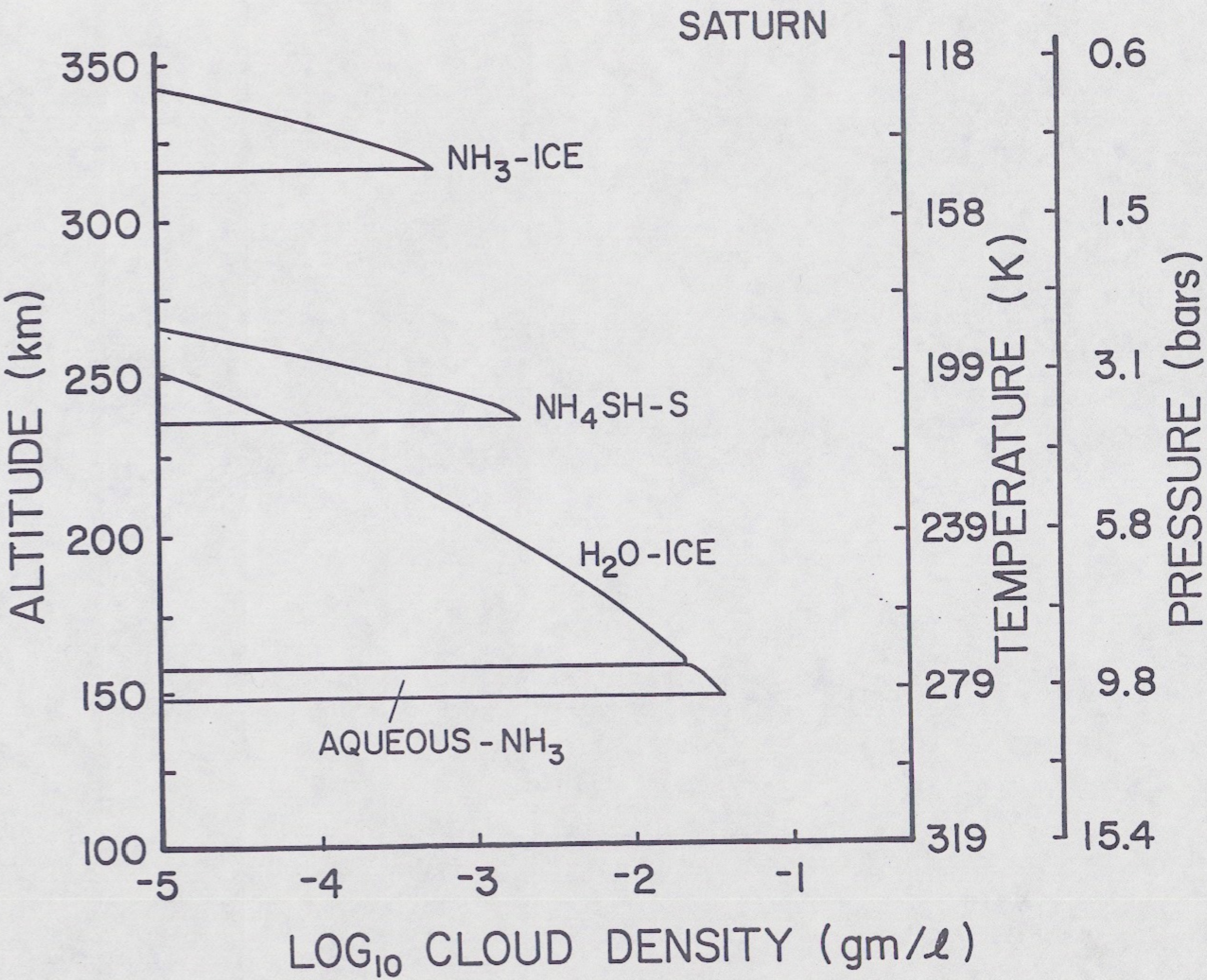
VOYAGER IR MEASUREMENTS OF MINOR SPECIES ON SATURN

(after Courtin, et al., 1984)

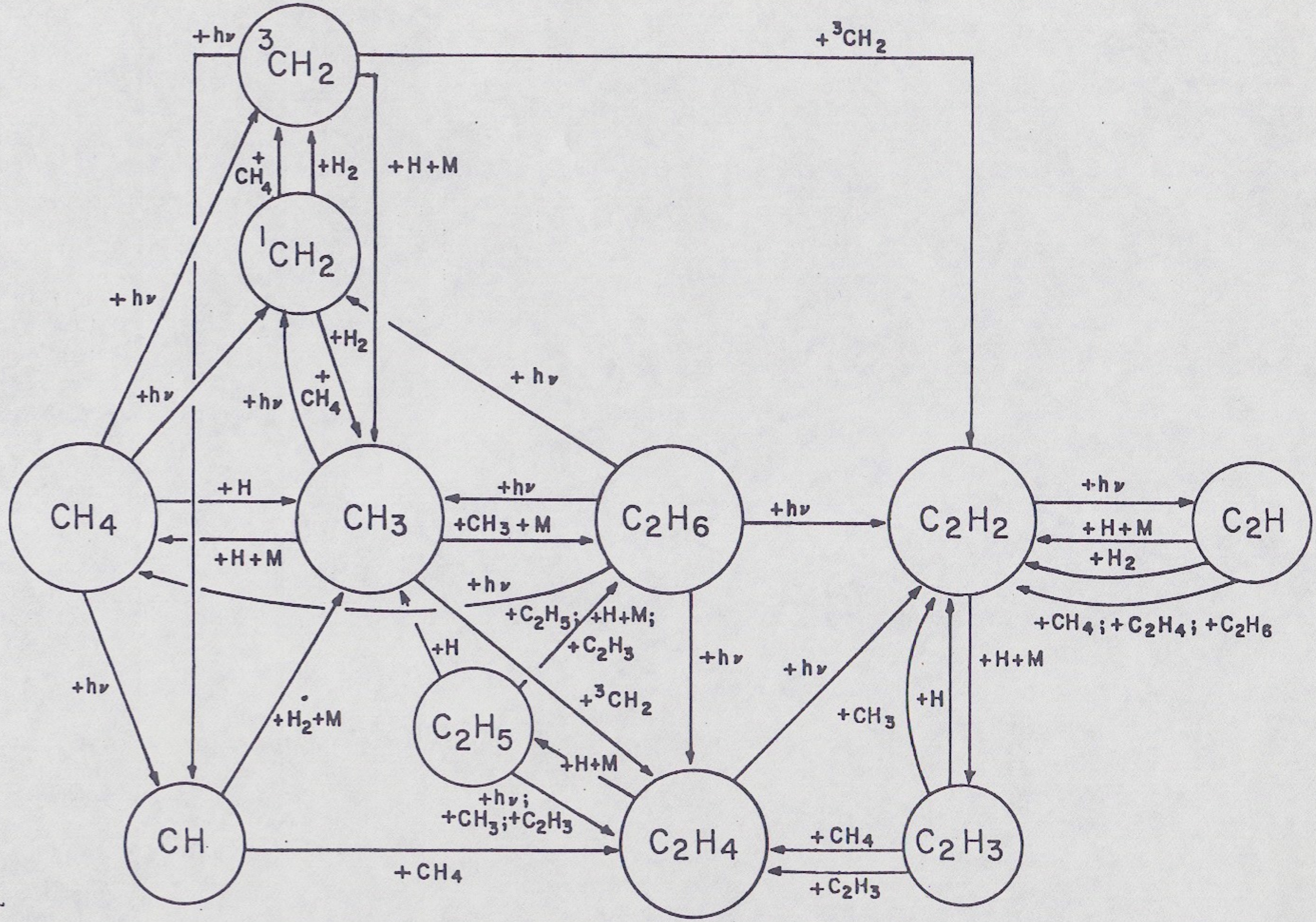
Constituent	Mixing Ratio Northern Hemisphere	Southern Hemisphere
CH_4	$4.5^{+2.4}_{-1.9} \times 10^{-3}$	
C_2H_6	$3.0 \pm 1.1 \times 10^{-6}$	$3.1 \pm 0.7 \times 10^{-6}$
C_2H_2	$2.1 \pm 1.4 \times 10^{-7}$ (20–50 mb)	$0.5 \pm 0.1 \times 10^{-7}$
$CH_2=C=CH_2$	8×10^{-7}	
CH_3D	$3.9 \pm 2.5 \times 10^{-7}$	
PH_3	$1.4 \pm 0.8 \times 10^{-6}$ (3–6 mb)	
NH_3	$0.5 - 2.0 \times 10^{-4}$ (2.5 bar)	



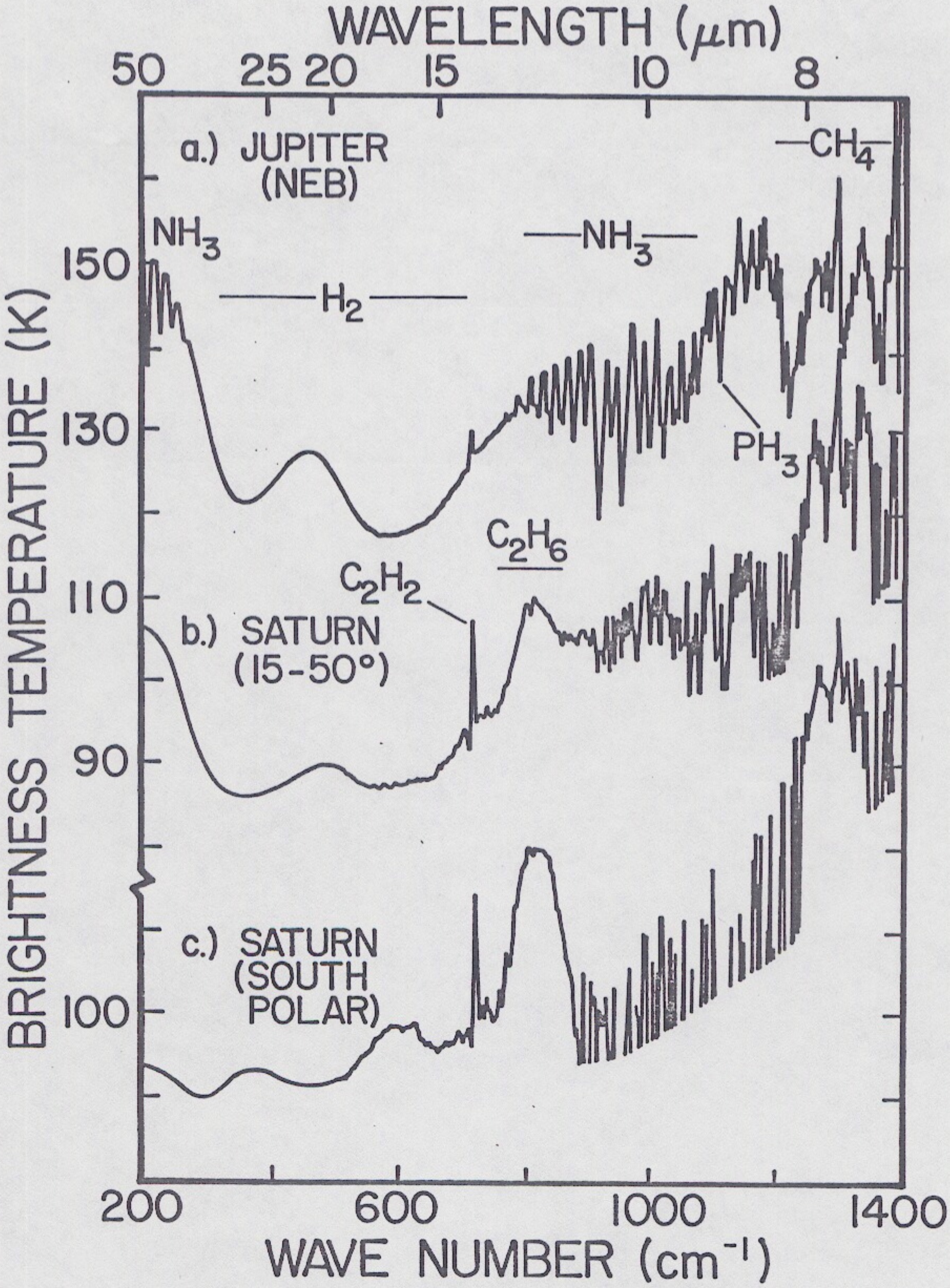
A cartoon showing measured and suspected (?) volume mixing ratios of constituents in Saturn's atmosphere. After



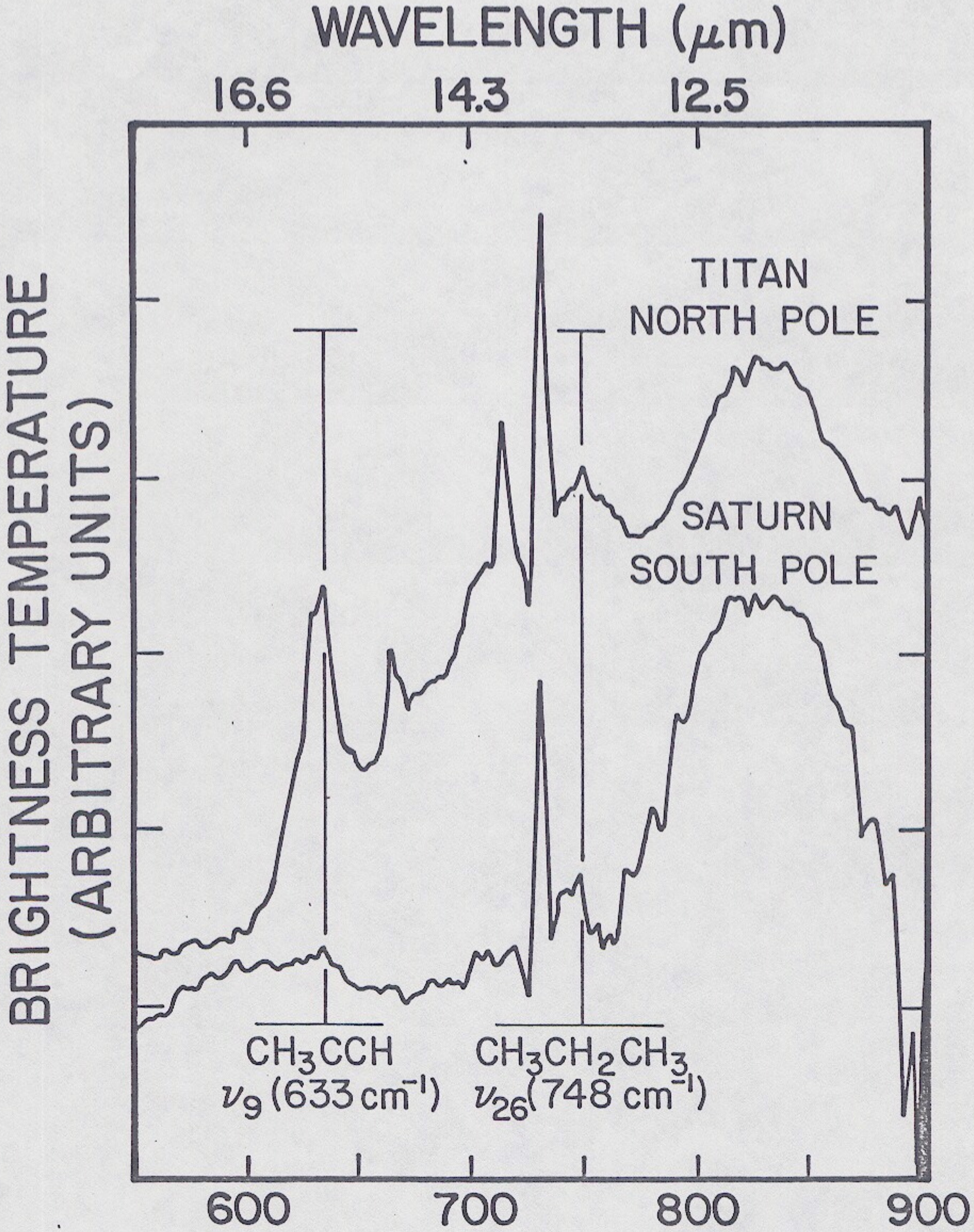
SATURN
ALTITUDE (km)
350
300
250
200
150
100
NH3-ICE
NH4SH-S
H2O-ICE
AQUEOUS-NH3
-5
-4
-3
-2
-1
LOG10 CLOUD DENSITY (gm/ℓ)
TEMPERATURE (K)
118
158
199
239
279
319
PRESSURE (bars)
0.6
1.5
3.1
5.8
9.8
15.4



CH_4-photochemistry. After S. K. Atreya, Reference 2.



Voyager IR spectra of Saturn and Jupiter. Figure after S. K. Atreya, Reference 2.



Voyager IR detection of methylacetylene (C_3H_4) and propane (C_3H_8). Figure after S. K. Atreya, Reference 2.

$$CH_2 = C = CH_2$$

(Allene)

$$CH_4 + h\nu \ (\lambda < 1600\text{Å})$$

$$\longrightarrow {}^1CH_2$$

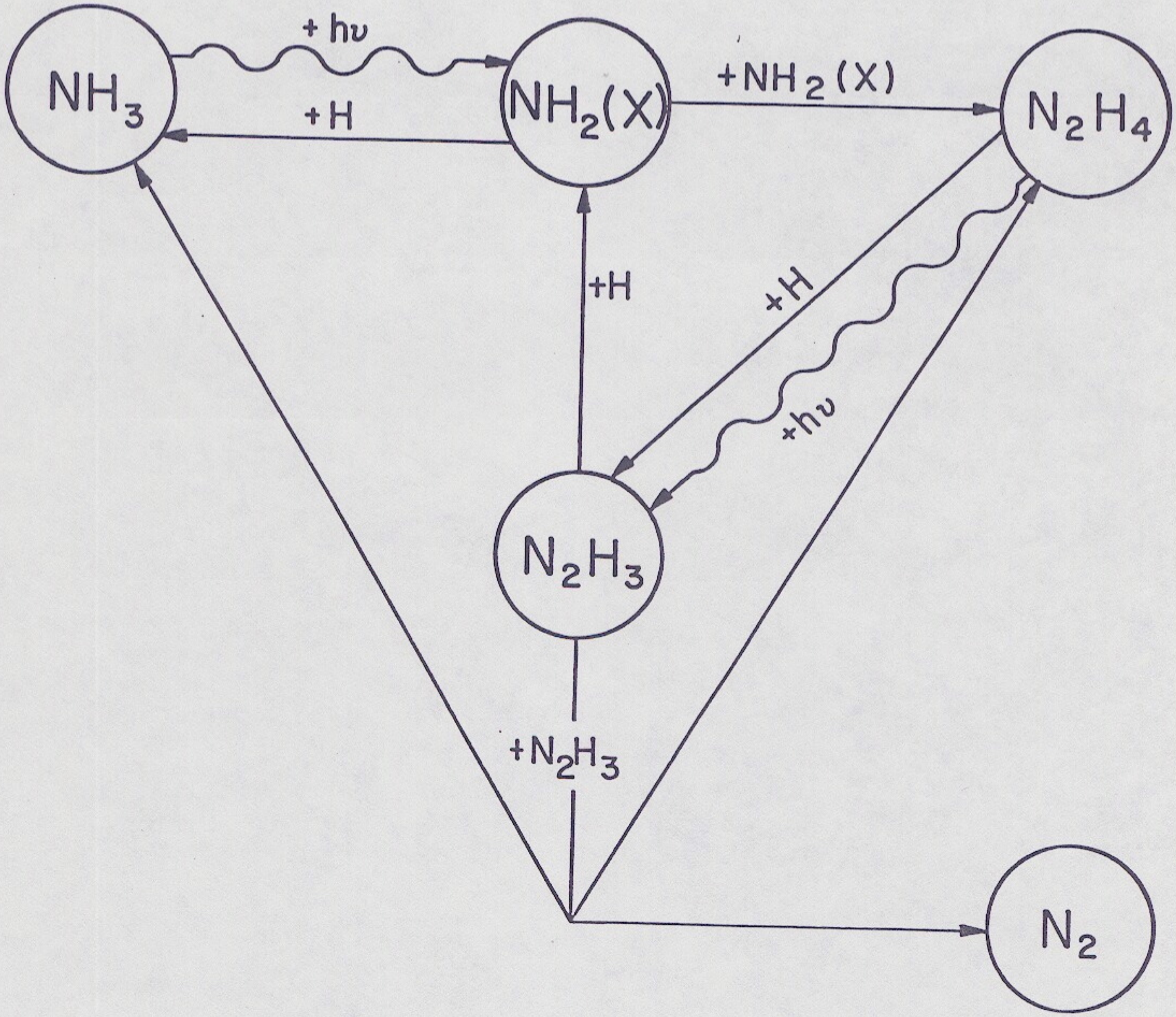
$$\longrightarrow {}^3CH_2$$

$${}^1CH_2 + M \longrightarrow {}^3CH_2 + M$$

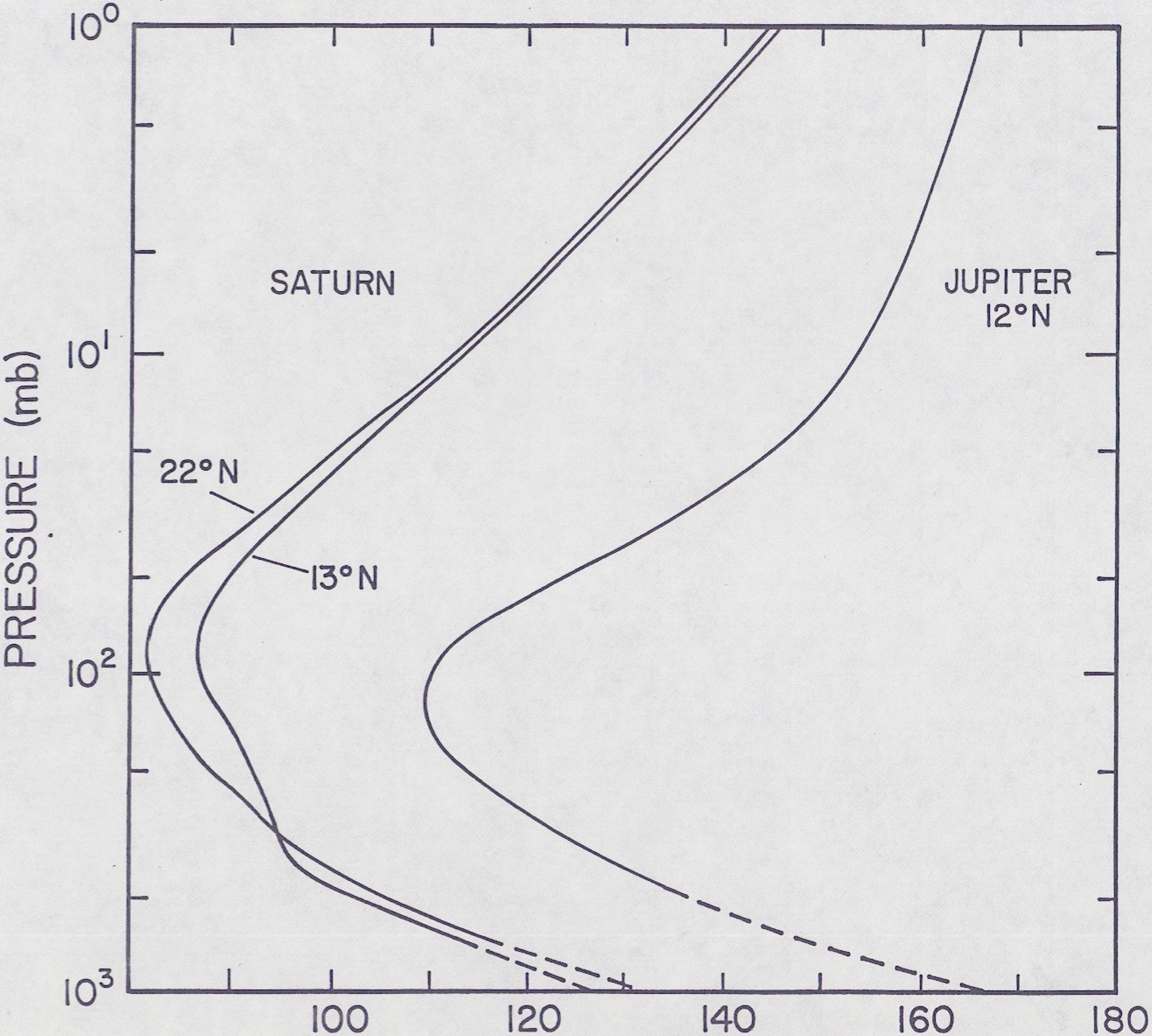
$${}^3CH_2 + C_2H_2 \longrightarrow C_3H_4$$

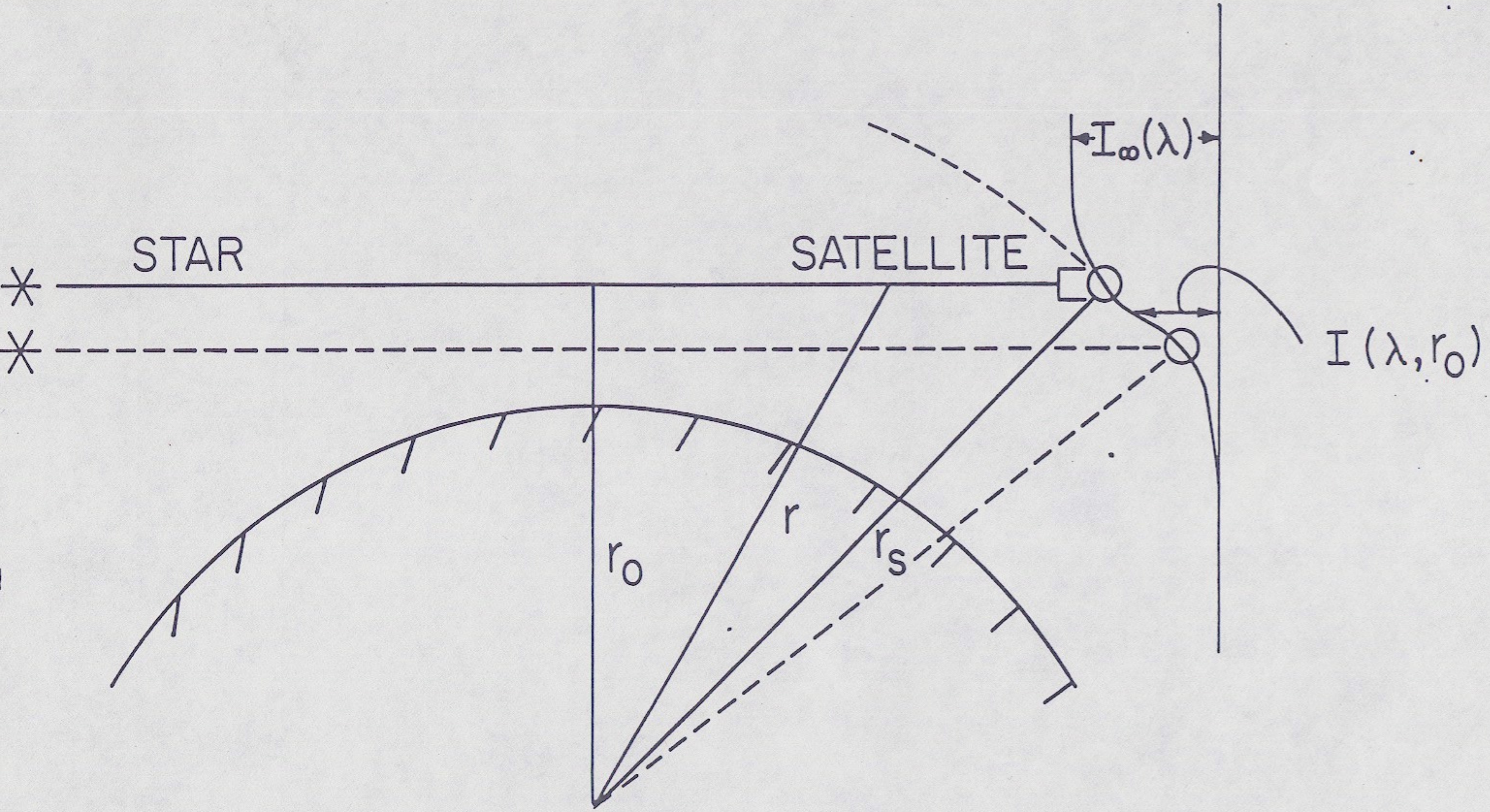
$$\longrightarrow \underline{CH_2 = C = CH_2}$$

Proposed mechanism for the formation of allene and methylacetylene. After S. K. Atreya, Reference 2.

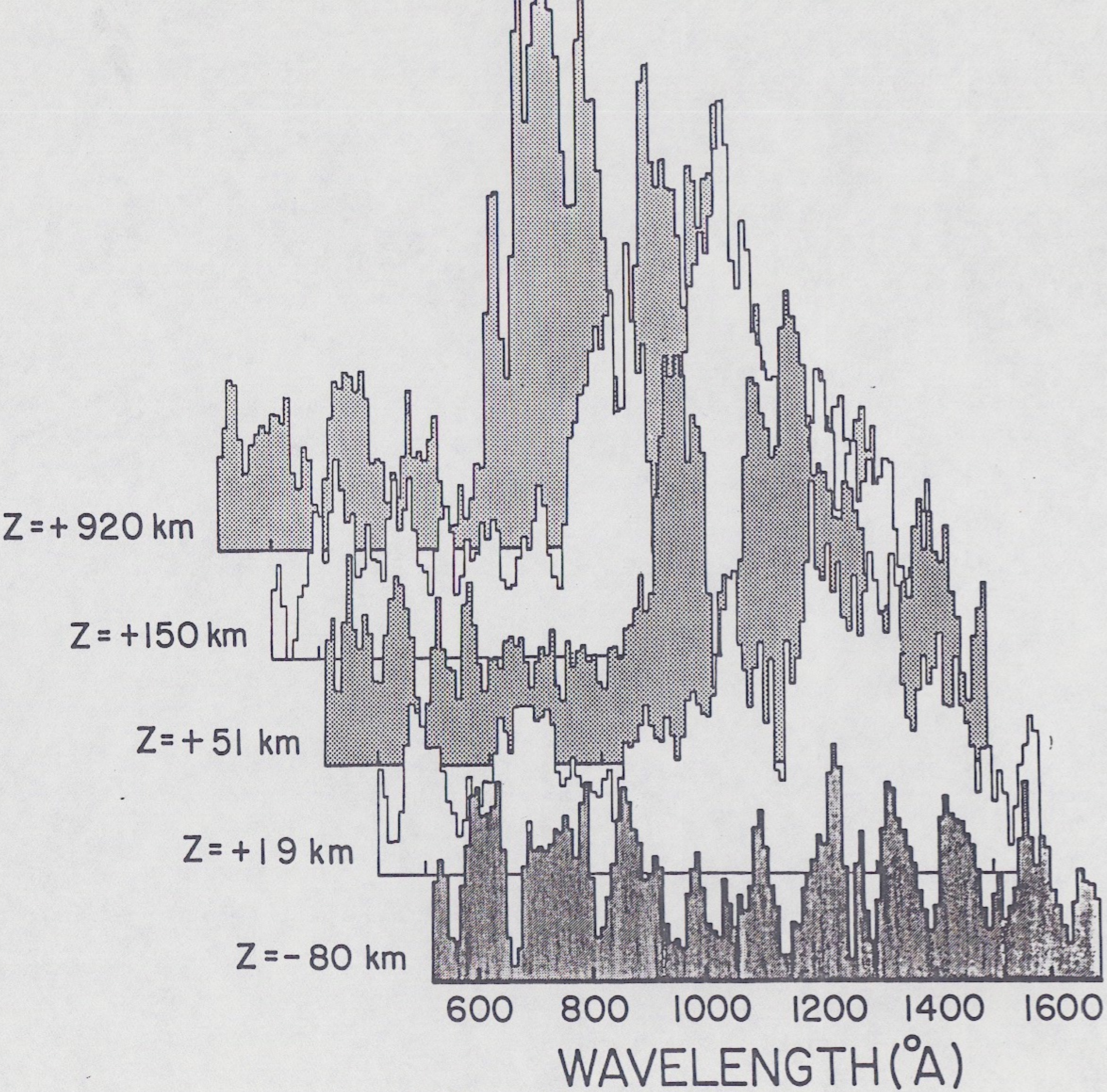


NH_3 photochemistry. After S. K. Atreya, Reference 2.

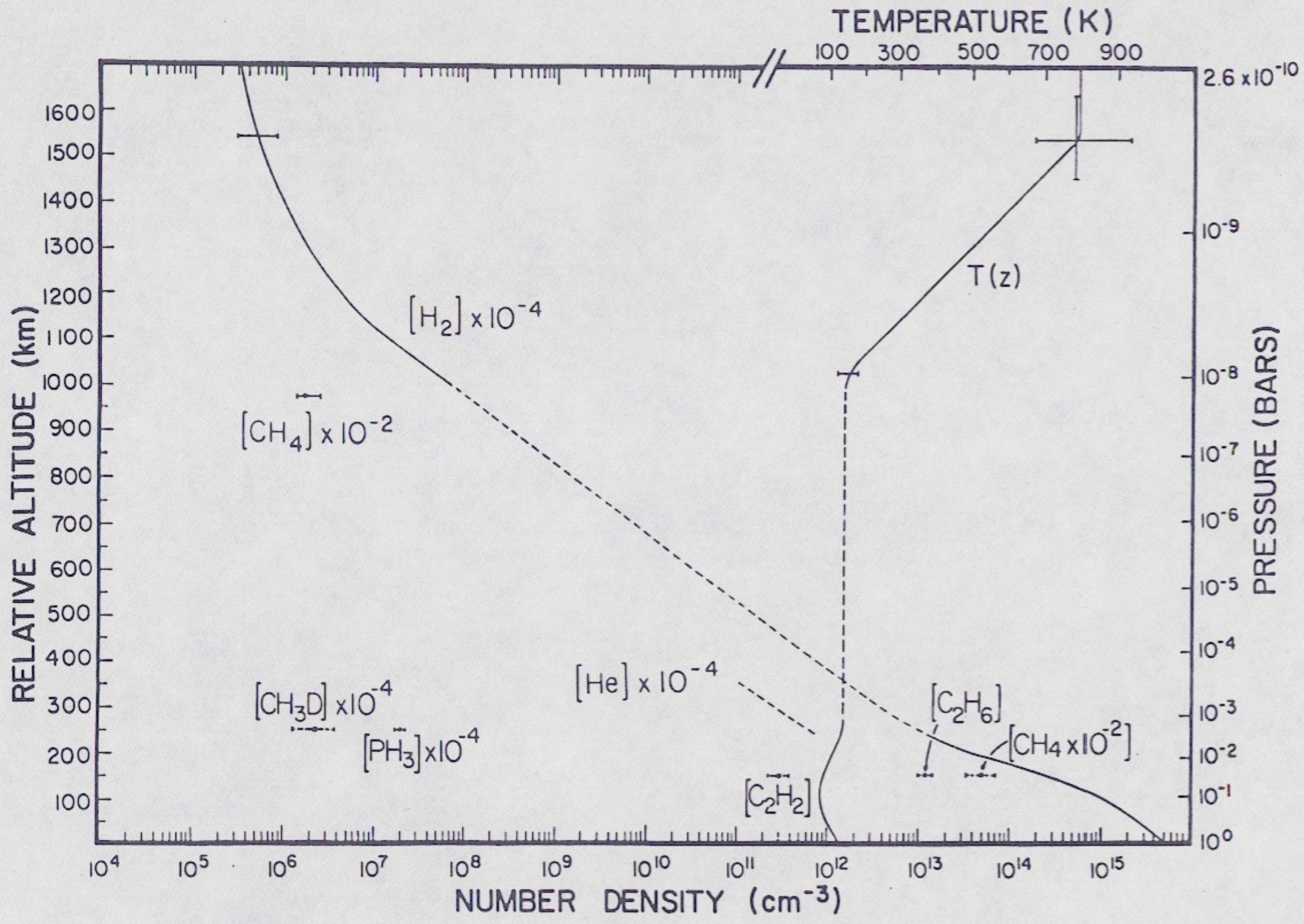

PRESSURE (mb)
10^0
10^1
10^2
10^3
100
120
140
160
180
SATURN
22°N
13°N
JUPITER
12°N



Stellar occultation geometry. After S. K. Atreya, *et al.*, Reference 1.



Stellar occultation in the Jovian atmosphere.

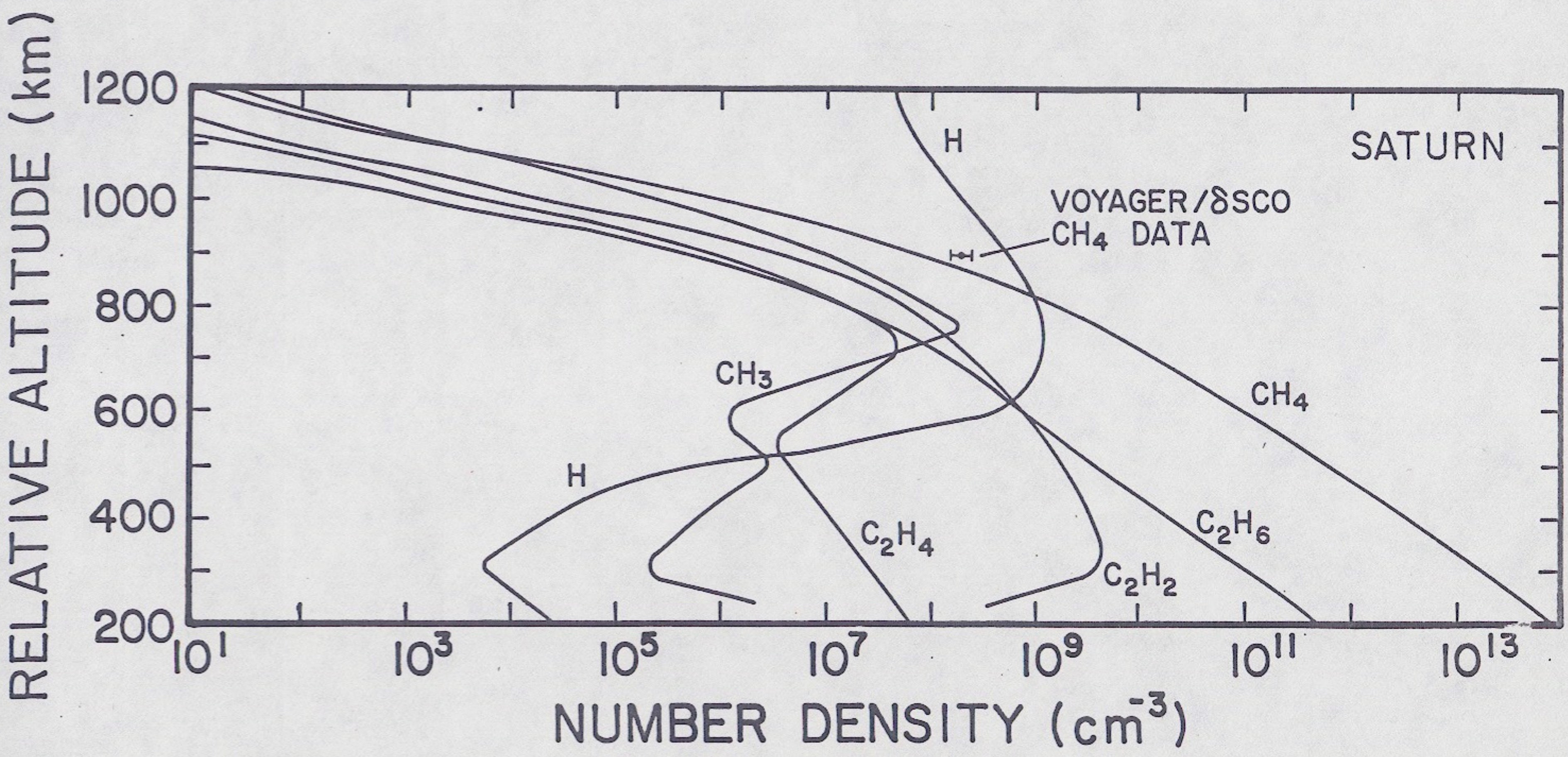


Thermal and composition profiles of Saturn atmosphere.
After S. K. Atreya, et al., Reference 1.

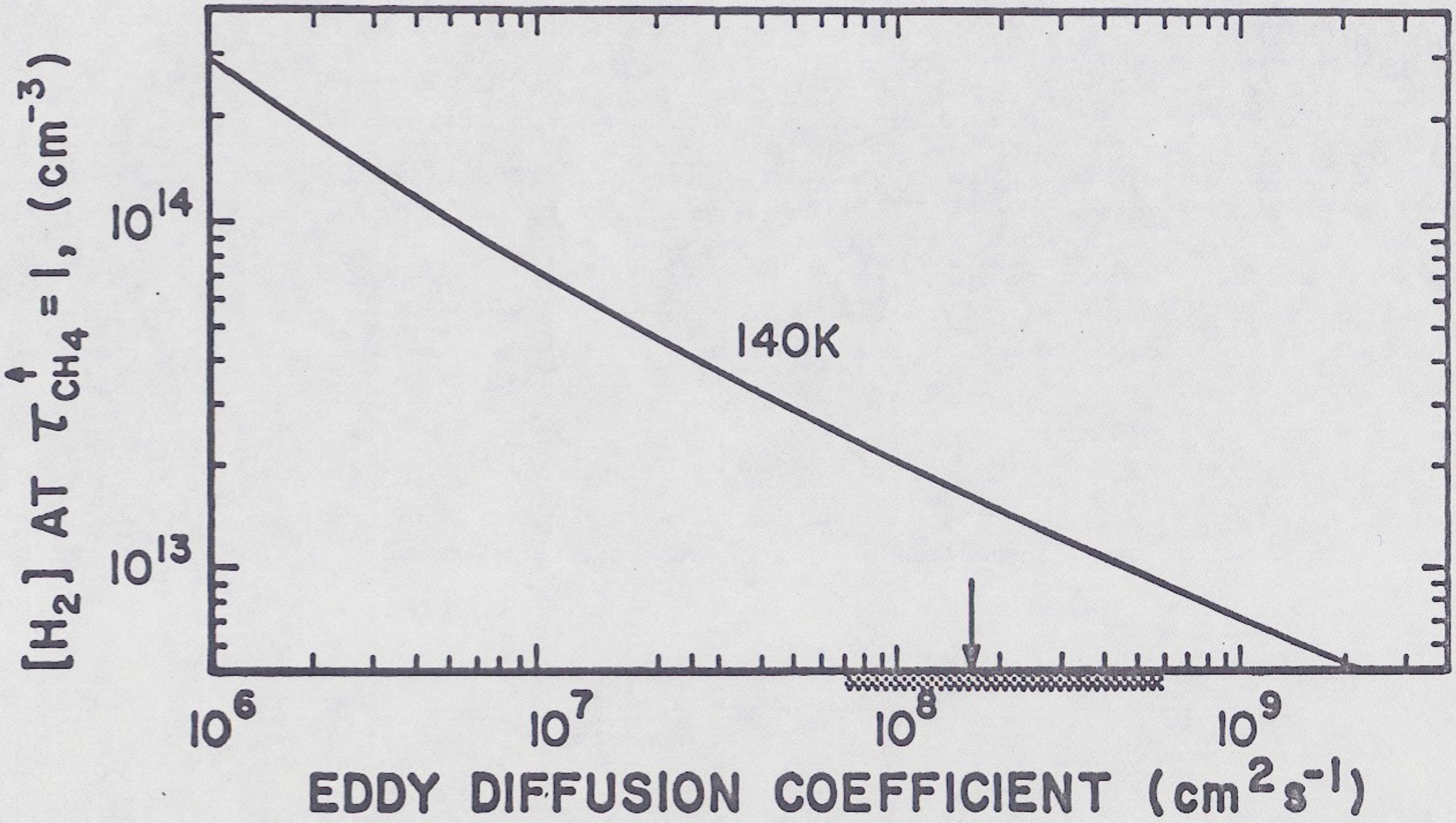
Fig 5.

AURORAL ENERGY INPUT

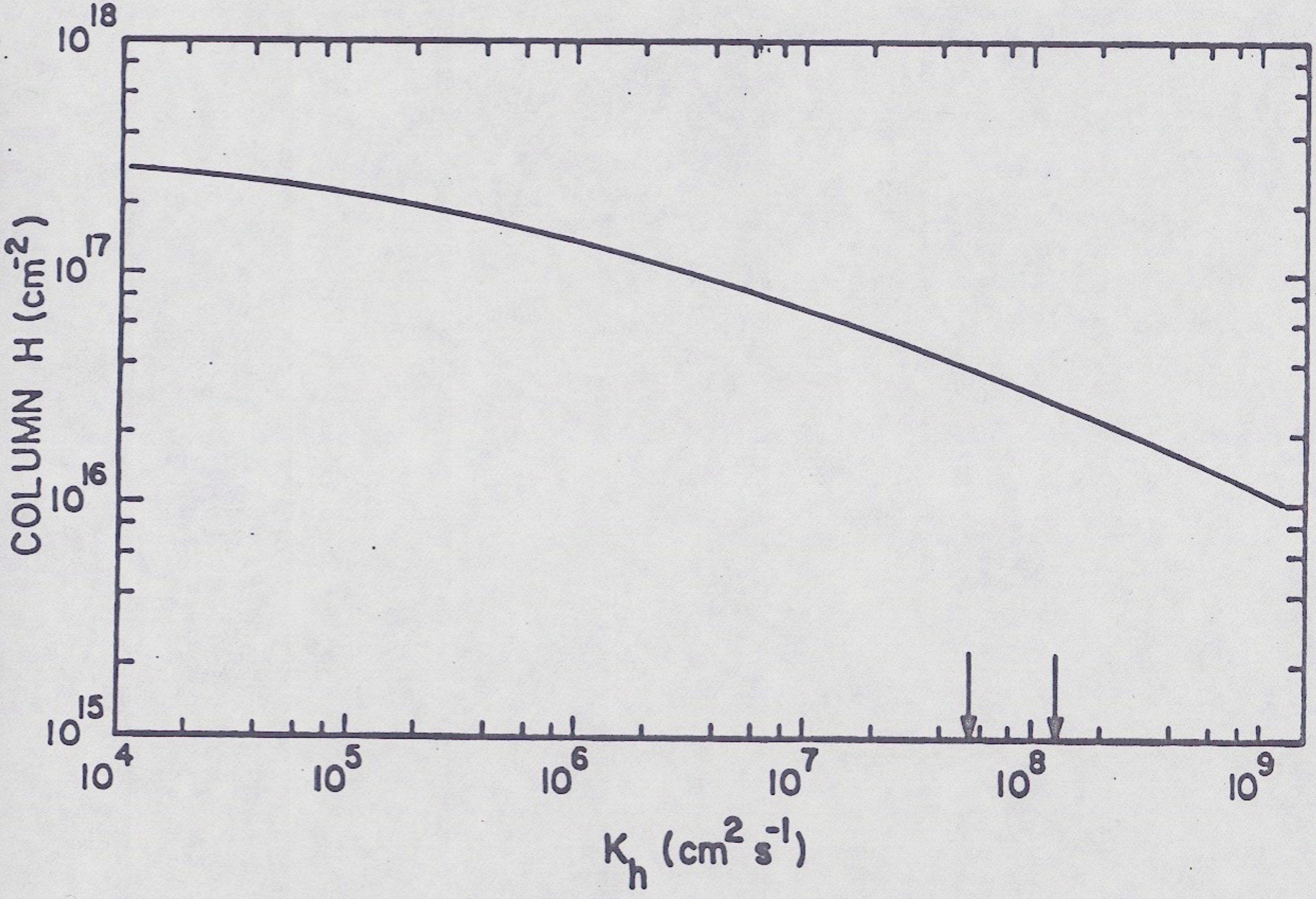
	JUPITER	SATURN	URANUS	
TOTAL	1.3×10^{13}	2×10^{11}	10^{11}	WATTS
GLOBALLY AVERAGED	0.3	0.01	0.02	ERG CM^{-2} S^{-1}



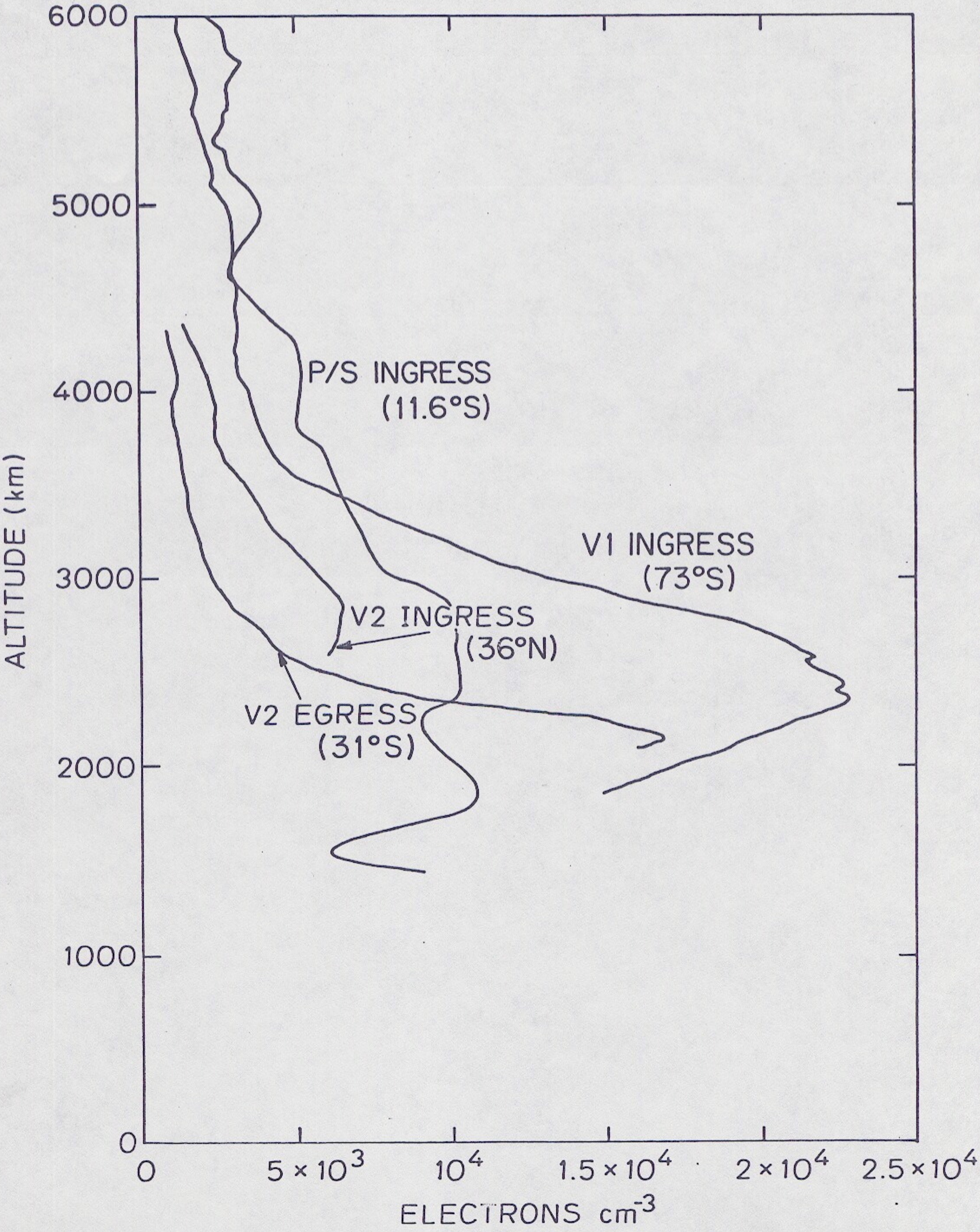
CH_4 photochemical model. Reference 1.



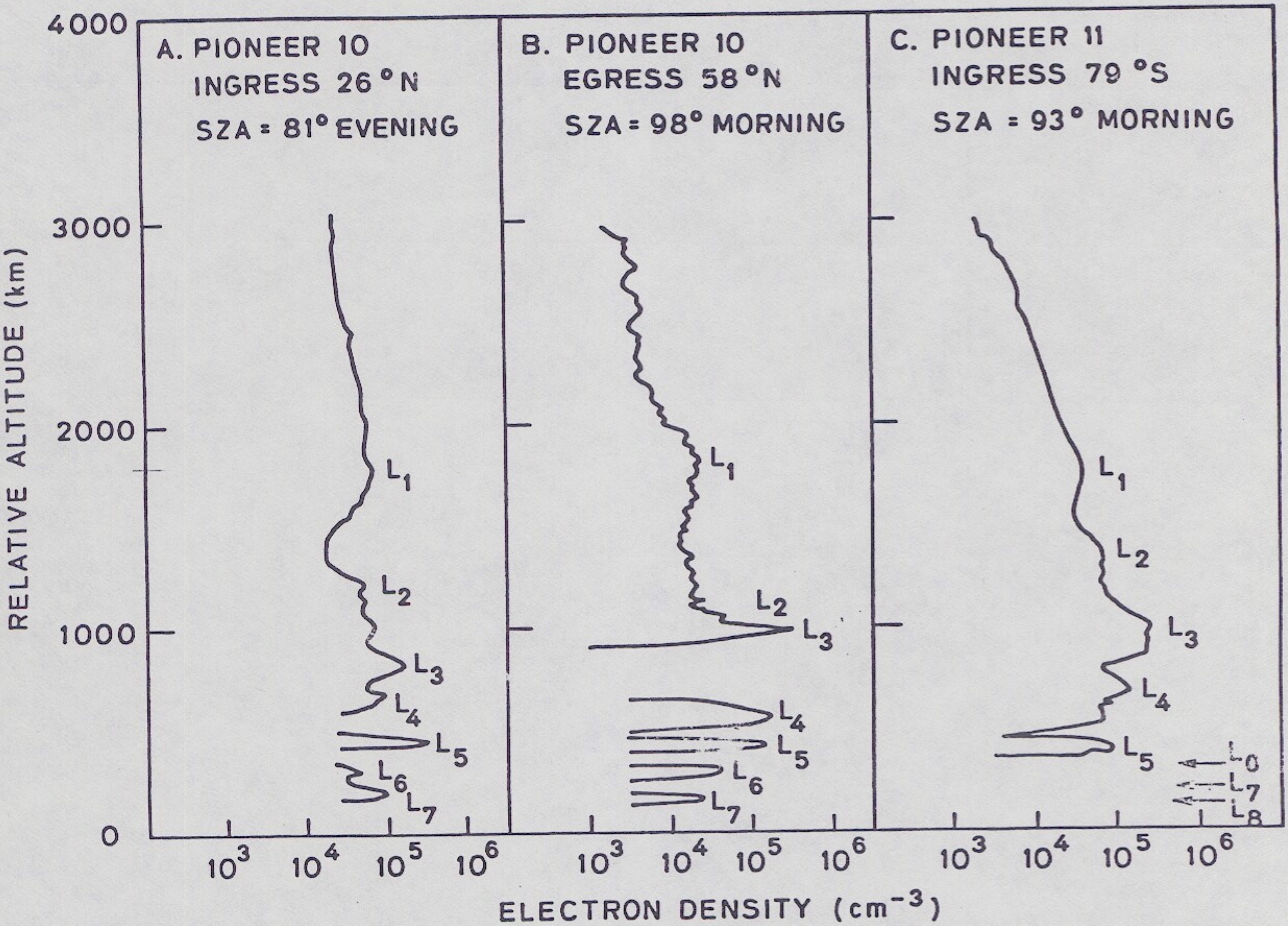
Eddy diffusion coefficient from CH_4 distribution.
After S. K. Atreya, et al., Reference 1.



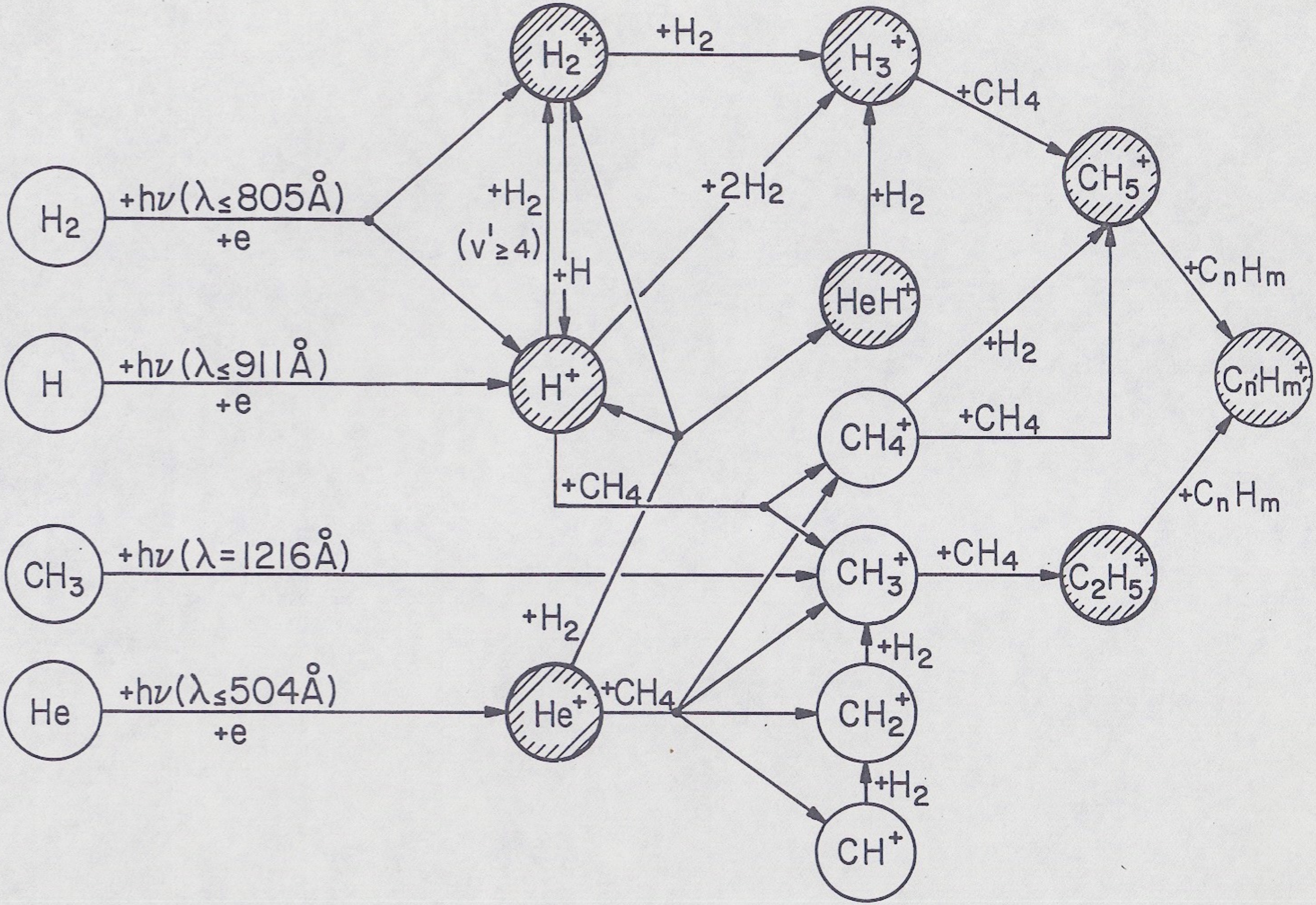
Eddy diffusion coefficient from H-Lyα (or H column abundance). After S. K. Atreya, et al., Reference 1.



Measured ionospheric profiles of Saturn. After S. K. Atreya, et al., Reference 1.



Measured Jovian ionospheric profiles.



Ionospheric scheme. After S. K. Atreya, Reference 2.

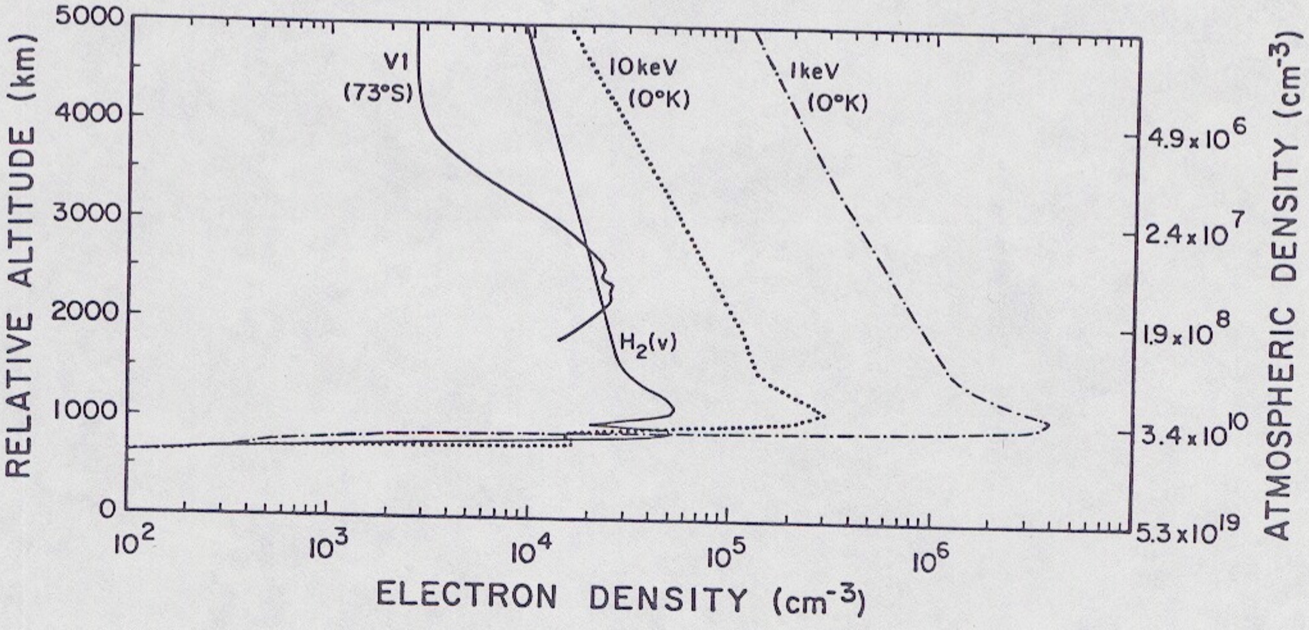
SIGNIFICANT IONOSPHERIC REACTIONS

$$
\left.\begin{array}{lcl}
H_2 + h\nu(e) & \longrightarrow & H_2^+ + e \\
 & \longrightarrow & H^+ + H + e \\
H + h\nu(e) & \longrightarrow & H^+ + e
\end{array}\right\}
$$

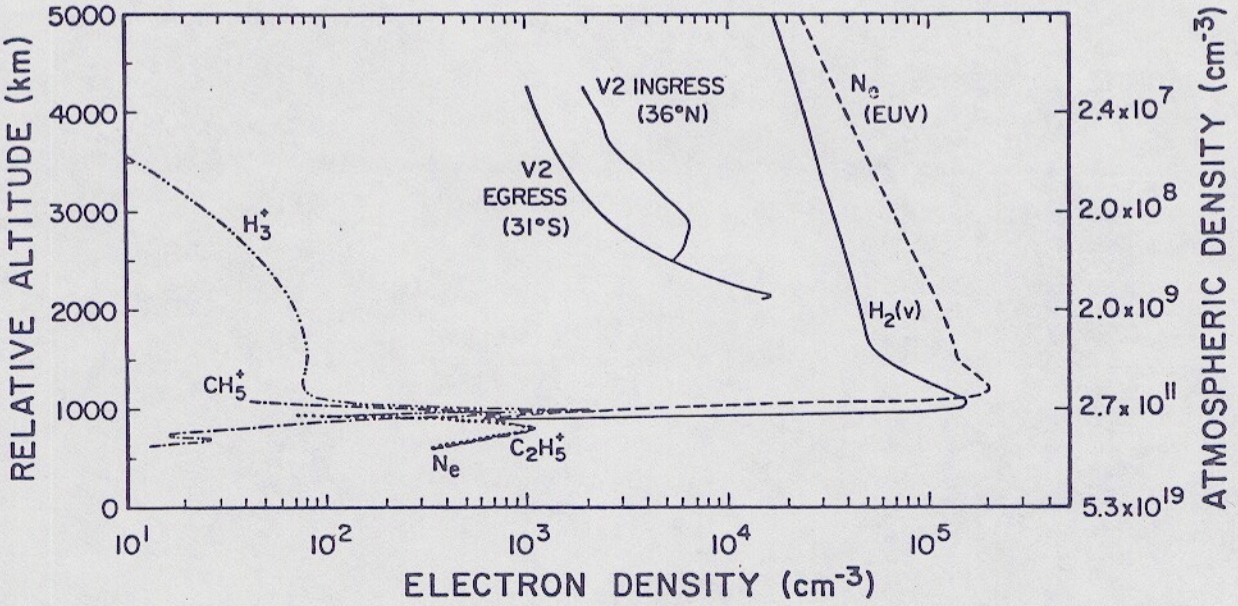
$$
\left.\begin{array}{lcl}
H_2^+ + H & \longrightarrow & H^+ + H_2 \\
H^+ + H_2\ (v' \geq 4) & \longrightarrow & H_2^+ + H \\
H_2^+ + H_2 & \longrightarrow & H_3^+ + H
\end{array}\right\}
$$

$$
H^+,\ H_3^+ \xrightarrow{+e} \text{NEUTRALS}
$$

(DIRECT IONIZATION OF H IMPORTANT ONLY AT HIGH ALTITUDES ABOVE THE PEAK)



Measured (V1) and model ionospheres. After S. K. Atreya, et al., Reference 1.



Measured (V2) and model ionospheric profiles.
After S. K. Atreya, et al., Reference 1.

SATURN IONOSPHERE

SUGGESTIONS FOR RECONCYCLING THEORY WITH DATA

(1) CHEMICAL LOSS OF IONS

$H^+ \longrightarrow H_3^+$	BY H_2 (v')
$H^+ \longrightarrow C_NH_M^+$	DOWNWARD DRIFT
$H^+ \longrightarrow H_3O^+$	BY H_2O INFLUX

(2) RING SHADOW EFFECT - EQUATORIAL

(3) DYNAMICAL/ELECTRODYNAMICAL

-- PLASMA NEAR MAGNETIC EQUATOR PUMPED TO HIGHER ELEVATIONS AND LOST ALONG FIELD LINES -- DYNAMO EFFECT.