MODEL IONOSPHERES OF JUPITER

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The principal concepts presently involved in modeling the Jovian ionosphere are reviewed. A model ionosphere is developed on the basis of our present knowledge of atmospheric composition, relevant chemical and ion-molecule reactions, with their associated rate constants. The shortcomings of this model are discussed when it is compared with the electron density profile obtained from the Pioneer 10 radio occultation data. It is demonstrated that the apparent great extent of the observed topside ionosphere may imply a hot thermosphere, as if Jupiter sustained a corona. Some of the layers observed in the electron density profile may be due to sporadic-E like clustering of protons and other ions.

Many models of the ionosphere of Jupiter have been developed in the past (Rishbeth 1959; Zabriskie 1960; Gross and Rasool 1964; Hunten 1969; Shimizu 1971; Prasad and Capone 1971; Tanaka and Hirao 1971; McElroy 1973; Capone and Prasad 1973; Atreya *et al.* 1974; Prasad and Tan 1974; and Atreya and Donahue 1975*b*). The recent flights of Pioneer 10 and 11 past Jupiter have contributed immensely to our knowledge of the environment of Jupiter. In view of the nature of the results obtained from the first direct detection of the Jovian ionosphere by the Pioneer 10 radio occultation experiment and their divergence from the models, it would be useless for us to devote much space to discussing each of the above mentioned models individually. We refer readers to articles by Hunten (1969), who has reviewed the progress in Jovian ionospheric modeling until 1969, by McElroy (1973) for progress until 1973, and by Atreya *et al.* (1974). The paper by McElroy is significant in pointing out the importance of dissociative ionization of H_2 among processes neglected in previous work, including the Hunten review. The paper by Atreya *et al.* (1974) draws attention to the three body association reaction

$$H^+ + H_2 + H_2 \rightarrow H_3^+ + H_2 \qquad (1)$$

as an important sink for ionization below 220 km. In this chapter we shall first outline a model of the Jovian ionosphere based on the latest available information on the relevant chemical reactions and rate constants, and a model atmosphere appropriate to a conventionally low value for the exospheric temperature, and then discuss how this model must be modified to conform to the measurements.

NEUTRAL ATMOSPHERE

Jupiter's upper atmosphere consists mostly of H_2 (67 km atm), He (< 34 km atm), CH_4 (45 m atm), C_2H_2 (2×10^{-6} m atm), C_2H_6 (10^{-4} m atm). The abundance of C_2H_2 and C_2H_6 is uncertain. Helium has been directly identified only recently by Judge and Carlson (1974) with the ultraviolet photometer on board Pioneer 10. Carlson and Judge (1974)[1] deduce a mixing ratio for He in the homosphere to be $0.18 \begin{array}{l} +0.46 \\ -0.12 \end{array}$; Elliott *et al.* (1974)[2] find the ratio to be $0.19 \begin{array}{l} +0.35 \\ -0.19 \end{array}$ from observation of the occultation of β-Scorpii by Jupiter. These results are not grossly different from the solar composition ratio of 0.11 (Hunten and Münch 1973), although the precision of both measurements is insufficient to determine this important quantity. Interpretation of Moos and Rottman's (1972) Lyman-α albedo data of Jupiter indicates an eddy diffusion coefficient K of 10^6 cm^2 sec^{-1} at the turbopause (Wallace and Hunten 1973).[3] Strobel (1973) derives a value of 2×10^4 cm^2 sec^{-1} in the lower atmosphere from consideration of the ultraviolet albedo. These values of K are, however, questionable (Atreya *et al.* 1974) since the rather high Lyman-α emission rate of 4.4 kR observed by Moos and Rottman (1972) may have had its origin partly in the hydrogen torus around Jupiter at the orbit of Io (McElroy *et al.* 1974). As a matter of fact Orbiting Astronomical Observatory-*Copernicus* measurements by Jenkins *et al.* (1973) indicated only 660 ± 350 R of Lyman-α attributable to Jupiter. Carlson and Judge's (1974) Pioneer 10 measurements show only 440 R of Lyman-α coming from the disk of Jupiter itself. From their observations of Lyman-α emission from Jupiter, Carlson and Judge (1974) derive a value for $K = 3 \times 10^{8 \pm 1}$ cm^2 sec^{-1}. Veverka *et al.* (1974) argue for $K \geqslant 7 \times 10^5$ cm^2 sec^{-1} from their interpretation of the spikes in the temperature profile deduced from the β-Scorpii occultation data. The weight of the evidence, therefore, argues for an eddy mixing coefficient greater than 10^5 cm^2 sec^{-1}, and perhaps as high as 10^9 cm^2 sec^{-1}. The upper atmospheric temperature profile now is derived from the Pioneer radio occultation data in the chapter by Kliore and Woiceshyn.[4] In view of the wide range of possible values for the He/H_2 mixing ratio, for K and for T we take Strobel's (1975) neutral model atmosphere to

[1]See p. 437.
[2]See p. 266.
[3]See p. 426.
[4]See p. 235.

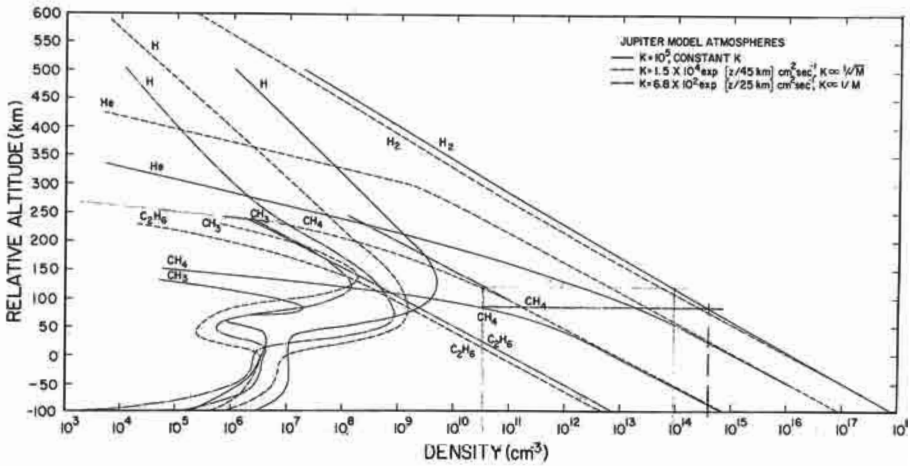

Fig. 1. Model atmospheres of Jupiter (hydrocarbon densities from Strobel 1975), for $K = 10^5$ cm^2 sec^{-1}, $K \propto M^{-\frac{1}{2}}$ and $K \propto M^{-1}$, where M is the atmospheric number density. Thermospheric temperature is assumed constant at 150°K and He/H_2 mixing ratio is taken as 0.1. Height scale refers to altitude above (or below) the level at which atmospheric density is 10^{16} cm^{-3}.

be as acceptable as any other for use in the illustrative calculations we shall present. Figure 1, adapted from Strobel (1975), assumes the He/H_2 ratio to be 0.1, and T_∞ to be 150°Kelvin and constant. Various values of K are assumed. Only those hydrocarbons which are suspected of playing a role in the ionosphere are included in Fig. 1. Further on in this chapter we shall show how this model atmosphere might be modified to explain the measured electron density profiles.

CHEMICAL MODEL AND IONOSPHERE

Reactions relevant to Jupiter's ionosphere are taken from Atreya and Donahue (1975*b*) and listed in Table I. Solar extreme-ultraviolet radiation provides the principal source of ionization in this model. (We are aware of a potentially important source from energetic magnetospheric particles, but do not yet know how to model that source.) Continuous absorption of radiation by atomic hydrogen occurs below 911 Å, by H_2 below 912 Å and by He below 504 Å. The appropriate photoabsorption and photoionization cross-sections are taken from Cook and Metzger (1964), Stewart and Webb (1963), Samson and Cairns (1965), and Samson (1966). Strobel (personal communication 1974) estimates an upper limit of 2×10^{-17} cm^2 for the photoionization cross-section of the methyl radical CH_3 whose ionization potential is 9.82 ± 0.04 eV (Elder *et al.* 1962). Photoionization of the methyl radical as an important process has been discussed recently by Atreya and Donahue (1975*b*) and also by Prasad and Tan (1974). The latter authors assume unacceptably large values for the ionization cross-section of CH_3 and the solar

Lyman-α flux at Jupiter. Photoionization of CH_3 is expected to be caused principally by solar Lyman-α. At the suggestion of Strobel (1975), Atreya and Donahue (1975*b*) investigated EUV photolysis of methane as an additional source of stratospheric ionization. They found that ionization of CH_4 contributes less than 3% of the total electron density. [At least 90% of the initial positive ions resulting from photoionization of CH_4 by radiation below 945 Å are CH_4^+ and CH_3^+ (Rebbert *et al.* 1973)]. Strong absorption by H_2 in the relevant wavelength region is responsible for the small contribution from this source. As far as ion production rates are concerned, we emphasize the importance of dissociative photoionization of H_2 as a source of H^+ (McElroy 1973). In this chapter we incorporate the recent data of Monahan *et al.* 1974), Browning and Fryar (1973), and Samson (1972) for the branching ratio for production of protons by dissociative photoionization of H_2. Ion production rates for a model in which K varies inversely as the square root of the atmospheric density ($K = 3 \times 10^7$ cm^2 sec^{-1} at the turbopause) are shown in Fig. 2. In this calculation the solar EUV fluxes of Hinteregger (1970), scaled to Jupiter, were employed. In the upper ionosphere where time constants for removal of the major ion (H^+) are much greater than a Jovian day, fluxes were halved in constructing diurnal average models. A solar zenith angle of 60° was assumed. The wavelength interval between 0 and 960 Å was divided into a mesh of 5 Å size, and appropriate cross-sections were averaged in each 5 Å interval. In Fig. 2 it will be seen that the

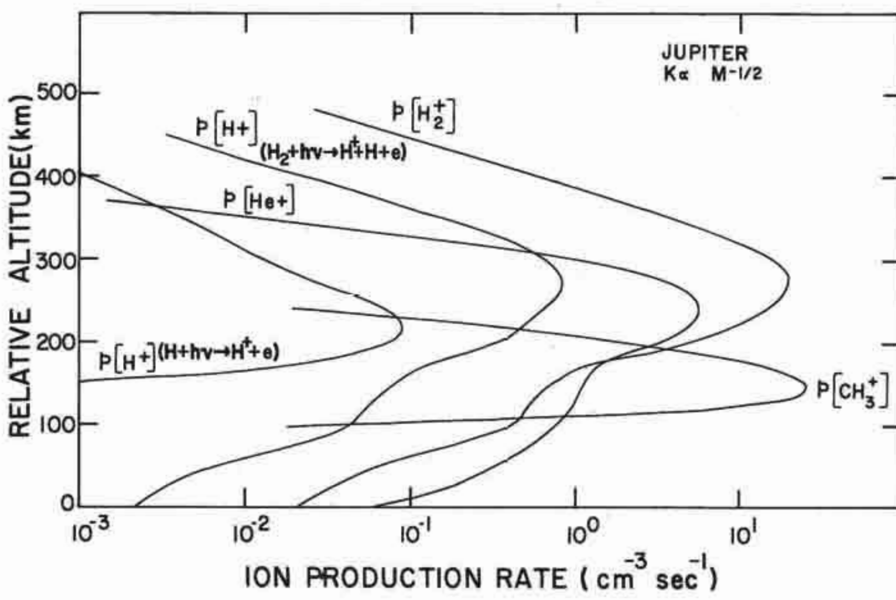

Fig. 2. Photo-ion production rates, $p(X^+)$ for the model with $K \propto M^{-\frac{1}{2}}$ ($K = 3 \times 10^7$ cm^2 sec^{-1} at the turbopause). Note that the photodissociative ionization of H_2 is the major source of H^+ production. Height scale is the same as in Fig. 1.

TABLE I
Important Reactions in the Ionosphere of Jupiter

Reaction Number	Reaction	Rate Constant[a]	Reference
	Ion Production:		
*p*1	$H_2 + h\nu \rightarrow H_2^+ + e$		
*p*2	$\rightarrow H^+ + H + e$		
*p*3	$H_2 + e \rightarrow H_2^+ + 2e$		
*p*4	$\rightarrow H^+ + H + 2e$		McElroy (1973)
*p*5	$H + h\nu \rightarrow H^+ + e$		
*p*6	$H + e \rightarrow H^+ + 2e$		
*p*7	$He + h\nu \rightarrow He^+ + e$		
*p*8	$He + e \rightarrow He^+ + 2e$		
	Ion Exchange:		
*e*1	$H_2^+ + H_2 \rightarrow H_3^+ + H$	2.0×10^{-9}	Theard and Huntress (1974)
*e*2	$H_2^+ + H \rightarrow H^+ + H_2$	$\sim 1.0 \times 10^{-10}$	Hunten (1969)
*e*3	$He^+ + H_2 \rightarrow H_2^+ + He$ (sum)	$\lesssim 20\%$	
*e*4	$\rightarrow HeH^+ + H$ (sum)	1.0×10^{-13}	Johnsen and Biondi (1974)
*e*5	$\rightarrow H^+ + H + He$ (sum)	$\gtrsim 80\%$	
*e*6	$He^+ + CH_4 \rightarrow CH^+ + H_2 + H + He$	2.4×10^{-10}	Huntress (1974)
*e*7	$\rightarrow CH_2^+ + H_2 + He$	9.3×10^{-10}	Huntress (1974)
*e*8	$\rightarrow CH_3^+ + H_2 + He$	6.0×10^{-11}	Huntress (1974)
*e*9	$\rightarrow CH_4^+ + He$	4.0×10^{-11}	Huntress (1974)
*e*10	$H^+ + H_2 + H_2 \rightarrow H_3^+ + H_2$	3.2×10^{-29}	Miller *et al.* (1968)
*e*11	$H^+ + CH_4 \rightarrow CH_3^+ + H_2$	2.3×10^{-9}	Huntress (1974)
*e*12	$\rightarrow CH_4^+ + H$	1.5×10^{-9}	Huntress (1974)
*e*13	$HeH^+ + H_2 \rightarrow H_3^+ + He$	1.85×10^{-9}	Theard and Huntress (1974
*e*14	$H_3^+ + CH_4 \rightarrow CH_5^+ + H_2$	2.4×10^{-9}	Huntress (1974)
*e*15	$CH^+ + H_2 \rightarrow CH_2^+ + H$	1.0×10^{-9}	Huntress (1974)
*e*16	$CH_2^+ + H_2 \rightarrow CH_3^+ + H$	7.2×10^{-10}	Huntress (1974)
*e*17	$CH_3^+ + CH_4 \rightarrow C_2H_5^+ + H_2$	8.9×10^{-10}	Huntress (1974)
*e*18	$CH_4^+ + CH_4 \rightarrow CH_5^+ + CH_3$	1.11×10^{-9}	Huntress (1974)
*e*19	$CH_4^+ + H_2 \rightarrow CH_5^+ + H$	4.1×10^{-11}	Huntress (1974)
	Ion Removal/Electron-Ion Recombination:		
*r*1	$H_3^+ + e \rightarrow H_2 + H$	3.8×10^{-7}	Leu *et al.* (1973)
*r*2	$H_2^+ + e \rightarrow H + H$	$< 1.0 \times 10^{-8}$	Hunten (1969)
*r*3	$HeH^+ + e \rightarrow He + H$	$\sim 1.0 \times 10^{-8}$	Hunten (1969)
*r*4	$H^+ + e \rightarrow H + h\nu$	6.6×10^{-12}	Bates and Dalgarno (1962)
*r*5	$He^+ + e \rightarrow He + h\nu$	6.6×10^{-12}	Bates and Dalgarno (1962)
*r*6	$CH_5^+ + e \rightarrow$ neutral	1.9×10^{-6}	Rebbert *et al.* (1973)
*r*7	$C_2H_5^+ + e \rightarrow$ products	1.9×10^{-6}	Rebbert *et al.* (1973)

[a]The rate constants are in units of $cm^3\ sec^{-1}$ for two-body reactions, and $cm^6\ sec^{-1}$ for three-body reactions (after Atrey and Donahue 1975*b*).

dissociative photoionization of H_2 provides the dominant source of Jovian protons, while production of H^+ due to direct photoionization of H can be ignored. Ion production in the very low altitude regions is due to penetration of *X*-radiation below 100 Å. We should, however, point out that both the solar EUV flux and the values of appropriate cross-sections are quite uncertain in the hard *X*-ray region. Therefore, the present picture of very low altitude ion-production may change as better data become available. H^+ ion production due to direct photoionization of H is negligible below 150 km because of absorption by H_2 in the relevant wavelength band. CH_3^+ ion production occurs in a very narrow altitude range since the radiation responsible for CH_3 ionization (principally solar Lyman-α) is strongly absorbed by methane below the turbopause. Neutralization of the ions formed proceeds via various reactions with other atmospheric constituents and eventual electron-ion recombination mechanisms listed in Table I. H_2^+ ions are converted to H_3^+ (reaction *e*1) in the lower atmosphere where the H_2 density is high, while in the upper atmosphere they form H^+ (reaction *e*2) or dissociatively recombine with electrons (reaction *r*2). Above the methane turbopause, He^+ is mainly removed by a series of reactions (*e*3–*e*5) with H_2, while the bulk of He^+ ends up as H^+. Below the methane turbopause He^+ preferentially combines with CH_4 to give various hydrocarbon ions (reactions *e*6 – *e*9). Protons at and above the altitude of the maximum electron density $[N_e]_{max}$ are removed by radiative recombination with electrons (reaction *r*4); by three body association (reaction *e*10) between the altitude of maximum electron density and the turbopause; and by methane (reactions *e*11 and *e*12) below the turbopause. The importance of the three body reaction (*e*10) as a fast sink of Jovian protons was first recognized independently by Dalgarno (1971) and by Donahue (see McElroy 1973). H_3^+ ions formed in reactions *e*1, *e*10 and *e*13 combine rapidly with CH_4 to give CH_5^+ ions in the vicinity of the turbopause above which they are neutralized in dissociative recombination with electrons (reaction *r*1). Various hydrocarbon ions resulting from chemical reactions eventually form higher-order hydrocarbon ions CH_5^+ and $C_2H_5^+$ which are rapidly neutralized in dissociative recombination with electrons (reactions *r*6 and *r*7). The importance of methane as a potential sink for H^+ ions at low elevation was first recognized by McElroy (1973). Later Atreya and Donahue (1975*a*) extended the sink to include He^+ and H_3^+ ions. As more hydrocarbon reaction rate constants have become available (Huntress 1974), the role of hydrocarbons in the lower ionosphere of Jupiter has been discussed by Prasad and Tan (1974) and Atreya and Donahue (1975*b*). Under assumptions of photochemical equilibrium, the ion distribution was obtained by numerically solving one-dimensional coupled continuity equations. Results of these calculations are shown in Fig. 3. Electron density (N_e) profiles are shown for a constant eddy coefficient of 10^5 cm^2 sec^{-1} and for a *K* that varies with altitude. The maximum electron density in the high *K* model is greater by almost a factor of 3 than in the model with *K* set at 10^5 cm^2 sec^{-1}. This is

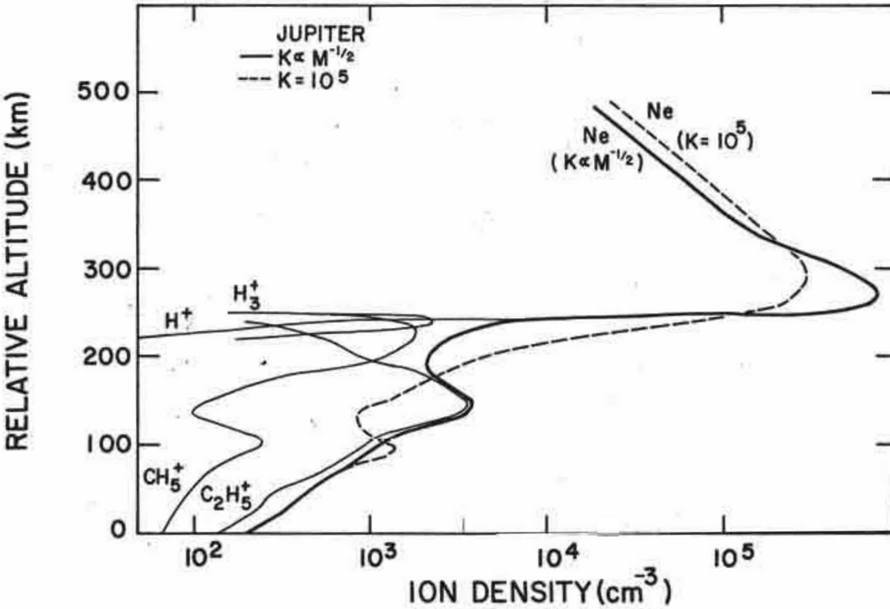

Fig. 3. Calculated electron density profiles in Jupiter's atmosphere for $K = 10^5$ cm^2 sec^{-1} and $K \propto M^{-\frac{1}{2}}$ cases. The secondary peak in Ne profile at lower elevation is due to CH_3^+ ions. Ion distribution is shown for $K \propto M^{-\frac{1}{2}}$ model only. Height scale is the same as in Fig. 1.

caused by the fact that the He density remains relatively great to a much higher altitude when K is large and becomes an important source of Jovian protons because of reaction $e5$. Precise determination of the rate constant of $e5$ compared to the combined rate of $e3$, $e4$ and $e5$ is essential to an understanding of the relationship between K and the He source. The ion distribution profiles in Fig. 3 correspond to the model in which K varies as previously described. H^+ is the major ion down to the altitude of maximum electron density; H_3^+ dominates over a small range below the density maximum and then CH_5^+ and $C_2H_5^+$ prevail. A slight increase in the CH_5^+ density between 140 and 220 km is due to eventual conversion of H_3^+, H^+ and He^+ to CH_5^+. A secondary peak in electron density near $\sim$ 150 km (in the variable K model) is due to a maximum in CH_3^+ ion production at that altitude.

CONCLUSIONS

The electron density profiles shown in Fig. 3 are, in essence, similar to the pre-Pioneer 10 model of Atreya *et al.* (1974); only various refinements discussed above have been included. Inversion of the Pioneer 10 radio occultation data is complicated due to effects of multipath propagation of the S-band signal (Kliore *et al.* 1974). Preliminary analyses of the closed loop Doppler data (Fjeldbo *et al.* 1975) indicate that the electron density profile shows considerably more structure than that given by the model just developed. In Fig. 4, we reproduce, by solid lines, electron density profiles de-

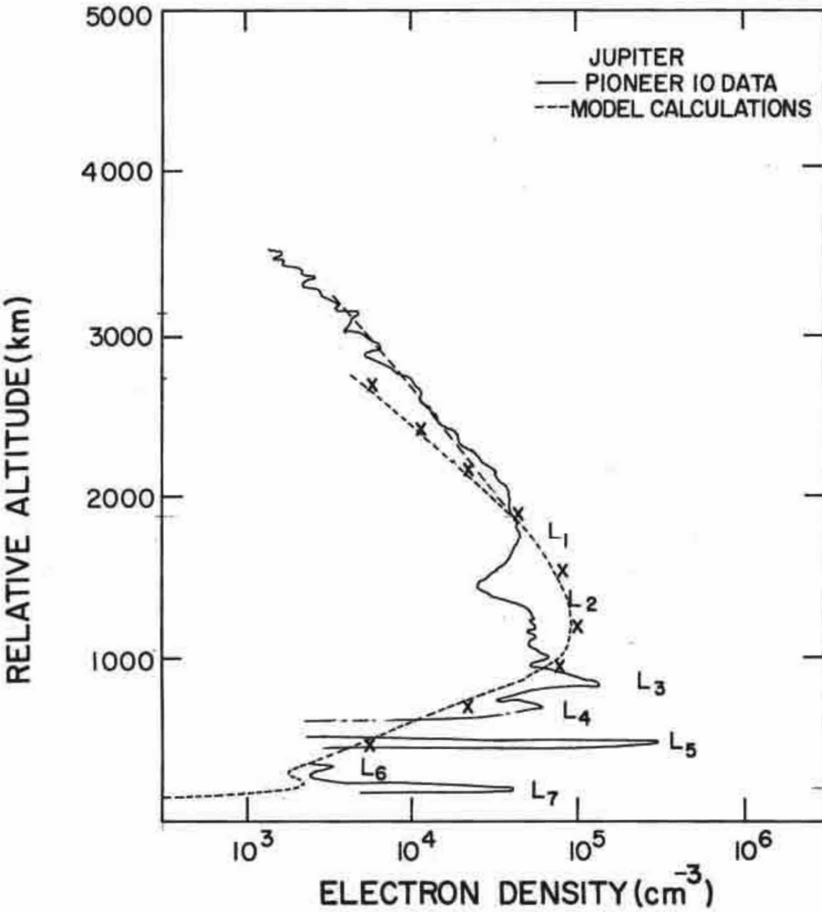

Fig. 4. Comparison of electron density profile measured by the Pioneer 10 radio occultation experiment with the model calculations based on a hot thermospheric model. Measured profile corresponds to late afternoon immersion at latitude 26°N and solar zenith angle, $\xi = 81°$. The short-dashed curve refers to calculations in which $\xi = 81°$, $T_e = T_i = T_n$ and the radiative recombination coefficient, α_r (of H^+ and He^+) varies as $T_e^{-0.5}$. If $\alpha_r \propto T_e^{-0.75}$, a curve may be drawn through the crosses (x's). Diffusive equilibrium distribution is shown by the long-dashed curve for the case where $\alpha_r \propto T_e^{-0.5}$. The height scale refers to altitude above the level where the refractivity is 10 (see Fjeldbo *et al.* 1975).

duced during immersion by the radio occultation experiment in late afternoon of December 4, 1973 when the solar zenith angle ξ was 81°. The height scale refers to the level at which the refractivity is 10. The model ionosphere of Fig. 3 for variable K has some resemblance to the measured one up to the altitude of the *L5* peak. Beyond this level, however, the electron density drops to about 10^3 cm^{-3} within 300 km in the model, whereas the measured electron density remains fairly large for another 3000 km or so. We shall attempt to explain this gross discrepancy in the topside ionosphere on the basis of a possible "hot thermosphere" implying that a given density would occur at a much higher altitude in the model atmosphere. The source of this thermospheric heating probably lies in the lower atmosphere in the form of inertia gravity waves. French and Gierasch (1974) first broached this possibility in order to explain the peculiar temperature profile obtained from the inversion of β-Scorpii occultation data by Veverka *et al.* (1974). French and Gierasch (1974) argue that the observed oscillations in the temperature profile are due to propagating inertia gravity waves and the absence of flashes (lightcurve spikes) at densities lower than 10^{13} cm^{-3} supports the interpretation of upward energy propagation with damping of the waves above the mesopause level. They calculate the associated energy flux to be about 3.4 ergs cm^{-2} sec^{-1}, some two orders of magnitude larger than the solar EUV flux absorption above the mesopause in Jupiter (Strobel and Smith 1973). McElroy (personal communication 1975) has extended Strobel and Smith's (1973) calculations to include dissipation and subsequent absorption of the inertia gravity wave energy in the thermosphere. Energy absorbed at a level z in the thermosphere is conducted downward and radiated in the neighborhood of the mesopause by species like CH_4, C_2H_2, C_2H_4, C_2H_6, etc. (Strobel and Smith 1973). The temperature difference ΔT between z_0 and z is given by the following relationship (after Strobel and Smith 1973):

$$\Delta T = T(z) - T_0 = \frac{\Delta z}{\kappa}\mathscr{F}(z) \tag{2}$$

where $\mathscr{F}(z)$ is the energy flux associated with the inertia gravity waves and κ is the conductivity of the background gas H_2—about 68.6 $T(z)$ ergs cm^{-1} sec^{-1} °K^{-2} according to Strobel and Smith (1973). In view of the electron density profile observed by Pioneer 10 (shown in Fig. 4) and the model ionosphere of Fig. 3, it appears that the bulk of the energy carried by the inertia gravity waves is dissipated nearly 250 km above the mesopause (i.e., $\Delta z =$ 250 km). With the above parameters we have calculated Jupiter's upper atmosphere temperature profile. The results of our calculations are depicted in Fig. 5; we estimate the exospheric temperature T_∞ to be nearly 900°K higher than the mesopause temperature. With the lower boundary at the mesopause ($T_0 = 150$°K, $n(H_2) = 10^{13}$ cm^{-3}) and T_∞ as calculated above, we obtain an atmospheric density profile, essentially H_2 insofar as the topside ionosphere is concerned, from the mesopause through the thermosphere. The electron density profile for this hot thermospheric model we have then calculated in the manner outlined earlier in this chapter. We assume after Henry and McElroy (1969) that thermal equilibrium is maintained between electrons, ions, and neutral molecules (i.e., $T_e \simeq T_i \simeq T_n$). Protons, which are the major ions at thermospheric heights, are lost by radiative recombination with electrons. We assume a $T_e^{-0.5}$ dependence on electron temperature for the radiative recombination rate α_r of the protons (Bates and Dalgarno 1962). The small-dashed curve in Fig. 4 shows the electron density profile calculated for this hot thermospheric model, when we assume $\xi = 81°$, $T_e \simeq T_i \simeq$

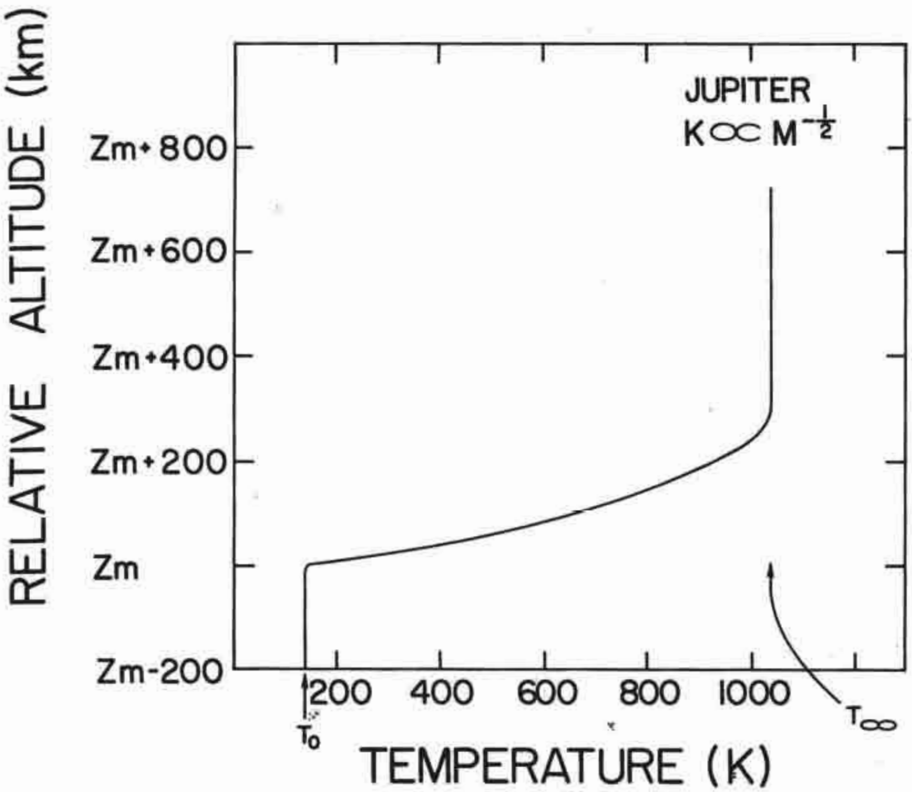

Fig. 5. Upper atmospheric temperature profile of Jupiter calculated on the basis of the dissipation of the upward propagating inertia gravity waves. The height scale refers to altitude above or below a mesopause level, Z_m assumed at density level 10^{13} cm^{-3}. The mesopause temperature, T_0 is assumed to be 150°K and the exospheric temperature T_∞ is estimated at ~ 1050°K.

T_n and $\alpha_r \propto T_e^{-0.5}$. If we assume α_r to vary as $T_e^{-0.75}$ (Bauer 1973) we obtain a profile drawn between the crosses (x's) in Fig. 4. As should be expected, the model in Fig. 4 does not differ appreciably from the one shown in Fig. 3 below the thermosphere. We also find that the transport effects begin to be important above ~ 1500 km (Fig. 4) where the time constant for diffusion is smaller than the photochemical time constant. We show the diffusive equilibrium distribution of protons above 1500 km by the long-dashed curve in Fig. 4. If we ignore the various layers, $L1$–$L7$ which the radio occultation data indicate to be present in the Ne profile shown in Fig. 4, we see reasonably good agreement (certainly within a factor of two at all altitudes) between the measurements and the model depicted by the broken line in Fig. 4. We do not attempt to construct a model that will match identically the measured profile since the measurements are not entirely unambiguous. The purpose of these calculations is to illustrate that our ideas of Jupiter's thermosphere probably must be modified in view of the apparent topside ionospheric profile measured by Pioneer 10. One can easily see, though, that only a slight modification of the thermospheric temperature structure would yield a better fit to the data.

The time constant for removal of protons at the altitude of *L*5 is on the order of 10^4 sec, and it increases to 10^7 at the altitude of *L*1. At these altitudes, long-lived protons will, under the combined influence of Jupiter's magnetic field and probable horizontal winds (or propagating vertical waves), cluster into layers at positions of null points or nodes. This phenomenon may be likened to the sporadic-*E* layering in the earth's ionosphere. Layer *L*7 appears to be at the level of maximum CH_3^+ ion production. Identification of layer *L*7 with CH_3^+ ion production would, however, be premature. This is due to the fact that a reduction in the ratio, $\sigma_I(CH_3)/r_7$ by as little as a factor of 4 would wipe out this feature in the N_e profile. Preliminary data of Maier and Fessenden (1975) suggest a value of r_7, twice as large as that given by Rebbert *et al.* (1973); and the value of $\sigma_I(CH_3)$ used here is the upper limit. Furthermore, a possibility exists that $C_2H_5^+$ may not be the terminal ion in the reaction e_{17}. New measurements indicate that $C_2H_5^+$ combines rapidly with C_2H_4 and C_2H_2 *at room temperature* to yield higher-order hydrocarbon ions, $C_3H_5^+$ and $C_4H_5^+$:

$$C_2H_5^+ + C_2H_4 \rightarrow (C_4H_9^+)^* \rightarrow C_3H_5^+ + CH_4 \quad (3)$$

and

$$C_2H_5^+ + C_2H_2 \rightarrow (C_4H_7^+)^* \rightarrow C_4H_5^+ + H_2 \,. \quad (4)$$

Thus it might be the recombination rate of $C_3H_5^+$ and $C_4H_5^+$ that should enter in the ratio $\sigma_I(CH_3)/r$. No information is yet available on the needed rates. In view of this, we regard identification of the peak *L*7 as due to CH_3^+ to be dubious at best. The height of the *L*7 layer coincides with the lower elevation peak (due to CH_3^+) in the variable *K* model; this layer is nearly 50 km lower in the low $K(K = 10^5\ cm^2\ sec^{-1})$ model (Fig. 3). Layers *L*6 and *L*7 could possibly be due to Io-related sodium ions which are expected to end up in Jupiter's lower ionosphere as surmised by Atreya *et al.* (1974) in their pre-Pioneer 10 model. Removal of Na^+ is extremely slow ($\tau = 10^6$ sec) by radiative recombination with a rate constant on the order of 10^{-12} cm^3 sec^{-1}. This is the only likely loss mechanism of these ions in Jupiter's atmosphere. Clustering with ammonia in the presence of a third body and subsequent dissociative recombination of the cluster may be an alternate avenue as in the following reactions:

$$Na^+ + NH_3 + M \rightarrow Na^+ \cdot NH_3 + M \quad (k \simeq 10^{-28}\ cm^6\ sec^{-1}) \quad (5)$$

followed by

$$Na^+ \cdot NH_3 + e \rightarrow Na + NH_3 \quad (k \simeq 10^{-6}\ cm^3\ sec^{-1})\,. \quad (6)$$

However, removal of the sodium ions by ammonia in Jupiter's atmosphere appears unlikely due to the extremely low NH_3 densities at ionospheric heights. Presence of metallic ions other than sodium, either intrinsic to Jupiter or those swept from the torus, is likely. Therefore, more than one stratospheric layer in the electron density profile may be attributed to these potential long-lived metallic ions. However, it has by no means been demonstrated that sodium ions from Io can penetrate into the Jovian atmosphere enough to provide a significant source.

Acknowledgements. We have benefited from enlightening discussion with D. M. Hunten on the Pioneer 10 radio occultation data, with M. B. McElroy on Jovian thermospheric heating and with D. F. Strobel on the EUV photolysis of hydrocarbons. This work was sponsored by the Kitt Peak National Observatory operating under contract with the National Science Foundation, and it was supported by the Jet Propulsion Laboratory, California Institute of Technology under NASA Contract NAS 7-100.

DISCUSSION

D. M. Hunten: The suggestion that Ionian sodium ions would fall down the fieldlines into Jupiter is interesting, but has one big problem. There has been a lot of work on Jupiter as a centrifugal accelerator, based on the idea that the magnetic field carries ions around much faster than the Kepler velocity. The net force on them is strongly outward. Perhaps a way can be found around this difficulty, but the situation is hardly as simple as Atreya *et al.* (1974) originally suggested.

S. K. Atreya: I have two comments on this remark: (1) as we have stated in the paper the source of potential sodium ions in Jupiter's stratosphere is not unequivocally established; and (2) we may be attempting to explain an unreal feature in the electron density profile as inferred from the Pioneer 10 data. Regarding the source of the sodium ions, I think Ionian sodium is only one of the several possibilities. Sodium intrinsic to Jupiter or that deposited by the meteorites, for example, is another likelihood. The validity of these hypotheses remains to be tested. My second comment refers to G. Fjeldbo's analysis of his Pioneers 10 and 11 data. Fjeldbo *et al.* (1975) state that the ionization peaks *L*6 and *L*7 do not have distinct signatures in the radio recordings and instead of being real layers, these computed ionization peaks may have been caused by scintillation noise or by deviations from spherical symmetry. It is for explaining precisely these "layers," *L*6 and *L*7, that we invoked the metallic ion hypothesis. At and beyond the altitude of layer *L*5, the lifetime of the protons is large enough for them to behave in a way similar to the metallic ions in the sporadic *E*-type layering.

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