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Ionospheric Models of Saturn, Uranus, and Neptune

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Model ionospheres are calculated for Saturn, Uranus, and Neptune. Protons are the major ions above 150 km altitude measured from a reference level where the hydrogen density is 1×10^{16} molecules cm^{-3}, while below 150 km quick conversion of protons to H_3^+ ions by a three-body association mechanism leads to a rapid removal of ionization in dissociative recombination of H_3^+. Electron density maxima are found at about 260 km for Saturn and Uranus and 200 km for Neptune. Present knowledge of the physical and chemical processes in the atmospheres of these planets suggests that their ionospheres probably will not be Jupiter-like.

INTRODUCTION

The Pioneer 10 radio occultation experiment has provided the first direct measurement of the electron density profile in the ionosphere of Jupiter (Kliore *et al.*, 1974). The magnitude and location of the principal maximum in the electron density profile resemble closely the predictions made in the model ionospheres of Atreya *et al.* (1974). The maximum electron density is found to be nearly 5×10^5 cm^{-3}; nearly 400 km above the level of the ammonia cloud tops. This level occurs about 220 km above an assumed reference level where the hydrogen density is 1×10^{16} molecules cm^{-3}, if we assume a cloud top density of about (7–8) $\times 10^{19}$ cm^{-3} (Giver *et al.*, 1969), an average temperature of about 140–150 K (Wallace *et al.*, 1974) and abundance ratio of 0.3 for He to H_2. In another paper in preparation we attempt to explain the discrepancies between the predictions and the measurements on the basis of Jovian dynamics and a peculiar electromagnetic interaction between Io and Jupiter (Goldreich and Lynden-Bell, 1969; Gurnett, 1972) which may result in relatively large concentrations of Io-related sodium ions (McElroy *et al.*, 1974) in the lower ionosphere of Jupiter. On others of the outer planets, however, magnetic fields have not been conclusively detected (Sonett, 1973) and no Io-Jupiter like planet–satellite interaction is known; therefore ionospheric models in these planets will not necessarily be similar to those measured by Pioneer 10 at Jupiter. Therefore, in the present paper we construct photochemical equilibrium models of the ionospheres of Saturn, Uranus, and Neptune, the calculations being similar to those for Jupiter (Atreya *et al.*, 1974). The implications of a possible Saturnian magnetic field and of the nature of the rings are discussed.

MODELS

The model atmospheres used are the same as given by McElroy (1973) in which H_2 and He are the major constituents with minor quantities of NH_3 and CH_4. Ridgway (1974) has recently discovered other hydrocarbons: acetylene and ethane in the Jupiter's atmosphere, however their abundance is not large enough to play a direct role in determining the ionization. Photoionization of H_2, H, and He (*p*1, *p*2, *p*5, and *p*7) are the principal ion-production processes. The relative importance of the production processes in Table I are illustrated by McElroy (1973) in his Fig. 6. The chemical model listed in Table I is the same as for Jupiter (Atreya *et al.*, 1974);

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TABLE I

IMPORTANT REACTIONS IN THE IONOSPHERE OF THE OUTER PLANETS[a]

Reaction number	Reaction	Rate constant	Reference
	Ion production:		
*p*1	$H_2 + h\nu \rightarrow H_2^+ + e$		McElroy (1973)
*p*2	$\rightarrow H^+ + H + e$		
*p*3	$H_2 + e \rightarrow H_2^+ + 2e$		
*p*4	$\rightarrow H^+ + H + 2e$		
*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	$H_2^+ + H_2 \rightarrow H_3^+ + H$	2×10^{-9}	Theard and Huntress (1974)
*e*2	$H_2^+ + H \rightarrow H_2 + H^+$	$\sim 1 \times 10^{-10}$	Hunten (1969), Prasad and Capone (1971)
*e*3	$He^+ + H_2 \rightarrow He + H_2^+$	$\lesssim 20\%$	Johnsen and Biondi (1974)
*e*4	$\rightarrow HeH^+ + H$	sum 1×10^{-13}	
*e*5	$\rightarrow He + H + H^+$	$\gtrsim 80\%$	
*e*6	$H^+ + H_2 + H_2 \rightarrow H_3^+ + H_2$	3.2×10^{-29}	Miller *et al.* (1968)
*e*7	$HeH^+ + H_2 \rightarrow H_3^+ + He$	1.85×10^{-9}	Theard and 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	$H_2^+ + e \rightarrow H + H$	$< 1 \times 10^{-8}$	Hunten (1969), Prasad and Capone (1971)
*r*3	$HeH^+ + e \rightarrow He + H$	$\sim 1 \times 10^{-8}$	Hunten (1969), Prasad and Capone (1971)
*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)

[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.

some reaction rates have, however, been brought up to date (that is to say, they have been measured). We emphasize the importance of the reactions (*e*6) and (*e*7) (Dalgarno, 1971) neglected prior to our paper on the Jovian ionosphere (Atreya *et al.*, 1974).

Protons are efficiently removed via the three-body association reaction (*e*6) below about 150km; and both reactions (*e*6) and (*e*7) result in an increased abundance of H_3^+ ions which are removed by the dissociative recombination reaction (*r*1). The recently measured value of the rate constant for (*r*1) is nearly a factor of 40 larger than used in the previous studies and the result is a much lower electron density in the lower ionosphere than will be found in earlier models. The electron density profile is found to be quite sensitive to the branching ratio of the reaction rates $k_5/k_3 + k_4 + k_5$; and in the present study reaction k_5 is assumed to account for at least 80% of the total reaction rate $(k_3 + k_4 + k_5)$ in accordance with the recent measurements by Johnsen and Biondi (1974).

Model ionospheres for Saturn, Uranus, and Neptune calculated on the basis of photochemical equilibrium are shown in Figs. 1, 2, and 3. These models differ from earlier models in many respects: (i)

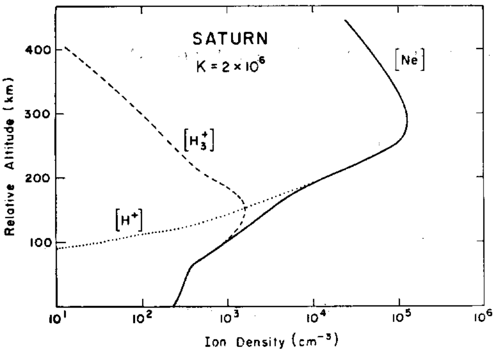

FIG. 1. A model for Saturn's ionosphere with eddy diffusion coefficient, $K = 2 \times 10^6 \mathrm{cm}^2 \mathrm{sec}^{-1}$, and He mixing ratio of 0.24. Maximum computed values of [HeH$^+$], [He$^+$], and [$H_2$$^+$] ions are smaller than can be drawn on the scale of this figure. The vertical scale gives the height above a reference level where the H_2 density is 1×10^{16} cm^{-3}.

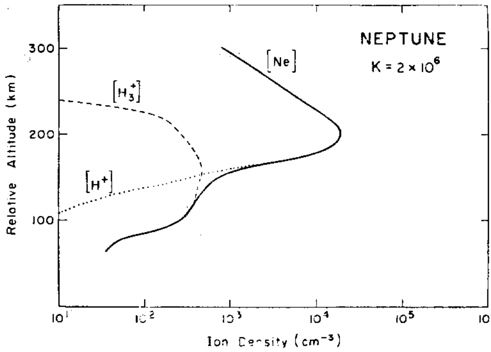

FIG. 3. A model for Neptune's ionosphere. Notation as for Fig. 1.

Protons are the major ions only above about 150km rather than throughout the entire ionosphere, (ii) H_3^+ ions are dominant below 150km, (iii) unlike earlier models, here the HeH$^+$ ion abundance is negligible, (iv) below 260km on Saturn and Uranus and below 200km on Neptune, the electron density is as much as a factor 100 smaller than calculated in the earlier models. The ionospheric models constructed in Figs. 1, 2, and 3 are with He/H_2 = 0.3 and eddy diffusion coefficient, $K = 2 \times 10^6 \mathrm{cm}^2 \mathrm{sec}^{-1}$; the value of these parameters has not yet been conclusively determined. The models are found to be essentially independent of the choice of the He/H_2 abundance ratio which was varied between 0.1 and 1 in these calculations. Changing K to 10^8, however changes the maximum electron density by nearly a factor of 3. The range of values selected for K is in accord with the recent Lyman-alpha measurements of Pioneer 10 (Judge and Carlson, 1974) and the Copernicus satellite (Jenkins *et al.*, 1974); and the interpretation of the Lyman-alpha albedo data of Rottman *et al.* (1973) by Wallace and Hunten (1973).

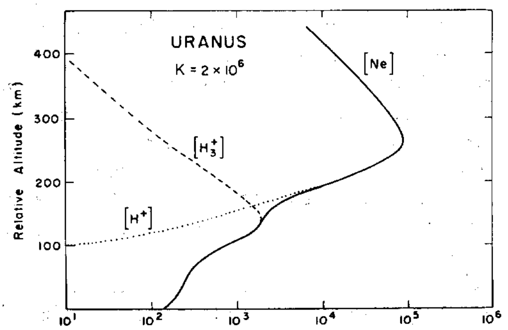

FIG. 2. A model for Uranus' ionosphere. Notation as for Fig. 1.

DISCUSSION

There are several obvious uncertainties in the chemical model on which these calculations are based. This is particularly true with regard to the role played by hydrocarbons in the lower ionosphere. For example, on Saturn where the value of the mixing ratio of CH_4 has been established it is possible to estimate that its role may be important below ~125km. H^+ and H_3^+ ions may react rapidly, possibly at gas kinetic rates, with CH_4 to form $C_2H_5^+$ and CH_5^+. The latter ions are then very efficiently neutralized by dissociative recombination with electrons (Rebbert *et al.*, 1973). However, since H^+ is already a minor ion at these altitudes and H_3^+ recombines dissociatively very rapidly, the overall effect on the electron density should be small. We now discuss the possible influence of the rings of Saturn on the planetary ionospheric profile. A consistent picture of the nature of the rings is beginning to emerge from the interpretations by Pollack *et al.* (1973) of the radar backscatter observations of Goldstein and Morris (1973); radio thermal observations of Berge and Muhleman (1973) and Rather *et al.* (1974); by Briggs (1973 and 1974) of his radio interferometric observations; and by Morrison (1974) of his infrared radiometry observations—all made during the period of maximum tilt. The consensus is that the rings are composed of particles of water ice or common Earth silicates or perhaps frost coated substances, with an upper limit of 10 cm on their size. Metallic particles are not believed to be present. Besides, lack of synchrotron radiation from Saturn (Sonett, 1973; Briggs, 1973) suggests the absence of a strong planetary magnetic field; therefore the electromagnetic coupling between the rings and the planet may be weak. Thus, it is not indicated that the rings will significantly affect the planetary ionospheric profiles. Clearly more sophisticated tests are desired before the presence of the planetary magnetic field and the metallic particles in the rings is entirely ruled out. If the magnetic field were present, however, and the rings had metallic particles, there is a possibility of these particles ending up in Saturn's lower ionosphere on their removal, perhaps by sputtering mechanism, and subsequent photoionization and sweeping by Saturn's magnetic field lines. The ionospheric profiles will then be substantially altered due to the transport of these long lived metal ions under the cumulative influence of the magnetic field and the neutral winds (the zonal winds of Saturn may be up to a factor of 10 larger than on Jupiter: Stone, 1973). Finally, we wish to point out that the "hydrogen gas ring" around Saturn proposed by McDonough and Brice (1973) is not expected to have any influence on the ionospheric profiles since the predicted density of the torus is extremely low.

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