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The Jovian Ionospheric E Region

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Abstract. We have constructed a model of the Jovian ionosphere that includes direct photoionization of hydrocarbon molecules. A high resolution solar spectrum was synthesized from Hinteregger's solar maximum spectrum (F79050N) and high resolution cross sections for photoabsorption by H_2 bands in the range 842 to 1116 Å were constructed. Two strong solar lines and about 30% of the continuum flux between 912 and 1116 Å penetrate below the methane homopause despite strong absorption by CH_4 and H_2 . We find that hydrocarbons (mainly C_2H_2) are ionized at a maximum rate of $55 \text{ cm}^{-3}\text{sec}^{-1}$ at 320 km above the ammonia cloud tops. The hydrocarbon ions produced are quickly converted to more complex hydrocarbon ions through reactions with CH_4 , C_2H_2 , C_2H_6 , and C_2H_4 . We find that a hydrocarbon ion layer is formed near 320 km that is about 50 km wide with a peak density in excess of $1 \times 10^4 \text{ cm}^{-3}$.

Introduction

Electron density profiles derived from the Pioneer 10 and 11 radio occultation data showed that the Jovian ionosphere is composed of a number of layers; the major one exhibits a density of about 10^5 cm^{-3} at an altitude of about 1800 km above the ammonia cloud tops (0.6 bar level). Up to seven secondary peaks are also present with maximum densities in the range $10^4 - 10^5 \text{ cm}^{-3}$ [Chen, 1981; Fjeldbo et al., 1975, 1976]. The radio occultation experiments aboard the Voyager spacecraft have so far yielded information about only the topside ionosphere [Eshleman et al., 1979a,b]. Ionospheric models have concentrated mainly on reproducing the densities and scale height of topside ionosphere and the main peak [Waite et al., 1983; McConnell et al., 1982]. Atreya et al. [1974] and Atreya and Donahue [1976] proposed that the lower layers may be composed of long-lived metallic ions, similar to those present in the terrestrial ionospheric E region, originating either from Io or from ablation of meteorites. Chen [1981] computed the heavy ion fluxes necessary to explain the observed densities and the wind speeds implied by the shapes of the layers, assuming that they are produced by wind shear.

Prasad and Tan [1974] constructed the first models of the hydrocarbon ion layers. They pointed out that CH_3 , with an ionization potential of 9.82 eV, would be ionized by solar Lyman alpha photons, which penetrate below the main ionospheric peak of H^+ or H_3^+ ions, although their assumed value for the cross section ($5 \times 10^{-17} \text{ cm}^2$) has been criticized as too large by Strobel [1975]. The

models of Atreya and Donahue [1975, 1976] neglected direct ionization of hydrocarbons other than CH_3 , including only reactions of He^+ , H^+ , and H_2^+ with CH_4 as sources of hydrocarbon ions. They estimated that photolysis of methane contributes less than 3% of the total electron density. Waite et al. [1983] neglected hydrocarbon ions in their model of the Jovian ionosphere, but Waite [1981] included photoionization of methane as well as CH_3 in his model of the ionosphere of Saturn. He found that CH_3^+ and $C_2H_5^+$ were the most important ions, with maximum densities of the order of 10^3 cm^{-3} in the lower ionosphere of Saturn. Atreya [1986] suggested that the terminal ions may be larger hydrocarbon ions that result from ion-molecule reactions, but he felt that insufficient data were available to construct a model. Capone et al. [1977] computed the density profiles of CH_3^+ and $C_2H_5^+$ produced by cosmic rays in the stratospheres of Saturn, Uranus and Neptune.

Recently, much new data has become available on reactions of hydrocarbon ions with neutral species and with electrons (dissociative recombination), often in connection with applications to models of the interstellar medium. Many of the ion-neutral reactions, including reactions of hydrocarbon ions with H , H_2 , and small hydrocarbons have been compiled by Anicich and Huntress [1986]. In previous models, dissociative recombination reactions of hydrocarbon ions such as $C_2H_5^+$ were considered to proceed with rather large rate coefficients of $2 - 4 \times 10^{-6} \text{ cm}^3\text{s}^{-1}$ at 300 K [Atreya and Donahue, 1976; Waite, 1981; Strobel and Atreya, 1983; Atreya, 1986]. These estimates were based partly on values measured in pulse radiolysis experiments in gases at relatively high pressure [e.g. Maier and Fessenden, 1975; Rebbert et al., 1973]. Because clustering occurs at these pressures, the rate coefficients obtained are often considerably larger than those measured by other methods and should be considered only as upper limits [Mitchell, 1990].

We have included photoionization of CH_4 , C_2H_2 , C_2H_4 , and C_2H_6 , in addition to photoionization of CH_3 , the only source included in previous Jovian ionospheric models. Solar photons in the 912-1100 Å range are absorbed by H_2 in discrete transitions, mostly in the Lyman and Werner band systems. Consequently, although the photons near the centers of the lines are absorbed above the CH_4 homopause (about 420 km), radiation in the far wings of the lines penetrates more deeply, causing direct ionization of hydrocarbon molecules down to about 300 km. We show here that these production rates are significant.

In addition, previous models assume diurnally averaged solar fluxes to account for the rapid rotation of the planet (period of 9.84 hours) and the long lifetime of H^+ , which, because it is destroyed finally by radiative recombination, has a lifetime of 600 hours (about 60 Jovian

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days) near 650 km. The hydrocarbon ions, by contrast, are destroyed ultimately by dissociative recombination, and the lifetime near 320 km is much shorter, about 15 minutes. The use of half the solar flux is not appropriate for these ions. We have therefore computed the steady state distribution of ions for half the solar flux to obtain the H^+ ion densities. We then carry out a time dependent calculation in which we compute the densities of the ions with the solar fluxes appropriate to the local time and latitude for a full Jovian day. The H^+ densities do not change perceptively during this time period and the hydrocarbon ions approach their daytime maximum values shortly after noon. We show here that a layer of hydrocarbon ions is produced with a total maximum density on the order of 10^4 cm^{-3} .

The Model

The density profiles of H_2 and He were taken from the model of Atreya et al. [1981], which is based on the Voyager ultraviolet stellar occultation measurements. The densities of CH_4 , C_2H_2 , and C_2H_6 were computed in the model, but the values at the lower boundary (200 km) were taken to be those determined in the mesospheric model of Gladstone [1982], which is consistent with data obtained from the Voyager UV stellar occultation experiment [Festou et al., 1981]. We assume that the electron and ion temperatures are in equilibrium with the neutral temperature below an altitude of 2500 km, as suggested by Waite et al. [1983].

A high resolution (0.001 Å) solar spectrum was synthesized from the F79050N solar maximum spectrum of Hinteregger [private communication; see also Torr et al., 1979] by assuming that all solar lines except Lyman β and γ are formed at a temperature of 10^8 K . For Lyman β we used the measured width and shape [Lemaire et al., 1978] and a similar profile for Lyman γ . High resolution cross sections for photoabsorption by H_2 bands in the range 842 to 1116 Å were constructed using a Voigt line shape. We include absorption in the Lyman and Werner bands and in the Rydberg band systems $B'^1\Sigma_g^+ \rightarrow X^1\Sigma_g^+$ and $B''^1\Sigma_g^+ \rightarrow X^1\Sigma_g^+$. Other higher Rydberg band systems lie in the spectral range where the H atom continuum absorption is dominant. The H_2 ground state population is assumed to be in a Boltzmann distribution of vibration-rotation levels characterized by the local neutral temperature. The oscillator strengths, transition probabilities, and dissociation probabilities were obtained from a compilation of J. H. Black [private communication; c.f. Black and van Dishoeck, 1987]. Electron impact ionization cross sections for H_2 were taken from Rapp et al. [1965]. Photoionization cross sections of H_2 , He, and H were adopted from Backx et al. [1976], Kirby et al. [1979], and Samson [1966], respectively. We have compiled photoionization and photoabsorption cross sections for methane, acetylene, ethylene, and ethane, including Samson et al. [1989] and Lee and Chiang [1983] for methane, Ibuki et al. [1989] for ethylene, and Hayashi et al. [1982] for acetylene. We have assumed that CH_3 is ionized by Lyman alpha photons with a cross section of $1.2 \times 10^{-17} \text{ cm}^2$ [Strobel, 1975].

The neutral hydrocarbon photochemistry was taken

mostly from the models of Strobel [1969, 1975] as updated by Yung and Strobel [1980], Waite [1981] and Gladstone [1982], although in our calculation the neutral and ion chemistry are coupled. The hydrocarbon densities near the methane homopause are affected by inclusion of ion chemistry because ion-molecule reactions convert some of the hydrocarbons (CH_4 , C_2H_2) to more complex hydrocarbon ions.

Ion-neutral reactions for hydrocarbon ions with one or two carbon atoms were taken from the compilation of Anicich and Huntress [1986]. Hydrocarbon ions generally react with methane and acetylene to yield larger hydrocarbon ions. The hydrocarbon ions thus formed then react to form even larger hydrocarbon ions. Ultimately these ions will be destroyed by dissociative recombination. We have individually included hydrocarbon ions with one or two carbon atoms. We have included all larger ions in the classes $C_3H_n^+$ and $C_4H_n^+$, and we have used an average dissociative recombination coefficient of $3.5 \times 10^{-7} (300/T)^{0.5} \text{ cm}^3 \text{ s}^{-1}$, based on the measurements of Adams and Smith [1988] for a mixture of $C_3H_5^+$ and $C_6H_5^+$. For hydrocarbon ions for which no measurements are available, we assume a dissociative recombination coefficient of $3 \times 10^{-7} (300/T)^{0.5} \text{ cm}^3 \text{ s}^{-1}$, which is similar to the values used currently in models of the interstellar medium [e.g. Millar et al., 1988; van Dishoeck and Black, 1986]. Products of dissociative recombination of hydrocarbon ions were deduced based on the considerations put forward by Bates [1986]. Equal branching ratios are assumed among dissociative channels. For H_3^+ recombination we have adopted a conservative value of $2 \times 10^{-8} \text{ cm}^3 \text{ s}^{-1}$ at 300 K as suggested recently by Hus et al. [1988].

In order to bring the H^+ densities in the topside ionosphere into agreement with the measurements, we have included loss of H^+ in the reaction with $H_2(v \geq 4)$ by assuming an effective reaction coefficient of $10^{-15} \text{ cm}^3 \text{ s}^{-1}$, which corresponds to a vibrational temperature of 1470 K with a rate of $2 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$. This value is close to that calculated by Cravens et al. [1987] for altitudes above 700 km [see also McConnell and Majeed, 1987].

We have first solved the steady state continuity equations for ions and neutrals, including chemical production and loss and transport by diffusion and eddy diffusion for neutral species and by ambipolar diffusion for ions. In the topside ionosphere, above 700 km, H^+ , H_2^+ , H_3^+ , He^+ , HeH^+ , and H were included. Below 700 km, the equations were solved for 32 species, including H^+ , H_2^+ , He^+ , H_3^+ , HeH^+ , CH_5^+ , CH_4^+ , CH_3^+ , CH_2^+ , CH^+ , C^+ , $C_2H_6^+$, $C_2H_5^+$, $C_2H_4^+$, $C_2H_3^+$, $C_2H_2^+$, C_2H^+ , C_2^+ , $C_3H_n^+$, $C_4H_n^+$, CH , 1CH_2 , 3CH_2 , CH_3 , CH_4 , C_2H , C_2H_2 , C_2H_3 , C_2H_4 , C_2H_5 , C_2H_6 , and H. The two regions were joined by matching the fluxes and densities of H^+ , H_2^+ , H_3^+ , He^+ , HeH^+ , and H at the boundary. A density dependent value of the eddy diffusion coefficient of $K_h = 1.4 \times 10^6 (10^{13}/M)^{1/2} \text{ cm}^2 \text{ sec}^{-1}$ was adopted, where M is the total number density [cf. Atreya, 1986; Waite et al., 1983]. A magnetic dip angle of 45° is used to represent the mid-latitude ionosphere. After obtaining the steady state densities of ions and neutrals, we solve the time dependent continuity equations with the steady state densities as initial conditions over a full Jo-

vian day. For the time integration we use a step size of 24.5 minutes.

Results

Two strong solar lines (C III at 977.02 Å and O VI at 1031.91 Å) and about 30% of the continuum flux between 912 and 1116 Å penetrate below the methane homopause despite strong absorption in the H₂ Lyman and Werner bands and by methane. Figure 1 shows altitude profiles of the production rates of the major hydrocarbon ions, with profiles of the direct production of He⁺, H⁺ and H₂⁺ shown also for comparison. We find that the maximum hydrocarbon ion production rate is about 55 cm⁻³sec⁻¹ at 320 km for a solar zenith angle of 22.5°, which is approximately the same as the maximum production rate of H₂⁺ ions in the F region. Direct production by photoionization of four ions, C₂H₂⁺, C₂H₄⁺, CH₄⁺, and C₂H₆⁺, is larger than the production of CH₃⁺ by Lyman alpha. We find that ionization of acetylene is the most important ionization process, but that conclusion depends on the ratio of C₂H₂ to CH₄ above 320 km, for which no measurements are available.

Fig. 1. Production rate profiles of ions in the Jovian ionosphere for solar maximum conditions. The solar zenith angle is 22.5°. Only the major hydrocarbon ions produced are shown and are labeled in order of increasing peak production rate. The curve labeled e-H₂ is the production rate of H₂⁺ ions by photoelectron impact ionization of H₂.

The resulting ion densities at local time of noon at 22.5° latitude are shown in Figure 2. The total density of hydrocarbon ions maximizes at 320 km with a value of about 1.1×10^4 cm⁻³. These densities are significantly greater than those computed by Prasad and Tan [1974] and Atreya and Donahue [1976]. Furthermore, Gladstone [1990, private communication] has recently pointed out that the density of propyne (CH₃C₂H) may be comparable or greater than that of ethylene at 300 km. If propyne has a similar density profile to that of ethylene around 320 km, production of CH₃C₂H⁺ would increase the peak electron density by about 15%. The lower ionospheric layers at mid-latitudes have been only observed by the Pioneer 10 ingress radio occultation and no observations

Fig. 2. Ion density profiles at a local time of noon for a latitude of 22.5° in the Jovian ionosphere for a magnetic dip angle of 45°. The thick line represents the total electron density.

for small solar zenith angles are available. It is, however, highly probable that part of L₆ or L₇ peak in the Pioneer 10 ingress profile is due to hydrocarbon ions. Similar hydrocarbon ion layers would be expected in the atmospheres of all the outer planets.

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References

- Adams, N. G. and D. Smith, Measurements of the dissociative recombination coefficients for several polyatomic ion species at 300 K, *Chem. Phys. Letters*, **144**, 11, 1988.
- Anicich, V. G. and W. T. Huntress Jr., A survey of bimolecular ion-molecule reactions for use in modelling the chemistry of planetary atmosphere, cometary comae, and interstellar clouds, *Ap. J. Suppl. Ser.*, **62**, 553, 1986.
- Atreya, S. K., *Atmospheres and Ionospheres of the Outer Planets and Their Satellites*, Springer-Verlag Berlin Heidelberg, pp. 124, 1986.
- Atreya, S. K., T. M. Donahue, and M. B. McElroy, Jupiter's ionosphere: prospects for Pioneer 10, *Science*, **184**, 154, 1974.
- Atreya, S. K. and T. M. Donahue, The role of hydrocarbon in the ionosphere of the outer planets, *Icarus*, **25**, 335, 1975.
- Atreya, S. K. and T. M. Donahue, Model Ionospheres of Jupiter, in *Jupiter*, ed. T. Gehrels, The University of Arizona Press, Tucson, Arizona, pp.304, 1976.
- Atreya, S. K., T. M. Donahue, and M. C. Festou, Jupiter: structure and composition of the upper atmosphere, *Ap. J. Lett.*, **247**, L43, 1981.
- Backx, C., G. R. Wight, and M. J. Van der Wiel, Oscillator strengths (10 - 70 eV) for absorption, ionization and dissociation in molecular hydrogen, molecular

- hydrogen-d₁ and molecular deuterium, obtained by an electron-ion coincidence method, *J. Phys. B.*, **9**, 315, 1976.
- Bates, D. R., Products of dissociative recombination of polyatomic ions, *Ap. J. Lett.*, **306**, L45, 1986.
- Capone, L. A. et al., The ionospheres of Saturn, Uranus, and Neptune, *Ap. J.*, **215**, 977, 1977.
- Chen, R. H., Studies of Jupiter's lower ionospheric layers, *J. Geophys. Res.*, **86**, 7792, 1981.
- Cravens, T. E., Vibrationally excited molecular hydrogen in the upper atmosphere of Jupiter, *J. Geophys. Res.*, **92**, 11083, 1987.
- Eshleman, V. L. et al., Radio science with Voyager 1 at Jupiter: Preliminary profiles of the atmosphere and ionosphere, *Science*, **204**, 976, 1979a.
- Eshleman, V. L. et al., Radio science with Voyager at Jupiter: Initial Voyager 2 results and a Voyager 1 measure of the Io torus, *Science*, **206**, 959, 1979b.
- Fjeldbo, G. et al., The Pioneer II radio occultation measurements of the Jovian ionosphere, in *Jupiter*, ed. T. Gehrels, The University of Arizona Press, Tucson, Arizona, pp.238, 1976.
- Fjeldbo, G. et al., The Pioneer 10 occultation measurements of the ionosphere of Jupiter, *Astr. and Ap.*, **39**, 91, 1975.
- Festou, M. F. et al., Composition and thermal profiles of the Jovian upper atmosphere determined by the Voyager ultraviolet stellar occultation experiment, *J. Geophys. Res.*, **86**, 5715, 1981.
- Gladstone, G. R., Radiative transfer and photochemistry in the upper atmosphere of Jupiter, *Ph.D. Thesis*, California Inst. Technol., 1982.
- Hayashi, T. et al., Photoionization mass spectrometric study of acetylene in VUV region, *J. Phys. B*, **15**, 79, 1982.
- Hus, H., F. Youssif, A. Sen, and J. B. A. Mitchel, Merged-Beam studies of the dissociative recombination of H₃⁺ ions with low internal energy, *Phys. Rev. A*, **38**, 658, 1988.
- Ibuki, T., G. Cooper, and C. E. Brion, Absolute dipole oscillator strengths for photoabsorption and the molecular and dissociative photoionization of ethylene, *Chem. Phys.*, **129**, 295, 1989.
- Kirby, K. et al., Photoionization and photoabsorption cross sections of He, O, N₂ and O₂ for aeronomic calculations, *At. Data Nuc. Data Table*, **23**, 63, 1979.
- Lee, L. C. and C. C. Chiang, Fluorescence yield from photodissociation of CH₄ at 1060-1420 Å, *J. Chem. Phys.*, **78**, 688, 1983.
- Lemaire, P. et al., Calibrated full disk solar H I Lyman-α and Lyman-β profiles, *Ap. J. Lett.*, **223**, L55, 1978.
- Maier, H. N. and R. W. Fessenden, Electron ion recombination rate constants for some compounds of moderate complexity, *J. Chem. Phys.*, **62**, 4790, 1975.
- McConnell, J. C. et al., A new look at the ionosphere of Jupiter in light of the UVS occultation results, *Planet. Space Sci.*, **30**, 151, 1982.
- McConnell, J. C. and T. Majeed, H₃⁺ in the Jovian ionosphere, *J. Geophys. Res.*, **92**, 8570, 1987.
- Millar, T. J. et al., The sensitivity of gas-phase models of dense interstellar clouds to changes in dissociative recombination branching ratios, *Astr. and Ap.*, **194**, 250, 1988.
- Mitchell, J. B. A., The Dissociative recombination of molecular ions, *Phys. Rev. A*, **186**, 216, 1990.
- Prasad, S. S. and A. Tan, The Jovian ionosphere, *Geophys. Res. Lett.*, **1**, 337, 1974.
- Rapp, D., P. Englander-Golden, and D. D. Briglia, Total cross sections for ionization and attachment in gases by electron impact. I. Positive ionization, *J. Chem. Phys.*, **42**, 4081, 1965.
- Rebbert, R. E., S. G. Lias, and P. Ausloos, Pulse radiolysis of methane, *J. Res. Nat. Bur. Stand.*, **77A**, 249, 1973.
- Samson, J. A. R. et al., Ionization yields, total absorption, and dissociative photoionization cross sections of CH₄ from 110-950 Å, *J. Chem. Phys.*, **90**, 6925, 1989.
- Samson, J. A. R., The measurement of the photoionization cross sections of the atomic gases, *Adv. in Atomic and Mol. Phys.*, **2**, 177, 1966.
- Strobel, D. F., The photochemistry of methane in the Jovian atmosphere, *J. Atmos. Sci.*, **26**, 906, 1969.
- Strobel, D. F., Aeronomy of the major planets, *Rev. Geophys. Space Phys.*, **13**, 372, 1975.
- Strobel, D. F., Discussion of paper by S. S. Prasad and A. Tan "The Jovian ionosphere", *Geophys. Res. Lett.*, **2**, 521, 1975.
- Strobel, D. F. and S. K. Atreya, Ionosphere, in *Physics of the Jovian Magnetosphere*, ed. Dessler, Cambridge Univ. Press, Cambridge, pp. 51, 1983.
- Torr, T. G. et al., Ionization frequencies for major thermosphere constituents as function of solar cycle 21, *Geophys. Res. Lett.*, **6**, 771, 1979.
- van Dishoeck, E. F. and J. H. Black, Comprehensive models of diffuse interstellar clouds: Physical conditions and molecular abundances, *Ap. J. Suppl. Ser.*, **62**, 109, 1986.
- Waite, J. H. Jr., The ionosphere of Saturn. *Ph.D. Thesis*, Univ. Michigan, 1981.
- Waite, J. H. Jr. et al., Electron precipitation and related aeronomy of the Jovian thermosphere and ionosphere, *J. Geophys. Res.*, **88**, 6143, 1983.
- Yung, Y. L., and D. F. Strobel, Hydrocarbon photochemistry and Lyman-alpha albedo of Jupiter, *Ap. J.*, **239**, 395, 1980.

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