

The Chemical Effects of Auroral Oxygen Precipitation at Jupiter

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Energetic oxygen precipitation is one possible explanation for the auroral molecular hydrogen emissions observed by the Voyager ultraviolet spectrometer. These ions deposit their energy in the Jovian thermosphere by means of ionization, dissociation, excitation, and heating processes. The photochemistry of both the neutral gas and the ionosphere is altered by the influx of atomic oxygen. The auroral oxygen flux is about $10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ if all the observed Lyman and Werner band emissions are due to heavy ion precipitation rather than to energetic electron precipitation. The O atoms react with H^+ ions forming O^+ ions, which then react with H_2 , starting a chain of chemical reactions involving H_2O^+ and H_3O^+ that ultimately leads to the formation of water. The O atoms can also react with CH_3 and will eventually form CO deeper in the atmosphere. A numerical model has been developed to study the effects of odd oxygen (i.e., O, OH, and H_2O) on the auroral ionosphere of Jupiter. In particular, we show that the electron density is reduced by about a factor of 4 due to the removal of H^+ ions by chemistry associated with odd oxygen species, whereas the electron density reduction required for consistency with observations is more than a factor of 20 suggesting that other H^+ loss mechanisms must be operating or that sources of oxygen or water other than auroral precipitation are present. The globally averaged flux of oxygen from the aurora is also about a factor of 20 too low to explain the Jovian CO measurements. © 1992 Academic Press, Inc.

1. INTRODUCTION

Intense molecular hydrogen Lyman and Werner band emissions were observed by the ultraviolet spectrometers on the Voyagers 1 and 2 spacecraft (Broadfoot *et al.* 1979, Sandel *et al.* 1979) and by the International Ultraviolet Explorer (IUE) satellite (Clarke *et al.* 1980, Yung *et al.*

1982) from the Jovian upper atmosphere at higher altitudes. These observed emissions are evidence that auroral particle precipitation occurs at Jupiter with a total power of more than 10^{13} W . The source of the precipitating particles is thought to be the Io plasma torus region of the Jovian magnetosphere; however, the identity of the precipitating particles remains undetermined, with suggestions of electrons, protons, and heavy (sulfur and oxygen) ions all having been made (cf. Horanyi *et al.* 1988, Waite *et al.* 1988).

Gehrels and Stone (1983) used observations of 1–20 MeV/nucleon of oxygen, sodium, and sulfur ions in the Jovian magnetosphere by the cosmic ray subsystems on Voyagers 1 and 2 to deduce that significant fluxes of these heavy ions must be precipitating into the Jovian atmosphere. However, the integrated power in the observed portion of the energetic particle spectrum only yields about 10^{12} W , which is a factor of 10 less than the power required to produce the observed UV emissions. Horanyi *et al.* (1988) (hereafter referred to as HCW) extrapolated the Gehrels and Stone (1983) energetic ion spectrum down to 40 keV/nucleon, in order to obtain the necessary power, and then constructed a numerical model to study the atmospheric energy deposition and aeronomical effects associated with the energetic heavy ion precipitation. HCW concluded that the aeronomical effects of heavy ion precipitation were not too different from those associated with energetic electron precipitation of comparable power (as calculated by Waite *et al.* 1983). The major difference is that oxygen and sulfur precipitation should result in the production of UV emissions from S and O species, but, as discussed by Waite *et al.* (1983), IUE observations do not seem to indicate the presence of such emission features. The X-ray observations made by the Einstein observatory (Metzger *et al.* 1983), however, fa-

vor the existence of ion precipitation rather than electron precipitation. Unfortunately, the evidence on the issue of the identity of the precipitating particle remains inconclusive. Waite *et al.* (1988) took the position that both electrons and ions are precipitating.

The energetic particles, whatever their species, deposit their energy in the Jovian thermosphere by means of ionization, dissociation, excitation, and heating processes. Model calculations of the ionosphere (see Waite and Cravens 1987, review) indicate that the extremely large auroral power input leads to model auroral ionospheres with peak electron densities of $>10^7 \text{ cm}^{-3}$ if standard chemistry is used in which the main loss process for H^+ is radiative recombination. The only available Voyager ionospheric profile relevant to the auroral region suggests a depleted topside ionosphere above 1000 km (cf. Atreya *et al.* 1987), indicating that some mechanism would be desirable for removing the major ion, H^+ . A popular suggestion has been the removal of ionospheric protons via reaction with vibrationally excited H_2 with $v \geq 4$ (cf. Cravens 1987); the vibrational excitation is needed because the $\text{H}^+ + \text{H}_2$ reaction is normally endothermic. Another suggestion made for Saturn's ionosphere was the removal of H^+ by reaction with H_2O from the rings (Connerney and Waite 1984). Similarly, the photochemistry of both the neutral gas and the ionosphere of Jupiter must be altered by the influx of atomic oxygen, as suggested by Strobel and Yung (1979).

We start with the premise in this paper that atomic oxygen associated with precipitation from the magnetosphere is entering the auroral atmosphere of Jupiter. We construct a numerical model of the ionosphere and thermosphere that includes the neutral odd oxygen constituents, O, OH, and H_2O , as well as the ionospheric species, H_2^+ , H_3^+ , H^+ , H_2O^+ , H_3O^+ , O^+ , and OH^+ . The neutral species are subject to molecular and eddy diffusion and the ion species are assumed to be in photochemical equilibrium. The background information for the model was taken from HCW and Waite *et al.* (1983).

The flux of oxygen (due to precipitation) into the auroral region is estimated in this paper to be approximately $10^7 \text{ cm}^{-2} \text{ sec}^{-1}$, if most of the auroral power is due to energetic ions and not to energetic electrons. Our calculations will show that the chemistry associated with this auroral oxygen flux can result in about a factor of 4 reduction in the electron density in the auroral ionosphere, although a factor of 20 or so reduction is really needed to bring the theoretical electron densities into line with the observations (cf. Waite and Cravens 1987). Other ionospheric loss mechanisms, such as the reaction of ionospheric protons with vibrationally excited molecular hydrogen, have also been suggested (cf. Waite and Cravens 1987), but an additional ionospheric source of oxygen or water (which can also act as a sink for ionospheric H^+ ions) would be desirable.

The observations of carbon monoxide in the atmosphere of Jupiter by Beer and Taylor (1978) also imply that oxygen, or molecules containing O, such as H_2O , enter the atmosphere of Jupiter and undergo chemistry that leads to the formation of CO. More recently, Noll *et al.* (1988) made high-resolution measurements of the CO 1–0 vibration–rotation band near $4.7 \mu\text{m}$ at Jupiter and concluded that tropospheric CO is more important than stratospheric CO, which suggests a source of CO from the Jovian interior. Nonetheless, the upper limit placed upon the stratospheric free oxygen flux by Noll *et al.* (1988) was a generous $3 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$. Strobel and Yung (1979) suggested oxygen atoms from the Galilean satellites and Prather *et al.* (1978) suggested water influx from meteoroidal impact. In either case, these authors indicated that a globally averaged flux of $\approx 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ is required to explain the Beer and Taylor (1978) observations. Unfortunately, the auroral oxygen input is only about $5 \times 10^5 \text{ cm}^{-2} \text{ sec}^{-1}$ when globally averaged and thus cannot by itself explain the CO observations if an internal source is not included. This issue is considered further in the Discussion section.

2. DESCRIPTION OF THE MODEL

The model is described in this section. Many parts of the model are the same as the ion precipitation model of HCW and the Jovian auroral model of Waite *et al.* (1983). In particular, the background neutral thermospheric model (i.e., atomic and molecular hydrogen density profiles and neutral temperature profile) is the same as in these papers. The aspects of the model new to this paper are emphasized in this section.

2.1. Chemical Species and Equations

Continuity equations were solved for the following species: H_2O , OH, O, H_2^+ , H_3^+ , H^+ , H_2O^+ , H_3O^+ , O^+ , and OH^+ . For some cases, the H^+ density was not solved for, but was adopted from HCW instead. The density of species s , as a function of altitude, is designated n_s , and the continuity equation for species s is

$$\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{u}_s) = P_s - L_s. \quad (1)$$

P_s and L_s are the production and loss rates, respectively, of species s . The production, P_s , can include both chemical production and primary production associated with either the aurora or absorption of solar radiation. The primary production rates are discussed in Section 2.2 and the chemical scheme is described in Section 2.3. The flux of species s is equal to $n_s \mathbf{u}_s$, where \mathbf{u}_s is the flow velocity of that species. Assuming transport only in the z -direction,

the divergence term in Eq. (1) becomes $\partial\phi_s/\partial z$, where ϕ_s is the vertical flux (in units of $\text{cm}^{-2} \text{sec}^{-1}$) of species s and z is the altitude above the cloudtops.

Transport was neglected for most species because their chemical time constants are much less than their transport time constants. However, transport was included for H_2O , H , and O with the vertical flux given by

$$\Phi_s = -D_s \left\{ \frac{\partial n_s}{\partial z} + \frac{n_s}{H_s} \right\} - K \left\{ \frac{\partial n_s}{\partial z} + \frac{n_s}{\bar{H}} \right\}. \quad (2)$$

D_s is the molecular diffusion coefficient for species s in an atmosphere of H_2 and H (cf. Waite *et al.* 1983, Waite 1981). The scale height of species s is $H_s = kT/m_s g$, where k is Boltzmann's constant, T is the neutral temperature, m_s is the mass of species s , and g is the acceleration due to the gravity of Jupiter. The average scale height of the atmosphere is designated \bar{H} ; this is essentially the H_2 scale height. The eddy diffusion coefficient was discussed by Waite *et al.* (1983) and is $K = 10^6 [10^{13}/M]^{1/2}$ in cgs units, where M is the total atmospheric number density (cm^{-3}).

Equations (1) and (2) together form a parabolic partial differential equation for the density n_s . We solved the coupled set of equations for all species numerically using an implicit method and ran the time-dependent solution out to long enough times so that steady-state conditions were reached. The lower and upper boundaries of the model were located at 300 and 820 km, respectively, although results will be shown only for the 350- to 750-km region. The grid size was 5 km. A fixed-density lower-boundary condition was adopted, although by an altitude of 350 km the effects of the lower boundary condition are not apparent. For most cases, diffusive equilibrium (i.e., zero flux) upper boundary conditions were assumed, although for a couple of cases a downflux of atomic oxygen of $10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ was adopted.

2.2. Primary Production Rates

The primary (i.e., not from chemical reactions) production rate profiles for H_2^+ and H^+ were taken from the energetic ion aurora model of HCW (Figs. 15 and 16 in that paper). The peak H_2^+ production rate is $3 \times 10^4 \text{ cm}^{-3} \text{ sec}^{-1}$ and takes place at an altitude of 440 km. The peak H^+ production rate is $10^4 \text{ cm}^{-3} \text{ sec}^{-1}$ for the "unconverged" case of HCW.

The energetic oxygen ions entering the atmosphere gradually lose energy and become neutrals, via charge exchange collisions (see HCW). Eventually, the oxygen atoms become "thermalized" and flow through the atmosphere as a minor neutral constituent, as described by Eq. (2), rather than as an energetic auroral species. This thermalization should take approximately where the au-

roras is depositing energy in the upper atmosphere. The energy deposition profile from the HCW model is shown in Fig. 1. Notice that there is also a total number density scale included in this figure, which indicates the correspondence between density and altitude in the model. The total flux of oxygen atoms entering the atmosphere in HCW is roughly $\phi_T \approx 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ in the auroral zone; the globally averaged flux is about a factor of 20–30 less than this value. For some cases, we input ϕ_T at the top of the model (i.e., at 820 km), but for other cases we obtain a primary oxygen production rate, $P_o(z)$, by assuming that ϕ_T is distributed according to the total energy deposition curve shown in Fig. 1. Note that the production rate of atomic oxygen $P_o(z)$ is normalized by the integral

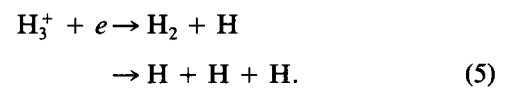
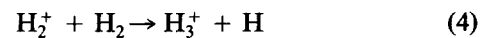
$$\int_{300 \text{ km}}^{820 \text{ km}} P_o(z) dz = \Phi_T. \quad (3)$$

We do not explicitly include the other sources of oxygen often mentioned for the outer planets, such as water flux from the rings or meteoritic impact, but if these sources have fluxes comparable to ϕ_T , as indeed they might (see the Discussion section), then our calculations would equally well apply to these scenarios.

2.3. Chemical Scheme

The basic ionospheric chemistry for Jupiter was discussed by HCW, Waite *et al.* (1983), and Waite and Cravens (1987). Like these earlier studies, we include the basic chemistry of H^+ , H_3^+ , and H_2^+ ; however, we do not include any hydrocarbon chemistry. We adopt profiles of H_2 and H from HCW. In this paper, we emphasize chemistry that is important for the odd oxygen (O , OH , H_2O) in the thermosphere. The chemical reactions used are listed in Table I. Only a few of these reactions are very important, as is discussed in this section.

The "standard" ionospheric chemistry in the absence of odd oxygen primarily involves the ions H^+ , H_2^+ , and H_3^+ (cf. Waite and Cravens 1987). Absorption of extreme ultraviolet radiation or auroral particle precipitation produce H_2^+ and H^+ ions with about 90 and 10% relative probabilities, respectively. The H_2^+ ions react very rapidly with the major atmospheric species H_2 to produce H_3^+ (reaction 24). The H_2^+ ions recombine dissociatively (reactions 33 and 34 in Table I). This is a relatively fast reaction.



On the other hand, H^+ only has inefficient loss mecha-

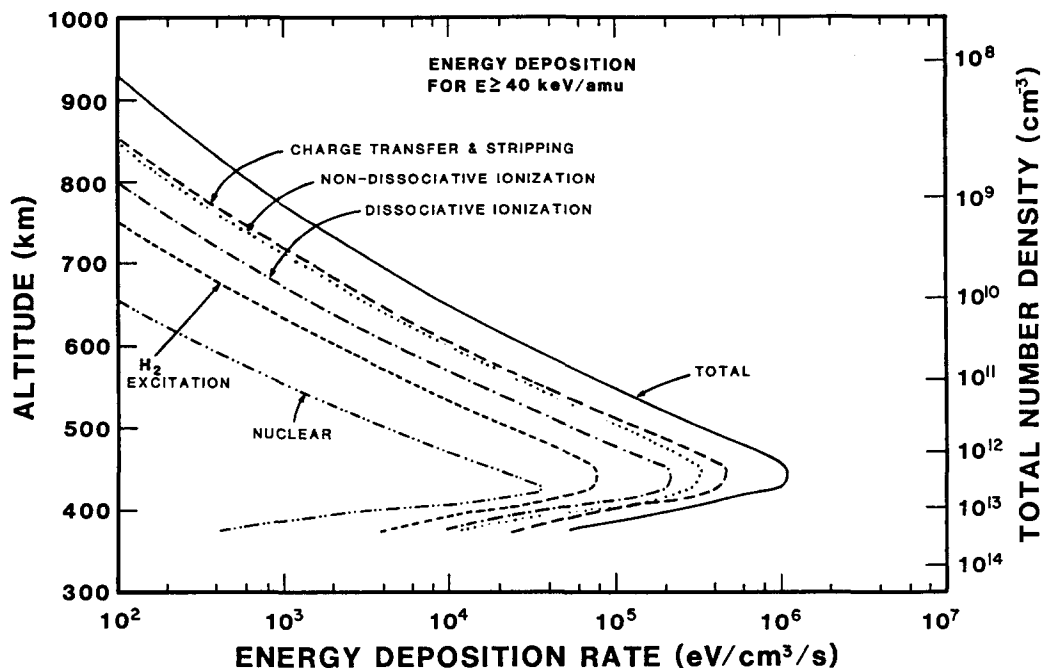
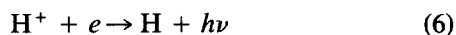


FIG. 1. Energy deposition rate in the Jovian thermosphere associated with heavy ion precipitation from the magnetosphere of Jupiter. The total Lyman and Werner band emission associated with this precipitation is 66 kR. Also shown is the total neutral number density (mostly H_2) as a function of altitude. Adapted from Horanyi *et al.* (1988).

nisms in the standard model, such as radiative recombination (reaction 2):



As a result of this inefficient loss process, H^+ is the major ion in the standard models and has a very large density. The models predict that for the ionospheric peak, $[H^+] \approx n_e \approx 10^6 \text{ cm}^{-3}$ at low latitudes, and $n_e \approx 10^7 \text{ cm}^{-3}$ in the auroral zone. However, measured densities are more than an order of magnitude less than the model densities in the auroral zone (cf. Waite and Cravens 1987). A number of ideas have been suggested for additional chemical loss processes for H^+ , which can thus lower the electron density.

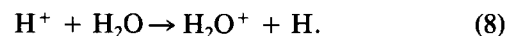
One possibility, suggested by McElroy (1973) and studied in more detail by Cravens (1987), is the loss of H^+ by reaction with vibrationally excited H_2 . This reaction is endothermic for ground-state H_2 but is exothermic if H_2 is vibrationally excited with vibrational quantum number $v \geq 4$ (reaction 35). The reaction rate is not known but is likely to be quite fast:



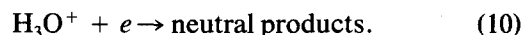
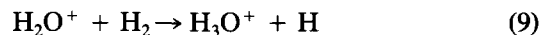
In this paper, we run the model both with and without

reaction (7). We use the $H_2(v \geq 4)$ concentrations calculated by Cravens (1987) for the 10 keV auroral case.

Odd oxygen chemistry can also remove H^+ ions. Connerney and Waite (1984) suggested that water can flow into the ionosphere of Saturn from the rings. H^+ ions react with H_2O via the fast ion-neutral reaction 8 in Table I:



H_2O^+ ions then quickly react with H_2 via reaction 13, producing H_3O^+ ions, which then recombine dissociatively:



The loss rate of H^+ depends then on the water concentration at ionospheric altitudes.

A somewhat different chemical scheme acts to remove H^+ ions from the ionosphere in the case in which atomic oxygen is precipitating, as summarized in Fig. 2. The accidentally resonant charge-exchange reaction 1 starts the chain:

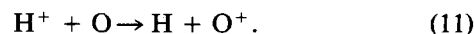
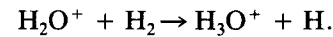
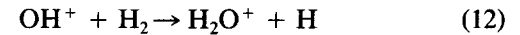
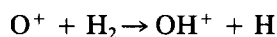


TABLE I
Chemical Reactions

Reaction	Rate coefficient (cm ³ sec ⁻¹)	Reference
(1) H ⁺ + O → O ⁺ + H	k ₁ = 7.0(-10)exp[-232/T]	I77
(2) O ⁺ + H → H ⁺ + O	k ₂ = k ₁	I77
(3) O ⁺ + H ₂ → OH ⁺ + H	k ₃ = 1.6(-09)	PH70
(4) O + OH → O ₂ + H	k ₄ = 3.0(-12)T ^{1/2}	BK73
(5) OH ⁺ + e → O + H	k ₅ = 2.0(-07)	PH80
(6) OH ⁺ + O → O ₂ ⁺ + H	k ₆ = 7.1(-10)	PH80
(7) OH ⁺ + H ₂ → H ₂ O ⁺ + H	k ₇ = 1.5(-09)	BK73
(8) H ⁺ + H ₂ O → H ₂ O ⁺ + H	k ₈ = 8.2(-09)	PH80
(9) H ₂ O ⁺ + O → O ₂ ⁺ + H ₂	k ₉ = 7.0(-11)	PH80
(10) H ₂ O ⁺ + H ₂ → H ₃ O ⁺ + H	k ₁₀ = 1.4(-09)	BK73
(11) OH + OH → O + H ₂ O	k ₁₁ = 5.(-12)T ^{1/2} exp[-1000/T]	BK73
(12) O ⁺ + OH → H ⁺ + O ₂	k ₁₂ = 2.7(-11)	GH78
(13) H ₂ O ⁺ + H ₂ O → H ₃ O ⁺ + OH	k ₁₃ = 4.9(-10)	BK73
(14) H ₂ O ⁺ + e → O + H ₂	k ₁₄ = 1.5(-07)[300/T] ^{1/2}	CW84
(15) → OH + H	k ₁₅ = 5.32(-07)[300/T] ^{1/2}	CW84
(16) H ₃ O ⁺ + e → H ₂ O + H	k ₁₆ = 2.33(-07)[300/T] ^{1/2}	CW84
(17) → OH + H ₂	k ₁₇ = 2.33(-07)[300/T] ^{1/2}	CW84
(18) → OH + H + H	k ₁₈ = 2.33(-07)[300/T] ^{1/2}	CW84
(19) OH + H ₂ → H ₂ O + H	k ₁₉ = 3.6(-11)	CW84
(20) H ⁺ + OH → OH ⁺ + H	k ₂₀ = 2.1(-09)	PH80
(21) H ⁺ + e → H + hv	k ₂₁ = 6.6(-12)[250/T] ^{1/2}	W83
(22) H ⁺ + H → H ₂ ⁺	k ₂₂ = 4.43(-19)	GH78
(23) H ₂ ⁺ + H → H ⁺ + H ₂	k ₂₃ = 1.0(-10)	PH80
(24) H ₂ ⁺ + H ₂ → H ₃ ⁺ + H	k ₂₄ = 2.1(-09)	PH80
(25) H ₂ ⁺ + O → OH ⁺ + H	k ₂₅ = 1.5(-09)	PH80
(26) H ₂ ⁺ + OH → H ₂ O ⁺ + H	k ₂₆ = 7.6(-10)	PH80
(27) → OH ⁺ + H ₂	k ₂₇ = 7.6(-10)	PH80
(28) H ₂ ⁺ + H ₂ O → H ₂ O ⁺ + H ₂	k ₂₈ = 3.87(-09)	GH78
(29) → H ₃ O ⁺ + H	k ₂₉ = 3.43(-09)	GH78
(30) H ₃ ⁺ + O → OH ⁺ + H ₂	k ₃₀ = 8.0(-10)	PH80
(31) H ₃ ⁺ + OH → H ₂ O ⁺ + H ₂	k ₃₁ = 1.3(-09)	PH80
(32) H ₃ ⁺ + H ₂ O → H ₃ O ⁺ + H ₂	k ₃₂ = 5.9(-09)	PH80
(33) H ₃ ⁺ + e → H ₂ + H	k ₃₃ = 1.0(-08)[200/T] ^{1/2}	HCW88
(34) → H + H + H	k ₃₄ = 1.0(-08)[200/T] ^{1/2}	HCW88
(35) H ⁺ + H ₂ (v>3) → H ₂ ⁺ + H	k ₃₅ = 1.0(-09)	C87

Note. The references are: I77, Iglesias (1977); PH80, Prasad and Huntress (1980); BK73, Banks and Kockarts (1973); GH78, Giguere and Huebner (1978); W83, Waite *et al.* (1983); HCW88, based on measurements by Michels and Hobbs (1984) and Hus *et al.* (1988), used by Horanyi *et al.* (1988); C87, Cravens (1987); CW84, cf. Connerney and Waite (1984).

The reverse reaction is not important due to the low O⁺ densities in the thermosphere, which is a consequence of the rapid reaction of O⁺ with the major neutral species in the Jovian atmosphere, H₂. A sequence of three rapid reactions (3, 7, and 10 in Table I) produces the terminal ion H₃O⁺.



The H₃O⁺ ion is lost via dissociative recombination (reactions 16–18 in Table I), producing H₂O in the process. Hence, the sequence of reactions given by Eqs. (11) and (12) and shown in Fig. 2 acts to convert atomic oxygen to water.

Photodissociation can reconvert H₂O to O, as can energetic electron impact dissociation. We did not include these dissociation processes in our model although they are indicated in Fig. 2; however, this omission should not affect our results for the ionosphere, as discussed in the next section.

2.4. Chemical and Transport Lifetimes

Let us consider some relevant chemical and transport time constants. The chemical lifetimes of O⁺, OH⁺, and H₂O⁺ are all very short near the region of peak energy deposition ($z \approx 400$ km): $\tau_c \approx 1/(kn_n) \approx 10^{-4}$ sec, where $k \approx 10^{-9}$ cm³ sec⁻¹ and $n_n \approx 10^{13}$ cm⁻³. The lifetime of the terminal ion, H₃O⁺, is $\tau_c \approx 1/(\alpha n_e) \approx 1$ sec near the ionospheric peak; this lifetime is much shorter than the H₃O⁺ transport time, although much larger than the other odd oxygen ion lifetimes. The total dissociative recombination coefficient is $\alpha = k_{16} + k_{17} + k_{18}$. The lifetime of H⁺ against reaction with O or H₂O depends on the densities of these neutrals and will be discussed later.

The chemical lifetime of O due to reaction with H⁺ is about 1000 sec near the ionospheric peak, but can be much longer at other altitudes where n_e is smaller. The H₂O

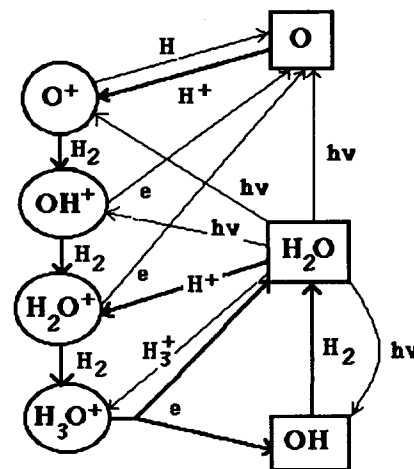


FIG. 2. Schematic of odd oxygen chemistry important for the Jovian ionosphere. Heavy lines show reaction paths that are especially important in the Jovian thermosphere. Basically, atomic oxygen is converted into water.

lifetime against photodissociation is approximately 2×10^6 sec. The vertical transport time for altitudes near 350–400 km is roughly $\tau_t \approx H^2/D \approx 3 \times 10^6$ sec, where $H \approx 30$ km and $D \approx 3 \times 10^6$ cm² sec⁻¹. Hence, near the bottom of our model region, the H₂O transport time is comparable to the chemical lifetime. However, in the ionospheric region most of the O that reformed is quickly converted back to H₂O; hence, most of the water will flow through the bottom of the model before it has a chance to dissociate. However, for altitudes below about 300 km, water will be more efficiently converted back to atomic oxygen, as discussed by Strobel and Yung (1979). Near the ionospheric peak, the H₂O lifetime against reaction with H⁺ is as low as 1000 sec, much less than the vertical transport time estimated above, but the H₂O⁺ and H₃O⁺ ions formed in this way are quickly reconverted to H₂O. Although our model does not include the photodissociation reconversion of H₂O to O, there is some minor reconversion due to the reaction of water with H⁺ (reaction 8 in Table I) followed by dissociative recombination of H₂O⁺ leading to O production. However, most H₂O⁺ ions react with H₂ rather than with electrons. There is also some (unimportant) conversion of OH to O via reaction 11 in Table I.

The lifetime against horizontal transport out of the auroral zone by thermospheric winds is difficult to estimate due to lack of knowledge of wind speeds. Guessing that the wind speeds are about the same as those in the Earth's auroral E-region (wind speed $u \approx 100$ m/sec; Killeen *et al.* 1986, Cravens and Killeen 1988) and for horizontal length scales of about 10⁴ km, then the time constant is $\tau_h \approx 10^5$ sec, which is less than the vertical transport time. Thus, horizontal transport could easily be affecting the behavior of auroral H₂O and O in the 350- to 400-km region. As recognized by Strobel and Yung (1979), any odd oxygen put into the atmosphere at auroral latitudes is distributed globally by the time it has diffused down to stratospheric and tropospheric regions. At altitudes higher than about 400–450 km (the ionospheric peak region), vertical transport should still be dominant; hence, our model should remain valid for determining the effects of odd oxygen on ionospheric processes.

3. RESULTS

3.1. Cases

Four cases were run with the model, as summarized in this section:

Case 1. A vertical flux of atomic oxygen is input at the top of the model ($z = 820$ km); $\Phi_T = 10^7$ cm⁻² sec⁻¹. The H⁺ density was held fixed at low values; the nonauroral (EUV or extreme ultraviolet radiation) profile of Waite *et al.* (1983) was adopted. The associated electron-density

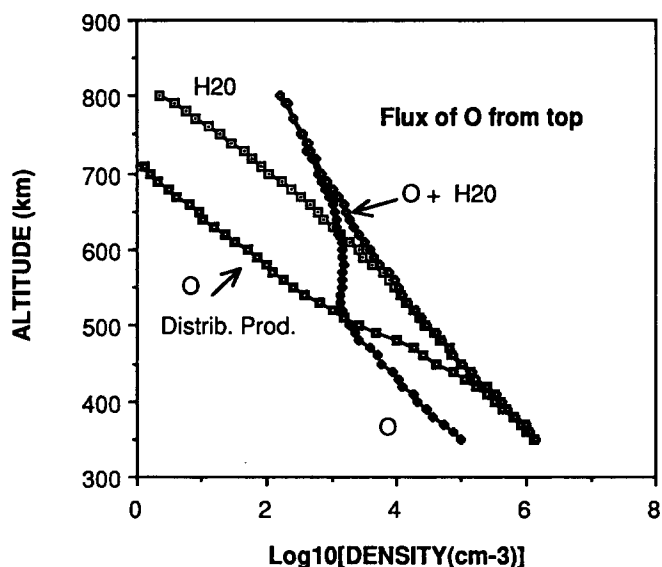


FIG. 3. Atomic oxygen and water density profiles for Case 1, in which a downward O flux of 10^7 cm⁻² sec⁻¹ at the top of the model is assumed. The total O plus H₂O density is also shown. The O density profile from Case 2 (distributed O production) is also shown. The H⁺ density profile is held fixed for Cases 1 and 2, as discussed in the text.

profile is also shown in Fig. 8 of this paper. Note that the H⁺ density is almost equal to the electron density. The results of this case are shown in Fig. 3.

Case 2. A distributed atomic oxygen-production rate is assumed, as discussed in Section 2. The total flux is $\Phi_T = 10^7$ cm⁻² sec⁻¹. The H⁺ is fixed as in Case 1. The results are shown in Fig. 4.

Case 3. A distributed atomic oxygen production rate is assumed, as discussed in Section 2, with a total flux of $\Phi_T = 10^7$ cm⁻² sec⁻¹. The H⁺ density is calculated self-consistently using the H⁺ production rates discussed in the text. The resulting H⁺ densities are much larger than those in Cases 1 and 2. The results are shown in Figs. 5, 6, 7, and 8.

Case 4. Some purely ionospheric runs were considered, without any odd oxygen. The effects of odd oxygen on the ionosphere are explored by comparing Cases 3 and 4 (in Fig. 8). The effects of the loss of H⁺ by reaction with vibrationally excited H₂ is also considered in this case.

3.2. Results for Cases 1 and 2

The density of atomic oxygen varies from about 10² cm⁻³ at an altitude of 800 km to 10⁵ cm⁻³ at 350 km for Case 1 (Fig. 3). The H₂O density is less than the O density above 630 km, but for altitudes between 350 and 630 km in the model, O is converted into H₂O via ion chemistry, and H₂O becomes the most important odd oxygen constit-

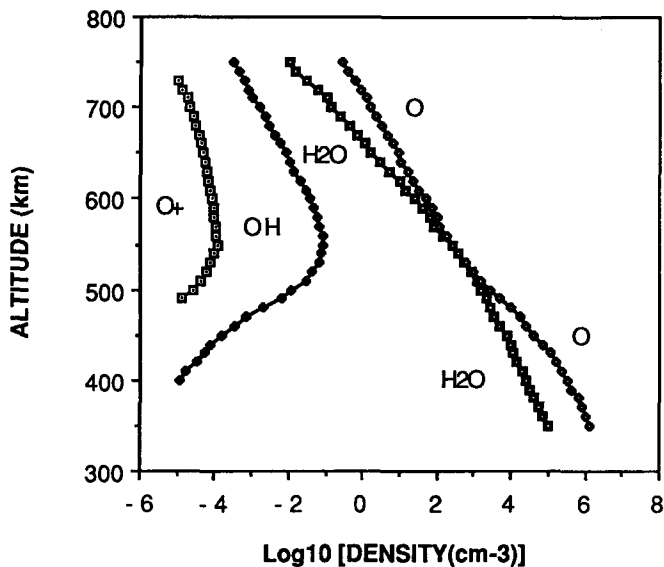


FIG. 4. Density profiles of O, OH, H₂O, and O⁺ for Case 2, in which a distributed atomic oxygen production rate profile is adopted. The H⁺ density is held fixed, as discussed in the text.

uent. The sum of the O and H₂O densities is also shown. The flux of total odd oxygen must equal the flux imposed at the top at all altitudes for Case 1, $\Phi_O + \Phi_{H_2O} = \Phi_T = 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$. The odd oxygen ion species do not make a significant contribution to the total flux.

Figure 4 shows the densities of some odd oxygen species versus altitude for Case 2 (distributed oxygen produc-

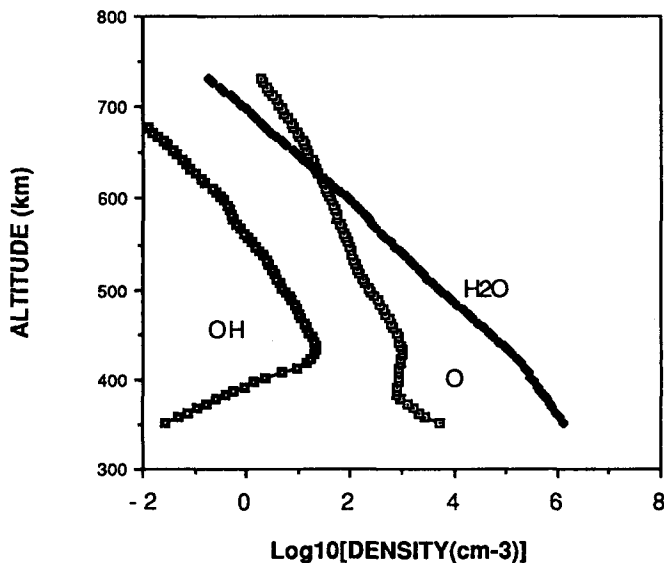


FIG. 5. Density profiles of O, OH, and H₂O for Case 3, in which a distributed atomic oxygen production rate profile is adopted. For this case, H⁺ participates in the chemistry, as described in the text.

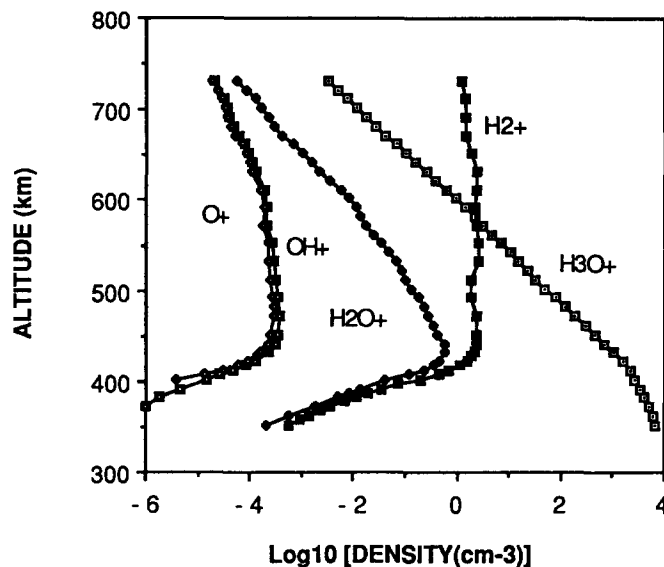


FIG. 6. Density profiles of odd oxygen ion species for Case 3.

tion). The O density for Case 2 is also shown in Fig. 3. The odd oxygen densities for Case 2 are less than for Case 1 at all altitudes, but especially at higher altitudes. For Case 2, the flux of odd oxygen, Φ_T , is not constant but varies as

$$\Phi_T(z) = \int_z^{820 \text{ km}} P_o(z) dz. \quad (13)$$

The H₂O and O densities are comparable near 500 km, but at lower altitudes the O density is greater than the

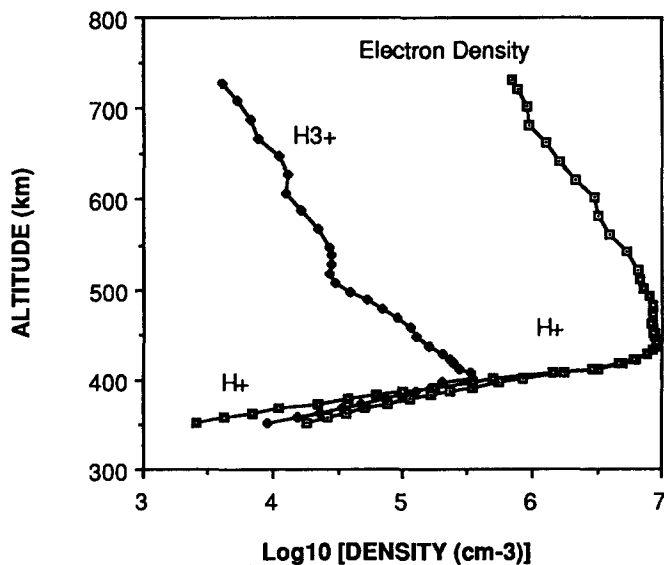


FIG. 7. Density profiles of H⁺, H₃⁺, and electrons for Case 3.

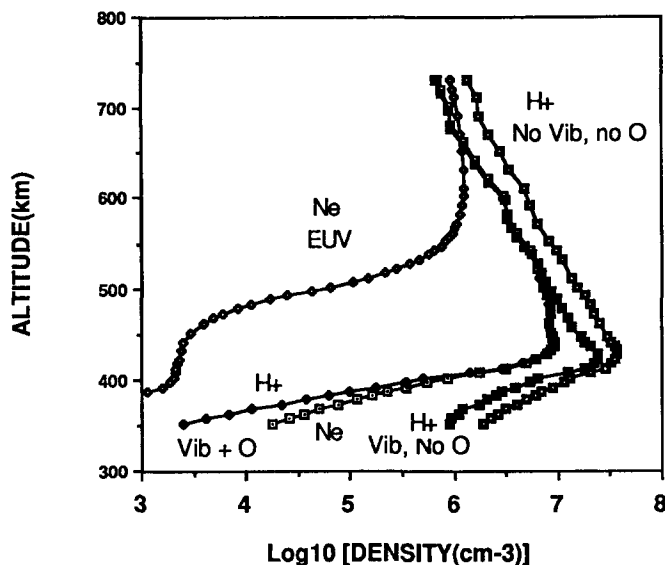


FIG. 8. Calculated electron density profiles for several cases, including Case 3 and Case 4 (ionospheric models without odd oxygen). The curve labeled "Ne EUV" is a nonauroral electron density profile from Waite *et al.* (1983). Note that the H^+ density is almost equal to the electron density. The curves labeled "Vib + O", plus "Ne" or " H^+ ", are the electron density and H^+ density profiles respectively, for Case 4 and include loss of H^+ via oxygen chemistry as well as by vibrationally excited H_2 . Two other curves are shown (called Case 4) and represent: (1) H^+ density profile from a calculation without vibrationally excited H_2 or oxygen chemistry (labeled "No vib, no O"), and (2) H^+ density profile from a calculation with vibrationally excited H_2 but without oxygen chemistry (labeled "Vib, no O").

H_2O density for Case 2, whereas the opposite is true for Case 1. The ion chemistry conversion of O to H_2O is effective only above 450–500 km for these low H^+ cases; thus, any O produced at lower altitudes (as in Case 2) is not converted to H_2O . H^+ also reacts with H_2O , but the ion chemistry tends to "recycle" H_2O rather than entirely remove it (see Fig. 2). Figure 4 also indicates that the density of OH is very low due to its rapid loss via reaction with H_2 .

3.3. Results for Case 3

The H^+ densities are solved for in this case and become very large due to the auroral production of H^+ (HCW). Not only are the H^+ densities larger, the peak density occurs at a lower altitude than in Cases 1 and 2. The "ionospheric" conversion of O to H_2O is very effective for this case, and H_2O , rather than O, is the major odd oxygen species below ≈ 625 km (Fig. 5). But like Case 2, the total flux of O plus H_2O is still equal to the flux given by Eq. (13).

The ion density profiles for Case 3 are shown in Figs. 6 and 7. The major odd oxygen ion is H_3O^+ , which is lost via dissociative recombination. The other odd oxygen ion

species react with H_2 and, as a consequence, have very low densities. Both the H^+ and H_3^+ densities are quite high. H_3^+ is produced by the reaction of H_2^+ with H_2 (essentially all the H_2^+ produced becomes H_3^+) and is lost via dissociative recombination. The H_3^+ density is roughly the same as that calculated by HCW. H^+ is lost via radiative recombination, by reaction with vibrationally excited H_2 , and by reaction with O and H_2O . The electron density is approximately equal to the density of the major ion, H^+ .

3.4. Case 4 and Ionospheric Comparison

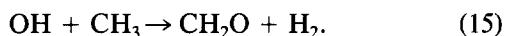
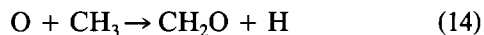
The electron density profiles are shown in Fig. 8 for Case 3 (odd oxygen included) as well as for some calculations without odd oxygen. Also shown is the electron density profile used for Cases 1 and 2; this profile was described by Waite *et al.* (1983) and included only ion production due to photoionization by solar extreme ultraviolet radiation. Three auroral electron density profiles are shown in Fig. 8. For the model case (case 4) with the highest electron densities, no odd oxygen loss and no vibrationally excited H_2 loss of H^+ were included. This ionospheric profile is almost the same as the profile calculated by HCW in the vicinity of the peak, although our profile and the HCW profile differ at higher altitudes because our model ionospheric model was strictly photochemical and the HCW model included ambipolar diffusion of H^+ . For the next highest electron density profile shown in Fig. 8, vibrationally excited H_2 was included as a loss process for H^+ but odd oxygen was not included (also designated Case 4). The electron density is reduced by a factor of 2 or so when vibrationally excited H_2 is included, and when odd oxygen loss processes are also included the peak electron density drops to about 10^7 cm^{-3} . The peak density is still quite large for this last case but the inclusion of odd oxygen clearly reduces the peak ionospheric density by a factor of ≈ 3 . Odd oxygen has a more dramatic effect on the bottom side of the electron density profile than on the peak, although it should be pointed out that the model ionosphere omitted hydrocarbon ions which start to become important on the bottom side (cf. Waite *et al.* 1983).

4. DISCUSSION

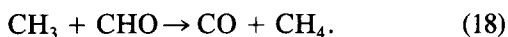
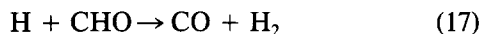
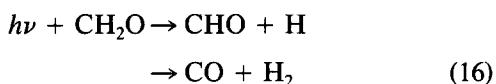
We presented in this paper a numerical model of the auroral ionosphere and thermosphere of Jupiter, which included odd oxygen species. The source of the oxygen atoms was assumed to be energetic heavy ions from the magnetosphere precipitating into the Jovian atmosphere, where they are thermalized. We calculated density profiles of the neutral species O, OH, and H_2O and the ion species H_2^+ , H_3^+ , H^+ , H_2O^+ , H_3O^+ , O^+ , and OH^+ . The total neutral odd oxygen density (i.e., O + OH + H_2O) was found to be $\approx 10^5$ cm^{-3} near the auroral ionosphere

peak. The major ionospheric ion, H^+ , reacts rapidly with both O and H_2O , and the presence of these species in the model calculations significantly reduced the H^+ density (and thus the electron density). The chemical lifetime against reaction of H^+ with odd oxygen is about 10^3 sec near the peak, whereas the radiative recombination lifetime is roughly 10^4 sec.

In addition to the ionospheric chemistry discussed above, odd oxygen species diffusing into the Jovian stratosphere undergo further chemical processing in which carbon monoxide is formed. Prather *et al.* (1978) suggested that an influx of water associated with meteoroidal material could supply odd oxygen to the atmosphere, and Strobel and Yung (1979) suggested that oxygen atoms from the Galilean satellites could supply the odd oxygen. The motivation for producing CO is the observations of this molecule by Beer and Taylor (1978). The chemical scheme suggested by Strobel and Yung (1979) starts with the reaction of either O or OH with the hydrocarbon species CH_3 ,



The CH_2O formed in this way is photodissociated, producing either CHO or CO. The CHO reacts with either H or CH_3 to produce CO;



This reaction scheme is displayed schematically in Fig. 9. In this figure, "ion" stands for the ionospheric chemical scheme shown in Fig. 2 that converts O either to H_2O or to OH. Our model did not include the photodissociation of H_2O back into O or OH because this occurs slowly enough so that it is not important above ≈ 300 –350 km; however, in general, this photodissociation reaction is very important. In the auroral zone, electron impact dissociation of H_2O could also be important. As discussed by Strobel and Yung (1979) and also in the Description of the Model section, the H_2O dissociation lifetime is long enough, and the vertical transport time below the thermosphere is also long enough, that odd oxygen should be globally distributed (rather than be concentrated just in the auroral region) by the time it has diffused down to the stratosphere. Strobel and Yung (1979) estimated that a globally averaged oxygen flux of $\approx 10^7$ $cm^{-2} sec^{-1}$ was required to explain the observed CO abundance at Jupiter. The auroral O flux estimated from HCW, and used in the current paper, was also $\approx 10^7$ $cm^{-2} sec^{-1}$; however,

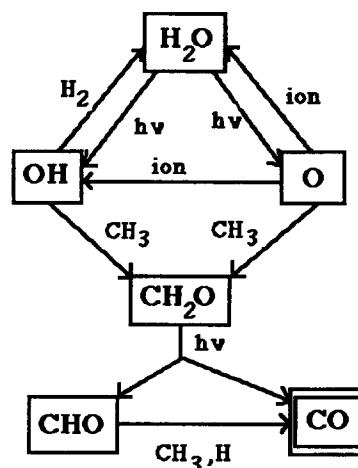


FIG. 9. Schematic of chemical scheme leading from O and H_2O to CO in the Jovian stratosphere. The lines designated with "ion" represent the set of ion-neutral (and dissociative recombination) reactions that lead to the production of H_2O or OH from O.

converting this to a globally averaged flux gives only about 5×10^5 $cm^{-2} sec^{-1}$. It seems that some nonauroral source of odd oxygen might also be required at Jupiter.

What effect would a globally averaged flux oxygen (or water) flux of 10^7 $cm^{-2} sec^{-1}$ have on the Jovian ionosphere? The auroral ionosphere for this scenario would look very much like the model results presented here in which the flux was also $\approx 10^7$ $cm^{-2} sec^{-1}$; whether the flux is 1 or 2×10^7 $cm^{-2} sec^{-1}$ will not make much difference. In order to sufficiently reduce the auroral electron density in the presence of heavy ion precipitation, either the non-auroral oxygen flux must be much greater than 10^7 $cm^{-2} sec^{-1}$ and/or the vibrationally excited H_2 loss mechanism must be more effective than we assumed in this paper. The effects of such an oxygen flux on the ionosphere at lower latitudes can also be estimated from the results presented in this paper. The oxygen and water density profiles in the thermosphere will roughly look like those shown in Fig. 3 (Case 1) if the oxygen is entirely input at the top of the atmosphere (as it would be for input from the Galilean satellites) and as shown in Fig. 4 (Case 2) if the oxygen is input in a distributed manner (as it would be for meteoroid impact). The ionospheric H^+ density profiles were fixed for Cases 1 and 2; the profile chosen was calculated by Waite *et al.* (1983) without auroral input (that is, only photoionization by solar EUV photons) and is thus appropriate for lower latitudes. Hence, the thermospheric oxygen and water profiles calculated for these two cases should also be appropriate for lower latitudes and for a globally averaged oxygen flux of about 10^7 $cm^{-2} sec^{-1}$, as well as for the auroral ionosphere where some unspecified mechanism keeps the H^+ density low.

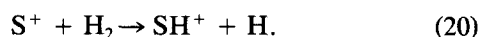
This paper considered the effects of oxygen that was

introduced into the Jovian atmosphere by auroral precipitation, but Gehrels and Stone (1983) showed that about as much energetic sulfur should be precipitating into the atmosphere as there is energetic oxygen. We will briefly discuss the chemical effects of sulfur on the ionosphere using the chemistry reviewed in the book by Duley and Williams (1984).

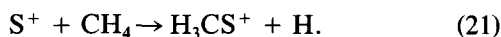
Does a system of chemical reactions analogous to that shown schematically in Fig. 2 for oxygen also exist for sulfur? That is, can sulfur chemistry act to reduce the H^+ or electron density in the Jovian ionosphere? The answer is that some H^+ ions can be chemically removed but the electron density will not be reduced significantly. The first step in the chain of reactions does work; the following charge transfer reaction is fast:



The next step, according to Fig. 2, is for the S^+ ions to react with H_2 :



However, this reaction is endothermic by 1 eV and will not proceed. Unfortunately, this stops the whole sequence of reactions and S^+ must be removed in some other way. Near the ionospheric peak and above, radiative recombination will work but is very slow and the substitution of a S^+ ion for an H^+ ion will not reduce the electron density. Below the homopause, where methane is present, the following rather fast reaction (a rate coefficient of $1.4 \times 10^{-10} \text{ cm}^3 \text{ sec}^{-1}$ (cf. Duley and Williams 1984)) will remove S^+ :



The H_3CS^+ ions can then rapidly dissociatively recombine, producing H_2CS or CS . This reaction does not help to reduce the peak electron density because the peak is located above the homopause.

Another possibility is that reaction (20) might proceed at a fast rate (i.e., $k \approx 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$) if the H_2 molecule were vibrationally excited enough to overcome the endothermicity of 1 eV, which would require a vibrational quantum number $v \geq 2$:



Reaction (22) is analogous to reaction (7) for H^+ . The SH^+ ions from reaction (22) could then recombine dissociatively with electrons which thus reduces the electron density and also produces neutral S and H. The neutral S could then start the chain of reactions over again with reaction (19). Hence, the role of sulfur chemistry in the

Jovian ionosphere is uncertain and depends on reaction (22).

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