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Densities and Vibrational Distribution of H$_2^+$ in the Jovian Auroral Ionosphere

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Observations of the H$_2^+$ infrared emission at 2 and 4 $\mu$m have suggested that H$_2^+$ is in local thermodynamic equilibrium (LTE) in the region of the Jovian ionosphere from which the emissions originate. We have tested this assumption by calculating the vibrational distribution of H$_2^+$ over the altitude range of 350 to 1500 km above the methane cloud tops (1 to 4 $\times$ 10$^{-3}$ bar). We have constructed a model of the Jovian auroral ionosphere in which the neutral temperatures are enhanced over those of the mid-latitude ionosphere, as suggested by observations and models of the auroral region. We have modeled the precipitation of 10-keV electrons with an energy flux of 1 erg cm$^{-2}$ s$^{-1}$. Both the energy and energy flux are less than those that are implicated in the production of the UV aurora. We have computed the densities and vibrational distribution of H$_2^+$ and find that the distribution of the six lowest states of H$_2^+$ can be determined fairly well in spite of uncertainties in the atomic and molecular data. Since the nearly resonant transfer of vibration from H$_2$(v=1) is an important process in populating the H$_2^+$ (v$_1$=0,v$_2$=2) state, it is necessary to model the vibrational distribution of H$_2$ as well. The computed altitude profiles and vibrational distributions of H$_2^+$ and H$_2$ are consistent with the observations of infrared emission in the 2- and 4-$\mu$m regions. The H$_2^+$ is not in LTE near and above the H$_2^+$ peak, since loss of the H$_2^+$ (v$_1$=0,v$_2$=1) and H$_2^+$ (v$_1$=0,v$_2$=2) states by radiation is approximately equal to the collisional loss rate.

INTRODUCTION

H$_2^+$ was detected spectroscopically for the first time in a celestial object in the Jovian southern auroral zone by Drossart et al. [1989]. They recorded high-resolution spectra of several infrared emission lines of the H$_2^+$ overtone transition, 2$\nu_2$($l=2$) $\rightarrow$ 0 near 2 $\mu$m. Trajfan et al. [1989] detected the lines but did not identify them. Drossart et al. derived a column density of H$_2^+$ (v$_2$=2,l=2) of (1.39 $\pm$ 0.13) $\times$ 10$^4$ cm$^{-2}$ and a rotational temperature of (1100 $\pm$ 100) K from the data. They suggested that although the emission appears to arise from altitudes above that of the UV aurora, electrons in the low-energy tail of the distribution could be responsible for production of H$_2^+$ above the ionospheric maximum. They also suggested that the v$_2$=2 vibrational levels could be produced either by resonant vibrational exchange with H$_2$(v=1) or by collisional excitation. More recently, Oka and Geballe [1990] identified the 4-$\mu$m fundamental band of H$_2^+$ in the Jovian polar region, and they estimated column densities of H$_2^+$ (v$_2$ = 1) ranging from 7 to 70 times the column density of v$_2$ = 2 reported by Drossart et al. [1989], and a lower rotational temperature of (670 $\pm$ 100) K. They failed to detect either the v$_2$ = 2 $\rightarrow$ 0 overtone transition or the v$_3$ = 2 $\rightarrow$ 1 hot band and concluded that the observed emissions did not arise from H$_2^+$ (v$_2$) produced directly in the reaction

$$H^+ + H_2 \rightarrow H_2^+ (v_2) + H,$$

but from the collisional excitation of H$_2^+$ (v$_2$=0) by H$_2$ or He. Miller et al. [1990] observed lines in the H$_2^+$ v$_2$ fundamental and overtone bands. From the ratios of the intensities, they derived a vibrational temperature of (1100 $\pm$ 100) K. They concluded that the agreement of this value with the rotational temperature measured by Drossart et al. [1989] implied that the vibrational distribution was in LTE.

H$_2^+$ has been known to be a major ion in the ionospheres of the outer planets, but the density profile has been uncertain because modelers have encountered difficulties reproducing the electron densities measured by the radio occultation experiments aboard the Voyager spacecraft [Waite et al., 1983; Cravens, 1987; McConnell et al., 1982; McConnell and Ma-Jeed, 1987]. Details can be found in the excellent review of measurements and models of the ionospheres of the outer planets by Atreya [1986]. The measured profiles showed electron densities about an order of magnitude smaller with a peak several hundred kilometers higher than those of models based on the chemistry of ground state species. In the models, H$^+$ was found to be the major ion over most of the ionosphere. McElroy [1973] had suggested that if sufficient quantities of H$_2$(v $\geq$ 4) were present, the H$^+$ densities could be reduced by the reaction

$$H^+ + H_2 (v \geq 4) \rightarrow H_2^+ + H,$$

which is endothermic for H$_2$ in the first four vibrational levels. The resulting H$_2^+$ ions would be rapidly converted to H$_2$ and then lost by dissociative recombination. McConnell et al. [1982] pointed out that in addition to including (2), imposing vertical flow along field lines could raise the height of the peak. Waite et al. [1983] constructed a detailed model of the ionosphere of Jupiter and found that the electron den-
ity profile could be brought into reasonable accord with the Voyager measurements if an H₂ vibrational temperature of 2500–4000 K, much higher than the neutral kinetic temperature, was assumed. Cravens [1987] modeled the H₂ vibrational distribution in the auroral and mid-latitude regions and showed that charge transfer from H⁺ to vibrationally excited H₂ (reaction (2)) is an important chemical sink for H⁺ in both the mid-latitude and auroral ionospheres. Moreover, the electron density profile for precipitation of 10-keV electrons with an energy flux of 10 erg cm⁻² s⁻¹ agreed fairly well with the Voyager 2 entry profile [Eshleman et al., 1979] when the H₂ densities were reduced to 10% of the auroral values calculated by Waite et al. [1983].

Although the models of Waite et al. [1983] and Cravens [1987] included detailed ionospheric chemistry of H⁺, H₂⁺, and H₂*, individual density profiles of the ions were not presented. Cravens did state, however, that for the auroral cases, the H₂⁺ density was almost as large as the H⁺ density. McConnell and Majeed [1987] studied the effects of enhanced vibrational temperatures of H₂ on the density profiles of H₂⁺ and H⁺ in the Jovian ionosphere, and they investigated the effect of different assumptions about the dissociative recombination (DR) coefficient for H₂⁺. The value of this rate coefficient has been a matter of some controversy over the last several years. In 1984, Adamsa et al. [1984] measured the DR coefficient of H₂⁺ in the vibrational ground state and found it to be "immeasurably small" (< 2 × 10⁻⁸ cm³ s⁻¹) at 95 and 300 K, in contrast to previous measurements, which were in the range (2–3) × 10⁻⁷ cm³ s⁻¹ [e.g., MacDonald et al., 1984]. Theoretical and experimental evidence suggested that higher vibrational levels recombined more rapidly [Michels and Hobbs, 1984], and the higher rates could be ascribed to the presence of vibrationally excited H₂⁺. McConnell and Majeed [1987] carried out a calculation in which two states of H₂⁺ were considered: the ground vibrational state and a pseudostate that represented all vibrationally excited states, which they referred to as H₂⁺*. They found that most of the vibrationally excited ions radiated to the ground state before recombining. They presented profiles of the ion densities for values of the DR coefficient for ground state H₂⁺ that were 0.1, 0.01, and 0.001 times the standard values (2 × 10⁻⁷ cm³ s⁻¹), which they assumed to be appropriate to vibrationally excited states. For values of the DR coefficient for ground state ions that were one thousandth of the excited state coefficient, H₂⁺* was the dominant ion over most of the ionosphere. They also reported that both enhanced loss of H⁺ by charge transfer to vibrationally excited H₂⁺ and vertical ion flows were necessary to reproduce the measured ion peaks.

After the manuscript of McConnell and Majeed [1987] was prepared, Adams and Smith [1987] lowered their upper limit on the DR coefficient for ground state H₂⁺ to 1 × 10⁻¹¹ cm³ s⁻¹, a factor of 10⁴ less than the standard values. Hus et al. [1988] measured the cross sections for DR of ground state H₂⁺ in a merged beam and inferred a value for the rate coefficient of 2 × 10⁻⁸ cm³ s⁻¹ at 100 K. Recently, however, Amano [1988, 1990], by measuring the decay of infrared absorption, reported a larger rate coefficient of 1.8 × 10⁻⁷ cm³ s⁻¹ for recombination from the J = 3, K = 3 rotational state of the ground vibrational level. The controversy has not been clearly resolved, and the possibility that ground state and vibrationally excited H₂⁺ recombine at radically different rates cannot yet be discounted.

Thus the vibrational distribution of H₂⁺ is of interest for a number of reasons, including its emissions and possible effects on the chemistry. We have carried out a detailed calculation of the vibrational distribution of H₂⁺ in the Jovian auroral ionosphere. We compare our computed distribution to the measured infrared emission rates. We then evaluate the effect of the distribution on the chemistry and structure of the ionosphere. In the rest of the discussion, altitude refers to height above the methane cloud tops, which is approximately the 0.6-bar level [cf. Atreya et al., 1981].

The Model

Measurements and models have shown that temperatures in the auroral thermosphere are probably higher than those of the mid-latitude thermosphere. Drossart et al. [1989] reported a rotational temperature of 1099 ± 100 K for the first overtone transition of H₂⁺; slightly smaller rotational temperatures of 670 ± 100 K were obtained by Oka and Geballe [1990]. If these temperatures apply to the region of the H₂⁺ maximum, near 700 km (just below the 0.1-µbar level) [cf. McConnell and Majeed, 1987], then the auroral temperature is significantly higher than the mid-latitude value of 200–250 K at the 0.1-µbar level given by the Voyager stellar occultation data [Atreya et al., 1981]. Higher temperatures in the auroral zone were also predicted by Waite et al. [1983], who computed a significant heat input due to precipitating electrons. S. J. Kim et al. [1990] measured emission in the H₂ quadrupole lines in the auroral region, which also originate near 0.1 µbar; the rotational temperature derived was 730 (+500, -200) K. The Voyager 2 entry radio occultation experiment indicated an ion temperature of 1600 K in the topside ionosphere [Eshleman et al., 1979]. We have constructed a model of the auroral thermosphere-ionosphere of Jupiter in which the temperatures and densities near the homopause are similar to the mid-latitude models, but the temperatures in the 1-µbar region and above increase to values that are consistent with the measured rotational temperatures. Our assumed temperature profile is shown in Figure 1 along with the density profiles of H₂, He, and H atoms that were constructed self-consistently with the temperature profile. The density at a given altitude is larger than that inferred from the Voyager stellar occultation experiment in the nonauroral thermosphere [Atreya et al., 1981]. The atomic hydrogen densities are greatly affected by electron precipitation [Waite et al., 1983], and the H profile shown was obtained self-consistently in the calculation described below.

To account for (2) in our ionospheric model, we found that it was necessary to calculate the vibrational distribution of H₂ and the densities of the ions and H atoms together. The sources of vibrationally excited H₂ in the Jovian upper atmosphere have been discussed by Cravens [1987] and include direct excitation by electron impact, cascade from electronically excited states (mainly the B⁺Σ_u⁺ and C⁺Π_g states) due to electron impact excitation, solar UV fluorescence of H₂, dissociative recombination of H₂⁺, and three-body recombination of H atoms. We essentially adopt the model of Cravens [1987] for all processes except solar UV fluorescence, which he did not include [cf. Majeed et al., 1990]. Vibrational excitation of H₂ due to solar UV fluorescence in the Lyman and Werner band system is calculated using the solar maximum flux of Hinteregger [see Torr et al., 1979] and the transition probabilities of Allison and Da-
The inclusion of fluorescence of solar UV radiation does not significantly affect \( \text{H}_2 \) vibrational distribution at low altitudes, but it becomes dominant at altitudes above 2500 km. Additional modifications to the model of Cravens [1987] include the adoption of the DR rate coefficient of \( 2 \times 10^{-9}(100/T)^{0.4} \) cm\(^3\) s\(^{-1}\) for \( \text{H}_2 \) with a branching ratio of 1:3 between products, \( \text{H}_2 + \text{H} \) and \( \text{H} + \text{H} + \text{H} \) as measured by Mitchell et al. [1983], and the distribution of \( \text{H}_2(v) \) in the three-body recombination of \( \text{H} \) atoms as calculated by Orel [1987].

We have included \( \text{H}_2(v=0) \), \( \text{H}_2(v=1) \), \( \text{H}_2(v=2) \), and \( \text{H}_2(v=3) \) separately, and we treat \( \text{H}_2(v\geq 4) \) as a pseudostate that represents all vibrational states higher than \( v=3 \). The production rate of \( \text{H}_2(v\geq 4) \) is thus simply the sum of production rates of individual states from the channels listed above plus collisional excitations from \( \text{H}_2(v=3) \) to \( \text{H}_2(v=4) \). The net loss of \( \text{H}_2(v\geq 4) \) includes collisional and radiative de-excitation from \( \text{H}_2(v=4) \) to \( \text{H}_2(v=3) \). In addition, \( \text{H}_2(v\geq 4) \) can be removed by the reaction with \( \text{H}^+ \) as assumed in previous Jovian ionospheric models [McConnell et al., 1983; Waite et al., 1983; Cravens, 1987; McConnell and Majeed, 1987].

The rate coefficient, \( k_3 \), has not been measured but is assumed to be \( 10^{-9} \) cm\(^3\) s\(^{-1}\) which is close to the gas kinetic value. The collisional processes include vibration-vibration (VV) energy transfer reactions between \( \text{H}_2(v) \) and \( \text{H}_2(v') \), and vibration-translation (VT) energy transfer reaction \( \text{H}(v) \) and \( \text{H}^+ \) and between \( \text{H}(v) \) and \( \text{H} \). The rate constants for these reactions are also adopted from expressions given by Cravens [1987]. The deexcitation of \( \text{H}(v) \) via quadrupole radiative transitions is ignored since the transition probabilities are small, of the order of \( 10^{-6} \) s\(^{-1}\). Diffusive equilibrium is assumed for the top boundary at 3700 km; photochemical equilibrium is assumed for the lower boundary at 200 km.

We have used a multistream electron transport code for the auroral electron precipitation. The code, which was developed by Porter et al. [1987], utilizes the full angular dependence of the differential elastic scattering cross section to track electron energy deposition. Twenty-one angular bins were used in our calculation along with 50 altitude bins and 200 energy bins. Both elastic and inelastic cross sections are needed for major constituents of Jovian thermosphere, \( \text{H}_2 \), \( \text{He} \), and \( \text{H} \). The sources of these cross sections are listed in Table 1. We consider here the precipitation of 10-keV electrons with an energy flux of 1 erg cm\(^{-2}\) s\(^{-1}\). The energy flux is less than the flux estimated from the observed UV auroral emissions [Broadfoot et al., 1981; Sandel et al., 1979], and 10 keV is less than the energy required to produce the UV aurora [Livengood et al., 1990; Gladstone and Skinner, 1989; Yung et al., 1982]. Our goal here is to show that the \( \text{H}_2 \) and \( \text{H}_2 \) infrared emissions could be produced by the lower energy part of the precipitating electron distribution. The downward pitch angle distribution is assumed to be isotropic, and the electrons are injected at an altitude of 3700 km. Figure 2 shows the production rates of \( \text{H}_2 \) and \( \text{H}^+ \) (from \( \text{H}_2 \)) and \( \text{H} + \text{H}^+ \) (from \( \text{H} \)) that are obtained from an iterative calculation in which the electron and \( \text{H} \) atom densities, which are produced mainly by electron precipitation, are computed self-consistently. In Figure 3 we present altitude profiles of the major sources of \( \text{H}_2(v=1) \) and \( \text{H}_2(v\geq 4) \),

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**TABLE 1. Electron Impact Cross Sections**

<table>
<thead>
<tr>
<th>Species</th>
<th>Processes</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2 )</td>
<td>ionization</td>
<td>Rapp and Engleuder-Golden [1965]</td>
</tr>
<tr>
<td>( \text{B}^1\Sigma_u^+, \text{B}'^1\Sigma_u^+, \text{B}''^1\Sigma_u^+ )</td>
<td></td>
<td>Shemansky et al. [1985], Ajello et al. [1988]</td>
</tr>
<tr>
<td>( \text{C}^1\Pi_u, \text{D}^1\Pi_u, \text{D}'^1\Pi_u )</td>
<td></td>
<td>Shemansky et al. [1985], Ajello et al. [1988]</td>
</tr>
<tr>
<td>( \text{E}^3\Sigma_g^+, \text{c}^4\Pi_u, \text{a}^3\Sigma_g^+ )</td>
<td></td>
<td>Shemansky et al. [1985], Ajello et al. [1988]</td>
</tr>
<tr>
<td>( \text{b}^3\Sigma_u^+, \text{3p}^2\Pi_u )</td>
<td></td>
<td>Khakoo and Trajmar [1986]</td>
</tr>
<tr>
<td>( \text{H}(2p), \text{H}(2s) )</td>
<td></td>
<td>Lima et al. [1985]</td>
</tr>
<tr>
<td>Balmer-( \alpha, \beta, \gamma )</td>
<td></td>
<td>Möhlmann and De Heer [1976]</td>
</tr>
<tr>
<td>( v = 0 \rightarrow 1, 2, 3, 4, 5, 6 )</td>
<td></td>
<td>Möhlmann et al. [1978], Freund et al. [1976]</td>
</tr>
<tr>
<td>elastic</td>
<td></td>
<td>Allan [1985], Ehrhardt et al. [1968], Linder and Schmidt [1971], Fink et al. [1975], Syny and Sharp [1981], Srivastava et al. [1975], van Wingerden et al. [1977]</td>
</tr>
<tr>
<td>( \text{He} )</td>
<td>ionization</td>
<td>Jacckman et al. [1977]</td>
</tr>
<tr>
<td>excitation</td>
<td></td>
<td>Jacckman et al. [1977]</td>
</tr>
<tr>
<td>elastic</td>
<td></td>
<td>Porter et al. [1987]</td>
</tr>
<tr>
<td>( \text{H} )</td>
<td>ionization</td>
<td>De Heer et al. [1977, and references therein]</td>
</tr>
<tr>
<td>excitation</td>
<td></td>
<td>Callaway and McDowell [1983]</td>
</tr>
<tr>
<td>elastic</td>
<td></td>
<td>Williams [1975a, b]</td>
</tr>
</tbody>
</table>
which include direct excitation from $H_2(v=0)$ and cascading from the $B^1Σ_u^+$ and $C^1Π_u$ states.

The calculated density profiles of $H^+$, $H_2^+$, $H_2(v=1)$, and $H_2(v>4)$ are shown in Figure 4. The lower peak in the $H_2(v>4)$ profile at 350 km in Figure 4 is due to the three-body recombination of $H$ atoms that produces $H_2(v>4)$. The increase of the $H_2(v>4)$ densities above 580 km is caused by a combination of excitation by precipitating electrons and VV transfer from $H_2$. For example, at 850 km the production rate of $H_2(v>4)$ from the electron precipitation is $129 \text{ cm}^{-3} \text{s}^{-1}$, while the rate of collisional excitation of $H_2(v=3)$ by $H_2(v=1)$ (VV transfer) is $526 \text{ cm}^{-3} \text{s}^{-1}$. The collisional deexcitation of $H_2(v=4)$ to $H_2(v=3)$ due to the VV reaction is the major loss channel, resulting in a lifetime of 2.4 s for $H_2(v>4)$. The estimated density of $H_2(v=2)$ is then about $1.8 \times 10^9 \text{ cm}^{-3}$. In general, the collisional excitation and deexcitation due to the VV reactions are more important than the other sources and sinks of $H_2(v>4)$ in this altitude region. The production of $H_2(v>4)$ by electron precipitation decreases with altitude (see Figure 3), whereas the production due to collisional excitation continues to increase as the temperature rises up to 1500 km ($\sim 4 \times 10^{-4} \mu\text{bar}$), where we have arbitrarily assumed the exospheric temperature of 1600 K is reached. Even if the actual temperature profile differs from our assumed profile above 0.1 $\mu\text{bar}$, the results will not change qualitatively.

We find that the ratio of $H_2(v=1)$ to $H_2(v=0)$ is close to the LTE value at all altitudes because the rate of production of $H_2(v=1)$ by electron precipitation is much smaller than the rate of VT reactions with $H_2$ and $H$. For example, at 750 km the peak production rate of $H_2(v=1)$ from the precipitation is $1.2 \times 10^{13} \text{ cm}^{-3} \text{s}^{-1}$, which is much smaller than $3.4 \times 10^{12} \text{ cm}^{-3} \text{s}^{-1}$, the production rate due to VT reactions with $H$ atoms. Thus the $H_2(v=1)$ density profile fully reflects the adopted temperature profile, which results in a broad peak around 700 km (near 0.1 $\mu\text{bar}$) where the assumed temperature is 950 K. The column density of $H_2(v=1)$ is $1.8 \times 10^{17} \text{ cm}^{-2}$. The density profile of $H_2(v=1)$ is therefore consistent with the observations of $H_2$ quadrupole line emissions, which imply a column density of $(1-4) \times 10^{17} \text{ cm}^{-2}$ for $H_2(v=1)$ [S. J. Kim et al., 1990].

The $H_2^+$ density is inversely proportional to the electron density, that is, the $H_2^+$ density at most altitudes, and proportional to the production rate of $H_2^+$. Therefore the density peak of $H_2^+$ occurs at the lower edge of the $H_2^+$ density profile at 650 km. The lower shoulder of $H_2^+$ at about 450 km in Figure 4 is caused by impact ionization of $H_2$ by photoelectrons released in photoionization by solar soft X rays. The profile of $H_2^+$ also forms a broad upper shoulder between 800 and 1500 km where the $H_2^+$ production by (1) and loss by DR vary with altitude at nearly the same rate. The density profile of $H_2^+$ at altitudes higher than 1500 km follows the $H_2(v>2)$ profile because the reaction between $H_2(v>4)$ and $H^+$ is the main source of $H_2^+$, which in turn produces $H_2^+$. The column density of $H_2^+$ is $2.6 \times 10^{12} \text{ cm}^{-2}$, which is within the range of $(0.1-1) \times 10^{13} \text{ cm}^{-2}$ estimated from the IR observations of Drossart et al. [1989]. The peak density and column density of $H_2^+$ are inversely proportional to the adopted DR rate constant but are rather weakly affected by the assumed energy flux of the precipitating electrons. An increase in the energy flux enhances both the production of $H_2^+$ and loss by DR as the electron density increases. The densities of $H_2^+$ and $H$ atoms, however, increase with the energy flux of the precipitating electrons. We show in Table 2 the results of alternative models in which the computed column densities of $H_2^+$ and $H^+$ are given for combinations of the energy flux of 0.1, 1, and 10 erg cm$^{-2}$ s$^{-1}$ and the DR
The observed $H_2^+$ infrared emission is due to radiative relaxation of vibrationally excited $H_2^+$. $H_2^+$ has two vibrational modes, a symmetric breathing mode $v_1$, with quantum number $v_1$, and a doubly degenerate asymmetric bending mode $v_2$, with quantum number $v_2$. The first-order energy separation of the symmetric and asymmetric modes are 0.39 and 0.31 eV, respectively. Reaction (1) is exothermic by 1.7 eV, and the $H_2^+$ produced is vibrationally excited, although the exact distribution is unknown [J. K. Kim et al., 1974; Smith and Futrell, 1975]. Anicich and Futrell [1983/1984] computed the nascent distribution assuming that the excess energy is partitioned between translation and vibrational modes in a statistical manner. We carried out a slightly more elaborate calculation in which we included the rotational degrees of freedom as well as translation and vibration, as discussed, for example, by Levine and Bernstein [1974] [cf. Fox, 1988]. We have included 55 states labeled by $(v_1, v_2)$ with $v_1 + v_2 \leq 9$, whose energies were computed from the term values given by Majewski et al. [1987]. The average vibrational energy of the nascent $H_2^+$ in our calculation, 0.90 eV, is less than that of Anicich and Futrell [1983/1984], 1.32 eV, because with the addition of rotational degrees of freedom, the lower vibrational levels become more probable.

The use of our distribution over that of Anicich and Futrell does not, however, substantially affect the results.

Vibrational levels are interchanged by radiation and collisional excitation and deexcitation. For radiative relaxation of levels whose energies are less than 0.9 eV, namely $(0,1) \rightarrow (0,0), (0,2) \rightarrow (0,1), (1,1) \rightarrow (0,0), (0,3) \rightarrow (0,0), (1,0) \rightarrow (0,1), (0,2) \rightarrow (0,1), (1,1) \rightarrow (0,1), (2,0) \rightarrow (1,1), (0,3) \rightarrow (0,1), (0,2) \rightarrow (1,0), (1,1) \rightarrow (1,0), (0,3) \rightarrow (1,0), (1,1) \rightarrow (1,1), (0,2) \rightarrow (0,2), (2,0) \rightarrow (1,1),$ and $(0,3) \rightarrow (1,1)$, we have adopted the Einstein $A$ coefficients (transition probabilities) computed by S. Miller (private communication, 1991) [cf. Miller and Tenyson, 1989]. The Einstein $A$ coefficients are of the order of $100 \text{s}^{-1}$ for transitions in which only $v_2$ changes by one quantum and of the order of $1 \text{s}^{-1}$ for transitions in which both $v_1$ and $v_2$ change. Transitions in which only $v_1$ changes are dipole forbidden. For radiative relaxation of levels with energy greater than 0.9 eV, we assume an average Einstein $A$ coefficient of 100 s$^{-1}$ for transitions of the type $(v_1, v_2) \rightarrow (v_1, v_2 - 1)$, and we ignore transitions in which both quantum numbers change.

Excitation and deexcitation can occur owing to collisions with the surrounding gas, mainly $H_2$ and $H$. Quenching by $H_2$ can occur either by vibrational transfer without atom transfer or by chemical reaction such as proton transfer. There are no direct measurements of rate coefficients of the elementary processes occurring during quenching by $H_2$, but J. K. Kim et al. [1974] measured a "phenomenological" rate coefficient of $2.7 \times 10^{-10} \text{cm}^3 \text{s}^{-1}$ for the deactivation of $H_2^+$ with vibrational energies of 0.5-2.5 eV by $H_2$. Little dependence of deactivation rate was observed with vibrational energy of $H_2^+$, although there was some evidence that the effective rate coefficient increased slightly with vibrational energy level. The phenomenological rate coefficient is close to the rate coefficient $3 \times 10^{-10} \text{cm}^3 \text{s}^{-1}$ for the proton transfer reaction $H_2^+ + D_2 \rightarrow HD_2^+ + H_2$, measured by Terao and Back [1969]. We treat the quenching reaction of $H_2^+$ by $H_2$ alternatively as a proton transfer reaction in which complete deactivation (to the $H_2^+$ vibrational ground state) occurs or as a VV transfer process in which the $H_2$ gains 1-3 quanta of vibrational energy. We then test the sensitivity of the model to these assumptions. In the former case, we adopt the phenomenological rate coefficient of J. K. Kim et al. [1974]. In the latter case, we assume the transfer of vibrational energy from $H_2^+$ producing $H_2(v)$, where $v = 1, 2, 3$, are equally
TABLE 3. Assumed Reaction Rate Coefficients of Vibration-Vibration Transfer from \( \text{H}_2^+ \) to \( \text{H}_2 \)

<table>
<thead>
<tr>
<th>Vibrational Energy of ( \text{H}_2^+ )</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.5 \leq E_{\text{vib}} &lt; 1.0 \text{ eV} )</td>
<td>( 2.7 \times 10^{-10} )</td>
<td>( 4.3 \times 10^{-10} )</td>
<td>( 4.3 \times 10^{-10} )</td>
</tr>
<tr>
<td>( 1.0 \leq E_{\text{vib}} &lt; 1.5 \text{ eV} )</td>
<td>( 6.3 \times 10^{-10} )</td>
<td>( 6.3 \times 10^{-10} )</td>
<td>( 6.3 \times 10^{-10} )</td>
</tr>
<tr>
<td>( 1.5 \leq E_{\text{vib}} )</td>
<td>( 6.3 \times 10^{-10} )</td>
<td>( 6.3 \times 10^{-10} )</td>
<td>( 6.3 \times 10^{-10} )</td>
</tr>
</tbody>
</table>

Rate coefficients are in unit of \( \text{cm}^3 \text{s}^{-1} \).

probable, and we adopt the rate coefficients shown in Table 3, which results in quenching rates approximately equal to those measured by J. K. Kim et al. [1974]. \( \text{VV} \) transfer cannot occur for states of \( \text{H}_2^+ \) for which the vibrational energy is less than the energy spacing of \( \text{H}_2 \), about 0.5 eV. Blakley et al. [1977] experimentally estimated a \( \text{VT} \) quenching rate coefficient

\[
\text{H}_2^+(v_1, v_2) + \text{H}_2 \rightarrow \text{H}_2^+(v'_1, v'_2) + \text{H}_2
\]

of the order of \( 10^{-12} \text{ cm}^3 \text{s}^{-1} \) for low vibrational levels, and we adopt this value.

\( \text{H}_2^+ \) can also be deexcited by collisions with \( \text{H} \) atoms:

\[
\text{H}_2^+(v_1, v_2) + \text{H} \rightarrow \text{H}_2^+(v'_1, v'_2) + \text{H}.
\]

The rate coefficient for this reaction is unknown, but quenching by reactive species such as \( \text{H} \) atoms has been observed to be efficient, especially where the reaction can take place by atom transfer. We therefore assume a gas kinetic rate coefficient of \( 3 \times 10^{-9} \text{ cm}^3 \text{s}^{-1} \) for (5), and we arbitrarily assume that the \( \text{H}_2^+ \) is quenched to the vibrational energy level immediately below the initial level.

Collisional excitation of \( \text{H}_2^+ \) by \( \text{H}_2 \) and \( \text{H} \), the reverse of (3), (4), and (5), is also included with rate coefficients determined by detailed balance. We ignore quenching of \( \text{H}_2^+ \) by electrons because the rate constant of about \( 5 \times 10^{-9} \text{ cm}^3 \text{s}^{-1} \), estimated from a general formula by Neufeld and Dalgarno [1989], is not large enough for this process to be significant.

RESULTS AND DISCUSSION

We have computed the vibrational distribution of \( \text{H}_2^+ \) assuming photochemical equilibrium. That this is a valid assumption over most of the \( \text{H}_2^+ \) layer can be seen by comparing the chemical lifetime of vibrational states at the \( 10^{-3} \mu \text{bar} \) level (2000 km), which is about 10 s, to the diffusion lifetime, about 10^6 s. In our standard model, we adopt the \( \text{VV} \) rate coefficients for (3) from Table 3.

The loss and production profiles of the \( (0,1) \) state are presented in Figure 5, where short dashed and solid curves represent the \( \text{VT} \) transfer reactions with \( \text{H}_2 \) and \( \text{H} \) (reactions (4) and (5)), respectively. Figure 5a shows the loss rates of the \( (0,1) \) state by collisional deexcitation to the \( (0,0) \) state, collisional excitation to the \( (1,0) \) state, and radiative decay to the \( (0,0) \) state. Figure 5b shows the production rates of the \( (0,1) \) state by the reverse collisional processes presented in Figure 5a. The rate of collisional production from the \( (0,0) \) state is much greater than the collisional loss to the \( (0,0) \) state at altitudes above the \( \text{H}_2^+ \) peak. The presence of radiative decay therefore causes the densities of the \( (0,1) \) state to be much less than those of a thermal distribution at high altitudes. Figure 5 also shows that the \( \text{VT} \) reaction with \( \text{H} \) controls the densities of the \( \text{H}_2^+(0,1) \) and \( \text{H}_2^+(1,0) \) states whose energies are less than the vibrational energy spacing of \( \text{H}_2 \). At 650 km the excitation rate from \( (0,0) \) to \( (0,1) \) by the reverse of (5) is \( 4 \times 10^8 \text{ cm}^{-3} \text{s}^{-1} \), whereas the production rate from any other channels is smaller by an order of magnitude. The specific loss rate for the \( (0,1) \) state by (5) is \( 150 \text{ s}^{-1} \) at 650 km, which is comparable to the Einstein A coefficient of 120 s\(^{-1}\). From these values one can estimate roughly a density of \( 2 \times 10^3 \text{ cm}^{-3} \) for the \( (0,1) \) state. The \( \text{VT} \) reaction with \( \text{H}_2 \) can also excite and deexcite the \( (0,1) \) state but is slower by 2 orders of magnitude than the \( \text{VT} \) reaction with \( \text{H} \) atoms.
A similar analysis can be carried out for the (0,2) state. The loss and production rate profiles are shown in Figures 6a and 6b, respectively. The VT reactions are shown as in Figure 5, along with excitation and deexcitation rates via the VV transfer reaction with H₂. Radiative decay is the dominant loss channel of the (0,2) state at altitudes near and above the H₃⁺ peak, and the dominant production rate is the VT reaction with H₂ (v=1). The rate constant for the excitation reaction from (0,0) to (0,2) is 57% of the deexcitation rate constant at 900 K due to the near resonance of vibrational energy levels between H₂ (v=1) and H₃⁺ (0,2). At 650 km, for example, the excitation rate from (0,0) to (0,2) is 4 x 10⁴ cm⁻³ s⁻¹, the density of H₂ (v=1) is 2.5 x 10⁸ cm⁻³, and the temperature is 900 K. The specific deexcitation rate from (0,2) to (0,0) due to the VV reaction is 500 s⁻¹ at this altitude, which is comparable to the Einstein A coefficient of 360 s⁻¹ for the (0,2) state. A rough estimate from these values gives a density of 40 cm⁻³ for the (0,2) state.

Computed altitude profiles of the densities of the six lowest states (v₁, v₂) are shown in Figure 7. We find that the distribution of the lowest states other than the (2,0) state is almost independent of the choice of the average Einstein A coefficient used for the higher states and is also insensitive to assumptions about the quenching of high vibrational states by H₂. The density of the (2,0) state is slightly affected by these assumptions, since it is produced partially by collisional deexcitation from the higher states. Different assumptions about the nascent distribution of H₃⁺ (v₁, v₂) have also virtually no effect on the resulting distribution of the lower states. The calculated column densities of (0,2) and (0,1) are 2.3 x 10⁹ and 6.1 x 10⁸ cm⁻², respectively, and are consistent with observations of H₃⁺ IR emissions, which indicate column densities of (0,2) and (0,1) of the order of 10⁷ and 10⁸ cm⁻², respectively [Drossart et al., 1989; Oka and Geballe, 1980; Müller et al., 1990]. The average temperature over the (0,2) column is also consistent with the observed rotational temperature of 1099 ± 100 K by Drossart et al. [1988] and the rovibrational temperature of 1100 ± 100 K by Müller et al. [1990] for our assumed temperature profile.

The fraction of vibrational levels as a function of energy at the H₃⁺ peak (~0.2 μbar) are shown in Figure 8, in which the solid polygons represent the model results, and the open polygons a Boltzmann distribution at the local temperature (LTE). The nascent distribution assumed is indicated by the stars. In the model distribution, the fractions of the vibrational states are shown by stars. A Boltzmann distribution of 900 K and the nascent distribution used in the model are also presented with open polygons and stars, respectively.
lowest vibrational levels (with energies less than 1.4 eV) are smaller than but close to those of a Boltzmann distribution. Our computed distribution of states with energies greater than 0.9 eV should be considered as qualitative, since the Einstein A coefficients and rate constants may differ significantly from the assumed values for the high-energy states. The total fraction of these states is, however, of the order of 10^-4, and their distribution therefore does not affect that of the five lowest states presented in Figure 7.

To demonstrate the role of H+ (v=1), we have constructed a model that excludes the VV reaction with H+ (v=1). The resulting densities of the (1,0) and (0,2) states of H+ are shown with the dashed curves in Figure 7. The densities of (0,2) are reduced by about an order of magnitude from the densities in the standard model. The observed H+ IR emissions are thus related to the observed H2 quadrupole emissions. The H+ (v=1) density of a few times 10^6 cm^-3 required for the VV transfer to H+ is consistent with a column density of H+ (v=1) of a few times of 10^17 cm^-2 estimated from H2 IR quadrupole line observations [S. J. Kim et al., 1990]. The precipitating electrons that are responsible for the observed H+ IR emissions should deposit most of their energy in an altitude region where a sufficient density of H+ (v=1) is available for the VV transfer to H+. Since the H+ (v=1) density cannot be larger than the total H2 density, the peak of the H+ emission must be below the 10^-3-μbar level. The emission must also be above the methane homopause because at those altitudes hydrocarbon molecules destroy H2 quickly by charge transfer reactions [cf. Kim and Fox, 1981]. The 10-keV electrons deposit most of their energy between these limits, namely, at around 0.1 μbar.

**Conclusions**

We have shown that precipitation of 10-keV electrons with a flux of about 1 erg cm^-2 s^-1 produces vibrational distributions of H2 and H2+ that are consistent with the IR line observations in Jovian auroral regions. We have examined the collisional relaxation processes of H2+ vibrational states, and we find that distribution of the six lowest vibrational states of H2+ can be determined fairly well in spite of uncertainties about H2+ vibrational relaxation. We find that the VV transfer reaction between the near-resonant H+ (v=1) and H2+ (v1=0,v2=2) states is important in determining the probability of the H+ (v1=0,v2=2) state. In our model, the H+ (v=1) and H2+ densities peak at about the same altitude, around 650 km (~0.2 μbar). At the peak of the H2+ profile, radiative decay of the (0,1) and (0,2) states is nearly as important as collisional deexcitation. Therefore the vibrational distribution at the peak is not a thermal distribution, as suggested by Miller et al. [1990] and Drossart et al. [1989], but the fractional populations of the (0,1) and (0,2) states at the H2+ peak are only slightly smaller than those of a Boltzmann distribution.

At the time of submission of this manuscript, images of H2 ν2 fundamental band emission at 3-4 μm in the Jovian polar regions have been presented [S. J. Kim et al., 1991; Baron et al., 1991]. These observations indicate that the maximum H2 emission does not coincide with the UV and IR hot spot, at least in the northern polar region. The precipitating electrons in our model are characterized by both lower energies and lower energy fluxes than those inferred from the UV aurorae. Our model is therefore not inconsistent with these observations.

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