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# $H_2$ FLUORESCENCE SPECTRUM FROM 1200 TO 1700 Å BY ELECTRON IMPACT: LABORATORY STUDY AND APPLICATION TO JOVIAN AURORA

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## ABSTRACT

A combined experimental study of the fluorescence spectrum of $H_2$ at wavelengths of 1200–1700 Å by electron impact and its application to modeling the Jovian aurora have been carried out. Our laboratory data suggest that at 100 eV the relative cross sections for direct excitation of Ly$\alpha$, Lyman bands ($B^1\Sigma_u{}^+ - X^1\Sigma_g{}^+$), and Werner bands ($C^1\pi_u - X^1\Sigma_g{}^+$) are 1, 2.3 ± 0.6, and 2.6 ± 0.5, respectively, in conflict with Stone and Zipf's (1972) results for the Werner bands. Cascade from $E, F^1\Sigma_g{}^+$ states contributes an additional 31% to the $B^1\Sigma_u{}^+$ state population. It is shown that the most likely fate for the metastable H($2^2S$) atoms produced in the Jovian aurora is collisional quenching to H($2^2P$), and this could add as much as 60% to the predicted Ly$\alpha$ emission. On the basis of detailed atmospheric and radiative transfer modeling, we conclude that the recent *IUE* and *Voyager* observations are consistent with precipitation of electrons with energy in the range of 1–30 keV or other energetic particles that penetrate to number densities of $4 \times 10^{10}$–$5 \times 10^{13}$ cm$^{-3}$ or column densities of $5 \times 10^{17}$–$2 \times 10^{20}$ cm$^{-2}$ in the atmosphere. The globally averaged energy flux and production of hydrogen atoms are 0.5–2 ergs cm$^{-2}$ s$^{-1}$ and 1–4 $\times 10^{10}$ atoms cm$^{-2}$ s$^{-1}$, respectively.

*Subject headings:* laboratory spectra — molecular processes — planets: atmospheres

## I. INTRODUCTION

Intense auroral emissions from Jupiter have recently been detected by *Voyager 1* and *2* in the range of 500–1700 Å with a resolution of 33 Å (Broadfoot *et al.* 1979; Sandel *et al.* 1979) and by the *International Ultraviolet Explorer* (*IUE*) in the range of 1200–1700 Å at about 10 Å resolution (Clarke *et al.* 1980). Clarke *et al.* (1980) also present a laboratory spectrum of $H_2$ by electron impact and conclude that qualitatively most emission features are associated with $H_2$. Modeling of the aurora offers a straightforward and sensitive tool for probing the nature of the interaction between the atmosphere and magnetospheric particles, which provides a major driving force for the aeronomy of the upper atmosphere.

The electron impact fluorescence spectrum of $H_2$ in the wavelengths 1200–1700 Å consists of Ly$\alpha$, produced in dissociative excitation, the Lyman bands, the Lyman dissociative continuum, and the Werner bands. The existing data base (Vroom and de Heer 1969*b*; McGowan, Williams, and Vroom 1969; Mumma and Zipf 1971; Möhlmann, Shima, and de Heer 1978; Srivastava and Jensen 1977; Stone and Zipf 1972; de Heer and Carrière 1971) is inadequate for generating a synthetic $H_2$ fluorescence spectrum with an accuracy on the order of 20% for interpreting the high-quality *IUE* observations. In this work the relevant cross sections are updated, and more realistic radiative transfer models than those in Heaps, Bass, and Green (1973) and Cravens, Victor, and Dalgarno (1975) are used for interpreting the observations.

## II. LABORATORY SPECTRUM OF $H_2$

A detailed description of the experiment is described in Ajello and Srivastava (1981) and Ajello, Srivastava, and Yung (1982). Figure 1*a* (dashed line) shows a typical $H_2$ fluorescence spectrum between 1200 and 1700 Å at 5 Å resolution taken at an electron energy of 100 eV. The data should be compared with the least-squares fit (solid line) obtained by the following procedure. First, we generate individual synthetic $H_2$ emission spectra due to the Lyman system, the Werner system, and the cascade-populated Lyman system (see Fig. 1*b*, *c*, *d*). The relevant molecular physics data for $X^1\Sigma_g{}^+$, $B^1\Sigma_u{}^+$, and $C^1\pi_u$ states are taken from Herzberg (1950), Stephens and Dalgarno (1972), Dalgarno, Herzberg, and Stephens (1970), and Huber

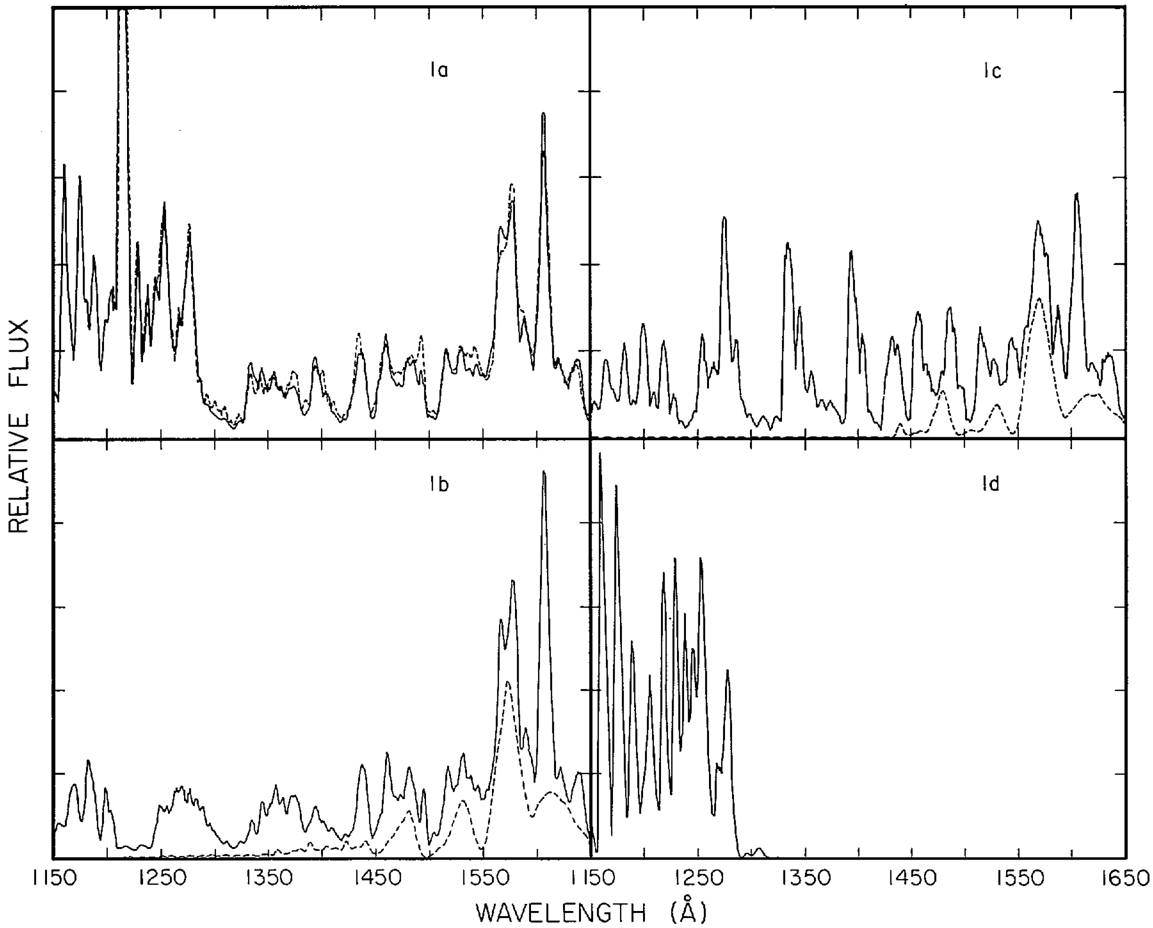


FIG. 1.—(*a*) *Dashed line*: calibrated laboratory spectrum of $H_2$ at 5 Å resolution for electron energy of 100 eV. *Solid line*: theoretical spectrum synthesized using cross sections for Ly$\alpha$, $B^1\Sigma_u^+$, $C^1\pi_u$, and cascade equal to $1.2 \times 10^{-17}$, $2.8 \times 10^{-17}$, $3.1 \times 10^{-17}$, and $9 \times 10^{-18}$ cm$^2$, respectively. The areas under Ly$\alpha$ are identically equal for both curves. (*b*) *Solid line*: total emission from Lyman system, $B^1\Sigma_u^+ - X^1\Sigma_g^+$, excluding cascade. *Dashed line*: emission due to Lyman dissociative continuum (Dalgarno, Herzberg, and Stephens 1970). (*c*) *Solid line*: Lyman emission excited via cascade, $E, F^1\Sigma_g^+ \rightarrow B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$. *Dashed line*: same meaning as in (*b*). (*d*) Werner bands $C^1\pi_u - X^1\Sigma_g^+$.

and Herzberg (1979). For computing cascade from the $E, F^1\Sigma_g^+$ state, we take the Franck-Condon factors from Lin (1974). The cross sections $\sigma_B$, $\sigma_C$, and $\sigma_{\rm cascade}$ relative to $\sigma_{\rm Ly\alpha}$ were obtained by a least-squares fit. The experiment was repeated for energies from threshold to 400 eV (Ajello, Srivastava, and Yung 1982).

### III. ATMOSPHERIC MODELING

The model atmosphere adopted here is similar to that given by Yung and Strobel (1981) and Festou *et al.* (1981), with the eddy diffusion coefficient at the homopause equal to $3 \times 10^6$ cm$^2$ s$^{-1}$ (McConnell, Sandel and Broadfoot 1981). To model the Jovian aurora, we assume that the auroral region atmosphere is bombarded by a monoenergetic beam of electrons with mean pitch angle $\theta_P = 60°$ and total energy flux equal to 10 ergs cm$^{-2}$ s$^{-1}$, normal to the atmosphere. The mean electron energy is 1, 3, 10, 30, and 100 keV for models, A, B, C, D, and E, respectively. The deposition of energy and excitation of various states are calculated using the continuous slowdown approximation. The energy loss function is taken from Cravens, Victor, and Dalgarno (1975). The cross sections for various excitation processes are taken from the discussion in the previous section, except for Ly$\alpha$. In most experiments, such as ours and Mumma and Zipf's (1971), the metastable H($2^2S$) with a lifetime $\tau = 0.12$ s (Shapiro and Breit 1959) is never detected. The works of Vroom and de Heer (1969*a*, *b*, *c*) and Möhlmann, Shima, and de Heer (1978) show that the fraction of H($2^2S$) produced is 0.6 relative to H($2^2P$) over a wide range of energy. The most likely fate for H($2^2S$) in the Jovian atmosphere is collisional quenching, H($2^2S$) + $H_2$ $\rightarrow$ H($2^2P$)

$+ H_2$ ($k = 2.5 \times 10^{-9}$ cm $^3$ s$^{-1}$), followed by $H(2^2P) \rightarrow H(1^2S) + Ly\alpha$. A small fraction is lost by other processes, such as chemi-ionization, $H(2^2S) + H_2 \rightarrow H_3^+ + e$ (Mentall and Gentieu 1970; Van Volkenburgh, Carrington, and Young 1973). In our model we use the Ly$\alpha$ cross section measured by Mumma and Zipf (1971), multiplied by 1.6. Multiple scattering of Ly$\alpha$ photons depends strongly on the velocity distribution of the radiating atoms. The velocity distribution of $H(2^2S)$ atoms is taken from Leventhal, Robiscoe, and Lea (1967) and Carnahan and Zipf (1977). The velocity distribution of $H(2^2P)$ atoms has not been measured, and we use the theoretical calculations of Lee and McKoy (1982). The volume excitation rate $V$ (photons cm$^{-3}$ s$^{-1}$), calculated by the above procedure, is treated as the internal source term, $S = (V/4\pi)(dz/d\tau)$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, in the equation of radiative transfer (see, e.g., Strickland and Donahue 1970), which is then solved using 8-stream approximation (the accuracy of this code for inhomogeneous atmospheres is within 3% of that of Sato, Kawabata, and Hansen 1977). The brightness of the aurora is taken to equal $4\pi I(\mu)$, where $I(\mu)$ is the emergent specific intensity (photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$) and $\mu = \cos 66°$. The effects of partial frequency redistribution are important for Ly$\alpha$ and have been included (Gladstone 1982).

The results of our calculations are summarized in Table 1. At $E = 1$ keV (Model A) the aurora is well above the homopause, and the atmosphere is optically thin. Beyond 10 keV the particles penetrate fairly deep in the atmosphere. Near and below the homopause, absorption of photons shortward of 1550 Å by $CH_4$, $C_2H_6$, and $C_2H_2$ becomes important, as shown in Figure 2*a*. We define two color ratios, $R_1 = 4\pi I_{Ly\alpha}/4\pi I_{1230-1650}$ and $R_2 = 4\pi I_{1230-1300}/4\pi I_{1557-1619}$, which are sensitive functions of the energy distribution of the precipitating electrons. Comparison of the theoretical values for $R_1$ and $R_2$ and the experimental values derived from the *IUE* observations in Table 1 leads us to the conclusion that the mean energies of the electrons are between 1–30 keV, and the varying color ratios of the aurora can be simply interpreted as due to variations in the mean energy of the electrons. Similar conclusions have been qualitatively discussed by Clarke *et al.* (1980). Figure 2*b* (solid line) shows a spectrum of the aurora with $E = 20$ keV. The results are in good agreement with the *IUE* observations SWP 8904 + 8905 + 8934 (dashed line). The reader is cautioned not to take the interpretation too literally. The critical data between Ly$\alpha$ and 1550 Å are not significantly above the noise level. Further, there seems to be a discrepancy between results of analysis based on $R_1$ and $R_2$. The high observed values for $R_1$ suggest that the electrons are in the energy range of 1–3 keV. We leave the question to be resolved by an improved data base in the future. Combining our results with those of Broadfoot *et al.* (1980), we estimate a globally averaged energy flux of 0.5–2 ergs cm$^{-2}$ s$^{-1}$. The associated rate of hydrogen atom

TABLE 1

SUMMARY OF *IUE* MEASUREMENTS AND MODEL CALCULATIONS

| *IUE* Image No. | $4\pi I_{Ly\alpha}$ | $4\pi I_{1230-1650}$ | $R_1$ | | $R_2$ |
|---|---|---|---|---|---|
| SWP 5307 .... | 17 | 55 | 0.31 | 0.38 | 0.46 |
| SWP 5309 .... | 42 | 100 | 0.42 | | |
| SWP 8904 .... | 20 | 28 | 0.71 | 0.70 | 0.55 |
| SWP 8905 .... | 28 | 30 | 0.93 | | |
| SWP 8934 .... | 16 | 34 | 0.47 | | |
| SWP 9480 .... | < 8 | 18 | < 0.44 | | ... |
| SWP 9481 .... | < 8 | 21 | < 0.38 | | ... |
| SWP 9508 .... | < 8 | 20 | 0.40 | | ... |
| SWP 9507 .... | 11 | 38 | 0.29 | | ... |
| SWP 9508 .... | < 8 | 17 | < 0.47 | | ... |
| SWP 9509 .... | 14 | 46 | 0.30 | | ... |
| | | Model | | | |
| Model A ...... | 71 | 99 | 0.72 | | 0.87 |
| Model B ...... | 55 | 106 | 0.52 | | 0.87 |
| Model C ...... | 33 | 107 | 0.31 | | 0.83 |
| Model D ...... | 10 | 75 | 0.13 | | 0.33 |
| Model E ...... | 1.2 | 58 | 0.021 | | 0.041 |

NOTES.—Aurora brightness is given in $kR$($10^9$ photons cm$^{-2}$ s$^{-1}$). $R_1 = 4\pi I_{Ly\alpha}/4\pi I_{1230-1650}$, $R_2 = 4\pi I_{1230-1300}/4\pi I_{1557-1619}$. The total energy flux in each model calculation is 10 ergs cm$^{-2}$ s$^{-1}$. The electron energy is 1, 3, 10, 30, and 100 keV for models, A, B, C, D, and E, respectively.

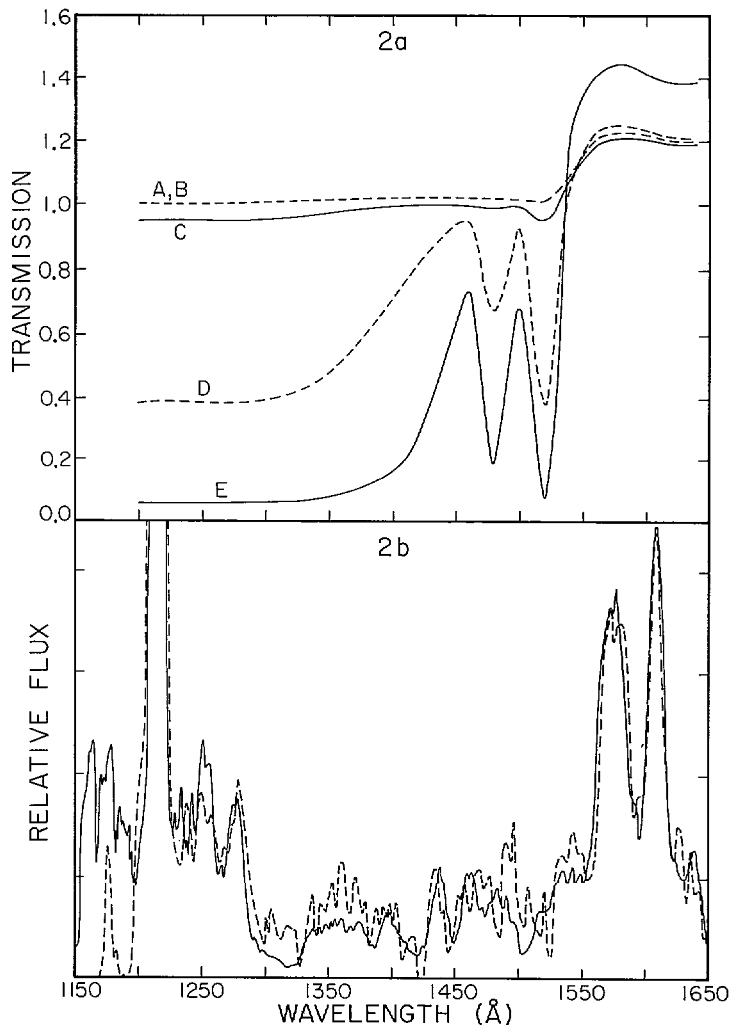


FIG. 2.—(*a*) Atmospheric transmission function for an electron aurora for models A–E (see Table 1). The absorption cross sections for $CH_4$, $C_2H_6$, and $C_2H_2$ are taken from Mount, Warden, and Moos (1977), Mount and Moos (1978), and Nakayama and Watanabe (1964), respectively. The incident electron beam enters the atmosphere at 60°, and the computed emergent radiation leaves the atmosphere at 65°.9; all angles being measured relative to the local zenith. The transmission is defined as the ratio $I_{scat}/I_{thin}$, where $I_{thin}$ = emergent specific intensity for a hypothetical optically thin atmosphere, and $I_{scat}$ = emergent specific intensity for the real atmosphere with multiple scattering and absorption. Transmission at Ly$\alpha$ is treated as a special case, not shown in this figure. The values are 1.00, 0.73, 0.47, 0.13, and 0.019, respectively, for models A–E. (*b*) *Dashed line*: *IUE* spectrum SWP 8904 + 8905 + 8934 (Clarke *et al.* 1980), with a slight adjustment to the baseline. *Solid line*: aurora calculation with $E$ = 20 keV and 11 Å resolution.

production is 1–4 × $10^{10}$ atoms $cm^{-2}$ $s^{-1}$, in excellent agreement with the hydrogen flux of 7 × $10^9$–2 × $10^{10}$ atoms $cm^{-2}$ $s^{-1}$ postulated by Yung and Strobel (1980) to account for the disk Ly$\alpha$ brightness of Jupiter during the *Voyager* encounters.

## IV. CONCLUSIONS

We have shown that the existing observations of Jovian aurorae can be explained by simple electron precipitation models, if the Werner bands cross sections of Stone and Zipf (1972) are revised downward by about a factor of 2, as required by our laboratory studies. It is shown that the observed color ratios $R_1$ and $R_2$ imply a very narrow energy range for the incident electrons of 1–30 keV. Alternative models requiring protons or heavy ions are not ruled out, but must be required to reproduce atmospheric extinction properties similar to those described here (McConnell, Sandel, and Broadfoot 1981; Broadfoot *et al.* 1980).

The $H_2$ fluorescence spectrum below 1200 Å must be quantitatively studied in the laboratory and should provide an independent check to the results we obtained at longer wavelengths. More observations with better signal to noise, especially in the region below 1600 Å, are required for detailed quantitative comparison with models. Long-term monitoring of the auroral activities and disk Ly$\alpha$ brightness is needed to establish a causal relation between the two.

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*Note added in proof.*—The reader is cautioned that there is a difference between the model atmosphere used in this study and that determined by Festou *et al.* (1981) that is due to different eddy diffusion profiles. For instance, the column density of $H_2$ above the level of unit optical depth of methane at Ly$\alpha$ is $1 \times 10^{20}$ cm$^{-2}$ in our model but $9 \times 10^{20}$ cm$^{-2}$ in the Festou *et al.* (1981) model.

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