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COPERNICUS MEASUREMENT OF THE JOVIAN LYMAN-ALPHA EMISSION AND ITS AERONOMICAL SIGNIFICANCE

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ABSTRACT

Observations of Jupiter made with the high-resolution ultraviolet spectrometer of the Orbiting Astronomical Observatory *Copernicus* in 1980 April and May yield the intensity of the Jovian Lyman-alpha emission to be 7 ± 2.5 kR. These measurements indicate that the Lyman-alpha intensity has decreased by about a factor of 2 from the time of the *Voyager* ultraviolet spectrometer measurements, nearly a year earlier. The *Copernicus* measurements, when combined with all other previous measurements of the Jovian Lyman-alpha emission, point to an unusually high column abundance of hydrogen atoms above the methane homopause at the *Voyager* epoch. Since the auroral charged particle bombardment of molecular hydrogen is expected to contribute significantly to the global population of the hydrogen atoms, it is suggested that at the time of the *Voyager* Jupiter encounter, unusually high auroral activity existed, and it was perhaps linked to the high concentration of the Io plasma torus. It should be pointed out that the temporal variation of the Saturn Lyman-alpha emission, when contrasted with the Jovian data, reveals that the auroral processes are not nearly as important in determining the Saturn Lyman-alpha intensity in the nonauroral region. The latest *Copernicus* observations also suggest an increase in the Jovian homopause value of the eddy mixing coefficient by about a factor of 5–10 since the *Voyager* epoch.

Subject headings: planets: atmospheres — planets: Jupiter — planets: Saturn — planets: spectra — ultraviolet: spectra

I. INTRODUCTION

The intensity of the Lyman-alpha emission is a good indicator of the principal aeronomical processes on the major planets. It reflects on atmospheric vertical mixing, mechanisms responsible for the production of atomic hydrogen (such as photochemistry, and electron and ion bombardment of molecular hydrogen), and of course, mechanisms for the excitation of the Lyman-alpha emission itself. Measurements of the intensity of Jovian Lyman-alpha made over the last solar cycle indicate large temporal variation. Because many of these measurements cannot be satisfactorily explained theoretically, it was decided to further monitor the Lyman-alpha intensity beyond the *Voyager* UV Spectrometer measurements in 1979. The high-resolution ultraviolet spectrometer aboard the Orbiting Astronomical Observatory *Copernicus* was used in 1980 April and May to detect the Jovian Lyman-alpha emission by spectroscopically discriminating it from other doppler shifted Lyman-alpha emissions such as those of the geocorona, and the interplanetary medium. Lyman-alpha emissions from Io and Io torus are relatively small and spatially separated. The results of the *Copernicus* Jovian Lyman-alpha measurements are surprising and have been useful in placing important constraints on theoretical considerations used for explaining the temporal behavior of both this emission and subsequent aeronomical phenomena on Jupiter. Saturn Lyman-alpha emission, on the other hand, does not seem to indicate the same temporal characteristics as the Jovian emission, thus pointing to a markedly different hydrogen production mechanism on Jupiter at certain times.

II. OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

a) *Technique*

Observations of the Jovian Lyman-alpha emission were carried out in 1980 April and May with the U1 spectrometer (resolution of 0.06 Å at 1216 Å) of the *Copernicus* satellite, which is in a geocentric orbit of

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approximately 750 km altitude and inclination 35°. The pointing accuracy of the telescope is a few arc seconds. The angular dimensions of the spectrometer slit are $0''.3 \times 39''$, and its nominal orientation is 45° to the ecliptic plane, hence to the rotation axis of the planet (see Figs. 3 and 4 of Bertaux *et al.* 1980). *Copernicus* was first used in 1976 to observe the Jovian Lyman-alpha emission. Since then, the detector sensitivity has deteriorated by about a factor of 10 as can be seen in Figure 1, which depicts the evolution of the Jupiter/geocorona signal from 1976 to 1980. Therefore, in 1980 a large number of observations were needed to reach an approximately 2:1 signal-to-noise ratio. Spectra of the geocorona and of the geocorona plus Jupiter were obtained during the following two periods:

1. 1980 April 1–April 9.—Eighty-two spectra of the geocorona were recorded by offsetting the instrumental slit by about 1° from the direction of Jupiter, and 144 spectra of the planet in which the emission appears on the long wavelength side of the geocoronal line profile were recorded.
2. 1980 April 26–May 7.—In this period, 101 spectra of the geocorona and 218 spectra of the geocorona plus Jupiter were obtained.

A typical scan of the U1 spectrometer consisted of 28 steps of 21.8 mÅ each. The integration time was 13.76 s. Triple scans of the geocorona plus Jupiter were obtained while the geocorona was studied with single scans. The fourth panel of Figure 1 represents the stacking of the two series of 144 and 218 spectra after the background signal was subtracted. The geocoronal and Jovian emissions were separated by 80 ± 5 mÅ and 100 ± 5 mÅ, respectively, during the two periods of April and May. The low signal-to-noise ratio and the imprecise background level in the 1980 observations demands a careful subtraction of the geocoronal signal to isolate the Jovian emission. The procedure developed for correcting the background level follows.

Although the instrumental width is 60 mÅ, the wavelength sampling rate is 21.8 mÅ, and a partial deconvolution of the signal is sometimes possible (see, for example, Drake *et al.* 1976). This is not the case with the present data. Due to the orbital motion of the spacecraft, data points were obtained at continuously changing wavelengths—an effect which results in different starting wavelengths of the individual spectra. Consequently, the real wavelength sampling rate was of the order of a few mÅ. The normal reduction procedure would have consisted of calculating the intensities at fixed wavelengths from the experimental data points. Owing to the irregular wavelength distribution of those points, we preferred to define a series of wavelength intervals of constant width (22 mÅ) and to distribute the observed intensities into the resulting bins. The individual spectra

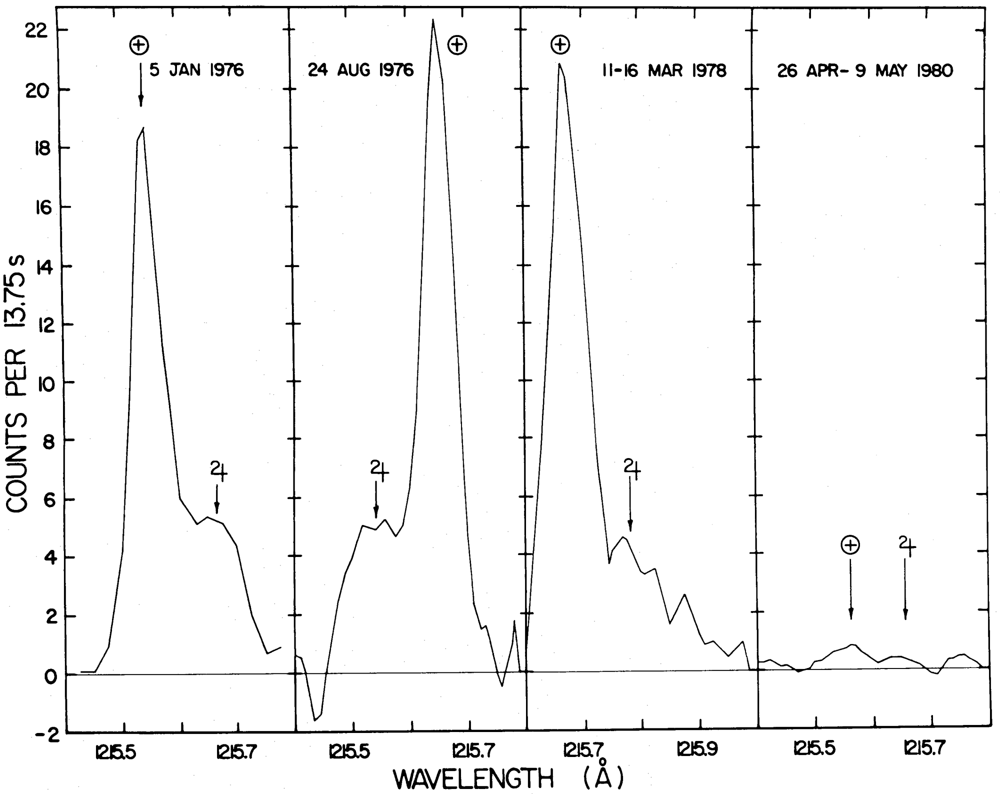

FIG. 1.—Evolution of the *Copernicus* signal level for the Jovian and geocoronal Lyman-alpha. Data presented here are uncorrected raw data. Note the extremely low count rates in the 1980 data caused by the loss in the detector sensitivity. All data are in the *Copernicus* frame of reference.

were then summed over portions of the *Copernicus* orbit for which both the geometry of the geocorona and the spacecraft background level were each approximately constant. Spurious spectra were eliminated by a visual inspection. The trial and error method showed that the orbit had to be divided into 24 equal segments to produce optimal results. In this manner, two series of spectra having the same geocoronal contribution and the same background were obtained for each period. The subtraction of the geocorona spectra from the combined geocorona plus Jupiter spectra results in the pure Jupiter spectra. Figure 2 shows the two Jupiter spectra for the 1980 April and May periods. A comparison with Figure 1 shows that the geocorona contribution has been correctly subtracted (both figures are drawn in the instrument wavelength scale). The standard deviation for an individual point is ±0.50 counts: the Jupiter emission is thus detected at the 3 σ level, and the two spectra are identical within the experimental uncertainties. Figure 3 shows the geocorona spectrum in the frame of reference of the geocorona for the May observations and the average spectrum of Jupiter for the entire April–May observational period. Superposed on the 1980 May geocorona signal, the normalized 1974 geocorona emission is shown by a dashed line: note the good reproducibility of the measurements obtained 6 years apart. The 1980 May geocorona spectrum has been used to calibrate the instrument.

The signal-to-noise ratio is not good enough to give the accurate width of the Jovian resonance line. However, there is no indication that the Jovian line width was larger than the geocorona line width. This implies that the observed Jovian Lyman-alpha line width was smaller than 70 mÅ. This value contrasts with those reported by Bertaux *et al.* (1980), 115 mÅ, and Cochran and Barker (1979), 207 mÅ. We do not consider these differences to be significant due to large uncertainties in the line widths resulting from a different reduction technique

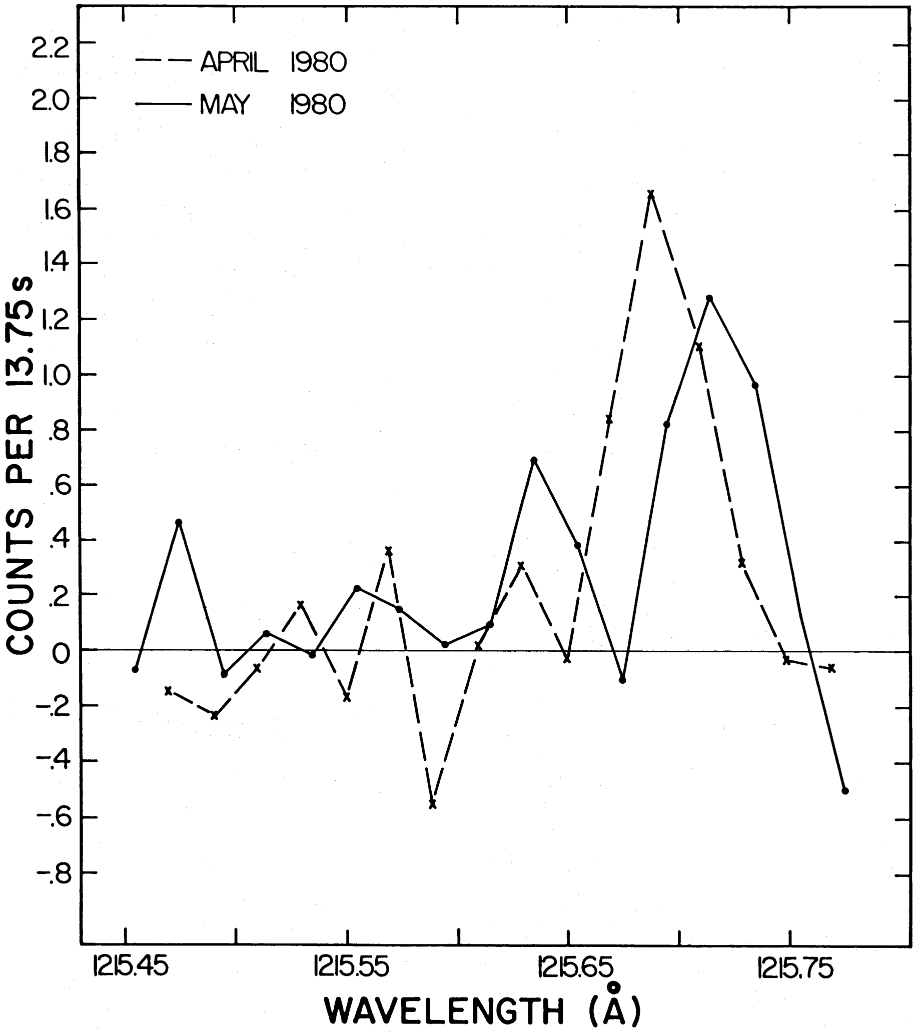

FIG. 2.—Jupiter Lyman-alpha emission profiles for the 1980 April and May sets of *Copernicus* orbits. The differences in the intensities of the two sets are statistically insignificant. The data are presented in the *Copernicus* frame of reference.

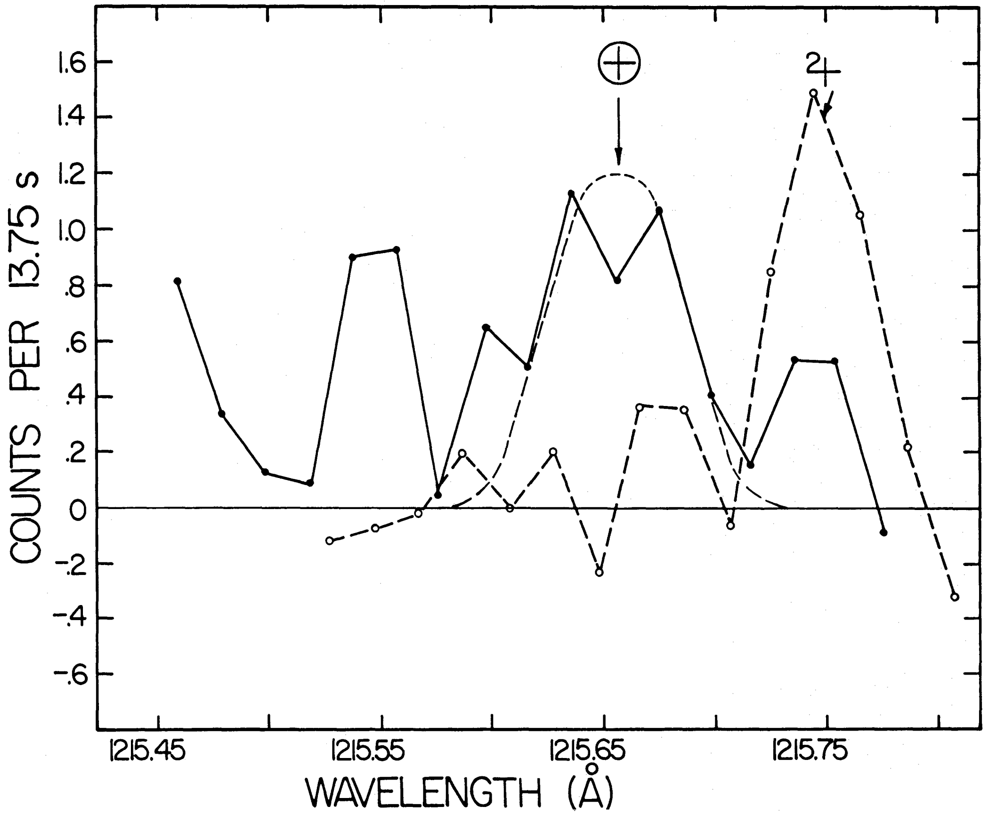

FIG. 3.—Geocorona and Jupiter Lyman-alpha in the geocorona frame of reference. The Jupiter data are the average of the April and May data shown in the previous figure. Superposed on the 1980 geocoronal emission (*solid line*) is the normalized geocoronal emission in 1974 (⊕, *broken line*).

used in the earlier studies. There is only an indication that the line was wider in 1978, implying greater column density of atomic hydrogen, and greater Lyman-alpha intensity.

b) *Calibration: The M-Factor*

The procedure for determining the *Copernicus* calibration at the Lyman-alpha wavelength has been described in detail in earlier publications (Bertaux *et al.* 1980; Barker *et al.* 1980). The validity of the technique has been successfully demonstrated for numerous previous Jovian, Saturnian, and cometary Lyman-alpha measurements on *Copernicus* (see discussion in Barker *et al.* 1980). The calibration factor, M, is defined as the ratio of the measured geocoronal intensity I_G (counts Å) to the computed value I_G (kR) for the same observational geometry. The technique for the computation of I_G is described by Drake *et al.* (1976). The model is defined by a uniform exospheric temperature of 1130 K and a density of $6.5 \times 10^4\ \mathrm{cm}^{-3}$ hydrogen atoms at the exobase level. The temperature was computed from the empirical model of Thuillier, Falin, and Barlier (1977), and the density for this temperature was derived from Vidal-Madjar (1978). These model parameters are typical of the observed or computed values for a high level of solar activity. Assuming a solar Lyman-alpha flux of 4.5×10^{11} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \text{Å}^{-1}$ as appropriate for 1980 May period (see § 3), the model mentioned above yields the geocoronal Lyman-alpha intensity to be 7.7 kR. The measured geocoronal intensity of 0.08 counts Å (Fig. 3) thus results in an "M-factor" of 0.0104 counts Å kR^{-1}. This calibration factor gives the Jovian Lyman-alpha intensity of 7 kR corresponding to Figure 3. The total uncertainty on the intensity measurements is estimated to be $\pm 35\%$ due largely to the loss in the instrumental sensitivity which has decreased by a factor of about 10 between 1976 September and 1980 April, necessitating enormous integration times even for bright sources such as Jupiter.

III. DISCUSSION

Jovian Lyman-alpha emission has been monitored since 1967 using spectrometers and photometers aboard rockets, earth orbiting satellites such as *Copernicus* and *IUE* (*International Ultraviolet Explorer*), and more recently *Pioneer and Voyager* spacecraft. Listed in Table 1 are all Lyman-alpha observations made to date. A large variation, by up to a factor of 30, has been observed. The very small value of 0.4 kR reported by the *Pioneer 11* UV photometer in 1973 contrasts with values in the neighborhood of 14 kR obtained in 1978 and 1979 by instruments on rocket, *IUE*, and *Voyager 1* and *2*.

TABLE 1

JUPITER LYMAN-ALPHA

Observation Date	Observation Technique	Lyman-Alpha Intensity[a] (kR)	References
1967 Dec 5	Rocket	4.0	1
1971 Jan 25..........	Rocket	4.4 ± 2.6	2
1972 Sep 1...........	Rocket	2.1 ± 1.0	3
1973 Dec 3	*Pioneer*	0.4 ± 0.12	4
1976 Jan 5...........	*Copernicus*	2.8 ± 1.0	5
1976 Aug, Sep	*Copernicus*	4.0 ± 1.4	5
1976 Aug, Sep	*Copernicus*	3.8 ± 1.0	6
1978 Mar	*Copernicus*	8.3 ± 2.9	7
1978 Dec 1	Rocket	13	8
1978 Dec 10	*IUE*	12–14	9
1979 Mar–July	*Voyager 1* and *2*	14	10, 11
1979 May, June......	*IUE*	10–13	12
1980 April, May.....	*Copernicus*	7.0 ± 2.5	13
1980 May 3..........	*IUE*	10	12, 14

[a] *Copernicus* intensities have been adjusted for the revised geocoronal calibration according to Bertaux *et al.* 1980.

REFERENCES.—(1) Moos *et al.* 1969. (2) Rottman *et al.* 1973. (3) Giles *et al.* 1976. (4) Carlson and Judge 1974. (5) Bertaux *et al.* 1980. (6) Atreya *et al.* 1977. (7) Cochran and Barker 1979. (8) Clarke *et al.* 1980*b*. (9) Lane *et al.* 1978. (10) Broadfoot *et al.* 1979. (11) Sandel *et al.* 1979. (12) Clarke, Moos, and Feldman 1981. (13) This paper. (14) Moos 1981.

The absolute calibration of the *Voyager* ultraviolet spectrometer has been discussed by Holberg *et al.* (1982); the *Copernicus* calibration is described in § II*b*. The change in the Jovian Lyman-alpha intensity, particularly from 1979 *Voyager* to 1980 *Copernicus* observations, is not related to the calibration uncertainties. *Copernicus* measurements have the advantage over others of measuring the Doppler line profile of the emission feature, thus spectroscopically discriminating the Jovian emission from other sources, most importantly the geocorona. In the case of *IUE* and rocket measurements, non-Jovian Lyman-alpha emissions must be specifically subtracted from the total observed signal. This advantage of *Copernicus* UV spectrometer measurements is due to a relatively high spectral resolution of the instrument, which has been achieved at the expense of throughput. Moreover, as mentioned earlier, the loss in the *Copernicus* detector sensitivity rendered the latest measurements of the Jovian Lyman-alpha intensity even more difficult.

The Jovian Lyman-alpha intensities of Table 1 and the Zürich sunspot number, R_z, are plotted in Figure 4. The two quantities show the same qualitative behavior with time, as was noted previously also by Cochran and Barker (1979). A quantitative evaluation of the correlation between the observed intensity and the possible excitation mechanisms is, however, not possible from a study of the intensity behavior with the sunspot number. We have, therefore, resorted to studying the intensity variation with other quantities, such as the solar Lyman-alpha flux and the $F_{10.7\,\mathrm{cm}}$ flux.

Equatorial and mid-latitude Jovian Lyman-alpha is excited by resonance scattering of the solar Lyman-alpha photons by hydrogen atoms in the Jovian upper atmosphere; it is, therefore, instructive to plot this intensity against the solar Lyman-alpha flux. Unfortunately, very few measurements of the solar Lyman-alpha flux, particularly with the same instrument, have been carried out during the last solar cycle. Bossy and Nicolet (1981) have recently compiled all available data on solar Lyman-alpha flux, applied their corrections for instrument calibration errors, and arrived at the

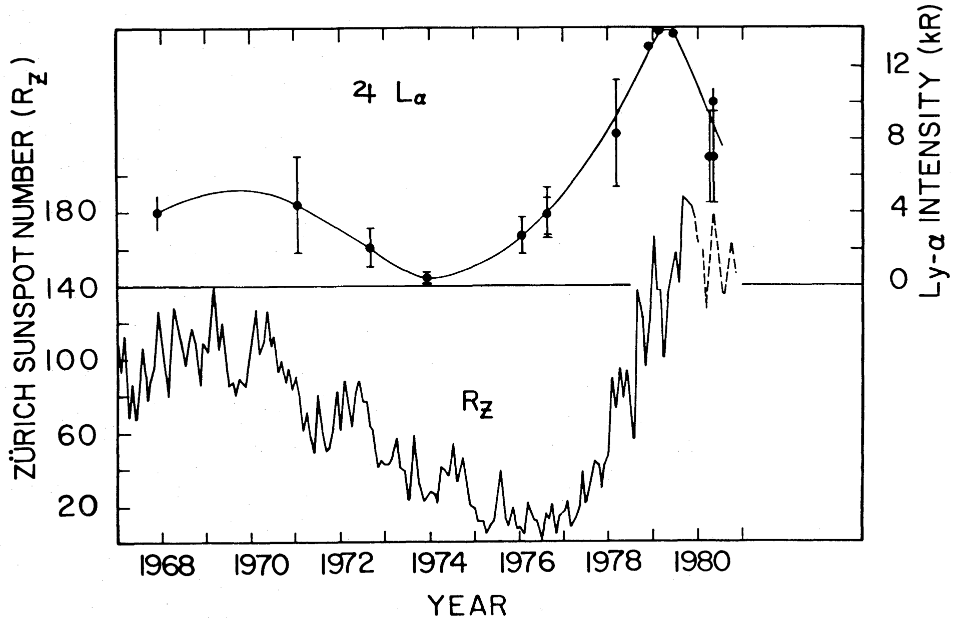

FIG. 4.—Jovian Lyman-alpha intensity vs. Zürich sunspot number. The broken line addition toward the end of R_z represents current "provisional values."

following empirical relationship between the solar Lyman-alpha flux ($\mathscr{F}$) and the $F_{10.7\ \mathrm{cm}}$-flux, F,

$$(\mathscr{F}) = 2.5 \times 10^{11} + 0.011(F - 65) \times 10^{11} \text{ photons cm}^{-2}\text{ s}^{-1} \quad (1)$$

Despite calibration corrections applied to the various measurements by Bossy and Nicolet, wide discrepancies between individual measurements remain. Besides, measurements of solar Lyman-alpha flux on the dates of the Jovian Lyman-alpha measurements are seldom available. For example, during the period of the latest *Copernicus* observations, 1980 April–May, measurements by Hinteregger (1981) from *Atmosphere Explorer* yielded approximately 6.7×10^{11} photons cm^{-2} s^{-1} solar Lyman-alpha flux, while rocket flights by Mount and Rottman (1981) in 1980 July gave $\sim 5 \times 10^{11}$ photons cm^{-2} s^{-1}. It is interesting that the empirical relation (1) also gives a value close to Mount's value for the solar Lyman-alpha flux. The *Copernicus* 1980 measurements of 7 kR for the Jovian Lyman-alpha intensity (Table 1) is based on an assumed solar Lyman-alpha flux of 4.5×10^{11} photons cm^{-2} s^{-1} Å^{-1} at the line center, and the method of absolute calibration of *Copernicus* at Lyman-alpha as discussed in § II*b*. If Hinteregger's (1981) value for the solar Lyman-alpha flux is assumed, the *Copernicus* 1980 Lyman-alpha intensity becomes 10.5 kR (line center flux is deduced from the total flux assuming 1 Å equivalent width). This latter value of the Jovian Lyman-alpha intensity is consistent with the *IUE* data of the same period (see Table 1). It is general consensus that Hinteregger's measurements give higher values of Lyman-alpha flux than those of other experimenters. We have, therefore, deliberately used a lower value for the solar flux at Lyman-alpha consistent with Mount's measurements and the above empirical relation. Note, however, that even with Hinteregger's fluxes, the *Copernicus* 1980 measurements yield significantly lower Jovian Lyman-alpha intensity than did the *Voyager* observations in 1979.

One further effect that could potentially result in a higher actual Lyman-alpha intensity at Jupiter than that observed by *Copernicus* from the Earth orbit is the absorption in the interplanetary medium. The absorption in the Sun-planet axis is approximately the same as in the line of sight. Calculations for interplanetary absorption in the line of sight yield a "maximum" one-way optical depth of approximately 0.1 for the Jovian observations (Bertaux *et al.* 1980). The angle between the line of sight and the downward interplanetary absorption for the 1980 *Copernicus* observations, however, was close to 90°; the appropriate optical depth for this geometry is nearly zero. Thus, correction for the interplanetary medium absorption is not required for the Jovian Lyman-alpha intensities measured by *Copernicus*. For Saturn observations from the Earth orbit, however, the correction due to the interplanetary absorption is large (see Barker *et al.* 1980).

The Jovian Lyman-alpha intensity is a function of the solar Lyman-alpha flux as well as the abundance of the hydrogen atoms in the Jovian thermosphere. In the absence of energetic particle impact on H_2, the hydrogen atoms are produced by the EUV dissociation and ionization of H_2, as discussed in detail later in this section. Therefore, we show in Figure 5 the behavior of the Jovian Lyman-alpha intensity both with the solar Lyman-alpha flux and the $\bar{F}_{10.7\ \mathrm{cm}}$ flux. The solar Lyman-alpha flux has been deduced from the empirical relation (1). The variation of the EUV flux is represented in Figure 5 by the variation in the $\bar{F}_{10.7\ \mathrm{cm}}$ flux which has been monitored continuously over the last solar cycle. Hinteregger, Fukui, and Gilson (1981) find that the solar Lyman-alpha flux and the EUV flux are generally correlated with the $\bar{F}_{10.7\ \mathrm{cm}}$ flux.

We will now examine the characteristics of the Jovian Lyman-alpha variation from 1967 through 1980. For the period from 1967 to 1971, the top panel of Figure 5 suggests that, within the range of statistical uncertainties, the variation of the Jovian Lyman-alpha intensity is proportional to the change in the $\bar{F}_{10.7\ \mathrm{cm}}$ flux. During the same period, however, there is virtually no change in the solar Lyman-alpha flux. This effect is illustrated even more dramatically in the bottom panel of Figure 5 where all parameters have been normalized to their respective 1976 January values. Between 1971 and 1974, the Jovian Lyman-alpha intensity decreased by about a factor of 10, while the decrease in the $\bar{F}_{10.7\ \mathrm{cm}}$ flux was only about a factor of 2, and the solar Lyman-alpha flux changed hardly any at all (Fig. 5, *bottom panel*). No observations were done from 1974 to 1976. Between 1976 and 1979, the Jovian Lyman-alpha intensity increased by about a factor of 5, the $\bar{F}_{10.7\ \mathrm{cm}}$ flux by a factor of 2.5 and the solar Lyman-alpha by a factor of 1.6. Although all the quantities increased between 1967 and 1979, there is no direct proportionality between them. Furthermore, from 1979 *Voyager* observations to the 1980 *Copernicus* observations, there is, in fact, a decrease in the Jovian Lyman-alpha intensity from 14 kR to 7 kR, while both the $\bar{F}_{10.7\ \mathrm{cm}}$ flux and the solar Lyman-alpha flux continue to increase. Thus, considering all the observations between 1967 and 1980, we do not find an obvious correlation between the Jovian Lyman-alpha intensity and the solar activity. Vidal-Madjar, Emerich, and Cazes (1980) also did not find the Jovian Lyman-alpha to be always linearly correlated with the solar activity, although their suggestion of solar wind effect for reconciling this discrepancy cannot be substantiated. In the pre-*Voyager* work of Cochran and Barker (1979), a nearly opposite conclusion was reached on the basis of the behavior of the Jovian Lyman-alpha intensities through 1978 and the Zürich sunspot number. As we mentioned earlier, quantitative correlation based on the Zürich sunspot number can be misleading. Indeed, one would reach a similar qualitative conclusion as in Cochran and Barker, by comparing in Figure 5 the behavior of the Jovian Lyman-alpha intensity at least through 1979 with the $\bar{F}_{10.7\ \mathrm{cm}}$ flux, i.e., the two go up or down in unison.

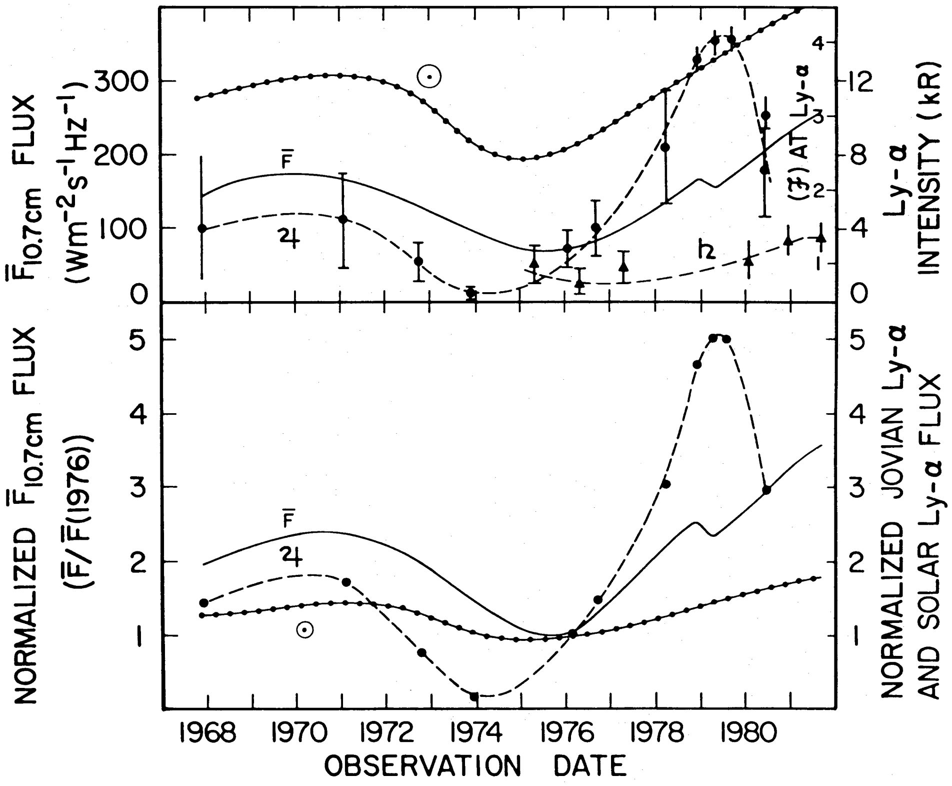

FIG. 5.—*Top panel*: temporal variations of Jupiter (♃) and Saturn (♄) Lyman-alpha intensities, solar $\bar{F}_{10.7\,\mathrm{cm}}$ flux ($\bar{F}$), and solar Lyman-alpha flux (⊙, $\mathscr{F}$ at Lyman-alpha in 10^{11} photons cm^{-2} s^{-1}). Open-ended error bars imply rough estimates of the uncertainties as the error analyses have not been completed. Actual $\bar{F}_{10.7\,\mathrm{cm}}$ fluxes are used for the dates of the planetary Lyman-alpha observations; monthly averages of the $\bar{F}_{10.7\,\mathrm{cm}}$ fluxes were used for periods between the dates of the planetary Lyman-alpha observations. *Bottom panel*: same as above, except that the solar $\bar{F}_{10.7\,\mathrm{cm}}$ and Lyman-alpha fluxes have been normalized to their corresponding values on 1976 Jan 5. The Jupiter Lyman-alpha intensities have been normalized to the Jupiter intensity on 1976 Jan 5. For normalization, the central values of the Jupiter Lyman-alpha intensities were used. To avoid crowding of the data points, the 1980 April, May and 1980 May 3 intensities (last two entries in Table 1) have been averaged in the bottom panel. For the 1979 March–July period, only *Voyager* data are shown, since they are not contaminated by the non-Jovian emissions, and since the calibration of the *Voyager* UV spectrometer has been verified and established at Lyman-alpha (see text).

Saturn Lyman-alpha data (Table 2) shown in Figure 5 (*top panel*) do not appear to behave in the same manner as the Jovian Lyman-alpha. Between the first *Copernicus* observations in 1976–1977 (average ~1.5 kR) and the latest one in 1981, there has been a factor of 2 increase in the Saturnian Lyman-alpha. The solar Lyman-alpha flux during the same period increased by a factor of 1.6. Caution must be used in interpolating between the Saturn Lyman-alpha data points; during the period when the Jovian Lyman-alpha intensity shows a large maximum (1979 March), there are no Saturn Lyman-alpha observations. Thus, it is not possible to exclude a maximum in the Saturn Lyman-alpha about 1979 March. We shall, however, argue later that the Saturn intensities may not in fact depart much from the broken line interpolation between data points shown in Figure 5 (*top panel*). The situation at Jupiter was probably unusual at the time of the *Voyager* encounter.

In order to understand the apparent lack of coherence between the variations of the Jovian Lyman-alpha intensity and the solar Lyman-alpha flux or the $\bar{F}_{10.7\,\mathrm{cm}}$ flux, we re-examine below the mechanisms responsible for the production of the Jovian hydrogen atoms and the excitation of the Lyman-alpha emission. The nonauroral Jovian (and Saturnian) Lyman-alpha is excited principally by resonance scattering of the solar Lyman-alpha photons by the hydrogen atoms which lie above the methane homopause, since methane is a strong absorber of the Lyman-alpha photons. Direct excitation by photoelectrons accounts for only a small percentage of the total (Waite *et al.* 1982). Excitation by magnetospheric soft electrons also makes a relatively small contribution to the Jovian Lyman-alpha emission rate on the dayside. During the *Voyager 1* encounter at Jupiter, for instance, the Lyman-alpha emission rate was almost 14 kR on the day side (Table 1), while at night it dropped to a meager 0.7 to 1 kR (Broadfoot *et al.* 1981*a*). The night side emission in the equatorial and mid-latitude region is most likely caused by the electron excitation. Photoelectrons and energetic electrons, however, influence the emission rate on the day side indirectly by contributing to the atomic hydrogen abundance in the upper atmosphere.

Whenever an H_2 molecule is ionized or dissociated by continuous absorption of solar EUV below 911 Å or in the Lyman and Werner bands above 911 Å, two

TABLE 2

SATURN LYMAN-ALPHA[a]

Observation Date	Observation Technique	Observed Lyα Intensity (kR)	Central Disk Lyα Intensity (kR)	References
1975 Mar 15	Rocket	0.7 ± 0.35	2.0 ± 1.0	1
1976 Apr 15	*Copernicus*	0.45 ± 0.25	1.1 ± 0.6	2
1977 Apr 28–30	*Copernicus*	0.8 ± 0.3	1.9 ± 0.7	2
1980 Jan 19	*IUE*	0.8	2.1	3
1980 May 5	*IUE*	1.8 (auroral)	5.0 (auroral)	3
1980 Nov 12	*Voyager 1*	3.3	3.3	4
1981 Aug	*Voyager 2*	3.0	3.0	5

[a] Intensities adjusted for interplanetary absorption, slit size, and limb darkening.

REFERENCES.—(1) Weiser *et al.* 1977. (2) Barker *et al.* 1980. (3) Clarke *et al.* 1981. (4) Broadfoot *et al.* 1981*b*. (5) Sandel *et al.* 1982.

hydrogen atoms are ultimately created. Once produced, the hydrogen atoms flow downward to a region where the dominant loss mechanism is three-body recombination involving H, C_2H_2, and H_2 near the homopause, or H, H, and H_2 in the deeper, denser atmosphere. This scheme is illustrated below:

$$\begin{array}{lll}
H_2 + h\nu & \rightarrow H + H & R1 \\
 & \rightarrow H_2^+ + e & R2 \\
 & \rightarrow H^+ + H + e & R3 \\
H_2^+ + H_2 & \rightarrow H_3^+ + H & R4 \\
H^+ + H_2 + H_2 & \rightarrow H_3^+ + H_2 & R5 \\
H_3^+ + e & \rightarrow H_2 + H & R6 \\
H + C_2H_2 + H_2 & \rightarrow C_2H_3 + H_2 & R7 \\
H + C_2H_3 & \rightarrow C_2H_2 + H_2 & R8 \\
H + H + H_2 & \rightarrow H_2 + H_2 & R9
\end{array}$$

Small amounts of atomic hydrogen are also produced in the pressure region greater than 0.1 mb by photolysis of CH_4, NH_3, and PH_3.

Energetic electrons or other charged particles and ions dissociate H_2 at high latitudes and provide additional source of H atoms. For example, our calculations indicate that the atomic hydrogen production rate in the auroral zone with a 10 keV monoenergetic beam of electrons and energy flux of 5 ergs cm^{-2} s^{-1} is about a factor of 100 greater than that due to the EUV dissociation of H_2 (Waite *et al.* 1982). Even if it is globally averaged, the auroral production rate of atomic hydrogen is found to be approximately 5 times greater than that due to the EUV source alone. Earlier calculations designed to explain a bulge observed in Jovian Lyman-alpha intensity on the basis of co-rotating magnetospheric convection also showed that energetic electrons can increase the hydrogen atom abundance by the required factor of 3 (Dessler, Sandel, and Atreya 1981). Hydrogen atoms produced at high latitudes would flow to lower latitudes; the efficiency of such transport is not known due to lack of data on the dynamics of the thermosphere.

Returning to the Jovian Lyman-alpha variation (Fig. 5, *bottom panel*), we find that the change between 1967 and 1971 is more or less directly proportional to the $F_{10.7\ \mathrm{cm}}$ flux, hence to the EUV production of atomic hydrogen. There is little change in the solar Lyman-alpha flux during this period. The 1973/1974 *Pioneer* data appear to be anomalously low; it should, however, be noted that the uncertainty in these data is large. The correlation between the 1967 to 1976 Jovian Lyman-alpha and the $F_{10.7\ \mathrm{cm}}$ would indeed be much better if the *Pioneer 10* data were ignored. We shall discuss later in this section the implications on the mixing terms, if the *Pioneer* data were not considered. Once again, between 1976 and 1979, there is hardly any correlation between the production of atomic hydrogen by EUV and the observed Jovian Lyman-alpha intensity—except that they are both increasing. At the time of the *Voyager* encounter, for instance, the EUV can produce a hydrogen atom column abundance of 2×10^{16} cm^{-2}; while 10^{17} cm^{-2} are needed to account for the 14 kR of Lyman-alpha observed (these estimates assume the homopause value of the eddy diffusion coefficient of 1.4×10^6 cm^2 s^{-1}, which is appropriate for the *Voyager* encounter—Atreya, Donahue, and Festou 1981). The additional atoms were probably produced by energetic charged particles in the auroral region (Yung and Strobel 1980) and were transported to the equatorial region where the observations were made. This explanation is compatible with the fact that although solar EUV and Lyman-alpha flux have increased somewhat since 1979, the observations from *Copernicus* in 1980 show a sharp reduction in the Jovian Lyman-alpha intensity. It is suggested that auroral activity was stronger at the time of the *Voyager* encounter than at the time of the recent *Copernicus* observations. The first detection of a diffuse Jovian aurora was reported by *Voyager 1* in 1979 (Broadfoot *et al.* 1979; Broadfoot *et al.* 1981*a*; Sandel *et al.* 1979). About 80 kR of H_2–Lyman and Werner band, and about 60 kR of H–Lyman-alpha emissions, were observed. These intensities imply an energy input of 5–10 ergs cm^{-2} s^{-1} in the region magnetically connected to the Io plasma torus (Atreya, Donahue, and Festou 1981; Broadfoot *et al.* 1981*a*). Auroral hot spots at Lyman-alpha detected by Atreya *et al.* (1977) are less than 1000 km in diameter. Their observed intensity of $\sim$300 kR would mean an energy influx of several hundred ergs cm^{-2} s^{-1}. Even if this energy were uniformly distributed over the entire planet, it would still be a small fraction of the global average energy input implied from the *Voyager* diffuse auroral data. As discussed in this section, the 1980 *Copernicus* data imply a lower auroral activity on Jupiter at that time, with an energy input considerably less than at the *Voyager* epoch, nearly a year earlier.

The auroral activity on Jupiter is related to the Io plasma torus (Broadfoot *et al.* 1979; Thorne and Tsuratani 1979), and there are numerous evidences of its temporal variability. The Io plasma torus consists of S^+, S^{++}, S^{3+}, O^+, O^{++}, and $S_2{}^+$ or $SO_2{}^+$ (Broadfoot *et al.* 1979; Bridge *et al.* 1979). The source of these ions is presumably SO_2 outgassed from the volcanoes on Io (Pearl *et al.* 1979; Hanel *et al.* 1979; Smith *et al.* 1979*a*; Smith *et al.* 1979*b*). Photolysis and subsequent ionization of SO_2 and products probably provide the ions seen in the torus (Kumar and Hunten 1981). The ions in Io's orbit are accelerated in the co-rotating magnetosphere and must transfer energy to the electrons in the plasma. The mechanism by which energy is supplied to the plasma torus is not entirely understood. Perhaps electron-electron heating plays a major role (Shemansky and Sandel 1981). In any event, it is expected that the variations in the Io-plasma torus density and temperature would lead to changes in the auroral energy input on Jupiter. Large fluctuations in the Io-plasma have been seen in the ground-based data spanning several years (see review in Pilcher and Strobel 1982). Recent observations of the S^+ doublet covering a period from 1980 January to 1981 May indicate change by a factor of 10 in the plasma electron concentration (Morgan 1981). Ionospheric density and conductivity considerations argue for greater Io plasma considerations at the time of the *Voyager* observations (Strobel and Atreya 1982). Re-interpretation of the *Pioneer 10* plasma data also indicates that the plasma torus was perhaps less dense in 1973–1974 than during the *Voyager* observations in 1979 (Intrilligator and Miller 1981; A. J. Dessler 1981, private communication). Another possibility is that the apparent lower Io plasma concentration detected by *Pioneer 10* might have been the result of a longitudinal effect—*Pioneer 10* did not go through the active sector, while *Voyager 1* did on the inbound trajectory. The present view, however, is that the plasma concentration in the Io torus at the time of the *Pioneer* encounter may have been approximately 1/25 of the concentration found by *Voyager* (Walker and Kivelson 1981*a*, *b*). Lower Io plasma concentrations are also consistent with the interpretation of *Pioneer* UV, and ground-based data (Mekler and Eviatar 1980). The auroral hot spots detected at the feet of the Io flux tube on Jupiter in 1976 by Atreya *et al.* (1977) can be understood if the torus plasma was less dense than during *Voyager* encounter. This would have facilitated the flow of current from Io to Jupiter (Dessler and Chamberlain 1979). During the *Voyager* observations when the Io plasma torus density was quite high, no auroral hot spots were apparent in the preliminary analysis of the UV spectrometer data (Broadfoot *et al.* 1981*a*). The absence of Io related hot spots in the *Voyager* data can also be explained by longitudinal gradient in the torus causing Birkeland currents to the Jovian ionosphere (Dessler 1980). Caldwell, Tokunaga, and Orton (1982) have observed 8 μm brightnings in the zenographic latitude range 65°–70° which is nearly identical with the range of auroral hot spot observations of Atreya *et al.* (1977). It is conceivable that Caldwell's data represent auroral hot spots. Some of Caldwell's observations were done at about the same time as the 1980 *Copernicus* Lyman-alpha dayglow observations; the others were done in 1981.

There is also great variability in the diffuse auroral H_2-band emissions. Between the time of *Voyager 1* and *Voyager 2* observations, their intensity dropped by a factor of 2 in the northern hemisphere (Broadfoot *et al.* 1981*a*). Larger daily variations in the auroral intensity have been noticed in the *IUE* data (Clarke *et al.* 1980*a*). The temporal variation in auroral activity on Jupiter would consequently lead to temporal variation in the atomic hydrogen abundance. Drastically lower auroral energy input during the time of the *Pioneer* observations would leave only dissociation by solar EUV as the source for H. Hence, the H–Lyman-alpha intensity would have been considerably below that detected at the time of *Voyager*. Again, the decrease in Lyman-alpha intensity between *Voyager 1* and *Copernicus* observations is most likely to be explained by a lower auroral energy input. It is interesting to note that the appearance of the hot spots at the Io footprint is associated with low Jovian Lyman-alpha airglow intensity (Atreya *et al.* 1977; Caldwell *et al.* 1982; and the present paper). It is consistent with the explanation mentioned above that low Io plasma concentration is needed to facilitate the flow of current (from Io to Jupiter) and permit excitation of the auroral hot spots. The lower Io plasma concentration is also expected to result in the lower auroral energy input on Jupiter, hence lower atomic hydrogen production, which would in turn lead to lower resonantly scattered Lyman-alpha airglow. The opposite would be true if the Io plasma concentration were large, as is indeed the case at the *Voyager* Jupiter epoch.

Although the major factor affecting the production of hydrogen atoms in the nonauroral region is solar EUV, vertical mixing in the atmosphere may play a significant role. Only during the *Voyager* encounter was it possible to directly determine the homopause level in a stellar occultation experiment and from it deduce the corresponding eddy diffusion coefficient, K_h, where $K_h = 1.4^{+0.8,-0.7} \times 10^6$ cm^2 s^{-1} (Atreya, Donahue, and Festou 1981; Festou *et al.* 1981). A similar value from the equatorial eddy diffusion coefficient follows from the analysis of He-584 Å airglow data (McConnell, Sandel, and Broadfoot 1980) once the appropriate temperature structure of the emitting region is taken into account (Festou *et al.* 1981; Atreya, Donahue, and Festou 1981). One can indirectly deduce the eddy coefficient at the homopause by determining the column abundance of H above the methane homopause from the knowledge of the observed Lyman-alpha intensity (Hunten 1969). According to a theory developed by Wallace and Hunten (1973), this column abundance would be an inverse function of the eddy mixing coefficient, provided that the hydrogen atoms are produced by the EUV absorption by H_2. After adjusting the Wallace and Hunten formulation for a hot thermosphere (their theory was for a cold exosphere without a temperature gradient in the thermosphere) and allowing for the loss of H by reaction with C_2H_2 (reactions *R*8 and *R*9 are important for a high homopause), we find that the vertical mixing in the Jovian atmosphere must have a large temporal variation. At the *Pioneer* epoch, the homopause value of the eddy diffusion coefficient, K_h, approaches 10^8 cm^2 s^{-1} while it is only about 10^6 cm^2 s^{-1} during the *Voyager* observations. An important caveat to remember in the determination of K_h is that one needs not only the knowledge of H abundance (from Lyman-alpha intensity) but also the temperature structure of the scattering region. Only a rough estimate of the "exospheric" temperature—not the temperature profile in the thermosphere—was available from the plasma scale height measurement at the *Pioneer* epoch. If the *Pioneer 10* Lyman-alpha data were ignored, and a thermospheric temperature profile similar to the *Voyager* epoch (Atreya, Donahue, and Festou 1981) assumed, we would find K_h to lie between 10^6 cm^2 s^{-1} and 10^7 cm^2 s^{-1} during the last solar cycle. The latest *Copernicus* data (Lyman-alpha = 7 kR in 1980) would imply K_h on the order of 10^7 cm^2 s^{-1}, assuming that 50% of the H atoms have been produced by the auroral electrons. Unlike in the case of *Voyager* Lyman-alpha, a relatively small auroral source of H atoms is needed, since our photochemical calculations alone yield the H abundance to be deficient by slightly less than a factor of 2 for explaining the *Copernicus* observations. The temperature profile and other relevant atmospheric parameters used for deducing the above value of K_h are the same as those determined by the *Voyager* UV occultation technique a year earlier (Atreya, Donahue, and Festou 1981). It should be emphasized that all the Lyman-alpha data shown in Tables 1 and 2 are for equatorial and mid-latitude regions. Therefore, except for the times when H atoms enhancement is expected due to high auroral activity, one should be able to determine the vertical mixing coefficient with reasonable accuracy from the observed Lyman-alpha intensity.

The Saturn Lyman-alpha data do not indicate contribution to the population of hydrogen by electron impact on H_2. Indeed, EUV absorption by H_2 is adequate to account for the hydrogen abundance needed to explain the observed Lyman-alpha intensity. Taking account of an increase by a factor of about 3 in the solar EUV flux between 1976 and 1980, and assuming an average Lyman-alpha intensity of 1.5 kR for Saturn Lyman-alpha in 1976–1977, and 3.3 kR for 1980 (Table 2), we find from our model (Atreya 1982) that K_h should have decreased only slightly from a value of approximately 10^8 cm^2 s^{-1}, in 1976. Meospheric turbulent mixing, particularly around 1979–1980, appears to be somewhat stronger on Saturn than on Jupiter.

IV. CONCLUSIONS

Taking into consideration the 1980 *Copernicus* Jovian Lyman-alpha emission data reported here, it is difficult to escape the conclusion that an unusually large energy input due to the particle precipitation in the auroral region must have been responsible for the large observed Lyman-alpha intensity during the *Voyager* encounter. At most other times, the observed Jovian Lyman-alpha intensity can be explained, within the range of statistical uncertainty, by a model that takes into consideration the solar EUV flux, the solar Lyman-alpha flux, the high exospheric temperature, and the eddy diffusion coefficient without energy input from the auroral sources. Since at the auroral latitudes of Saturn the energy input is only about 1% of that in the Jovian high latitudes (Atreya and Waite 1981; Broadfoot *et al.* 1981*a*; Broadfoot *et al.* 1981*b*), hydrogen atom production due to the energetic particle impact on H_2 on Saturn should not be appreciable. The *Copernicus* 1980 Jovian Lyman-alpha data also indicate that the upper atmospheric vertical mixing on Jupiter is highly variable and is likely less efficient on Jupiter now than on Saturn.

Discussion with A. J. Dessler on the variability of Io plasma torus has been beneficial. The research at the University of Michigan was sponsored by the National Aeronautics and Space Administration under grants NAG5-109 from the *OAO-Copernicus* program, and NSG-7404 from the Planetary Atmospheres Program of the Earth and Planetary Exploration Division. E. S. B. and W. D. C. acknowledge the support from NASA grants NAG5-114 and NGR 44-012-152.

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Note added in proof.—We have learned recently that the *Pioneer 10* UV photometer has been recalibrated so that the revised *Pioneer 10* Jovian Lyman-alpha intensity is 1 kR (Judge 1982). The higher value (up from the earlier 0.4 kR) would be more consistent with the variation in the Jovian Lyman-alpha at other times, as discussed in § III of this paper. It would also imply a much lower value of the eddy mixing coefficient, K_h, in 1973/1974 than that based on 0.4 kR Lyman-alpha intensity. The new value of K_h lies within the range 10^6–10^7 cm^2 s^{-1} as discussed in § III.

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