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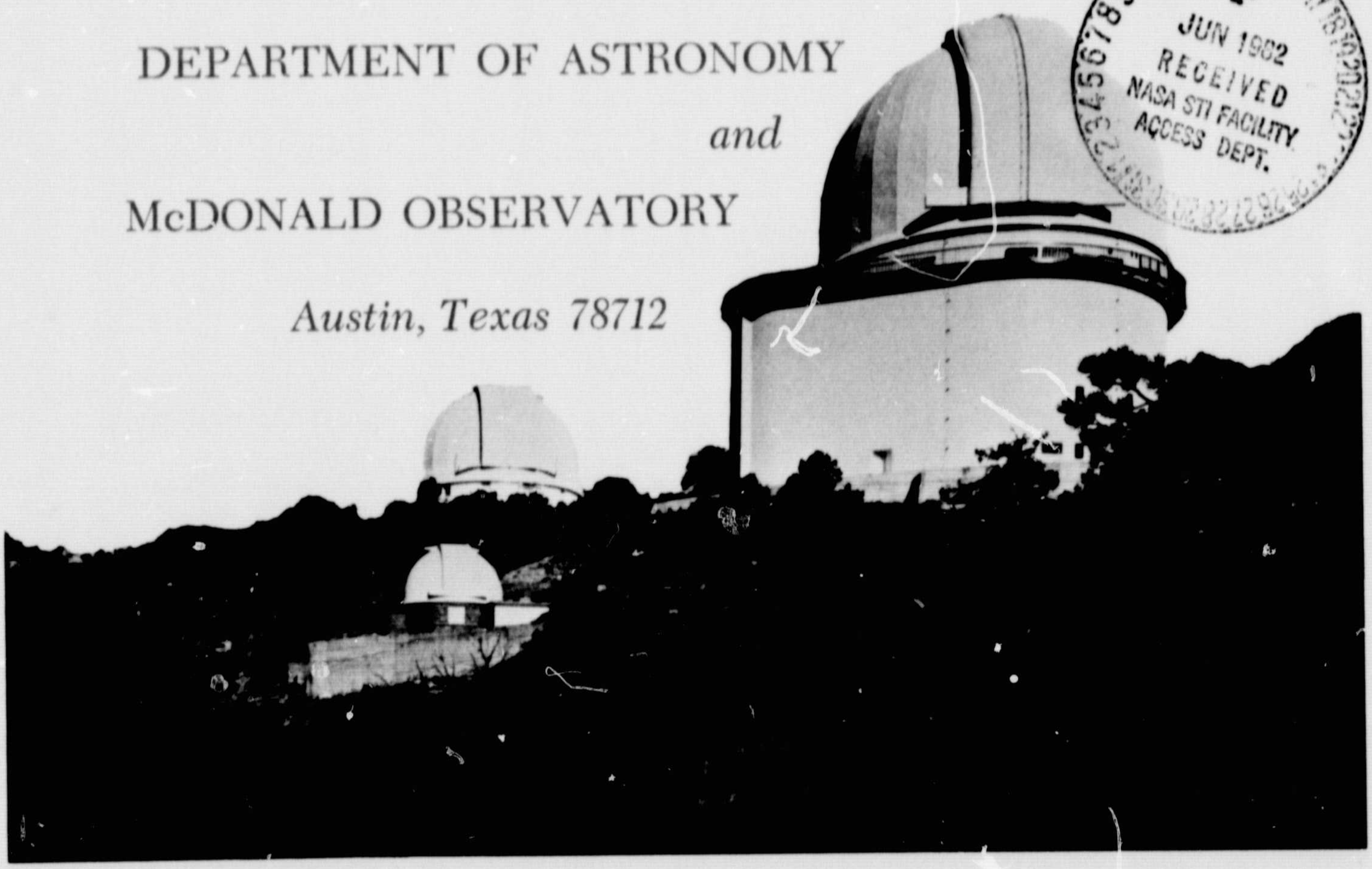

Doppler Line Profiles Measurement

Of The Jovian Lyman Alpha Emission with OAO-C

FINAL TECHNICAL REPORT UNDER NAG 5-114

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INTRODUCTION

We proposed to study the shape of the Jovian Lyman alpha line during the 1979/1980 period using the high resolution spectrometer aboard _Copernicus_ (OAO-C). Previously published observations using the spectrometers on _Copernicus_ (OAO-C), Voyager I and II, and IUE indicated an increase in the Lyman alpha signal strength and line width between 1976 and 1979. We proposed to measure both the line width and line strength in the spring of 1980 during the period of maximum Doppler shift between the Jovian and telluric Lyman alpha emission lines. Since similar proposals were also submitted from others, a team of co-investigators was assembled from these proposals, consisting of Drs. Sushill Atreya, Thomas Donahue, and Michael Festou from the University of Michigan; Edwin Barker and William Cochran from the University of Texas at Austin; Jean Bertaux from the Centre National de la Recherche Scientifique, France; and the observations were coordinated by Walter Upson, II from Princeton University.

SUMMARY

In this section we will briefly summarize the data acquisition and reduction procedures and present the conclusions derived from these observations. The appendix contains the scientific paper which gives a detailed description of the observations and development of the conclusions. This paper has been accepted for publication in the Astrophysical Journal.

The data were acquired during two periods of concentrated _Copernicus_ viewing from April 1 to April 9 and from April 26 to May 7, 1980. Jupiter and the geocorona were observed on alternate orbits when possible to insure a concurrent calibration of the geocoronal and Jovian signals.

This technique proved to be quite valuable later in the data reduction procedures. Because the sensitivity of Copernicus at Lyman alpha had decreased about a factor of ten since launch, a large number of scans were required to reach a signal-to-noise ratio of 2:1. After removing the noisy scans, 82 spectra of the geocorona and 144 spectra of Jupiter plus geocorona were recorded during the first period. The second observing period yielded 101 spectra of the geocorona alone and 218 spectra of Jupiter plus geocoronal emission. Initial processing of the data at Princeton by Barker and Upson using the standard techniques indicated a more detailed and complicated data reduction procedure was needed to extract the much weaker the expected Jovian signal for the geocoronal contamination. This new procedure was developed and carried out by Festou and Kerr at the University of Michigan. We were able to subtract the geocorona by using geocoronal orbits with the same viewing geometry as the Jovian orbits. Several iterations were carried out and the results were circulated to the team members for approval and comments. This process culminated in the spectra plotted in Figures 2 and 3 of the paper in the appendix.

Using the geocoronal scans separately to calibrate the sensitivity of the spectrometer, we found two unexpected results: (1) The Jovian Lyman alpha emission of 7$\pm$2.5kR was significantly lower than the 14kR found by Voyager I and II about a year before. This is contrary to the predictions that the Lyman alpha signal depends on the level of solar activity. (2) The line width was comparable to the geocoronal width of 70 mA. This value is smaller than measured in 1976, 77 and 78. Since the line width values have been determined by different data reduction procedures and the very low signal-to-noise ratio in the wings of the 1980 profile, we do not consider this apparent variation to be significant. There is only an indication that the line was wider in 1978 implying a greater column density of atomic hydrogen and a greater Lyman alpha intensity.

The following arguments have been developed (primarily by S. Atreya) to explain the variation of the Jovian line strength. 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 bonbardment 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 which was observed during the Voyager encounters.

APPENDIX

The following paper has been accepted for publication in the Astrophysical Journal.

COPERNICUS MEASUREMENT OF THE JOVIAN LYMAN-ALPHA EMISSION IN 1980, 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 April and May, 1980, 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 two 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 is interesting to note 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 non-auroral region.

Subject headings: planets: atmospheres -- planets: Jupiter -- planets: Saturn -- planets: satellites -- planets: spectra

Running Title: Jovian Lyman-Alpha

1. INTRODUCTION

The Jovian Lyman-alpha intensity is a good indicator of the principal aeronomical processes on that planet. 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 Spectromter measurements in 1979. The high-resolution ultraviolet spectrometer aboard the Orbiting Astronomical Observatory Copernicus was used in April and May, 1980 to detect the Jovian Lyman-alpha emission by spectroscopically discriminating it from other doppler shifted Lyman-alpha emissions such as geocorona, Io, Io-torus, etc. The results 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.

2. OBSERVATIONS AND DATA REDUCTION

Observations of the Jovian Lyman-alpha emission were carried out in April and May, 1980, with the U1 spectrometer (resolution of 0.06Å at 1216Å) of the Copernicus satellite, which is in a geocentric orbit of approximately 750 km altitude and inclination 35°. The pointing accuracy of the telescope is a few arc sec. The angular dimensions of the spectrometer slit are 0.3" x 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) April 1 to April 9, 1980: 82 spectra of the geocorona were recorded by offsetting the instrumental slit by about one degree 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) April 26 to May 7, 1980: 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

4th panel of Fig. 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 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 April and May 1980 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 3σ 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. Superimposed on the May 1980 geocorona signal, the normalized 1974 geocorona emission is shown by a dashed line: note the good reproducibility of the measurements obtained six years apart. The May 1980 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 linewidth 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. Because those values have been obtained by different reduction procedures implying very large error bars on this particular parameter, we do not consider this apparent variation of the linewidth of the Jovian emission to be signficant. 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 *Copernicus* calibration procedure has been described in detail in previous publications (Bertaux, et al., 1980; 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 6.5×10^4 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. The Lyman-alpha flux used in the Bertaux, et al. calculations was 2.13×10^{11} photons cm^{-2} $Å^{-1}$ s^{-1} and the geocorona emission computed for the May 1980 period is found to be 3.65 kR. Thus, the M-factor if calculated to be 0.022 counts Å kR^{-1} using the above flux. The solar Lyman-alpha flux appropriate for the May 1980 period, however, is 4.5×10^{11} photons cm^{-2} s^{-1} $Å^{-1}$ (see Section 3) which results in the proper value of the 'M-factor' to be 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 ±35% due largely to the loss in the instrumental sensitivity which has decreased by a factor of about 10 between September 1976 and April 1980, necessitating enormous integration times even for bright sources such as Jupiter.

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3. 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 UV 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 Voyager 1 and 2 and IUE. *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 potential sources, such as the geocoronal, Io, and the Io-torus. 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. Because equatorial and mid-latitude Jovian Lyman-alpha is presumably excited by resonance scattering of the solar Lyman-alpha photons by hydrogen atoms in the Jovian upper atmosphere, it is instructive to plot this intensity against the solar Lyman-alpha flux. Unfortunately, very few measurements of 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 following empirical relationship between the solar Lyman-alpha flux ($\mathcal{F}$) and the $F_{10.7\ cm}$-flux, F,

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

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, April - May, 1980, 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 July 1980 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 measurement 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 $cm^{-2}\ s^{-1}\ \text{Å}^{-1}$ at the line center. If Hinteregger's (1981) value for the total solar flux is assumed, the Copernicus 1980 Lyman-alpha intensity becomes 10.5 kR (line center flux is deduced from the total flux assuming 1Å 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 optical depth of 0.1 for the Jovian observations (see Bertaux, et al., 1981). Such small values of the optical depth do not require a correction in the Jovian Lyman-alpha intensities measured from the earth orbit. This fact is also evident from a comparison of the IUE and Voyager data taken at about the same time in 1979 (Table 1) -- no discrepancy exists between the IUE observations made from the earth orbit and the Voyager observations from the proximity of Jupiter. For Saturn observations from the earth orbit, however, the correction due to the interplanetary absorption is large (see Barker, et al., 1981).

In view of the above uncertainties in the solar Lyman-alpha flux, and the fact that solar Lyman-alpha is generally correlated with the variation in the $\overline{F}_{10.7\ cm}$ flux, we have chosen also to study the variation of the Jovian Lyman-alpha intensity with the $\overline{F}_{10.7\ cm}$ flux, which has been continuously monitored in the 1967-1980 period. The top panel of Figure 5 shows variation of the Jovian and Saturnian Lyman-alpha intensities, solar Lyman-alpha flux (obtained in the abovementioned manner), and the $\overline{F}_{10.7\ cm}$ flux. The Saturn Lyman-alpha intensity shown for comparison with Jovian Lyman-alpha, has been monitored only since 1975, and the statistical uncertainties there are larger owing to a weaker signal. This is a consequence of the factor of four decrease in the solar flux from Jupiter to Saturn. The bottom panel of Figure 5 displays the same information as the top panel except that all variables have been normalized to their values at the time of the solar minimum in January, 1976.

An examination of the top panel, Figure 5, suggests that within the range of statistical uncertainties there is a linear correlation between the $\overline{F}_{10.7\ cm}$ flux and the Jovian Lyman-alpha intensity from 1967 to 1971. Beyond 1971, however, no such agreement is noted. This effect is illustrated even more dramatically in the bottom panel -- there is practically no change in the solar Lyman-alpha flux between 1967 and 1971, while the quantitative change in the Jovian Lyman-alpha intensity and the $\overline{F}_{10.7\ cm}$ flux is about the same. Again, there is very little change in the solar Lyman-alpha flux between 1971 and 1974, the Jovian Lyman-alpha intensity however, decreased by a factor of 10 during the same period. Between January 1976 and March 1979, the solar Lyman-alpha flux increased by a factor of 1.6 ($\overline{F}_{10.7\ cm}$ flux increased by a factor of 2.5) while during the same period, the Jovian Lyman-alpha intensity increased by more than a factor of 5. Moreover, between the Voyager observations in 1979 and the Copernicus observations in 1980, there is, in fact, a decrease in the Jovian Lyman-alpha intensity from 14 kR to 7 kR while both the solar $\overline{F}_{10.7\ cm}$ and the solar Lyman-alpha flux continue to increase. Thus, no obvious correlation is found to exist between the Jovian Lyman-alpha intensity and the solar activity.

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 <u>Copernicus</u> 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 (March, 1979) there are no Saturn Lyman-alpha observations. Thus, it is not possible to exclude a maximum in the Saturn Lyman-alpha about March, 1979. 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 $\overline{F}_{10.7\ cm}$ flux, we re-examine below the mechanisms responsible for the production of Jovian hydrogen atoms and the excitation of the Lyman-alpha emission. The non-auroral 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. During the Voyager 1 encounter at Jupiter, for instance, the Lyman-alpha emission rate was almost 14 kR on the dayside (Table 1) while at night it dropped to a meagre 0.7 to 1 kR (Broadfoot, <u>et al</u>., 1981a). The nightside 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 dayside 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 911Å or in the Lyman and Werner bands above 911Å, two 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.

$H_2 + h\nu$	$\rightarrow$	$H + H$	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

Small amounts of atomic hydrogen are also produced in the pressure region greater than 0.1 mbar 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 with a 10 keV monoenergetic beam of electrons is calculated to be a factor of 100 greater than that due to the EUV dissociation of H_2 (Waite, et al., 1982). 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 three (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 (Figure 5, bottom panel), we find that the change between 1967 and 1971 is more or less directly proportional to the $F_{10.7\ cm}$ flux, hence to the EUV production of atomic hydrogen. There is little change in the solar Lyman-alpha flux during this period. The 1973/74 Pioneer data appear to be anomalous. It should be noted that the uncertainty in these data is large. 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, et al., 1981). The additional atoms were probably produced by energetic charged particles in the auroral region, and were transported to the equatorial region where the observations were made. This explanation is supported by 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 and 1981a; 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, et al., 1981; Broadfoot, et al., 1981a). Auroral hot-spots at Lyman-alpha detected by Atreya, et al. (1977) are less than 1000 km in diameter. Their observed intensity of ~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. The 1980 Copernicus data imply a lower auroral activity on Jupiter at that time, with an energy input perhaps 50% 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^{+++}, 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., 1979a and 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, 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 groundbased data spanning several years (see review in Pilcher and Strobel, 1981). Recent observations of the S^+ doublet covering a period from January, 1980 to May, 1981 indicate change by a factor of ten in the plasma electron concentration (Morgan, 1981). Re-interpretation of the Pioneer 10 plasma data also indicates that the plasma torus was perhaps less dense in 1973-74 than during the Voyager observations in 1979 (Intrilligator and Miller, 1981; A. J. Dessler, personal communication, 1981). 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 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, 1981a and b). Lower Io-plasma concentrations are also consistent with the interpretation of Pioneer UV, and groundbased 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 UVS data (Broadfoot, et al., 1981a). 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). 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 two in the northern hemisphere (Broadfoot, et al., 1981a). Larger temporal variation in the auroral intensity have been noticed in the IUE data (Clarke, et al., 1980).

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.

Although the major factor affecting production of hydrogen atoms in the non-auroral 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, et al., 1981; Festou, et al., 1981). A similar value from the equatorial eddy diffusion coefficient follows from the analysis of He-584Å airglow data (McConnell, et al., 1980) once the appropriate temperature structure of the emitting region is taken into account (Festou, et al., 1981 and Atreya, et al., 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 upon 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 R8 and R9 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. 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. 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-atom 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 any 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 that K_h decreased by a little less than a factor of 3 (from 5×10^7 cm^2 s^{-1} in 1976) during the same period. Mesospheric vertical mixing, particularly around 1979 - 1980, appears to be stronger on Saturn than on Jupiter.

4. 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 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 while Jovian Lyman-alpha was being monitored the observed 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 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., 1981a and b), hydrogen atom production due to 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.

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TABLE 1

JUPITER LYMAN ALPHA

OBSERVATION DATE	OBSERVATION TECHNIQUE	LYMAN ALPHA* INTENSITY (kR)	REFERENCES
1967, Dec. 5	Rocket	4.0	Moos, *et al*. (1969)
1971, Jan. 25	Rocket	4.4±2.6	Rottman, *et al*. (1973)
1972, Sept. 1	Rocket	2.1±1.0	Giles, *et al*. (1976)
1973, Dec. 3	Pioneer	0.4±0.12	Carlson and Judge (1974)
1976, Jan. 5	Copernicus	2.8±1.0	Bertaux, *et al*, (1980)
1976, Aug., Sept.	Copernicus	4.0±1.4	Bertaux, *et al*. (1980)
1976, Aug., Sept.	Copernicus	3.8±1.0	Atreya, *et al*. (1977)
1978, Mar.	Copernicus	8.3±2.9	Cochran and Barker (1979)
1978, Dec. 7	IUE	13	Clarke, *et al*. (1980)
1979, Jan., Mar., and May	IUE	14	Clarke, *et al*. (1980)
1979, Mar. to July	Voyager 1 and 2	14	Broadfoot, *et al*. (1979)
1980, April, May	Copernicus	7.0±2.5	Atreya, *et al*. (1982), this paper
1980, May 3	IUE	10	Moos (1981)

* *Copernicus* data have been adjusted for the revised geocoronal calibration according to Bertaux, *et al*. (1980).

TABLE 2

SATURN LYMAN ALPHA

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	Weiser, et al., 1977
1976, Apr. 15	Copernicus	0.45±0.25	1.1±0.6	Barker, et al., 1980
1977, Apr. 28-30	Copernicus	0.8±0.3	1.9±0.7	Barker, et al., 1980
1980, Jan. 19	IUE	0.8	2.1	Clarke, et al., 1981
1980, May 5	IUE	1.8 (Auroral)	5.0 (Auroral)	Clarke, et al., 1981
1980, Nov. 12	Voyager 1	3.3	3.3	Broadfoot, et al., 1981b

* Intensities adjusted for interplanetary absorption, slit size, and limb darkening.

FIGURE CAPTIONS

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

Figure 2. Jupiter Lyman-alpha emission profiles for the April and May 1980 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.

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

Figure 4. Jovian Lyman-alpha intensity *vs.* Zürich Sunspot number. The broken line addition toward the end of R_z represents current "Provisional values".

Figure 5. Top panel: temporal variations of Jupiter (♃) and Saturn (♄) Lyman-alpha intensities, solar $\overline{F}_{10.7\ cm}$ flux ($\overline{F}$), and solar Lyman-alpha flux (⊙, $\mathcal{F}$ 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 $\overline{F}_{10.7\ cm}$ fluxes are used for the dates of the planetary Lyman-alpha observations; monthly averages of the $\overline{F}_{10.7\ cm}$ fluxes were used for periods between the dates of the planetary Lyman-alpha observations. Bottom panel: same as above, except that the solar $\overline{F}_{10.7\ cm}$ and Lyman-alpha fluxes have been normalized to their corresponding values on 1976, January 5. The Jupiter Lyman-alpha intensities have been normalized to the Jupiter intensity on 1976, January 5. For normalization, the cen-

tral 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.

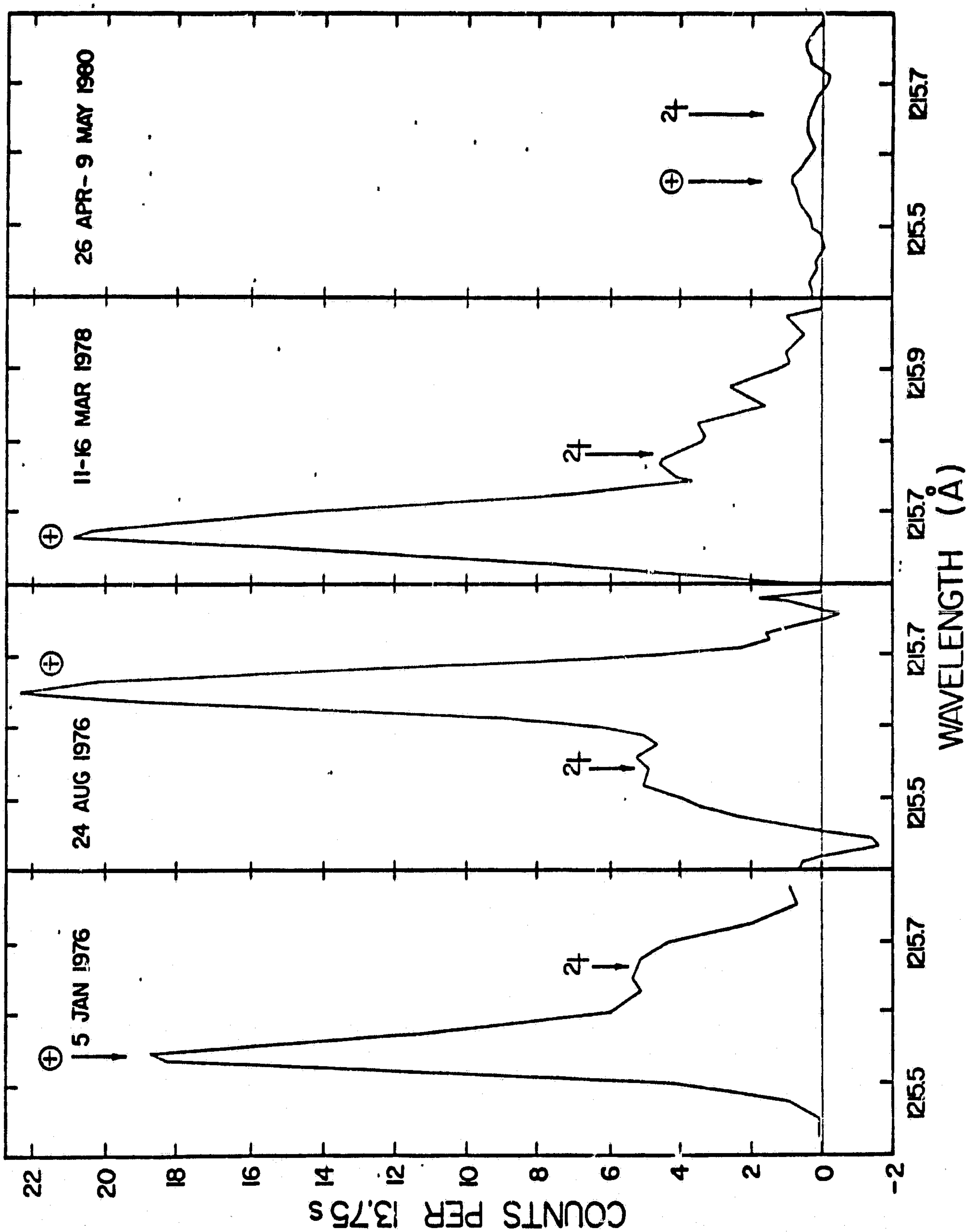
5 JAN 1976
24 AUG 1976
11-16 MAR 1978
26 APR - 9 MAY 1980
♃
⊕
1215.5
1215.7
1215.9
WAVELENGTH (Å)
COUNTS PER 13.75 s
22
20
18
16
14
12
10
8
6
4
2
0
-2

Fig. 1

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OF POOR QUALITY

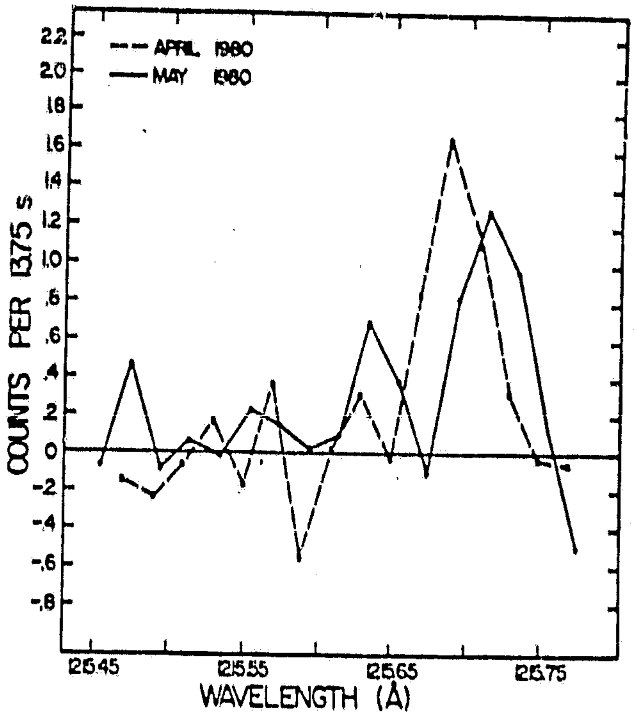
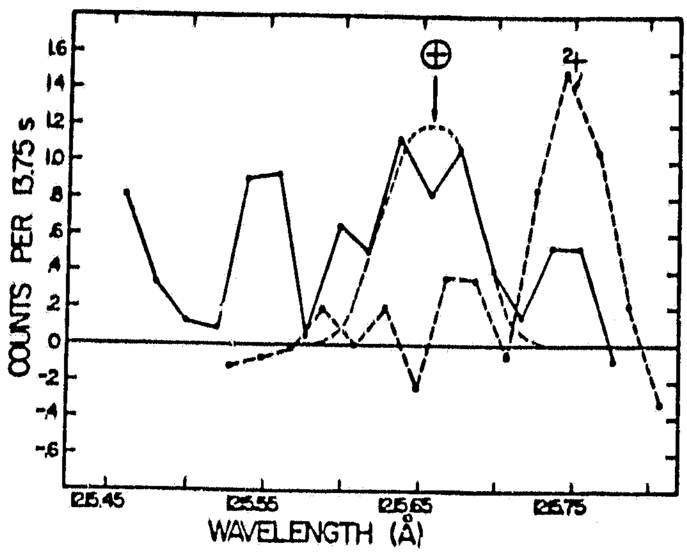


Fig. 2


COUNTS PER 13.75 s
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
-.2
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⊕
2+
1215.45
1215.55
1215.65
1215.75
WAVELENGTH (Å)

Fig. 3

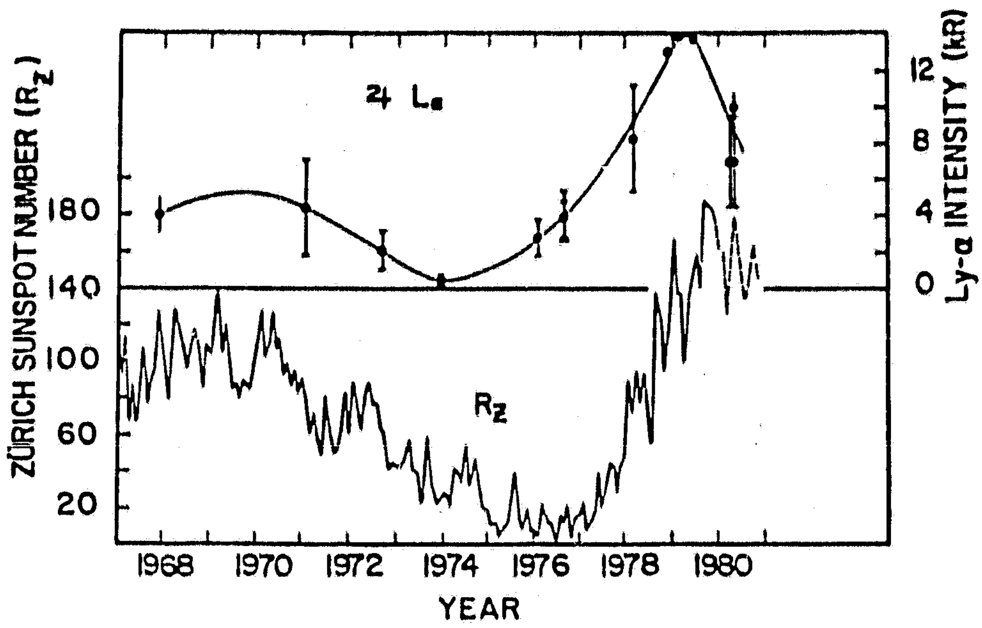
2I L_α
R_Z
ZÜRICH SUNSPOT NUMBER (R_Z)
Ly-α INTENSITY (kR)
20
60
100
140
180
0
4
8
12
1968
1970
1972
1974
1976
1978
1980
YEAR

Fig. 4

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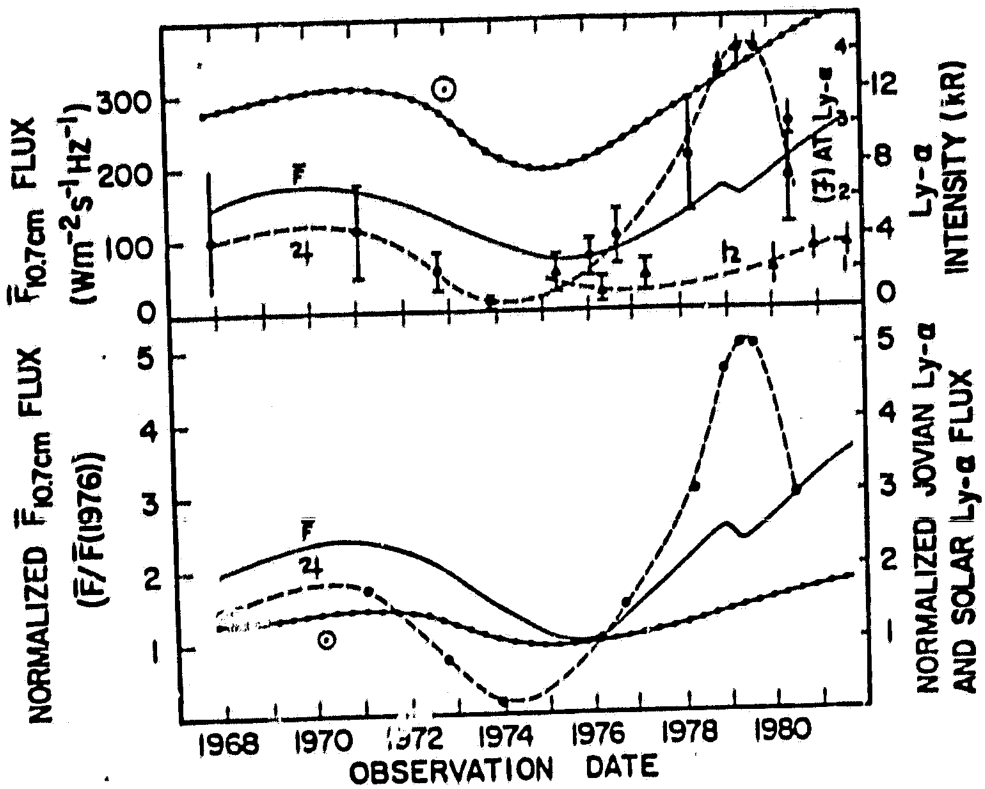

Fig. 5