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Dr. Genevieve E. Wiseman
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Dear Dr. Wiseman,

Enclosed is the final technical report for NASA Grant NSG 5236 entitled "Copernicus Satellite Observations of Raman Scattered Lyman Alpha Radiation from Jupiter". Principal investigations for this grant are Drs. L. M. Trafton and W. D. Cochran. This technical report is the text of a research paper being submitted to Astrophysical Journal Letters. We apologize for the delay in submitting this report.

Sincerely,

William D Cochran

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WC:df
enc.

VARIABILITY OF LYMAN-ALPHA EMISSION FROM JUPITER

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and

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ABSTRACT

The Jovian Lyman-alpha emission line was reobserved in March 1978 using the high resolution spectrometer on the Copernicus satellite. In intensity of 8.4 ± 3.0 kilo Rayleighs was measured. This value represents a significant increase in intensity over previous (1976) Copernicus observations, but is lower than the recent (1979) values obtained by Voyager I and IUE. The increase in intensity has been accompanied by a significant increase in line witdth, giving strong support to the theory that the emission results from resonant scattering of the solar Ly-α line by H atoms in the upper Jovian atmosphere. The strength of Jovian Ly-α emission correlates well with the level of solar activity. The solar extreme ultraviolet radiation varies with the solar cycle. This radiation causes the dissociation of H_2 and CH_4 into H atoms in the Jovian atmosphere. Therefore, in times of high solar activity, the H column density will increase, causing the observed stronger Jovian Ly-α emission.

I. INTRODUCTION

The intensity of Lyman-alpha emission from Jupiter has been measured several times during the last decade. These results, obtained from a wide variety of instruments, are summarized in Table 1. The observed intensities range from 0.4 kR (Carlson and Judge, 1974) to about 14 kR (Broadfoot et al., 1979; Clarke et al. 1979). At first glance, it is not clear whether this large discrepancy in results is due to genuine temporal variability in the Jovian upper atmosphere, or is produced by uncertainties in the instrumental calibrations and data reduction procedures among the several experimenters.

In this Letter we report results of a reobservation of the Jovian Lyman-alpha emission using the Princeton telescope spectrometer on the *Copernicus* satellite in March 1978. The observations were made using the high spectral resolution U1 tube enabling us to measure the actual line profile as well as the intensity of the Jovian Ly-α emisison. Comparison of these data with previous *Copernicus* results enables us to verify the reality of the apparent temporal variability of the Jovian Ly-α line and to suggest a possible cause of these variations.

II. OBSERVATIONS

The Princeton telescope spectrometer on the Copernicus satellite was used to observe Jupiter during the interval 11 March - 16 March 1978. The spectrograph entrance slit projected to 0".3x39" on the sky and was inclined at 45° to the polar axis of Jupiter. At the time of observation the equatorial and polar diameters of Jupiter were 39".5 and 36".9 so Jupiter very nearly filled the slit. The high spectral resolution U1 tube has a bandpass of 0.05Å at Lyman-alpha for a stellar image. Drake et al. (1976) have calculated an instrumental profile with a width of 0.060Å for extended sources which fill the slit. The spacecraft altitude of 750km is low enough that geocoronal Ly-α emission is easily detected. Jupiter was observed near quadrature so the Jovian line has a large enough Doppler shift to resolve it from geocoronal emission.

The original purpose of the observing program was to search for possible Raman shifted ghosts of the solar Ly-α line. This search gave negative results. As part of this program, the Jovian Ly-α emission line was also observed.

In addition to this airglow Ly-α line, strong Jovian auroral Ly-α emission has been detected by Atreya et al.(1977) using Copernicus and confirmed by the Broadfoot et al.(1979)

observations with the Voyager I ultraviolet spectrometer. The auroral emission seems to be associated with the point of intersection of the Io magnetic flux tube and the Jovian atmosphere. In order to avoid contamination of our Jovian Ly-α airglow observation by Ly-α emission from the Io cloud or flux tube hot spot, Ly-α observations were made only during the periods when Io was in the half of its orbit which passes behind Jupiter. The 45° inclination of the slit to the axis of Jupiter also helps to eliminate possible auroral emission from being observed since the hot spots are confined to latitudes greater than 65°. (Atreya <u>et al</u>. 1977; Broadfoot <u>et al</u>. 1979; Acuna and Ness, 1976).

The sum of 45 spectral scans across the Ly-α region is shown in Figure 1. In the summation process, each individual scan was corrected for Doppler shifts due to the spacecraft orbital motion. The original data were sampled every 0.022Å. The summed spectrum has been Fourier smoothed and interpolated to a finer wavelength grid. The ordinate is in units of photon counts per SET (14 second integration period). The strong feature centered at 1215.67 is the geocoronal emission. The weaker feature at longer wavelength is the Jovian Ly-α.

Since the profiles of the Jovian and geocoronal lines are blended; some technique must be used to separate the two lines in the region of overlap. In previous Copernicus observations of the Jovian Ly-α line (Atreya et al. 1977, Bertaux et al. 1979) this separation was achieved by using the half of the geocoronal line opposite the Jovian line to determine an "uncontaminated" geocoronal line and then subtracting this from the observed profile. This technique assumes that the intensity of the Jovian line is zero at the center of the geocoronal line. Inspection of Figure 1 shows that our observed Jovian line is wide enough that this would be a poor assumption for these data. Instead, we determined the profiles of the geocoronal and Jovian lines by doing a least-squares fit to the sum of two gaussian profiles to the data. The derived fit is shown as the dashed line in Figure 1. The geocoronal line is fit by a gaussian with height of 19.2 counts, a full-width at half maximum of 0.066Å, and an integrated intensity of 1.35 count Å. The Jovian line has a height of 3.90 counts, a FWHM of 0.207Å and an intensity of 0.86 count Å. The separation of the two lines is 0.105Å, in good agreement with the expected value of 0.110Å.

Determination of the Jovian Lyman alpha emission intensity depends upon knowledge of the Copernicus U1 sensitivity at the time of observation. Bertaux et al. (1979) determined

the instrumental response at the Ly-α wavelength by using the geocoronal emission as a calibration source. They calculated a model of the geocorona for the dates and geometry of their observations. From this model, they computed the intensity of the geocoronoal Ly-α emission. They determined a sensitivity of M=0.16 to 0.18 count Å/kilo Rayleigh for their August-September 1976 observations. The Copernicus U1 tube has shown a steady decrease in sensitivity with time (Upson, 1979). The ratio of U1 sensitivity at 1215Å in
March 1978 to that in September 1976 is 0.60. Therefore the calibration factor M, at the time of our observations is 0.60x0.17=0.10 count Å/kR. This yields a Jovian Lyman-alpha intensity of 8.4 kR.

The uncertainty in the calculated intensity is due in part to the photon statistics of the detected signal and in part to the uncertainties of the Bertaux et al. (1979) calibration factor. The detected signal is a sum of the desired spectrum and the background counts (approximately 20 counts per channel). The uncertainty in the calculated Jovian Ly-α intensity due to photon statistics is about 25%. Bertaux et al. (1979) claim an uncertainty in the sensitivity factor M of 25%. Therefore, the overall uncertainty in the Jovian Ly-α emission is about 35%, or 3.0 kR.

III. DISCUSSION

The *Copernicus* results reported here yield a significantly larger Lyman-alpha intensity than the *Copernicus* observations of Bertaux *et al*. (1979). To ensure that this increase in intensity is real and is not an artifact of the different data reduction techniques, we have reprocessed the Bertaux *et al*. data of September 18, 1976 using our least squares fitting process. The calculated profile of their Jovian line has a full width at half maximum of 0.127Å, and a total intensity of 4.3 kR. This intensity is very close to the value calculated by Bertaux *et al*., so the results of the 1976 *Copernicus* observations seem to be independent of data reduction techniques.

The increase in the Jovian Ly-α intensity from 1976 to 1978 appears to be primarily due to a significant increase in the width of the line profile. The geocoronal Lyman-alpha line had a FWHM of 0.068Å in the 1976 data and 0.066 Å in the 1978 observations. Therefore, there appears to have been no degradation of the *Copernicus* spectrometer system which might lend to systematically wider line profiles. The fast rotation of Jupiter gives a Doppler broadening across the slit of about 0.071Å. If we subtract this value and the slit profile width of 0.060 Å in quadrature from the observed line widths, we calculate an intrinsic line width of about 0.185Å for our data, and 0.087Å for the Bertaux et al. data. The increase in line width of the Jovian line appears to be a result of a real change in the Jovian atmosphere.

It is widely assumed that the Jovian Ly-α emission is due to resonant scattering of the solar Ly-α line by H atoms in the upper Jovian atmosphere. Details of this theory have been developed by Hunten (1969), Carlson and Judge (1971), and Wallace and Hunten (1973). In this theory, atomic hydrogen is produced in the upper atmosphere via dissociation of H_2 and CH_4 by extreme ultraviolet (EUV) solar radiation. The recombination of H atoms into H_2 is a slow, three body reaction which occurs lower in the atmosphere. The downward motion of H atoms in the atmosphere is controlled by the processes of molecular and eddy diffusion. The intensity of the observed Ly-α line is then a measure of the column density of H atoms above the atmospheric level at whcih CH_4 absorbs the Ly-α photons. Following the nomenclature of Hunten (1976), we shall refer to the region in which Ly-α scattering occurs as the thermosphere.

As the H column density increases, the Doppler core quickly saturates. Further increases in intensity are due to the growing contribution of the radiation damping wings, causing the observed line profile to become braoder. This is exactly the type of behavior we have observed; the intrinsic line width increased by a factor of 2.1 and the intensity increased by a factor of 2.0. Our data thus give strong support to the theory that resonant scattering is the source of most of the Jovian desk Ly-α emission.

The details of radiative transfer for resonant scattering of Ly-α photons were calculated by Carlson and Judge (1971). For an assumed solar Ly-α flux of $\pi F = 1.15 \times 10^{10}$ photons cm^{-2} s^{-1} incident on the Jovian atmosphere, saturation of the Doppler core will give an emission rate of 2 kR. The contribution due to scattering in the wings becomes appreciable when the H column density reaches 0.6×10^{16} cm^{-2}, and dominates at $N > 2 \times 10^{16}$ cm^{-2}. Our observed emission intensity of 8.4 kR corresponds to a H atom column density of about 13×10^{16} cm^{-2}. The Voyager I and IUE results of 14 kR correspond to $N = 40 \times 10^{16}$ cm^{-2}.

Carlson and Judge (1974) have discussed alternative mechanisms for production of Ly-α emission. These mechanisms (photodissociation of H_2, dissociative excitation of H_2 by photoelectrons, radiative recombination of ionospheric protons, dissociative recombination of H_3^+) not only are incapable of producing the observed intensities, but would not give the observed variation of line width with intensity. Auroral Ly-α emission can give large intensities in localized areas, but this emission is confined to the polar regions (Atreya et al.

1977, Broadfoot et al. 1979).

The data in Table 1 indicate that there has been a steady increase in the Jovian Ly-α intensity over the past five years. We interpret this increase as the result of a large increase in the atomic hydrogen column density in the Jovian thermosphere. This increase must have been caused by some fundamental physical change in the mesosphere and thermosphere. It seems highly unlikely that the eddy diffusion constant could unilaterally decrease and cause this major increase in the H abundance. There must, instead, have been a change in some basic physical parameter of the Jovian thermosphere.

A possible explanation for this change is suggested by the work of Shimizu (1971). His calculations show that the H density profile depends not only on the eddy diffusion coefficient, but is also a sensitive function of the temperatures at the mesopause and in the thermosphere. His models with a "cold mesopause" (T_{meso}= 95°K) give significantly lower H densities, especially at higher altitudes, than models with a "warm mesopause" (T_{meso}=140°K) for all values of K. Shimizu points out that the thermospheric temperature has a great dependence on the level of solar activity. The thermosphere is heated by the solar extreme ultraviolet flux. In a time of low solar activities the solar EUV and soft x-ray flux is at a minimum

(Hinteregger, 1970; Kreplin 1970). The H atom density falls to a minimum level which is determined by K and T_{meso}. Increases in solar activity are accompanied by large increases in the solar EUV radiation. The thermosphere will be heated and the production rate and scale height of H atoms will be increased. The value of K is unlikely to be affected by these changes. The net result is to drastically increase the H column density above the mesopause. The calculations of Shimizu (1971) indicate that this increase from normal solar minimum to maximum could easily be at least an order of magnitude. Such an increase in H atom column density would be observable by the increased Ly-α resonant scattering.

It appears quite likely that the observed variations in Jovian Lyman-alpha intensity may be attributed directly to the variations in solar activity. Figure 2 shows the mean monthly Zürich sunspot number for each month since 1967. Also plotted on the same abscissa are the Jovian Ly-α observations from Table 1, as well as the result reported here. The correlation between Ly-α intensity and solar activity, especially the sharp increase since 1976, is quite striking. The observed variation of Ly-α intensity appears to confirm the mechanism proposed by Shimizu (1971). The increased solar activity was accompanied by increased solar EUV flux.

This heated the Jovian thermosphere and increased the production rate and scale height of the H atoms. The increased H atom column density caused increased resonant scattering of the solar Ly-α line in the wings of the line profile. The observed result is an increase in the intensity and width of the Jovian Ly-α emission.

We wish to thank Dr. W. L. Upson II and the Copernicus staff for their assistance in obtaining these data. We are very grateful to Drs. J. L. Bertaux and J. T. Clarke for allowing us to us to quote their results prior to publication. This work was supported by NASA Grants NGR 44-012-152 and NSG 5236.

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TABLE 1

Jupiter Lyman-alpha Observations

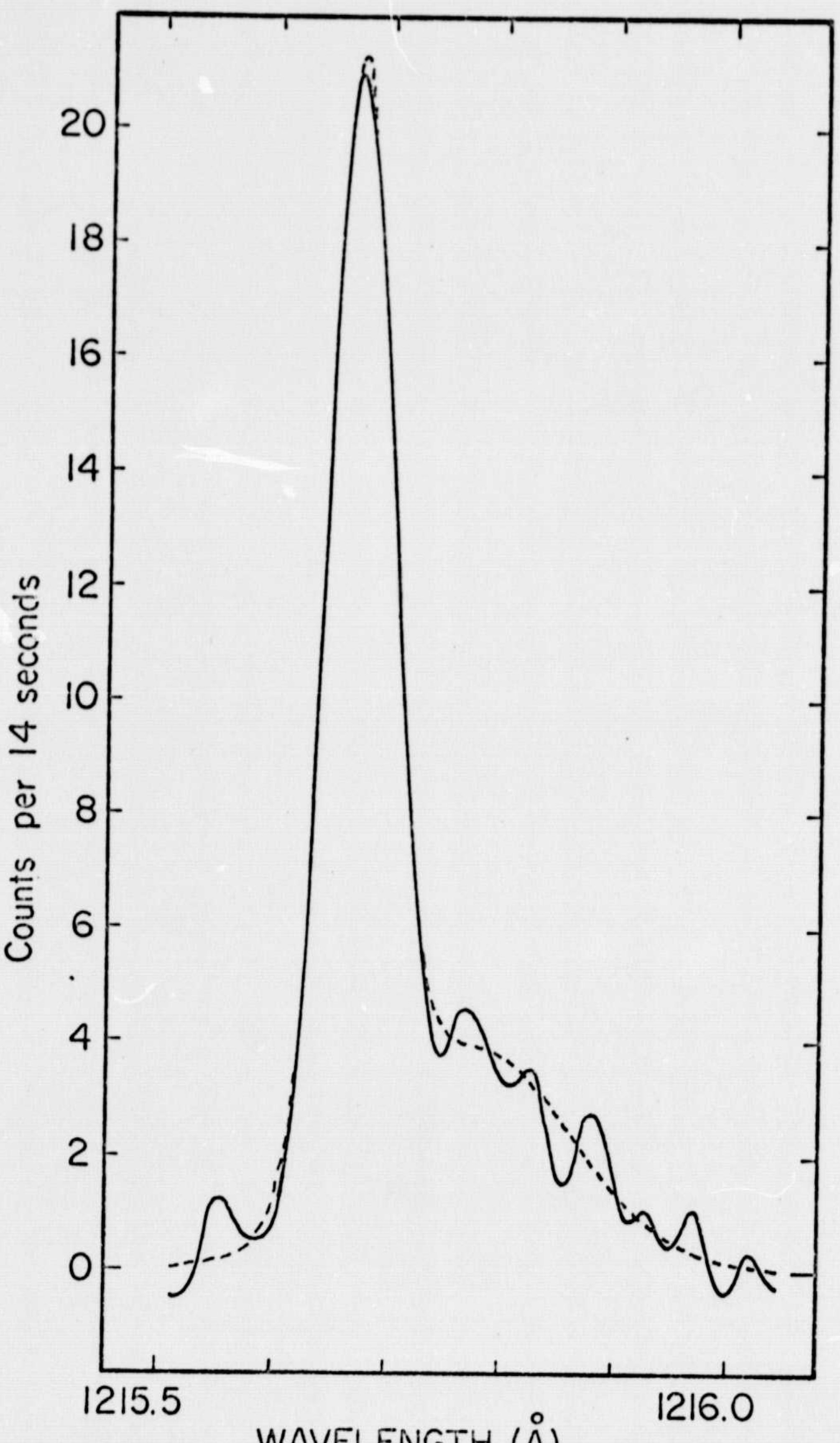
Experimenter	Date of Observation	Instrument	Intensity
Moos *et al.* (1969)	Sept. 5, 1967	Sounding rocket	4.0± kR
Rottman *et al.* (1973)	Jan. 25, 1971	Sounding rocket	4.4±2.6
Giles *et al.* (1976)	Sept. 1, 1972	"	2.1±1.0
Jenkins, Wallace and Drake*	May 2-3, 1973	*Copernicus*	0.66±0.35
Carlson and Judge (1974)	December 1973	Pioneer 10	0.40±0.12
Bertaux *et al.* (1979)	Jan. 5. 1976	*Copernicus*	2.7±1.0
Bertaux *et al.* (1979)	Aug-Sept. 1976	*Copernicus*	3.6±1.3
Clarke *et al.* (1979)	Dec. 1, 1978	Sounding rocket	13
Clarke *et al.* (1979)	Dec. 7, 1978	IUE	14
Broadfoot *et al.* (1979)	Jan 1979	Voyager I	14
Clarke *et al.* (1979)	Feb. 28, 1979	IUE	15

*Quoted by Carlson and Judge (1974) as a private communication.

FIGURE CAPTIONS

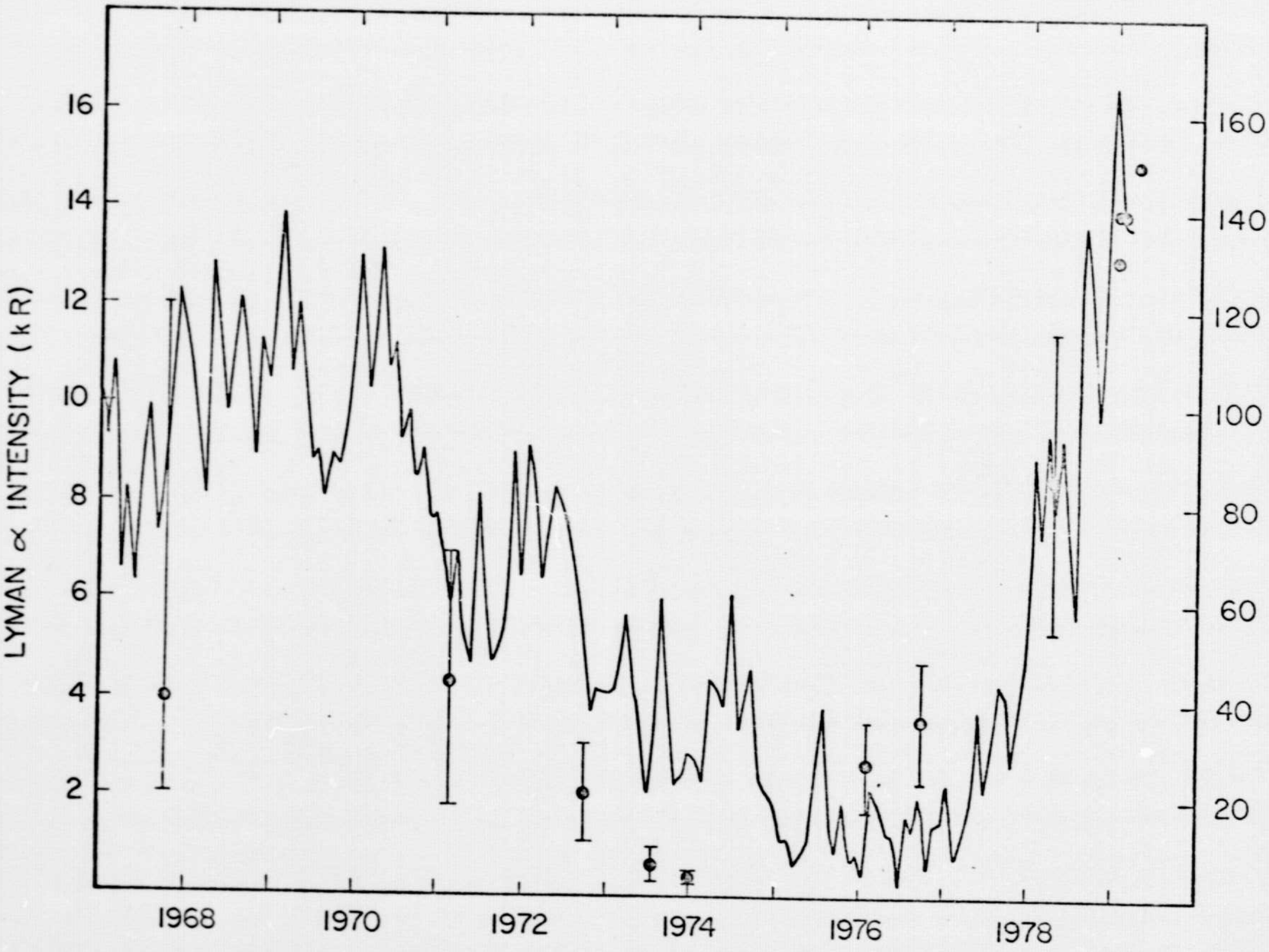
Figure 1. Lyman-alpha emission profile observed by Copernicus from Jupiter in March 1978 (solid line). The solid line is the Fourier smoothed sum of 45 spectra. The original data were sampled every 0.022Å. The geocoronal line is centered at 1215.673Å, and the Jovian line is at 1215.778Å. The dashed line is a least-squares fit of the sum of two gaussians to the observed profile.

Figure 2. Intensity of Lyman-alpha emission from Jupiter is a function of time. The values from Table 1 are plotted as solid dots plus error bars (if any were reported). The continuous line is the mean monthly Zürich sunspot number for each month.



20
18
16
14
12
10
8
6
4
2
0
Counts per 14 seconds
1215.5
1216.0
WAVELENGTH (Å)

Figure 1



LYMAN α INTENSITY (kR)
16
14
12
10
8
6
4
2
160
140
120
100
80
60
40
20
1968
1970
1972
1974
1976
1978