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LYMAN-ALPHA OBSERVATIONS OF COMET KOHOUTEK 1973 XII WITH *COPERNICUS*

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ABSTRACT

Comet Kohoutek 1973 XII was observed with the Princeton telescope-spectrometer on the *Copernicus* satellite on six occasions over a 1-month period starting on 1974 January 29. Positive detection of the cometary Lα emission profile was obtained on January 29 and February 2. Earlier observations of the geocoronal Lα emission profile allowed an instrumental intensity calibration and confirmation of the computed instrumental profile for an extended source at the Lα wavelength.

After allowing for broadening by the instrument, we derived from the width of the Lα emission on January 29 a hydrogen-outflow velocity of 10.6 ± 1.8 km s^{-1}. The intensity calibration combined with an appropriate cometary model led to cometary water-production rates with average values of $1.3 \pm 0.4 \times 10^{28}$ molecules sr^{-1} s^{-1} for January 29 and $6.0 \pm 2.5 \times 10^{27}$ molecules sr^{-1} s^{-1} for February 2. Only upper limits were obtained for Lα on and after February 14. Searches for OH and D led to negative results.

Subject headings: abundances — comets — line profiles — molecular processes — ultraviolet: spectra

I. INTRODUCTION

Emission at Lα from comets has been theoretically predicted by Biermann (1968) and observed, initially by OAO-2 in comet Tago-Sato-Kosaka in 1970 January (Code, Houck, and Lillie 1970). Since then several observations of comets in the Lα resonance line have occurred. Comet Bennett was observed from OAO-2 (Code, Houck, and Lillie 1972); comet Tago-Sato-Kosaka was observed by a sounding rocket (Jenkins and Wingert 1972). Comets Bennett and Encke were observed by OGO-5 (Bertaux and Blamont 1970; Bertaux, Blamont, and Festou 1973). More recently, observations of comet Kohoutek were made from *Skylab* (Carruthers *et al.* 1974; Keller, Bohlin, and Tousey 1975) by sounding rocket (Opal *et al.* 1974) and by the *Mariner* Venus-Mercury spectrograph (Broadfoot *et al.* 1974).

An ambitious program was undertaken to observe comet Kohoutek with the Princeton telescope-spectrometer on the *Copernicus* satellite, in conjunction with the Guest Investigator program sponsored by NASA. This equipment has the potential of high spectral resolution (0.05 Å) and small spatial motion (20″ increments), together with a limiting sensitivity of about 1 kR at Lα. The program was designed to provide spectral and spatial scans and a temporal monitoring of comet Kohoutek. Observations with *Copernicus* are limited, in that the minimum angle permissible between the satellite viewing direction and the Sun is 60°; this constrained the *Copernicus* observations to the time 1974 January 28–March 18. Due to the rapid decline in intensity of comet Kohoutek, several of the projects attempted yielded null results; this is described in more detail later.

Spectral scans and temporal information were obtained on 1974 January 29 and February 2. Interpretation of these data in terms of a cometary hydrogen model and the determinations of the hydrogen-production rate are presented as well as comparison with other Lα observations. In addition, the calibration of *Copernicus* for Lα emission from an extended source necessary to the comet analysis, is presented.

II. OBSERVATIONS

Observations of comet Kohoutek with the Princeton telescope-spectrometer on the *Copernicus* satellite were programmed between 1974 January 29 and February 26. The objective of this observing program was to obtain spatial, temporal, and spectral information on cometary Lα and OH emission. A total of 36 orbits was devoted to these observations, occurring

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in six-orbit blocks roughly every 6 days. In each orbit 10–20 min were used for the comet observation. Observations were restricted to satellite night to minimize geocoronal Lα interference. For a majority of the orbits (24), the satellite was programmed to point at the comet nucleus.

Data were obtained simultaneously by detectors on each of the spectrometer's mobile carriages; see Rogerson, Spitzer *et al.* (1973) for a more complete description of the instrumentation. The high-resolution far-ultraviolet detector (U1) during 27 orbits covered an interval two scans in width (0.72 Å total), centered to cover both the hydrogen and deuterium Lα lines from the comet. A null result was obtained in the case of the deuterium data. For six orbits U1 scanned just one interval centered on the hydrogen Lα wavelength. For another three orbits, U1 was held stationary at the central wavelength expected for the Lα line while pointing changes were performed about the cometary nucleus (a "stairstep" over 20′ centered on the nucleus and a grid over a square 2′ per side with a nominal 40″ between positions). No positive results were obtained from these spatial motions because the Lα signal had decayed by this time (February 14) below the *Copernicus* detection threshold.

The low-resolution near-ultraviolet detector (V2) scanned the (0, 0) and (1, 0) bands of OH; the interval 3080–3102 Å was covered 33 times, while the interval 3134–3156 Å was covered three times. A null result was obtained in this search for OH emission.

A positive detection of cometary Lα emission was obtained on two dates (1974 January 29 and February 2) and provides the basis for the remainder of this paper. The emission detected is confidently attributed to the comet, because the line is Doppler shifted properly in accord with ephemeris predictions, and the signal disappeared when the satellite was pointed 10′ and 30′ off the comet nucleus.

The relative pointing error between the satellite optical axis and the comet nucleus must be considered in detail. The observation was performed when the anti-Sun-to-Earth-to-comet angle β was between 112° and 120°; the normal operating range for this angle for *Copernicus* is 20°–90°. Due to the unfavorable power situation for this observation, the inertial reference was obtained on a star 40°–60° from the observing attitude in the pitch axis. An engineering test simulating the spacecraft slew sequence necessary for the comet observation indicated an error of −95″ for the sequence needed to reach the comet with a repeatability of 3″. A slew-calibration exercise yielding improved slew parameters was completed by 1974 February 2 observation and all subsequent observations; the error at the comet with the improved slew parameters should be 0″ ± 25″.

The spacecraft attitude could be checked between observations after the slew back down from the comet attitude. If the slewing parameters were completely understood, an accurate prediction of the errors could be made. For 75 percent of the slew cases, the errors were predictable to within ±25″. More extreme deviations did occur up to a maximum error of 3′.

Two additional complications affect the pointing accuracy. The comet motion during a 20-min observing interval was 85″–90″; a single position, that for the center time of the observation interval, was used. Coordinates used inadvertently did not have light travel time to Earth included; this amounted to an error ranging from 36″ to 41″ and was a systematic effect.

Consideration of the pointing errors above leads to an estimate of the net displacements in pointing halfway through the observations of 70″ ± 25″ for January 29 and 40″ ± 25″ for February 2.

III. CALIBRATION

The design of the *Copernicus* spectrometer was optimized for resolving spectra from stellar sources; the exit slit in front of the U1 photomultiplier is shaped to match approximately the slight curvature of the astigmatic image from a star focused on the spectrometer's entrance slit. While we are able to achieve an instrumental profile whose width is only about 50 mÅ for stars, somewhat poorer resolution is obtained for extended sources which fill the entire length of the entrance slit, since the curved image is smeared in a direction perpendicular to the dispersion plane. Jenkins (1975) has computed the shape of the instrumental profile for both a star and an even illumination of the entrance slit, assuming the nonexistence of either higher-order aberrations or an out-of-focus condition. Results of these computations for $\lambda = 1216$ Å are shown in Figure 1.

The observations by Spitzer and Morton (1976) confirm Jenkins's (1975) computations for stellar images, but we need yet to verify the profile width for an extended source. In order to provide a check for this computed profile as well as an absolute calibration at Lα for an extended source, observations with *Copernicus* of geocoronal Lα emission conducted on 1973 April 4 and 14, were compared with a geocoronal model. Such information on the instrumental characteristics is essential for our analysis of the Lα emission measurements from comet Kohoutek. The distribution of hydrogen atoms in the geocorona and the radiative transfer of Lα photons of solar origin is sufficiently well established for this exercise.

The intensity $I(\boldsymbol{r}, \boldsymbol{\Omega})$ (photons s^{-1} cm^{-2} sr^{-1}), observed from a point $\boldsymbol{r}$ in the direction $\boldsymbol{\Omega}$, is

$$I(\boldsymbol{r}, \boldsymbol{\Omega}) = (g/4\pi)\int_{r}^{\infty} S(\boldsymbol{r}')T(\tau)ds\,, \qquad (1)$$

where the integral is along $\boldsymbol{\Omega}$ and $T(\tau)$ is a function of the optical depth between $\boldsymbol{r}$ and $\boldsymbol{r}'$ (Holstein 1947). The normalized source function $S(\boldsymbol{r}')$ is related to the emissivity $\epsilon(\boldsymbol{r}')$ (photons s^{-1} cm^{-3}) by

$$\epsilon(\boldsymbol{r}') \equiv gS(\boldsymbol{r}') \equiv F_s(\pi e^2/m_e c) f S(\boldsymbol{r}')\,, \qquad (2)$$

where g is the excitation rate for a single H atom subjected to a solar flux F_s in photons cm^{-2} s^{-1} Hz^{-1}.

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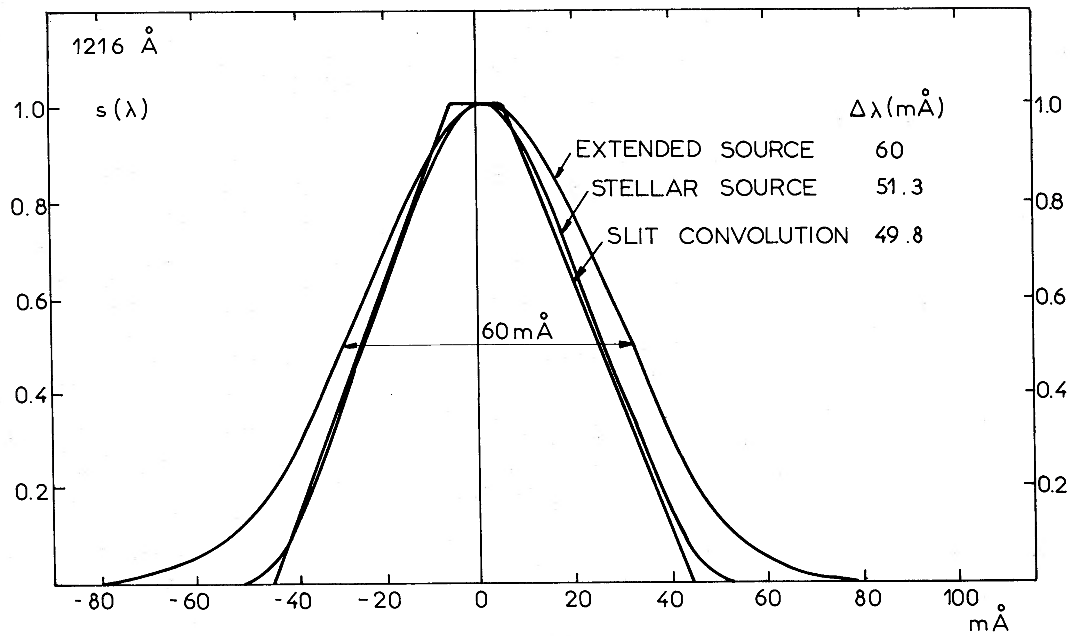

FIG. 1.—Theoretical instrumental profiles of the *Copernicus* spectrometer were computed by Jenkins (1975) for a star imaged on the slit center and for an extended source. In addition to a slight broadening over the trapezoid from the slit convolution, the profile centroids are displaced toward shorter wavelengths. In order to facilitate the comparison of shapes, they were shifted back on the figure toward center of trapezoid, respectively, by 9 and 5.9 mÅ. The widths (FWHM) are indicated for the three profiles. The equivalent width for an extended source is 63 mÅ.

For the dates of geocoronal observations with *Copernicus*, F_s was estimated from the work of Vidal-Madjar (1976) who established a statistical relationship between F_s and solar-activity indicators. Values of the Zurich sunspot number R_z, F_s, and g are given in Table 1.

The line emission profile $I(\boldsymbol{r}, \boldsymbol{\Omega}, \lambda)$ was computed, as well as total Lα intensity [expression (1)] for each *Copernicus* observation of geocoronal emission on 1973 April 4 and 14:

$$I(\boldsymbol{r}, \boldsymbol{\Omega}, \lambda) = (1/4\pi\Delta\lambda_D\sqrt{\pi}) \int_r^\infty \epsilon(\boldsymbol{r}') \times \exp[-(\lambda - \lambda_0)^2/\Delta\lambda_D{}^2] \times \exp\{-\tau \exp[-(\lambda - \lambda_0)^2/\Delta\lambda_D{}^2]\} dr' , \quad (3)$$

where λ_0 is the central wavelength of Lα and $\Delta\lambda_D$ is the Doppler width of the resonance line.

The distribution of H atoms in the geocoronal model was assumed to be spherically symmetrical, with a density of 5×10^4 atoms cm^{-3} at an altitude of 500 km. This model provided the best fit to observations of Lα emission in 1968 and 1969 with a photometer on OGO-5 (Bertaux 1974). The exospheric temperature was assumed to be uniform and equal to 1000 K.

The numerical solution of the radiative-transfer equation provided the normalized source function $S(\boldsymbol{r}')$ of Lα photons at each point $\boldsymbol{r}'$ in the geocorona (Thomas 1963).

The observed spectral profile is compared with the convolution of the computed theoretical intensity $\Psi(\lambda) = I(\boldsymbol{r}, \boldsymbol{\Omega}, \lambda)$ with the computed instrumental spectral response for an extended source:

$$P(x) = \int_{-\infty}^{\infty} \Psi(\lambda) s(\lambda - x) d\lambda , \quad (4)$$

where $P(x)$ (see Fig. 2) is the predicted spectral profile (counts per 13.75 s integration period), x is the spectrometer carriage position in wavelength units, and $s(\lambda)$ is the computed instrumental response shown in Figure 1.

For each of the 2 days of geocoronal observations, the arithmetic mean of the observed profiles was compared with the arithmetic mean of the convoluted theoretical profiles (solid curve of Fig. 2). The widths (FWHM) of these profiles are indicated in Table 1, showing an excellent agreement between observed widths (67 and 69 ± 3 mÅ) and computed profiles (68.3 and 68.2 mÅ). This exercise validates the *Copernicus* profile for an extended source as computed by Jenkins. An error in the geocoronal temperature would have an insignificant effect on the results. Recent measurements of the geocoronal line profile made with a hydrogen cell have confirmed expression (3) (Blamont, Cazes, and Emerich 1975).

Only a fraction of the total number of observations was considered in the convolution computation (13 of 57 for April 4 and 34 of 66 for April 14), in order

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TABLE 1

PARAMETERS FOR GEOCORONAL AND COMET OBSERVATIONS

Parameter	1973 April 4	1973 April 14	1974 January 29
Zurich sunspot number R_z	93	37	7
Solar flux at line center F_s (10^{11} photons cm^{-2} s^{-1} Å^{-1})	2.49 ± 0.33	2.26 ± 0.33	2.13 ± 0.33
Excitation rate at 1 AU g (s^{-1})	1.35×10^{-3}	1.22×10^{-3}	1.16×10^{-3} / 1.57×10^{-3}*
Copernicus sensitivity M (counts Å kR^{-1})	0.47 ± 0.06	0.59 ± 0.08	...
Intrinsic geocoronal line width FWHM (mÅ)	38.9	38.0	...
Observed geocoronal line width FWHM (mÅ)	69 ± 3	67 ± 3	...
Line width of geocoronal profile convoluted with theoretical instrumental profile (mÅ)	68.3	68.2	...
Observed comet line width FWHM (mÅ)	...	...	87 ± 8
Deduced intrinsic comet line width FWHM (mÅ)	...	...	63 ± 11

* Value obtained after multiplying by a correction factor of 1.35 to account for the Doppler shift of the comet with respect to the incident solar Lα line profile.

to save computer time. Those observations selected were representative, as far as line width is concerned, but were selected with respect to peak intensity to increase the statistical quality of the following fit (the more intense observations were used).

The sensitivity M of the U1 detector to diffuse Lα emission may be defined as the ratio of N_C/I, where N_C represents the integral over wavelength of the counts above background (for a time-integration interval of 13.75 s), and I is the line emission rate expressed in kilorayleighs. Figure 3 shows plots of measurements of N_C versus the respective estimates of I for observations taken on 1973 April 4 and 14. From the slopes of the least-squares fit to the points, we found the values of M given in Table 1. We adopted a value of 0.53 ± 0.06 counts Å kR^{-1} in the analysis which will follow. A comparison of continuum fluxes near 1153 and 1358 Å for observations of the star ζ Oph in 1973 April and 1974 April reveals no perceptible degradation of optical and photoelectric efficiencies over that period of time. Hence our adopted value for M appears to be valid for the comet observations which occurred almost a year after the geocoronal observations.

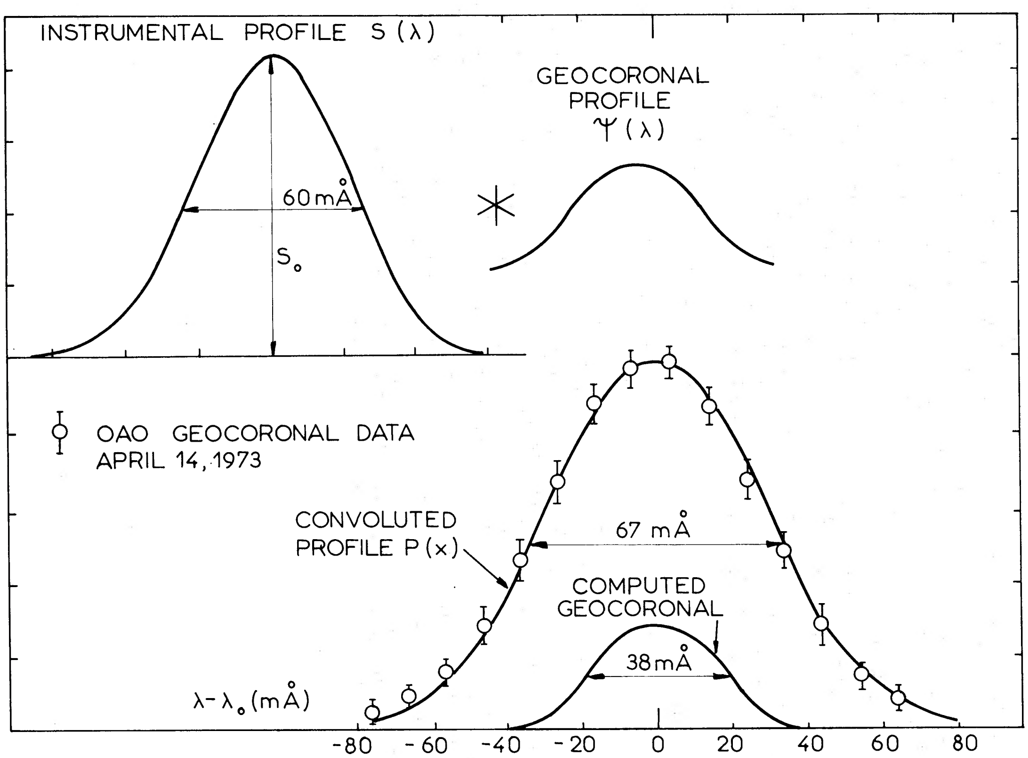

FIG. 2.—The convolution $P(x)$ of the instrumental profile $s(\lambda)$ with the computed geocoronal profile $\Psi(\lambda)$ is compared with the *Copernicus* data points for the geocoronal measurements.

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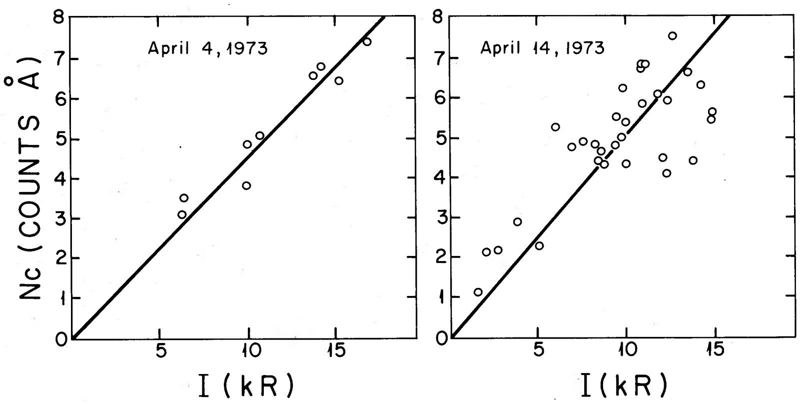

FIG. 3.—For both 1973 April 4 and April 14, the measured integrated number of counts N_C is compared with I, the intensity from the theoretical geocoronal model. The slope M of the straight line drawn through the data points yields the sensitivity of *Copernicus* to an extended source of Lα.

IV. RESULTS

Positive detections of Lα emission from comet Kohoutek obtained on 1974 January 29 and February 2 are shown in Figure 4, parts *a* and *b*, respectively. A correction for particle background effects has been subtracted in each case. The outer envelopes are 2 σ error estimates based on the counting-rate statistics. Six scans have been averaged for the central portion of Figure 4*a* and all of Figure 4*b*; 3 scans were averaged in the outer portions of Figure 4*a*. Wavelengths are in the comet's rest frame. The geocoronal Lα contribution at shorter wavelengths by about 0.14 Å is clearly seen in each figure.

The comet line observed on 1974 January 29 has a measured FWHM of 87 $\pm$ 8 mÅ. Convolution of the above-determined instrumental profile with Gaussian lines of various widths leads to the determination of the intrinsic cometary FWHM of $\Delta\lambda_c = 63 \pm 11$ mÅ, if the cometary emission line is assumed to have a Doppler profile. The uncertainty of ± 11 mÅ for $\Delta\lambda_c$ corresponds strictly to the uncertainty of ± 8 mÅ on the measured FWHM.

The several ways to describe the velocity dispersion of the hydrogen atoms are related as follows:

$$\Delta\lambda_D = \frac{\Delta\lambda_c}{2(\ln 2)^{1/2}} = \frac{\lambda_0}{c} v_W = \frac{\lambda_0 \pi^{1/2}}{2c} v_H \,, \tag{5}$$

where $\Delta\lambda_D$ is the Doppler width, v_W the most probable speed, v_H the mean outflow velocity, λ_0 the Lα wavelength, and $\Delta\lambda_c$ the measured comet line width. The resulting values for these parameters for comet Kohoutek are

$$\Delta\lambda_D = 38 \pm 7 \text{ mÅ} \,, \tag{6}$$

$$v_W = 9.4 \pm 1.6 \text{ km s}^{-1} \,, \tag{7}$$

$$v_H = 10.6 \pm 1.8 \text{ km s}^{-1} \,. \tag{8}$$

After the omission of counts which appear to be attributable to geocoronal Lα, our measures of N_C and the determination of M yield total intensities I of 10.3 $\pm$ 2.0 kR and 3.4 $\pm$ 0.9 kR for January 29 and February 2, respectively.

V. INTERPRETATION

The production rate of hydrogen atoms can be derived from the observed Lα emission rate by comparison with a suitable model density distribution. If we assume water is the evaporating parent molecule, hydrogen atoms are produced by successive photodissociations of H_2O and OH. Haser's (1957) model was generalized for the two-step dissociation. All species move radially outward without collisions. If no distinction is made in the outflow velocities for hydrogen atoms of the first and second dissociation of the hydrogen, the hydrogen-density distribution is then given by

$$n_H(r) = \frac{Q_{H_2O}}{v_H r^2} (Ae^{-r/\gamma_0} + Be^{-r/\gamma_1} + Ce^{-r/\gamma_2}) \,, \tag{9}$$

where Q_{H_2O} = water-production rate (molecules s^{-1} sr^{-1}), r = distance from nucleus, and

$$A = \frac{\gamma_1(2\gamma_0 - \gamma_2)}{(\gamma_1 - \gamma_0)(\gamma_2 - \gamma_0)}$$

$$B = \frac{\gamma_1(2\gamma_1 - \gamma_2)}{(\gamma_1 - \gamma_2)(\gamma_1 - \gamma_0)}$$

$$C = -A - B = \frac{-\gamma_1 \gamma_2}{(\gamma_1 - \gamma_2)(\gamma_2 - \gamma_0)} \,. \tag{10}$$

The scale lengths γ of H_2O, H, and OH at 1 AU were taken as

$$\gamma_0 = v_{H_2O} \times t_{H_2O} = 1.1 \times 10^5 \text{ km} \,,$$

$$\gamma_1 = v_H \times t_H = 2.5 \times 10^7 \text{ km} \,, \tag{11}$$

and

$$\gamma_2 = 1.2 \times 10^5 \text{ km} \,.$$

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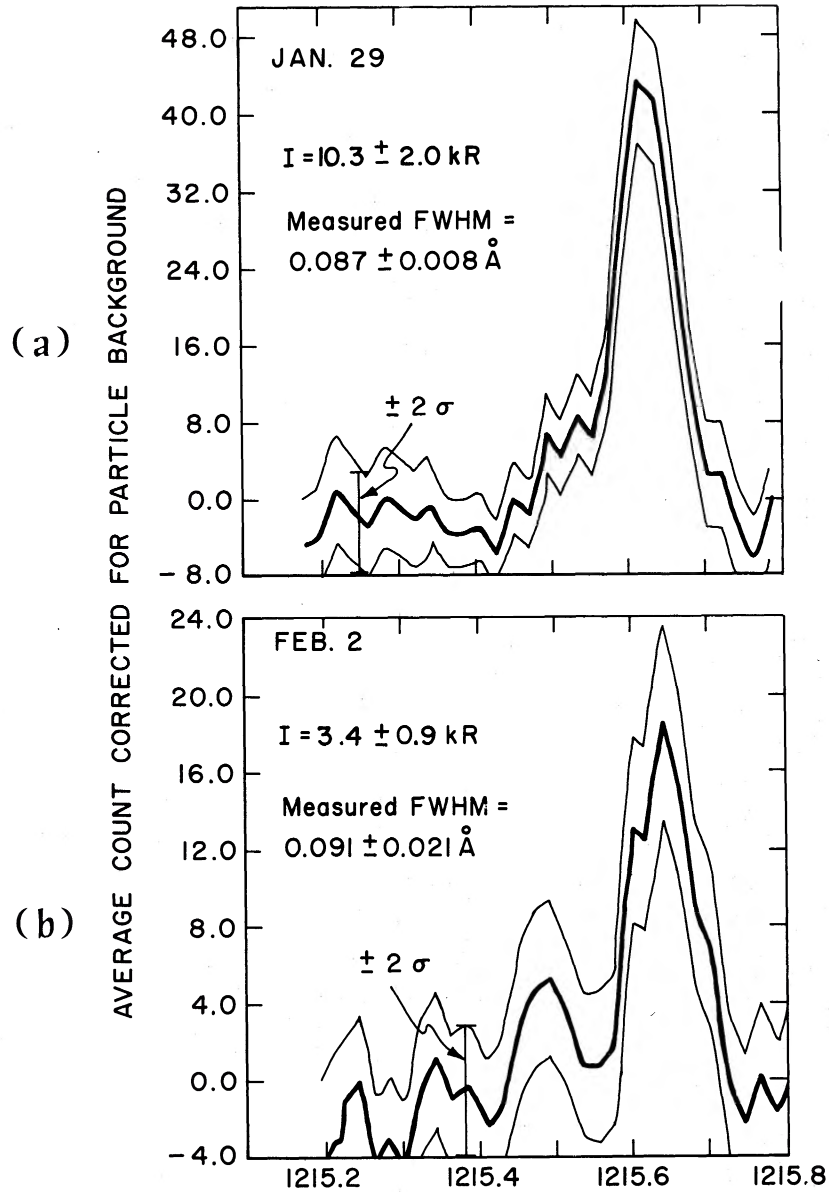

FIG. 4.—The Lα emission profiles observed from comet Kohoutek by *Copernicus* on (*a*) 1974 January 29 and (*b*) 1974 February 2 are presented as the average counting rate (corrected for particle background) as a function of wavelength in the comet rest frame. The outer envelopes represent $\pm 2\,\sigma$ due to counting-rate statistics. Geocoronal Lα can be seen influencing the blue wing of the comet line.

Only γ_2 was directly observed for comets Bennett (Keller and Lillie 1974) and Kohoutek (Blamont and Festou 1974). The lifetime of water, t_{H_2O}, was calculated (Bertaux, Blamont, and Festou 1973) and combined with an assumed outflow velocity of 1 km s^{-1} (Mendis, Holzer, and Axford 1972). The hydrogen lifetime, $t_H = 2.4 \times 10^6$ s, was determined from usual values of photoionization and charge-exchange rates (see Bertaux, Blamont, and Festou 1973) and combined with the mean outflow velocity of 10.6 km s^{-1}.

The Lα radiation pressure was not taken into account, as observations pertain to the central zone where the trajectories of H atoms are approximately straight lines. The Lα excitation factor g, defined by expression (2), is proportional to the solar flux F_s' at the excitation wavelength which is slightly displaced from the line center due to the Doppler shift of the comet (39 km s^{-1} is equivalent to a wavelength shift

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of 0.16 Å to the red wing). This leads to an upward correction factor F_s'/F_s of 1.35, after consideration of the solar Lα line profile which has a central reversal. The flux F_s at the center was estimated from the statistical relationship between F_s and R_z established by Vidal-Madjar (1976). With the very low solar activity reported on the cometary observation dates, a flux $F_s = 2.13 \times 10^{11}$ photons cm^{-2} s^{-1} Å^{-1} was estimated at 1 AU, with a corresponding value $g = 1.57 \times 10^{-3}$ s^{-1} (after the Doppler-shift correction).

It should be noted that the same relationship between F_s and R_z was used for the geocoronal and cometary observations. Thus, even if the absolute value of F_s as published by Vidal-Madjar (1976) were in error, neither the relative value of F_s at the two epochs (1973 April and 1974 January) nor the cometary density estimated from *Copernicus* observations would be in error.

It was assumed that the density was such that the line of sight was optically thin ($\tau \ll 1$). In this case the emission rate is related to the integral of the number of atoms in the line of sight by

$$E(\mathrm{kR}) = 10^{-9}\, g \int n_{\mathrm{H}}(l)dl\,. \qquad (12)$$

If the emission rate is larger than 30 kR, the assumption $\tau \ll 1$ does not hold. This happens for small values of the perpendicular distance of the line of sight from the nucleus r and for high values of production rate. For $Q_{\mathrm{H_2O}} = 10^{28}$ molecules s^{-1} sr^{-1}, the saturated region is less than 7×10^3 km in diameter, corresponding to approximately 10″, a value significantly lower than our lowest estimate for the pointing offsets of the observations. [An approximate allowance for saturation at small r was made for the curves in Figure 5 by never allowing $E(r)$ to exceed 30 kR.]

The mean optical thickness τ may be evaluated for the observed intensity of 10 kR by using equation (12) and the relationship between τ and the integrated number density

$$\tau = \frac{\pi e^2 f}{m_e c \pi^{1/2} \Delta\nu_{\mathrm{D}}} \int n_{\mathrm{H}}(l)dl\,. \qquad (13)$$

The result is $\tau = 0.44$, proving the validity of the optically thin medium assumption. Such an optical thickness in a resonant medium introduces only a small increase ($\sim 5\%$) in the observed line width.

The intensity (12) was integrated along the slit of length 39″. To take into account the pointing uncertainties, the intensity in the field of view of *Copernicus* was computed for the above-described model

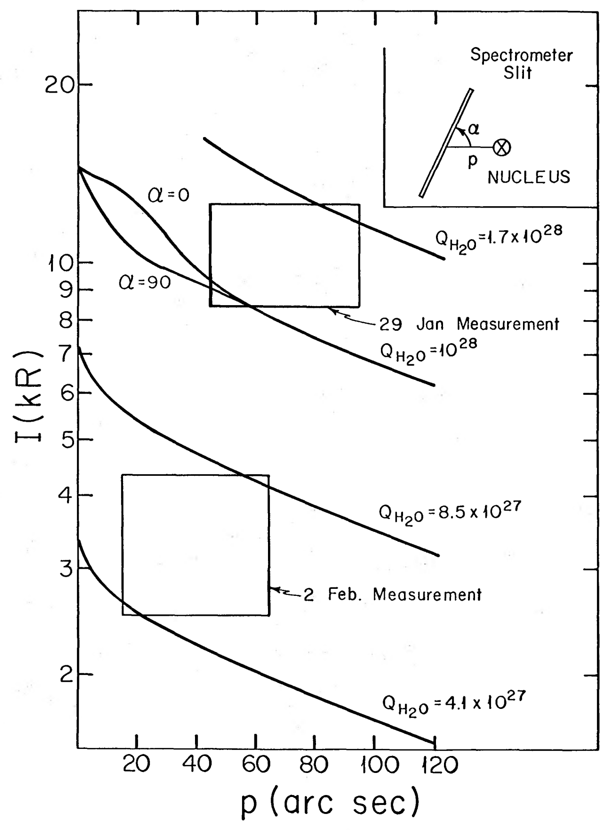

FIG. 5.—For both dates of cometary observations, the *Copernicus* intensity measurement is compared with a computed intensity which is plotted as a function of the distance p between the nucleus and the center of the slit for various values of slit orientation α and for two values of $Q_{\mathrm{H_2O}}$ on each date. The *Copernicus* measurement is represented by a rectangle, the height of which is the intensity uncertainty and the length of which is the pointing uncertainty. The comparison of measurement and theory allows the determination of $Q_{\mathrm{H_2O}}$ between two limits.

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as a function of angular distance p between the nucleus and the center of the slit and also as a function of the poorly defined roll orientation α (Fig. 5). The result of this computation is presented in Figure 5 for the observations of 1974 January 29 and February 2. The different curves for $Q_{H_2O} = 10^{28}$ molecules s^{-1} sr^{-1} are for different values of α. Since it is clear that α has little influence on the result, only one curve was drawn for other values of Q_{H_2O}.

Since the region of saturation is negligible, two estimates of Q_{H_2O} can be derived by a simple linear relationship between intensity and Q_{H_2O}. Two assumptions concerning pointing accuracy are considered.

1) The pointing was as near to the nucleus as allowed by the pointing error estimates, and I was at the lowest error limit. A minimum value of Q_{min} is then derived.

2) The pointing was as far from the nucleus as we would have expected, and I was at the upper permitted limit. A maximum value Q_{max} is then derived.

These values are listed for each date in Table 2, along with most probable values Q_{mp} whose lines penetrate the central portions of the boxes in Figure 5.

TABLE 2

H_2O PRODUCTION RATES, Q_{H_2O} (Molecules sr^{-1} s^{-1})

	January 29.5–29.9	February 2.5–2.8
Q_{min}	1.0×10^{28}	4.1×10^{27}
Q_{max}	1.7×10^{28}	8.5×10^{27}
Q_{mp}	1.3×10^{28}	5.9×10^{27}
Sun–comet distance R (AU)	0.99	1.08
Comet–Earth distance Δ (AU)	0.96	1.04

VI. DISCUSSION

The production rate of hydrogen is twice that of the assumed parent molecule water: $Q_H = 2Q_{H_2O}$. For comparison, *Copernicus* values are plotted together with the ground-based observations of Hα emission (Huppler *et al.* 1975) and mostly preliminary results of other ultraviolet observations of comet Kohoutek in a log Q_H versus log R diagram (Fig. 6). The straight line indicates a production-rate variation proportional to R^{-2}. The production rates from the ultraviolet measurements are in relatively good agreement, considering the different instruments and methods used in the determinations. The determinations by Huppler *et al.* (1975) are conspicuously lower; they state that a major source of uncertainty in their Q_H determination is the character of the solar Lβ emission of the time of observation and that an error in the assumed Lβ profile is a likely cause of the discrepancy between their values and those derived from Lα emission. The somewhat high value of Q_H for January 29 might be connected with cometary activity. Visual-magnitude observations of comet Kohoutek (Angione *et al.* 1975) show a standstill in brightness on January 22–26, following a slight brightness increase on January 19. After January 27 the visual magnitudes decreased again relatively rapidly. Narrow-band filter photometry (Angione, Roosen, and Lanning 1975) shows enhanced emission on January 23 and 25 for CN, CO$^+$, and C_2. A fast decay following an outburst of gas production would also explain the rapid decrease in Lα emission after January 29. *Copernicus* observations on February 14 did not lead to a positive detection of the cometary Lα signal; the corresponding upper limit for Q is not much less than our measured value for February 2 and hence is of little value in portraying the decline of Q with increasing R.

The data are in agreement with a production-rate slope of -2, similar to the case of comet Bennett 1970 II (Keller and Lillie 1974). The production rate is rather sensitive to a change of the dimension of the

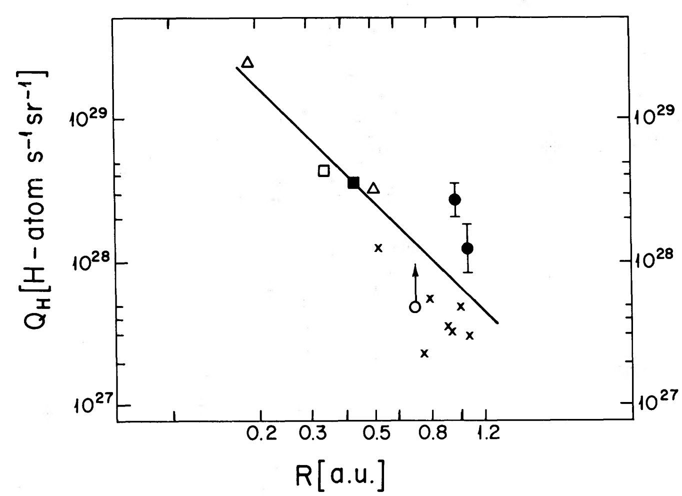

FIG. 6.—The hydrogen-production rates of comet Kohoutek 1973 XII are plotted versus the heliocentric distance of the comet. △ = *Skylab* electrographic camera (Carruthers *et al.* 1974); □ = rocket spectrometer (Feldman, Takacs, and Fastie 1974); ■ = rocket electrographic camera (Opal *et al.* 1974); ○ = MVM spectrograph (Broadfoot *et al.* 1974); × = Hα emission (Huppler *et al.* 1975); and ● = OAO-*Copernicus* spectrometer. The line represents an R^{-2} dependence for the production rate.

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extended hydrogen source, i.e., to the scale lengths of the assumed parent molecules. A strong hydrogen contribution from an unknown parent molecule with a scale length significantly different from 10^5 km would change the resulting production rates. Also, if the hydrogen atoms are created with different excess energies, i.e., with different mean velocities (e.g., $v_H = 20$ km s^{-1} of the H_2O and $v_H = 8$ km s^{-1} of the OH dissociation; see below), the resulting production rates would change (increase by $\leqslant 50\%$). These uncertainties are not included in the error limits.

The *Copernicus* observations represent the first direct determination of the width of an optically thin cometary Lα emission line. Observations of comet Kohoutek around perihelion passage with the extreme-ultraviolet spectrograph on *Skylab* (Keller *et al.* 1975) revealed a strongly broadened, obviously optically thick Lα emission line. The FWHM of the cometary line was 130 mÅ, about twice as large as the value of 68 mÅ presented here. The *Skylab* instrument also pointed at the central part of the hydrogen coma. The hydrogen-production rate at a heliocentric distance of only 0.2 AU was about a factor 10 higher than at the end of January (Fig. 6). Therefore the optically thick region was about a factor 10 larger, which explains the line broadening. Keller, Bohlin, and Tousey (1975) estimated the opacity influence and found their results in agreement with an optically thin line width as small as 53 mÅ, assuming a Doppler profile for the cometary emission line.

The deduction of the mean hydrogen-outflow velocity from the observation is limited by the complexity of the kinematics of the inner hydrogen coma. Since the hydrogen atoms are created in a region whose diameter (2×10^5 km) is substantially larger than the projected slit length (3×10^4 km), a strong contribution of almost isotropically distributed velocity components which are partly thermalized may be expected, resulting in a Doppler emission profile. This deviation from the assumed purely radial outflow also influences the hydrogen-density distribution and hence the production-rate determination. Outside the production region (an extended source), the hydrogen atoms become increasingly directed radially outward.

Meier (1976) recently investigated the emission line profiles of a radially expanding hydrogen coma for the strictly optically thin case. The emission line profile of a radial Maxwellian velocity distribution is almost 40 percent broader than the Doppler profile of the corresponding isotropic distribution. In the present case, a mixture of the contributions of the two regions and hence of the two line profiles is to be expected. The lack of knowledge of the *a priori* cometary line profile and our assumption it is a pure Gaussian should have only minor influence on the determined cometary line width. This is particularly true because the cometary line is only about as broad as the instrumental profile.

The outflow velocity $v_H = 10.6$ km s^{-1} deduced under the assumption of the isotropic motions must be interpreted as an upper limit. The corresponding lower limit for purely radial outflow is 7.6 km s^{-1}. These values are in excellent agreement with results of the first cometary hydrogen Hα line (6563 Å) observations in 1973 December and 1974 January by Huppler *et al.* (1975), who found 7.8 ± 0.5 km s^{-1} for the mean hydrogen velocity, assuming a purely radial Maxwellian velocity distribution. The profile width (outflow velocity) remains stable, while the hydrogen production rate changes by more than one order of magnitude. This indicates that the observed velocity is not determined by cooling processes (see Keller 1973) but, rather, is intrinsic to the creation process of the hydrogen atoms, probably the dissociation of OH (Bertaux, Blamont, and Festou 1973).

The first determinations of the hydrogen outflow velocity in comets used the Lα isophotes of the optically thin outer regions of the cometary hydrogen cloud which are distorted by solar Lα radiation pressure. Bertaux, Blamont, and Festou (1973) and Keller (1971, 1973) found values of 9 and 8 km s^{-1}, respectively, from OGO-5 observations of comet Bennett. Opal *et al.* (1974) found 8 km s^{-1} for the hydrogen outflow velocity for comet Kohoutek.

A second outflow velocity component at a higher velocity of about 20 km s^{-1} was found necessary for the interpretation of Lα observations of comet Bennett by Keller and Thomas (1975). This component may well be linked to the first dissociation of water (Keller 1971). The resulting hydrogen atoms should have velocities larger than 16.5 km s^{-1} (the most probable velocity is 19 km s^{-1}). Thermalization by collisions is negligible for the present case, since the region where collisions dominate has a radius of only 2×10^3 km (see Bertaux, Blamont, and Festou 1973). This high-velocity component is strongly masked by the slower atoms and would influence only the line wings. The peak intensity of the line is proportional to $1/v_H$ [see eq. (3)] and to the density of hydrogen atoms which is also proportional to $1/v_H$ [see eq. (9)], assuming a fixed production rate (see also the calculations of Meier 1976). Thus a velocity ratio of about 2.5 leads to a decrease of a factor 6 in the peak intensity of the high-velocity emission line, as compared with the low-velocity emission.

The *Copernicus* results are consistent with the assumption of water as the parent molecule and with the resulting high-velocity component. Resolved profiles in future observations and detailed, realistic calculations of the hydrogen-velocity distribution are necessary to yield further information on the production mechanisms of the hydrogen atoms.

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