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THE LYMAN-ALPHA IMAGE OF COMET TAGO-SATO-KOSAKA (1969g)

Edward B. Jenkins and David W. Wingert
Princeton University Observatory, Princeton, New Jersey
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ABSTRACT

On 1970 January 25.105 UT an f/2 objective-grating spectrograph aboard an Aerobee rocket recorded a faint image of Comet Tago-Sato-Kosaka (1969g) in Lα emission. Some sharpening of the image and reduction of film grain noise was accomplished by multiplying the picture's Fourier transform by an optimum filter function. After this processing, which was carried out digitally, the Lα comet image appeared as a nearly circularly symmetric diffuse glow approximately 8×10^6 km in diameter. There was also the suggestion of a faintly visible core of emission whose dimensions are less than 10^5 km.

The sublimation of ice in the nucleus of the comet and the subsequent dissociation of the free water molecules by sunlight could produce a large cloud of hydrogen atoms around the comet. Resonant reradiation of solar Lα emission by this cloud is probably responsible for most of the observed emission, although much of the brightness near the center may be caused by an excitation of the hydrogen by energetic electrons and ions within an MHD shock in the solar wind.

I. OBSERVATION

By good fortune, the apparition of an unusually bright comet, Comet Tago-Sato-Kosaka (1969g), coincided with the scheduled launch of an Aerobee sounding rocket which had an ultraviolet objective-grating spectrograph aboard. This flight was one of a series which has photographed spectra of early-type stars with 1 Å resolution in the ultraviolet. On the basis of favorable Lα flux levels from the comet measured by the Orbiting Astronomical Observatory (OAO-2), together with Biermann's (1969) theoretical prediction that large comets should exhibit a bright Lα emission of large angular extent, we decided to spend 46 s of the flight's 250 s total observing time for viewing the comet. The payload instrument was identical to the wide-angle, all-reflective spectrograph described earlier by Morton, Jenkins, and Bohlin (1968), and it recorded a faint image on the Kodak type 101-01 film. The center of this image was positioned to within 14 arc minutes of where one would expect to find a first-order diffraction of 1216 Å from the direction of the comet.

The camera would have been able to record emissions anywhere between the 1100 Å short-wavelength sensitivity cutoff and 1800 Å at the long-wavelength edge of the film. No comet images corresponding to wavelengths other than Lα within this interval were evident. This is hardly surprising in view of the fact that atomic hydrogen is probably a major constituent of the outer regions of a comet, and for resonant reradiation of sunlight, the supply of Lα photons is far more plentiful than that from emissions at other wavelengths.

Unfortunately, zero-order star images which were recorded along with the comet revealed that the image quality was somewhat disappointing; two abnormalities caused a smearing which degraded a point source into what appeared to be a nearly uniform rectangle of dimensions 5×26 arc minutes. First, the camera was in a defocused condition because of a deformation of the grating flatness by mounting stresses. An additional blurring resulted from a uniform drift of the rocket's roll orientation caused by an attitude control malfunction during the exposure.

II. IMAGE PROCESSING

It was apparent that some advantage could be gained by a selective processing of the picture information, whose intelligibility had been compromised by the image smearing and film grain noise. The blurred recording $J(x, y)$ is the result of a two-dimensional convolution of the original scene $J_0(x, y)$ and a point-spread function $S(x, y)$. It is conceptually easier to discuss the blurring process as a multiplication of the original scene's Fourier transform $\mathbf{J}_0(u, v)$ by the transform of the point-spread function $\mathbf{S}(u, v)$. Typically, the high-frequency components of $\mathbf{J}_0$ are severely attenuated, but in principle one can restore the original Fourier amplitudes by multiplying the recorded image's transform $\mathbf{J}$ by $\mathbf{S}^{-1}$. The extent to which this may be done in practice is limited by the signal-to-noise ratio of the attenuated components. For those Fourier amplitudes where the recorded signal J still predominates over the noise N a full restoration is called for, but it is better to leave alone (or even further attenuate) those spatial frequencies where image information has been so weakened by the smearing that what remains is almost all noise. For the whole range of reamplification factors in $\mathbf{S}^{-1}$, one must choose between restoring the finer detail of J_0 and magnifying unwanted high-frequency noise.

A straightforward resolution of this choice is to employ a restoration which may be expected to minimize the integral $\int\int \epsilon^2\, dxdy$, where ϵ is the error difference between the reconstructed image and the true scene. This condition is satisfied when the restoration function with which one multiplies the recorded picture's transform is

$$\mathbf{F} = \frac{\langle \mathbf{J}_0\mathbf{J}_0^* \rangle \mathbf{S}^*}{\langle \mathbf{J}_0\mathbf{J}_0^* \rangle \mathbf{S}\mathbf{S}^* + \langle \mathbf{N}\mathbf{N}^* \rangle} . \qquad (1)$$

The function $\mathbf{F}$ is sometimes referred to as an "optimum filter," and it makes use of the fact that our estimation of the true image power spectrum $\langle \mathbf{J}_0\mathbf{J}_0^* \rangle$, after it has been attenuated by $\mathbf{S}\mathbf{S}^*$, has a frequency distribution which differs from that of the expected noise power spectrum $\langle \mathbf{N}\mathbf{N}^* \rangle$ in the recording. A derivation of equation (1), together with some examples of filters, has been given by Helstrom (1967).

A raster scan of the comet image by a digital microdensitometer encoded the picture into a two-dimensional array of density values for computer processing. In the analysis which followed, we assumed that the image intensity was directly proportional to the recorded film density minus the background fog level. This assumption was reasonable since the comet image was weak enough to have all of the densities well within the linear section (toe) of the film's characteristic curve. There was a sufficient amount of diffuse background light collected (presumably from the terrestrial Lα glow) to gently fog the film, which was fortunate since it eliminated any complications from the low-level exposure threshold of the film.

A playback of the originally recorded densitometry is shown in figure 1*a* (pl. 6). The x-axis is parallel to the dispersion direction of the spectrograph. The densitometer slit was set to measure the average density within a rectangle 20 μ wide and 50 μ high, and these dimensions corresponded to the sampling intervals along the x- and y-axes, respectively. The computer added in four synthetic star images of various strengths in the lower left corner to show the appearance of the point-spread function and later to demonstrate the effectiveness of the restoration's sharpening. These synthetic stars essentially represent $S + N$ and are reasonable facsimiles of actual zero-order stars recorded elsewhere on the film.

The expected noise power $\langle \mathbf{N}\mathbf{N}^* \rangle$ was evaluated from a sampling of N in a region of the picture which was quite removed from obvious film flaws and the comet image. Except for the very lowest frequencies, the noise power had a nearly flat spectral distribution. The determination of $\langle \mathbf{J}_0\mathbf{J}_0^* \rangle$ was less straightforward. At frequencies where the image power spectrum became somewhat comparable to the noise power, it was

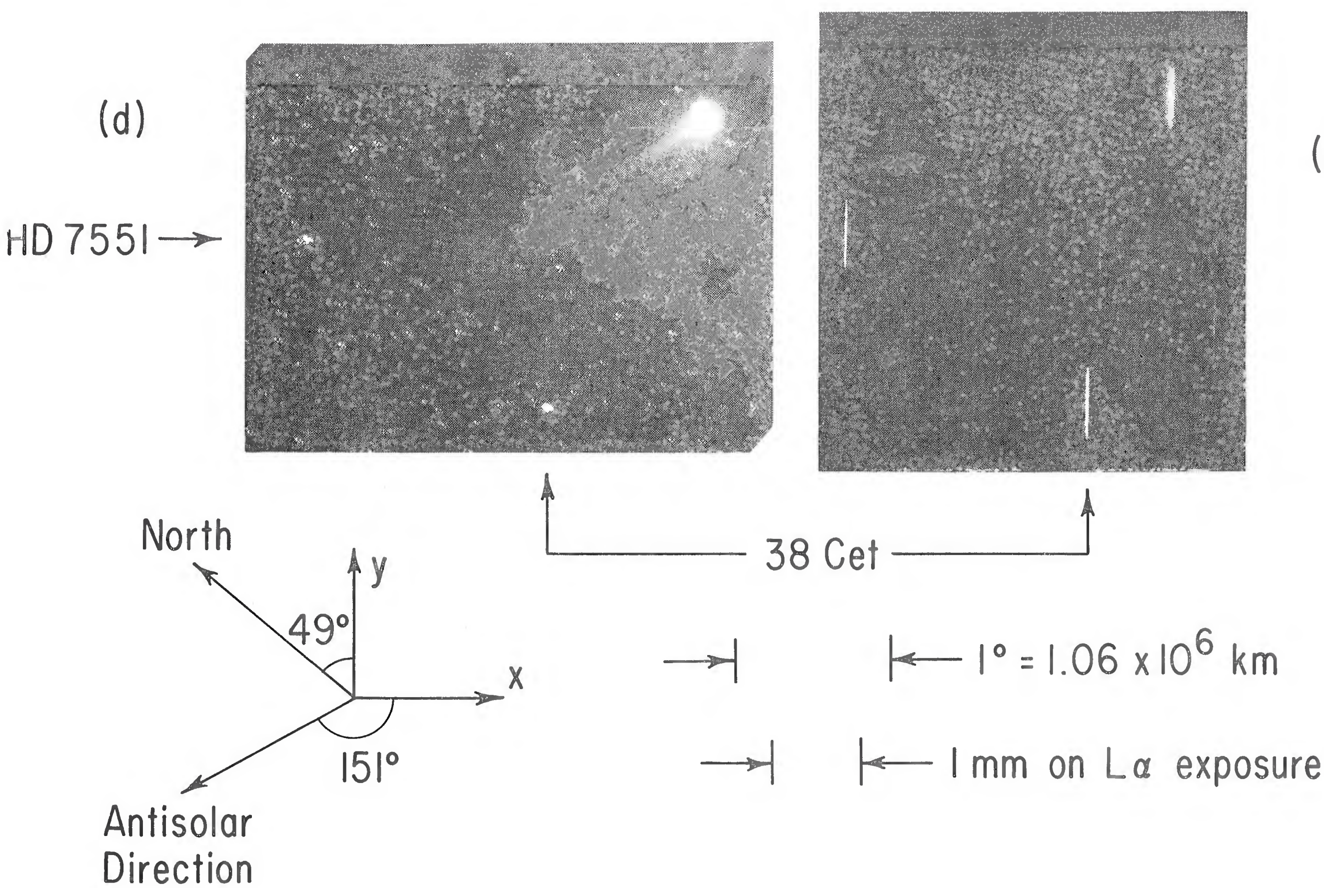

FIG. 1.—*Continued*

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understandably difficult to distinguish even an approximate value for $\langle \mathbf{J}_0\mathbf{J}_0^* \rangle$. We adopted the procedure of actually computing the image power $\mathbf{JJ}^*$ in the recording up to frequencies where it was at least 4 times the noise power (at about 3.1 cycles mm^{-1} in the dispersion direction), and then we assumed that the original signal power distribution remained flat as one went to higher frequencies. We judged this to be a reasonable assumption to make in the absence of any *a priori* knowledge on the existence of fine spatial structure in the noiseless, unsmeared comet image J_0.

The actual restoration operation was performed in the computer by evaluating the convolution $J*F$, where F is the Fourier inverse transform of $\mathbf{F}$ defined in equation (1). In actual practice we truncated F to zero for $x > 300\ \mu$ and $y > 750\ \mu$. In addition to saving computer time, this truncation automatically smoothed out irregularities and kinks in $\mathbf{F}$ produced by chance fluctuations in the evaluated $\mathbf{J}_0\mathbf{J}_0^*$. The representation of $\mathbf{F}$ in figure 2 is actually the Fourier transform of the truncated F and is effectively what was used for processing.

III. RESULT

Figures 1*b* and 1*c* show the appearance of the image after processing with the optimum filter $\mathbf{F}$. The output array from the computer is displayed at different contrast scalings in these two pictures. The gray levels in figure 1*b* were adjusted to show the entire Lα image. In comparing the processed picture with its original form in figure 1*a*, it is easy to see that much of the higher-frequency film grain noise has been eliminated. In addition, a noticeable sharpening of the display is demonstrated by the transformation of the synthetic stars.

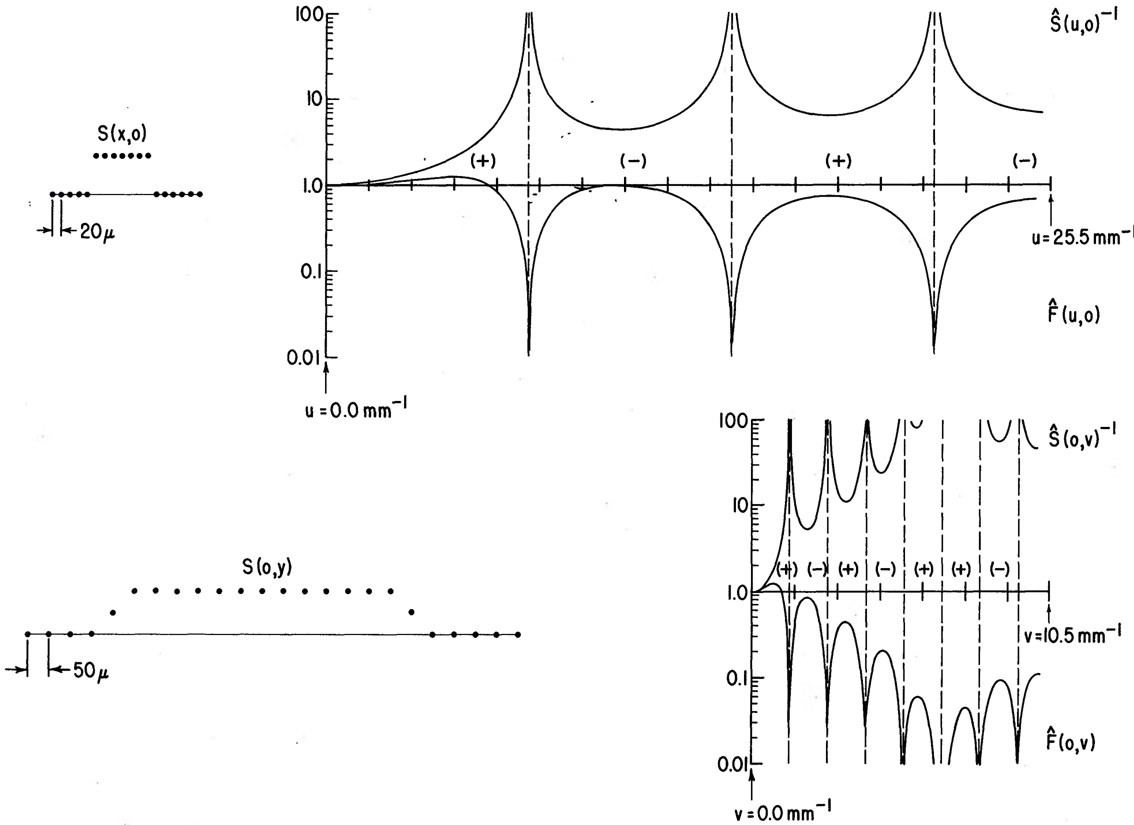

FIG. 2.—Cuts through the x- and y-axes of S and the u- and v-axes of $\mathbf{S}^{-1}$ (restoration for no noise) and $\mathbf{F}$ (least-squares restoration for a picture with noise). The sign of each lobe in $\mathbf{S}^{-1}$ and $\mathbf{F}$ is indicated by a $+$ or $-$ in the logarithmic plots.

The outer boundary of the image recorded here is almost circularly symmetric and has a diameter of approximately 45′ (8×10^5 km). Had we obtained a better sensitivity, we suspect we would have been able to record a larger-diameter image. For instance, the outermost contours in the Lα image of Comet Bennett (1969i) recorded by Bertaux and Blamont (1970) are as far as 6×10^6 km from the coma.

There appears to be a core of brightness within the larger diffuse glow, and the higher contrast in figure 1*c* emphasizes the detail of this inner component. In view of the rather limited quality of the Lα image, even after processing, it is difficult to say the existence of this central condensation of emission is altogether conclusive. Nonetheless, the patch shown in figure 1*c* is reasonably uniform and has well-defined borders. We therefore feel it is unlikely that random intensity fluctuations on top of the central portion of the larger glow could account for the observed bright spot. One can also faintly see in the unprocessed playback of figure 1*a*, as well as in a high-contrast print of the original piece of film, what appears to be the vertical edges of a point-source image (i.e., the rectangular box) in the middle of the comet. Interestingly enough, the data of Bertaux and Blamont (1970) likewise suggest the presence of an inner core of Lα emission in Comet Bennett.

Figure 3 graphs the intensity within a 14′ (2.5×10^5 km) wide slice through the center of the image. Although this tracing gives better quantitative information on the nature of the comet's intensity distribution, some of the benefits of a two-dimensional display are lost. For example, it is difficult to distinguish from the main comet profile the core we have just identified. We have indicated with a dotted line in the graph an approximate division between these two components to show their relative intensities.

Comet Tago-Sato-Kosaka was monitored over a period of several weeks by the Orbiting Astronomical Observatory (OAO-2). From a study of the time behavior of the Lα intensity reduction caused by telluric absorption at perigee, Code (1970) concluded the emitting hydrogen cloud around this comet had a characteristic velocity dispersion equivalent to a temperature of 1600° K (i.e., $\sigma = 0.015$ Å). The width at half-maximum of the telluric hydrogen absorption profile observed from rocket altitudes is typically on the order of or less than 0.04 Å (Tousey 1963), and hence the comet's radial velocity at the time of our observation (see table 1) was sufficient to ensure that only a small fraction of the Lα radiation could have been absorbed by telluric hydrogen. The radial velocity from the Sun was small enough that all of the comet's hydrogen could effectively scatter Lα radiation from the 1 Å wide solar emission profile.

IV. DISCUSSION

It is now appropriate to consider the origin of the hydrogen around the comet. In addition to the Lα flux, the spectrometer aboard OAO-2 also showed a strong emission from the comet cloud which has been identified as the 3068 Å band of OH (Code 1970). Code estimates the density of OH as a function of distance r from the coma to be approximately

$$n_{\rm OH} = (2 \times 10^{23} \text{ molecules cm}^{-1}) r^{-2} .$$

TABLE 1

LYMAN-ALPHA EXPOSURE AND COMET* PARAMETERS

Time interval: 1970 Jan. $25^{d}02^{h}31^{m}43^{s}$ to $32^{m}29^{s}$ UT	Approximate visual magnitude of coma = 4
Rocket altitude interval: 106–146 km	Elongation of comet from Sun = 69°
Comet zenith angle = 49°	Phase angle of comet = 87°
Camera effective focal length = 100 mm (f/2)	Comet-Earth distance Δ = 0.409 a.u.
Dispersion at Lα = 52 Å mm^{-1}	Comet-Sun distance r = 0.931 a.u.
Film density:	
Background fog = 0.485	$d\Delta/dt$ = +18.2 km s^{-1} ($\Delta\lambda$ = 0.074 Å at Lα)
Comet center = 0.645	dr/dt = +30.2 km s^{-1} ($\Delta\lambda$ = 0.122 Å at Lα)

* Comet position data are from Marsden (1970).

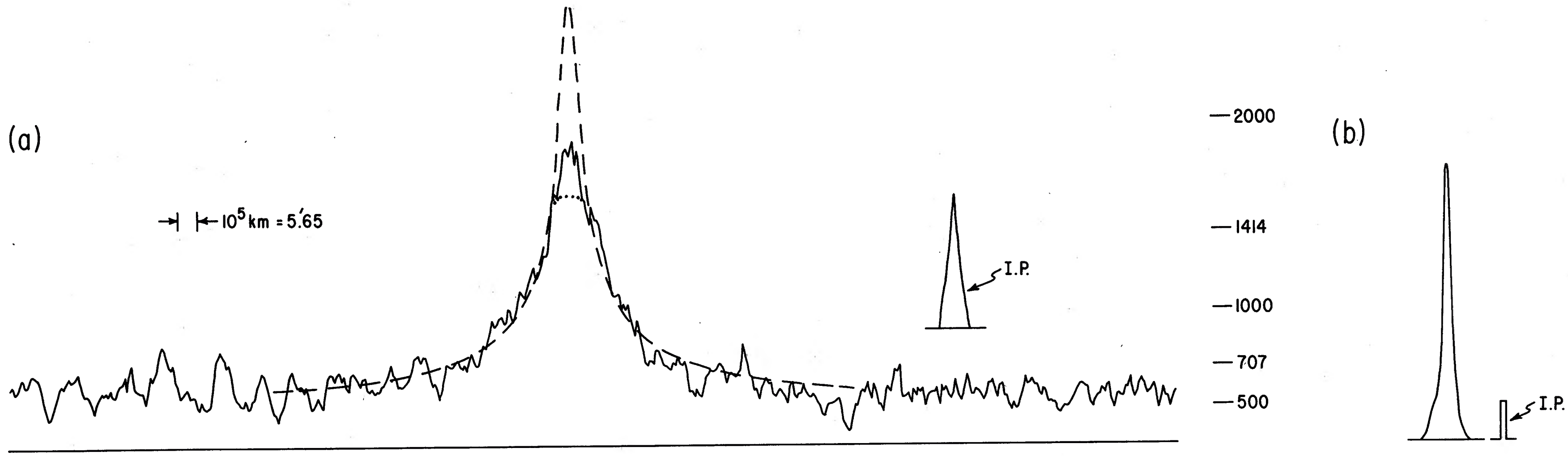

FIG. 3.—(*a*) An average of 8 scans along the dispersion direction (x-axis) through the center of the comet. The dotted line near the peak is an approximate division between the bright core shown in fig. 1*c* and the rest of the emission seen in fig. 1*b*. If the hydrogen cloud were optically thin to Lα radiation and had a density proportional to r^{-2}, we would have seen a profile whose shape is shown by the dashed line. The numbered horizontal lines toward the right indicate the intensity levels for the gray boxes in figs. 1*b* and 1*c*. For comparison, a photometric drift scan at visible wavelengths by Minton (1970) on 1970 January 27.12 (Δ = 0.437 a.u.) is shown to the same angular scale in (*b*). The effective instrumental profile (I.P.) is shown for each tracing.

The most plausible origin of the OH is from the dissociation by sunlight of H_2O evaporated off the comet's nucleus (Delsemme 1971), and for each OH radical present there has been a free H atom produced. It is interesting to note that a calculation by Squires and Beard (1961) predicts an H_2O evaporation rate of 1.5×10^{17} molecules cm^{-2} s^{-1} off the surface of a solid cometary nucleus when it is 0.93 a.u. from the Sun. Roemer (1971) estimates the radius of the nucleus of comet Tago-Sato-Kosaka to range somewhere between 1 and 7 km, depending upon what one assumes for the albedo of the nucleus (Roemer 1966). For the 7-km radius, we would expect an outward flux of 1.8×10^{28} H_2O molecules sterad^{-1} s^{-1}. If the dissociation of water were complete and the OH molecules had a mean outward velocity corresponding to $[8k(1600° \text{ K})/\pi m_{OH}]^{1/2} = 1.4 \times 10^5$ cm s^{-1}, the density of OH would be roughly two-thirds the value obtained from Code's observations. In view of the uncertainty in the effective surface area of the nucleus, the agreement of the prediction and observation is quite satisfactory. If we equate the outward flux of H atoms to that observed by Code for OH and assume the mean radial velocity of H atoms is higher by a factor of $17^{1/2}$ (i.e., $T_H = T_{OH}$), we would expect a density of at least $n_H = (5 \times 10^{22}$ atoms $cm^{-1})$ r^{-2}. If one were to look radially toward the comet's center, at 1600° K an optical depth τ_0 of unity in the middle of the line profile would be reached at a distance of 7.5×10^4 km from the center.

Tolk, White, and Graedel (1970*b*) have suggested the hydrogen may come from solar-wind protons which have been neutralized by charge exchange with cometary molecules (principally carbon monoxide). If all of the protons colliding with the coma (diameter $\approx 10^5$ km) were neutralized, the flux of neutral hydrogen would be comparable to that estimated to come from the cometary H_2O. However, the mean outward velocity of the neutralized protons should be significantly larger than 1 km s^{-1}, which would bring the overall density to a much lower value that that predicted for hydrogen from the comet itself. In addition, it would be difficult to reconcile the observed 1600° K velocity spread with the hypothesis that the neutralized solar wind was the dominant source of hydrogen.

Clark *et al.* (1971) have attempted to detect microwave emission from H_2O in the central region of Comet Bennett, and from the absence of any measurable signal they were able to define an upper limit for the overall density. It appears that their upper limit for the total H_2O evolution rate is about 1500 times the representative value we have just suggested, even though Comet Bennett was a more spectacular comet than Comet Tago-Sato-Kosaka.

It is possible that dissociation of molecular species other than H_2O could be an additional source of hydrogen. Biermann (1969) has suggested the existence of hydrogen densities on the order of $(5 \times 10^{23}$ atoms $cm^{-1})$ r^{-2} around a large comet. With Biermann's value we would reach $\tau_0 = 1$ at 7.5×10^5 km from the comet.

An interpretation of the distribution of hydrogen around the comet from the shape of the image is largely dependent upon how far from the comet's center we assume $\tau_0 \approx 1$ for Lα radiation, which in turn is dependent on the overall density and temperature (or velocity dispersion) of the cloud. Although from the previous discussion it seems reasonable to assume that the most likely situation is that $\tau_0 \lesssim 1$ down to the radius of the inner core component ($\sim 10^5$ km), it would not be unreasonable for $\tau_0 \approx 1$ at some distance $r \gg 10^5$ km. If the latter condition holds, one must solve the radiative-transfer problem to derive a density distribution, but this task will not be attempted here.

On the other hand, if attenuation of the solar Lα flux and self-absorption of the resonantly scattered radiation is negligible, the observed brightness is simply proportional to the column density of hydrogen along a particular line of sight through the cloud, provided there are no other processes which contribute additional Lα radiation. Considering the simple case where n_H is proportional to r^{-2} (i.e., the hydrogen is produced at the center of the comet and streams away at a constant velocity), one would expect the brightness to decrease as r^{-1} in a perfectly sharp image of the comet. For comparison purposes, we have shown with a dashed line in figure 3 the profile shape which would have been recorded if the Lα intensity were proportional to r^{-1}. This expected profile is essentially a plot, along a line through the center of the comet, of the convolution $r^{-1}{*}S{*}F$ (S and F were defined in § II) which has been averaged over eight elements in the vertical (y) direction. Assuming $\tau_0 \lesssim 1$, we find the excellent agreement of the intensity tracing and the dashed line in figure 3 for $r > 10^5$ km suggests that n_H is indeed proportional to r^{-2} except near the center of the comet. Since the mean time for dissociation of H_2O by sunlight is on the order of 10^5 s (Delsemme and Miller 1970), it is not surprising that the density gradient inside $r = 10^5$ km could be much shallower than r^{-2} if the mean velocity of the H_2O molecules were on the order of 1 km s^{-1}.

As we mentioned earlier (in § III), a principal feature in our Lα image of Comet Tago-Sato-Kosaka is a central bright spot which seems to stand out on top of the large, diffuse glow. We feel that figure 1*c* suggests some likelihood that this core may be a separate component and not just a continuation of the general intensification toward the center. To explain this central brightness, we might explore physical processes other than resonance reradiation which would act as a separate source of Lα photons from the comet. One such possibility is an interaction of the solar wind with gas in the relatively dense coma. The exact way the photons are produced remains an open question however.

Tolk, White, and Graedel (1970*a*, *b*) have suggested that an important source of Lα radiation may be the de-excitation of H atoms formed by the charge exchange of solar-wind protons with cometary CO. Unfortunately, we feel that this straightforward proposal fails from a quantitative standpoint. We have no measure of the absolute strength of the Lα emission from the center of the comet, but it is likely to be not a great deal less than the 24 kR (i.e., 2.4×10^{10} photons cm^{-2} s^{-1}) brightness observed for the center of Comet Bennett (at $r = 0.6$ a.u.) by Bertaux and Blamont (1970). However, an average value for the solar-wind flux at 1 a.u. is only 3×10^8 protons cm^{-2} s^{-1} (Ness 1968), and since the newly formed H atoms may emit other Lyman lines, on the average we would expect somewhat less than one Lα photon to be emitted for each proton consumed.

To find a more powerful mode of generating Lα photons in the vicinity of the coma, we might consider the theoretical interpretation by Beard (1966) for a means of ionizing comet molecules much more rapidly than one could expect from simple charge exchanges with solar-wind protons. Beard has discussed how electrons within a thin magnetohydrodynamic shock region in front of the coma may be accelerated to kilovolt energies. He has proposed that these electrons and their secondaries rapidly ionize cometary neutral gas molecules and that significant acceleration of the ions may occur. We could propose that within this transition layer collisions by these electrons may likewise excite enough hydrogen atoms to generate an appreciable flux of Lα photons. It is also possible that the accelerated cometary ions themselves could excite many of the hydrogen atoms escaping from the inner portion of the comet. Moreover, we could reasonably expect considerable momentum to be imparted to the excited H atoms, and the resulting Doppler shifts would yield an emission profile whose width is significantly greater than that of the Lα emission from undisturbed atoms in the main cloud. This has the interesting consequence that much of the core emission would not be absorbed by the surrounding hydrogen, and hence its visibility would be insensitive to the value of τ_0 through the main cloud.

An alternative interpretation of the bright core is that the Lα photons still come from resonance reradiation of solar Lα as in the rest of the cloud, but that in the central region there is a sharp discontinuity in the radial density distribution of hydrogen. As the gas streams away from the nucleus, it must somehow be heated from the evaporation temperature to around 1600° K. If a good portion of this heating occurs in a thin zone a short distance away from the center (such as the interface between the comet and the solar wind), then we might well expect an upward jump in density inside the zone where the radial velocities are lower.

V. CONCLUSION

The presence of a cloud of atomic hydrogen, considerably larger than the coma, is revealed by the strong resonance reradiation of solar Lα emission from a region surrounding the comet. A very plausible source for this hydrogen is from the dissociation by solar radiation of H_2O evolving off the nuclear material. An estimate for the vaporization rate of H_2O off a nucleus of reasonable size predicts that there should be an adequate supply of parent molecules (H_2O plus possibly other more volatile compounds) to produce enough hydrogen to be observable. The OAO observation of strong emission by OH seems to confirm the importance of water as the origin of the hydrogen.

In addition to the diffuse Lα glow coming from the large cloud, our recording suggests that there also may be a central bright spot. The evidence for this bright core is not compelling, owing to our poor image quality, but we feel its existence is a strong enough possibility to warrant serious consideration. It is difficult to say whether the core of Lα emission, if it exists, is a truly distinct component on top of the general glow and has its own physical origin, or whether it merely represents a steeply rising density gradient toward the comet's center which we can observe within a cloud of low optical depth for Lα radiation. We look forward to the possibility that future observations of the Lα radiation from large comets may clarify the general interpretation of the hydrogen cloud's structure and dynamics, as well as the mode of excitation for Lα emission.

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