

O(¹D) AND H₂O⁺ IN COMET BENNETT 1970. II.

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ABSTRACT

Two sets of brightness profiles have been determined across the coma of comet Bennett from two spectra taken 20 minutes apart on 1970 April 18 ($r = 0.841$ AU). In the monochromatic light of H₂O⁺, they show wave patterns moving tailward with a velocity of 17 km s^{-1} . The general slope of the two tailward profiles can be explained by a kinematic model where the ions are blown away tailward with a rather large and variable acceleration. The wavy patterns are probably induced first in the sunward direction by the irregularities in the magnetic lines, where cometary ions interact with turbulent plasma of the solar wind. No stagnation point can be identified, and the role of the contact surface with the solar wind is de-emphasized. The upper limit established for the Alfvén velocity suggests a total production rate of ions not larger than $3 \times 10^{27} \text{ s}^{-1}$. The revised production rate of the observed H₂O⁺ is $2.0 \times 10^{26} \text{ s}^{-1}$, that of the observed O(¹D) is $1.7 \times 10^{29} \text{ s}^{-1}$. Two scale lengths are needed to describe the profile of O(¹D) with a central flattening; they are equal within 10%, and their sum is $2.1 \times 10^4 \text{ km}$. One-fourth of the observed red photons can be traced back to water as a parent molecule; the rest could be attributed to a production of $12(+6, -3) \times 10^{28}$ molecules of CO₂, although other possibilities from neglected ion-molecular reactions cannot be ruled out.

Subject headings: comets — molecular processes

1. INTRODUCTION

The present authors have published, for the first time, the brightness profiles of a comet, sunward and opposite to the Sun, in the monochromatic lights of [O I] and H₂O⁺ (Delsemme and Combi 1976*a, b*, hereafter Papers I and II). These profiles were deduced from a composite of two spectra and had been limited to 10^5 km from the nucleus, because of the assumed vignetting of the spectrum for larger distances. Our results implied rather strongly that the H₂O⁺ ions were *inside* the surface discontinuity, suggesting the need to extend these profiles beyond 10^5 km in order to detect the upstream stagnation point of the cometary plasma against the solar wind. Another strong motivation to extend the profiles came from the desire to verify the [O I] calibration by reaching distances where the cometary contribution was vanishing and where a plateau of pure airglow [O I] could be identified easily. The calibration of Paper I was indeed a model-dependent extrapolation that had yielded an uncomfortably high value of the cometary production rate of O(¹D). Both profiles of [O I] and H₂O⁺ have now been extended to their total available length by using the mercury lines of the Toledo night sky as an unanticipated but welcome internal calibration of the vignetting of the spectrum perpendicular to the dispersion.

The data reduction technique has also been improved. For Papers I and II, chart-recorder transmission tracings, obtained with the McMath Hulbert Observatory microdensitometer, were reduced by hand. The accuracy was then limited mainly by the

reading of the nonlinear intensity scale on the transmission tracings. The new data were obtained from digital density scans made with the PDS microdensitometer at Kitt Peak National Observatory, written on magnetic tape, and reduced on a Univac 1110 computer. Considerably finer discrimination in intensity and integration steps about 5 times narrower in wavelength have greatly decreased the scatter of the data, improved the space-resolving power, and allowed the measurement of two more points closer to the nucleus; whereas the extension into the presumed vignettted area has added nine points antisunward.

As far as the [O I] profile is concerned, we were not able in Paper I to reach the plateau of the airglow level. In order to deduce this level, we fitted a model to the inner portion of the composite profile (where the airglow contribution can clearly be neglected because the cometary contribution is one to two orders of magnitude larger); at larger distances, we attributed the difference between the composite profile and the model to the airglow only. This critically depends on the outer few points, which happen to be just the place where vignetting of the spectrum started influencing the profile, as has been established now by using the profiles of the mercury lines. After vignetting correction, the outer half of the observed [O I] profile, using a single spectrum of 10 minute exposure time, reaches now a constant level both sunward and antisunward that can be unambiguously attributed to the airglow (see Fig. 2). Contrary to the calibration of Paper I, the present calibration is therefore no longer model-dependent; because of the vignetting correction, it is 7 times higher than the extrapolated value used in

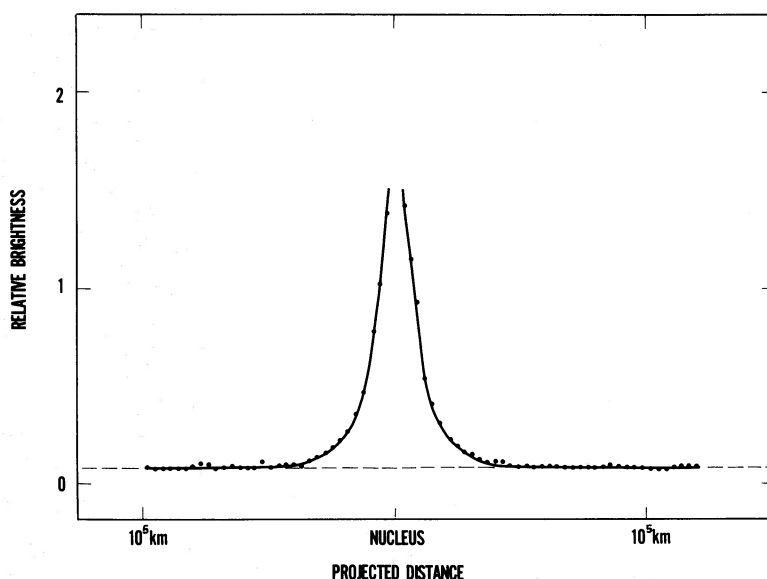


FIG. 2.—Solid line, relative brightness of the observed (cometary plus airglow) forbidden oxygen line plotted versus the projected distance from the nucleus (sunward is to the right). Dotted line, level of the airglow contribution which is clearly reached far from the nucleus.

Paper I. Since the new value significantly diminishes the cometary contribution of [O I] at large distances, it also diminishes the production rate of [O I] by an even larger factor.

Another previously unpublished profile of H₂O⁺ has been reduced by the same technique from a spectrum taken 20 minutes earlier on the same night of 1970 April 18. Comparison of the two profiles reveals for the first time a regular pattern of moving waves in the plasma; this pattern will be discussed in § V. Figure 1 (Plate 1) shows the portion of the spectrogram of comet Bennett containing the 6300 Å forbidden line of oxygen, the H₂O⁺ (8–0) band, the 5770 Å and 5790 Å mercury sky lines, as well as an average microdensitometer tracing.

A revision of the radiative lifetimes of several molecules and ions (including H₂O⁺ ²A₁) of particular interest in cometary physics has been made by Curtis and Erman (1977). For excited states with lifetimes greater than 1 μs which have been determined from delayed coincidence measurements following the pulsed excitation (e.g., electron beam) of a gas, they have compensated for the escape of the excited gas molecules from the detection region due to thermal motions (in the case of neutrals) and electrostatic repulsion (in the case of ions). They found that previous lifetime measurements were too short by a factor of up to 3–4. The previous lifetime of the ²A₁ state of H₂O⁺ was originally determined to be 0.8 μs (Erman and Brzozowski 1973). Curtis and Erman have revised this value upward to 3.0 ± 0.3 μs. This leads to a change in the emission-rate factor for the entire $\tilde{A}^2A_1 \rightarrow \tilde{X}^2B_1$ band system by resonance-fluorescence with solar light at 1 AU from 0.9 photons ion⁻¹ s⁻¹ (Wyckoff and Wehinger 1976) to 0.24 photons ion⁻¹ s⁻¹. The results contained herein use

this revised value. Previous determinations of H₂O⁺ column densities are all too small by a factor of 3.75.

II. RESULTS FOR O(¹D)

Figure 2 shows an ordinary diagram of the brightness profile, where the airglow plateau is clearly reached at large distances. Figure 3 shows a log-log diagram of the cometary profiles after removal of the airglow contribution. The data points much below the airglow contribution could be neglected but do not change the fitting of the model; they therefore seem significant. The O(¹D) cometary profiles remain completely symmetric, ruling out a dissymmetric plasma contribution (from the solar wind) for the excitation of the oxygen into the ¹D state. Haser's (1957) single-parameter model cannot explain the flattening of the slope to absolute values smaller than 1, which seems to imply the existence of an extended source of about 10⁴ km for the *grandparent* molecule of O(¹D) [since the brightness profile is proportional to the column density of the O(¹D) *parent*]. Using Haser's two-parameter model (scale lengths γ_1 and γ_2 for the parent and grandparent, respectively) the data from Figure 3 can be fitted to the following values of the parameters:

$$\gamma_1 + \gamma_2 = (2.1 \pm 0.2) \times 10^4 \text{ km},$$

$$\gamma_1 \gamma_2^{-1} = 1.0 \pm 0.1,$$

$$Q(\text{O } ^1D) = (1.7 \pm 0.7) \times 10^{29} \text{ s}^{-1} \text{ at } 0.841 \text{ AU},$$

$$Q_0(\text{O } ^1D) = 12 \times 10^{28} \text{ s}^{-1} \text{ at } 1 \text{ AU}.$$

Q is the production rate of photons, and is therefore the assumed production rate of that fraction of the

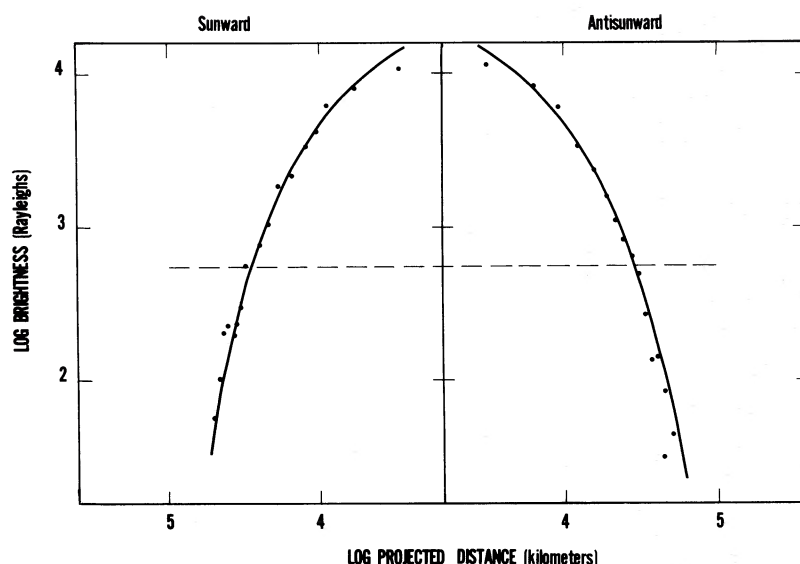


FIG. 3.—Brightness profile of cometary $O(^1D)$ plotted on a log-log diagram. Filled circles, observed cometary data; solid curves, the best fit of Haser's two-parameter symmetric model; and dashed line, level of the airglow.

parent molecule that dissociates into O in the ^1D state; Q_0 is the same production rate, reduced for 1 AU by an inverse square law. The uncertainty on Q is 40%, 25% coming from the actual intensity of the airglow line and 15% from the position of the airglow level in the profile. The other [O I] profile deduced from another spectrum 20 minutes earlier gives consistent results, with only a higher scattering of the data, presumably coming from a poorer seeing, because the comet was lower on the horizon.

III. DISCUSSION FOR $O(^1D)$

Haser's two-parameter model is clearly used for heuristic purposes; the parameters may not necessarily have the physical meaning of production and removal rates. Taken at its face value, however, the model implies the existence of a chain of grandparent and parent particles (icy grains) or molecules necessary to produce $O(^1D)$; the extended source of parents is described by an exponential scale length of 10^4 km, which coincides rather well with the icy-grain halo (Delsemme and Miller 1971a, b). The flattening of the profile inside 10^4 km is much too large to be exclusively explained by the convolution with spatial resolving power along the spectral slit, and no collisional model (e.g., charge-exchange reactions) has yet been able to explain it numerically.

The origin of $O(^1D)$ is likely to be found in the photodissociation of a neutral molecule (Biermann and Trefftz 1964); the best candidate would possibly be among H_2O , CO_2 , CO, and OH. Not only is OH observed, it would also have H_2O as grandparents. Unfortunately, the scale length for OH decay in the coma is now observationally known (Delsemme 1976; Blamont and Festou 1974; Keller and Lillie 1974) and it is more than one order of magnitude larger than that

observed for the $O(^1D)$ parent. Because of the large (11.15 eV) dissociation energy of CO, its scale length is likely to be even larger than that of OH, ruling out these two molecules as the $O(^1D)$ parents. We are left with H_2O and CO_2 as most likely parents. Delsemme (1978) has recently shown that about 12% of H_2O on the average is to be photodissociated by solar light into $H_2(^1\Sigma^+_g) + O(^1D)$ through a predissociation band irradiated by the solar ultraviolet between 1000 and 1250 Å, with a large contribution of $L\alpha$. Delsemme (1978) also reports that $67 \pm 21\%$ of the CO_2 would be dissociated into $CO(X^1\Sigma^+) + O(^1D)$, the $\pm 21\%$ uncertainty coming from the gaps in the known absorption cross section of CO_2 , mainly between 900 and 1100 Å.

If we make the reasonable assumption that OH and H come mainly from water in comet Bennett, reported production rates (Delsemme 1977) imply 30×10^{28} molecules s^{-1} of water at 1 AU, yielding 3.6×10^{28} red photons from $O(^1D)$ per s; approximately one-fourth of the observed photons can therefore be traced back to water as a parent molecule. If we now accept the present evidence, which seems to confirm Delsemme's (1975) circumstantial arguments for the presence of CO_2 , the three-fourths of the observed photons (nominally 8.4×10^{28} photons s^{-1}) can be attributed to a production rate of $12(+6, -3) \times 10^{28}$ molecules of CO_2 , i.e., from 30% to 60% of the production rate of water. A halo of icy grains of 70% H_2O + 30% CO_2 , with a fast preferential vaporization of CO_2 , can easily explain the features of the $O(^1D)$ profile. It is clear, however, that the error bars may be such that we cannot totally rule out a grain composition of about 85% H_2O + 15% CO_2 that would correspond to the solid clathrate-hydrate of CO_2 (Delsemme and Swings 1952). This halo could explain the observed scale length of the source term of

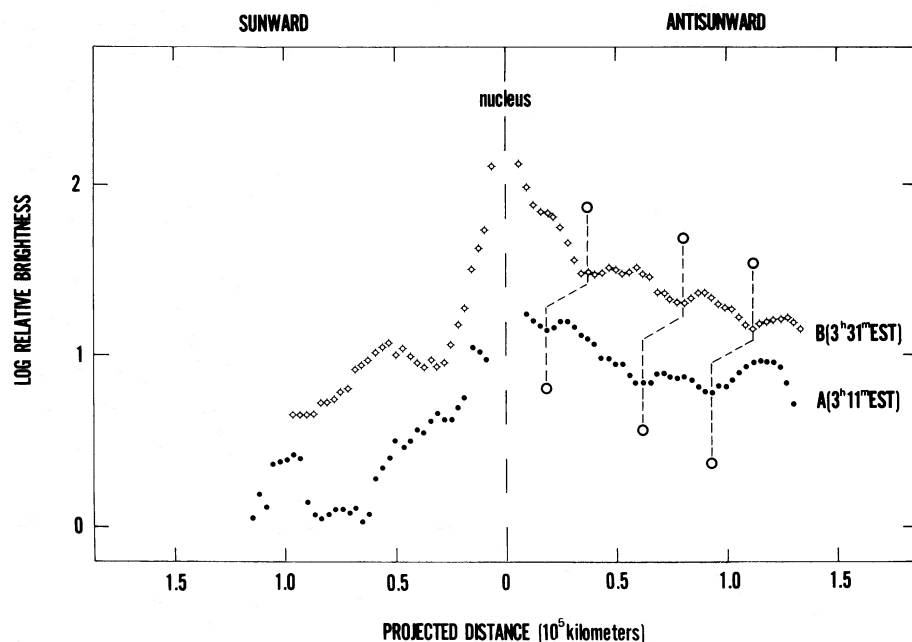


FIG. 4a.—The brightness profiles of H₂O⁺ plotted as log of the relative brightness versus projected distance. Filled circles, profile from spectrum A; small open circles, profile from spectrum B; large open circles, three major troughs shifted profile. Profile A has been arbitrarily shifted downward for easy comparison.

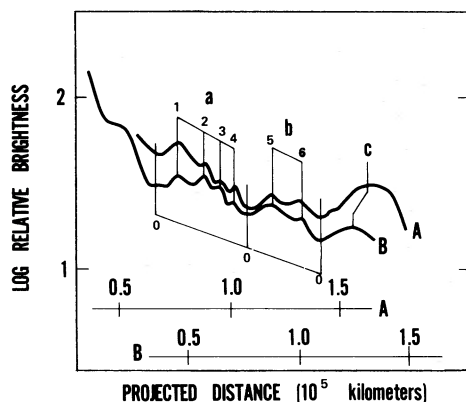


FIG. 4b.—The antisunward profiles for spectra A and B have been shifted by 18,000 km such that the three major troughs coincide, also yielding six coincident peaks.

the O(¹D) profile, and would have no effect on the H₂O⁺ profile discussed later.

In order for this explanation to hold—the grandparent scale length (of about 10⁴ km) being interpreted as the size of an icy-grain halo—the parent scale length (also of about 10⁴ km) should be identified with that of CO₂. Since CO₂ is not observed, only theoretical predictions can be compared. The lifetime of CO₂ against photodissociation is given as 10^{5.6} s at 1 AU (Feldman *et al.* 1974); however, Delsemme (1978) has published all the details of the integration and revised this assessment down to 10^{5.1} s at 1 AU. This would yield a photolifetime of 10^{4.9} s at the present distance, or possibly 10^{4.5} km for the scale length of

thermal CO₂ against photodecay only. Since most other observed scale lengths are smaller than those predicted theoretically by photodecay, our result is not inconsistent with all other values published for other molecules (Potter and Del Duca 1964).

However, the very fact that all these values are smaller than those of photodecay is a powerful argument in favor of neglected ion-molecular reactions. For instance, could the electron recombination process CO⁺ + e → C + O or OH⁺ + e → O + H play any role in the production of O(¹D)? So far, nobody knows. All we can say is that the symmetry of the O(¹D) profile excludes a large contribution of fast electrons coming from the solar wind.

The general conclusion of this discussion is that the O(¹D) producers act in an extended source that can be described by two exponential scale lengths, both of about 10⁴ km; one is attached to a source term, the other to a sink term of the O(¹D) parent, whatever it is (photomolecular and/or ion-molecular reactions). These scale lengths correspond rather well to the size of the collisional zone.

IV. THE H₂O⁺ BRIGHTNESS PROFILES

The brightness profiles for H₂O⁺ (Figs. 4 and 5) show for the first time not only the instantaneous brightness distribution of an ion in the cometary head in two known directions, sunward and antisunward, but also structural details with a high spatial resolution. They also show a variation and a shift of the profiles' structures after 20 minutes, and therefore suggest motions of wave patterns. Figures 4a and 4b (semi-log) show at their best the observed wave

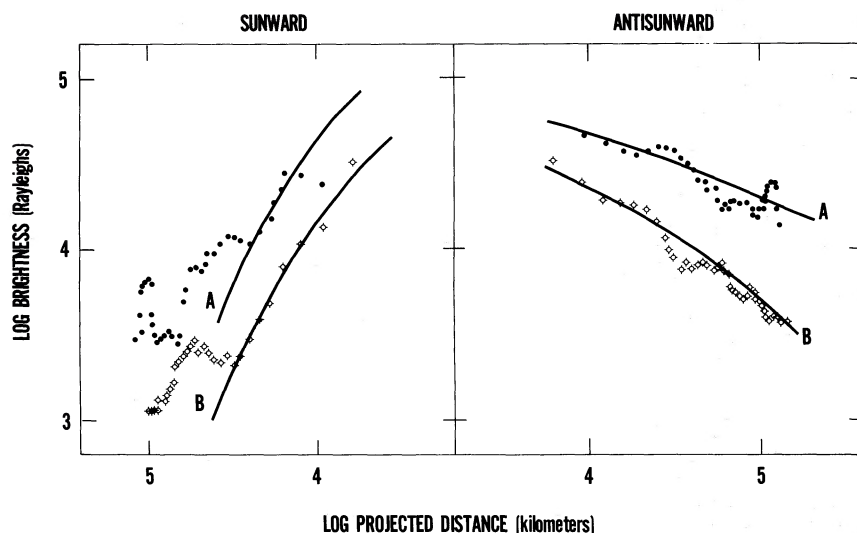


FIG. 5.—The brightness profiles of H_2O^+ from spectra *A* and *B* plotted as log brightness versus log projected distance. The absolute calibration refers to spectrum *B* (open circles), whereas spectrum *A* (filled circles) has been shifted arbitrarily by about 0.3 upward in log *B* for easy comparison.

patterns, whereas Figure 5 (log-log) is better for theoretical considerations.

Because of the early belief that the profile irregularities were spurious, Paper II had used a two-spectrum composite profile that had inadvertently smoothed out the wave patterns. The idea, one that had been used with success for already smooth profiles of neutrals (Delsemme and Moreau 1973), was to work with spectra of two different exposure times (3 and 10 minutes) to extend the range of the photographic plate. Each spectrum is used for the distance range where the slope of its characteristic curve is at its best; at the steady state, the overlapping of the ranges allows an easy connection from the shorter to the longer exposure.

The present study of two individual spectra (labeled *A* and *B* on Figs. 4*a*, 4*b*, and 5) and the better space-resolving power of the new reduction technique now show that a steady state of the ion profiles does not exist when a time resolution of 20 minutes is used. Spectrum *A*'s midpoint time was 3^h11^m LST, spectrum *B*'s was 3^h31^m LST; each had an exposure time of 10 minutes. Each spectrum shows a wavy pattern with waves much longer than the space resolution, and amplitudes much larger than the background noise. Their reality for H_2O^+ is also confirmed by their total absence for [O I] on the same plate (Figs. 2 and 3). It is clear, however, that the two exposure times of 10 minutes each act as a high-frequency cutoff filter, smoothing out the shortest waves.

V. MOTION OF WAVE PATTERNS IN H_2O^+

Comparison of the two spectra suggests that the motion of wave patterns is antisunward, whereas no such correlation appears sunward. In order to identify wave patterns, we first identify the three major troughs

of the waves (Fig. 4*a*, open circles). We check that each of them can be retrieved 20 minutes later by the same shift of 18,000 km (perpendicular to the line of sight; i.e., about 20,500 km along the tail axis, which is 28°5' from the plane of the sky). In order to confirm our identification, we superpose (Fig. 4*b*) profile *B* on profile *A*, after a shift of 18,000 km. We can now identify six crest coincidences; the only major crest whose coincidence is not satisfactory is crest *c*, the last and farthest away (it seems to move more slowly). We assume that nine coincidences (six crests, three major troughs) cannot be random.

Because of the appearance of a quasi-wavelength (the most frequent distance between crests is 12,000 km) and because of the depth of the troughs, only another coincidence can be found for twice the 18,000 km displacement (this yields a shift of two troughs and of three wavelengths); but then the total number of good coincidences falls off by one-half. We therefore accept that the wave pattern has moved (with some distortion) at a velocity of about 17 km s⁻¹ along the tail axis and toward the tail. Because of the probable acceleration of the ions into the tail, this velocity compares very favorably with a tentative interpretation of a Doppler-shift observation (Huppler *et al.* 1975) which indicates down the tail of comet Kohoutek a bulk velocity for H_2O^+ of 20–40 km s⁻¹, almost twice as far from the nucleus (2×10^5 km) as our longest distance. The comparison strongly suggests that, in spite of the repeated wavy features, our observed velocity is primarily a *bulk* velocity, and the waves should possibly be interpreted as induced by a periodicity in the activity of the comet. The period associated with the quasi-wavelength (16,400 km along the tail axis) is about 800 s. This could easily be twice that period because the tail axis is not seen at a right angle; since we see throughout the tail, we could

possibly see twice the same features of the hollow envelope projected onto the sky at two different distances from the nucleus. Wurm (1947) had already mentioned an upper limit of 3200 s for the average lifetime of the CO⁺ parent from the fluctuations in the stream of CO⁺ moving into the plasma tail.

A period on the order of 13 minutes (or twice this amount) is too short to be associated with a rotation period of the nucleus, but could easily be associated with characteristic times found within the collision zone (10⁴ km), which may be the source of most ions. Ip and Mendis (1976) also propose large cross-tail currents which could be disrupted by ion-sound current instabilities leading to short time scales smaller than 10⁴ s for outbursts of rapid ionization. Here we detect fluctuations that are even one order of magnitude shorter than this limit. They could possibly come from the solar wind turbulence and be driven by the time scale of its instabilities.

Whatever the mechanism of these short fluctuations, their existence must initiate and drive plasma waves of the same frequency. The observed velocity sets an upper limit for the Alfvén velocity V_A , since the plasma wave may ride on a bulk motion of sizable velocity. The condition $V_A \leq B(4\pi\rho)^{-1/2}$, applied to an average molecular weight of 25 for the ions, implies rather large plasma densities ($n > 10^3 \text{ cm}^{-3}$) for a moderately strong magnetic field ($B = 150\gamma$) or a rather small magnetic field ($B < 15\gamma$) for moderate plasma densities ($n = 10 \text{ cm}^{-3}$). Since B is likely to cover this range for the cross section of the onset of the tail ($1.4 \times 10^4 \text{ km}$ diameter; see § IX), this is consistent with a total production rate of $3 \times 10^{27} \text{ ions s}^{-1}$ or less going into the plasma tail, that is, at most 1% of the total production rate of neutrals. Since all neutrals become ionized eventually by the solar UV, this also implies that some 99% of the ions form beyond the contact surface and are diluted into the interplanetary space, whereas only 1% of the potential ions form early enough to be imprisoned within the plasma tail. This is also consistent with what we know about the different scale lengths of major neutrals against ionization (Delsemme 1976), since most of them diffuse through the contact surface freely before being ionized. The role of the contact surface that separates the cometary ions from the solar wind is therefore de-emphasized, since it affects only some 1% of the cometary stuff.

VI. INTERACTION WITH THE SOLAR WIND

We have just derived an upper limit of $3 \times 10^{27} \text{ ions s}^{-1}$ within the contact surface with the solar wind. This implies that the stagnation point of the contact surface is probably within 10⁴ km, in order to balance the stagnation pressure of the solar wind. This result, coupled with the previous remark, seems to be confirmed by the sunward profiles, where no contact surface is apparent, whereas they show complex and variable patterns clearly coming from the strong interaction of the variable production rate of cometary ions with a turbulent plasma. It is also possible that no

stagnation point can be identified because its position keeps changing with a time constant short as compared with the building up of the brightness profile (10⁴ s). Indeed, in 20 minutes, the average slope sunward (Fig. 5) remains more or less the same and steeper than -1 (implying a fountain effect), but the structural details cannot be identified any more. Wave crests near 10⁵ km seem to recede backward to the nucleus, suggesting the building up of large ion density waves drifting backward with the magnetic lines, but no wave pattern can be identified for sure, and the interpretation therefore remains uncertain. It is clear, however, that we detect (this time quantitatively) the phenomenon of the inward-moving envelopes so well described for comet Morehouse (1908 III) by Eddington (1910); this was visible in Eddington's photographs probably because of the large intensity of CO⁺ in its peculiar spectrum (Fowler 1912).

VII. VELOCITY FIELD OF H₂O⁺

Before discussing the antisunward profiles, we must first elucidate the velocity field of H₂O⁺. From the steepness of the brightness profiles, a source of H₂O⁺ ions clearly exists in a zone that is not resolved and that is tempting to assimilate to the collision zone. The neutral gas that vaporizes from the nucleus has, of course, a thermal velocity ($\leq 1 \text{ km s}^{-1}$). Exothermic charge-exchange reactions (Oppenheimer 1975) may heat up the gas; however, because of the small number of collisions, many ions may be incompletely thermalized. We assume that the neutrals' velocity will remain (for molecules like water) within 1–1.5 km s⁻¹, whereas water-ion velocities could be between 1.5 and 2 km s⁻¹. In spite of a moderate velocity of, say, 1.7 km s⁻¹, the deceleration of the solar light alone is small enough to allow a "fountain effect" up to a range of 10⁵ km sunward. Indeed, the acceleration of the plasma induced by the absorption of solar light may be assessed by taking into account the major absorption bands where the solar flux is maximum (namely, for CO⁺, H₂O⁺, and N₂⁺); a weighted average shows that it cannot be more than 1 or 2 cm s⁻², and could be much less if a large number of (undiscovered) ions do not absorb in the visible. The fountain effect will therefore be effective sunward, with an almost-negligible acceleration, until the ions hit the first magnetic lines of the solar wind, at some 10⁴ km.

At that time, they will be deflected sideways along the magnetic lines present in the contact surface, and will acquire a much larger acceleration. According to the magnetohydrodynamic picture (Ioffe 1967), this acceleration comes from the magnetic pressure drop because the magnetic lines open up. For the 17 km s⁻¹ measured tailward at an average distance of $0.8 \times 10^5 \text{ km}$, the average acceleration along the curvilinear path is 130 cm s⁻². This is consistent with accelerations deduced from displacements of tail features much farther away, although this may be irrelevant because the mechanisms may not be the same. Because of the observed closing-in of the filamentary structures

toward the tail axis, it is generally believed that a cylinder antisunward is a good approximation of the contact surface (Biermann, Lüst, and Wegmann 1974). This assumption, combined with the velocity field just described, can explain the antisunward profiles, but there are alternate explanations.

VIII. ANTISUNWARD SLOPES OF H_2O^+

Let us first explore the purely kinematic model, with a constant ion flux in a cylinder. The lines labeled *A* and *B* on Figure 5 are heuristic models that duplicate rather well the average slopes of the profiles. The slope of model *A*, which is in the vicinity of -0.4 , is obtained with a velocity field defined by an acceleration of 164 cm s^{-2} , whereas the slope of model *B*, which is in the vicinity of -0.7 , needs variable acceleration of growth from 4 to almost 600 cm s^{-2} . Both velocity fields have been normalized to a velocity of 17 km s^{-1} at the average distance of $8 \times 10^4 \text{ km}$. Admittedly, the models show variable velocities that do not coincide with our finding of an average constant velocity for the wavy patterns. For instance, in model *A* the velocity goes from 10 to 22 km s^{-1} , in the range from 2 to $15 \times 10^4 \text{ km}$. In model *B* the velocity goes from 7 to 29 km s^{-1} . Smaller accelerations could be obtained by widening the contact surface from a cylinder to a cone, which would probably be more realistic, but as we have no indication of the opening angle of the cone, no model could be computed. It must also be emphasized that all point-source kinematic models with constant acceleration (Wallace and Miller 1958; Combi 1976) have as a common feature, an antisunward slope of exactly -1 , even when the tail axis is not in the plane of the sky. Hence they completely disagree with our observations.

The construction of the ion flow within a cylindrical tube is needed to explain the flattening of the profiles: cylindrical tube models with a constant flux have an antisunward slope between 0 and $-\frac{1}{2}$ for a constant acceleration. To go beyond $-\frac{1}{2}$ and -1 , they need a growing acceleration.

IX. PRODUCTION RATE OF H_2O^+

The production rate of H_2O^+ is set by the asymptote of the *sunward* profile for small distances, and by the initial velocity of H_2O^+ . For a velocity $v_0 = 1.7 \text{ km s}^{-1}$, the production rate is $Q = 2 \times 10^{26} \text{ H}_2\text{O}^+$ per s (at 0.841 AU). The model fitted to the sunward profile *B* has a tailward component of the acceleration of 9 cm s^{-2} , but it is clear that a constant acceleration does not tell the whole story. We believe that the acceleration starts from a very small value ($1\text{--}2 \text{ cm s}^{-2}$) at 10^4 km and goes to rather high values ($20\text{--}100 \text{ cm s}^{-2}$) near 10^5 km sunward, but the picture is blurred by the collision with a turbulent plasma, and at that distance the tailward component is a small fraction of the total acceleration. When the production rate Q and the initial velocity v_0 of the ions are known, the diameter D of the cylindrical contact surface antisunward is set if we make the assumption that the ion density is constant across the cylinder and nil outside.

Its diameter is deduced directly from the ratio of the two surface brightnesses sunward and tailward (which is a parameter independent of any other assumption) by the following reasoning: The production rate (for those short distances that are not affected by distortion) is $4v_0\rho_0N_0$, where v_0 is the initial velocity, ρ_0 the distance sunward from the nucleus projected onto the sky, and N_0 the column density. This production rate must be retrieved in the cylinder flux, which is $\frac{1}{4}\pi v N D$ (where v is the velocity at any distance tailward in the cylinder, N the column density at that point, and D the diameter of the cylinder). Since we have the same number of photons s^{-1} per ion, sunward or tailward, solving for D we find

$$D = \frac{16}{\pi} \left(\frac{v_0}{v} \right) \left(\frac{B_0}{B} \right) \rho,$$

where B_0 is the surface brightness at distance ρ sunward, and B is the surface brightness at the place tailward where velocity v is observed. The diameter D of the cylinder is, for profiles *A* and *B*, respectively, $D_A = 1.4 \times 10^4 \text{ km}$ and $D_B = 1.2 \times 10^4 \text{ km}$. If another source were acting tailward, such as the ionization produced by the cross-tail current induced by the folding of the magnetic lines along the tail, as proposed by Ip and Mendis (1976), the total production tailward could have an added source term, and the observed brightness profiles could be extended to a larger cylinder to carry away this larger production. However, the models developed so far (Ip and Mendis 1977) still suggest a concentrated source of ions within the inner coma, and not an extension tailward, clearly because the neutrals' density falls off too fast. On the other hand, electron recombinations could be used to *diminish* the flux tailward up to possible distances of the order of 10^5 km , since the density falls off slowly and the cross sections for recombination are the limit, the whole profiles antisunward could be explained by electron recombinations and a constant velocity (of 17 km s^{-1}) of H_2O^+ . Of course, this would imply that most of the plasma acceleration is achieved near the head in the sunward side. The need of reaching a velocity of 17 km s^{-1} in no more than $(1\text{--}2) \times 10^4 \text{ km}$ would imply an average acceleration of the order of 10^3 cm s^{-2} .

X. SUMMARY AND CONCLUSIONS

The spatial distribution of $\text{O}(\text{I}D)$ in comet Bennett on April 18 implies the existence of an average scale length of about 10^4 km for the source of one or several parents, and an average scale length also of about 10^4 km for their destruction. A numerical interpretation that is reasonably consistent with all data is that the nucleus and a halo of icy grains (radius 10^4 km) produce 30×10^{28} molecules of water and 12×10^{28} molecules of CO_2 per s. Then 25% of the red line comes from the dissociation of water and 75% from that of CO_2 (a small amount of CO_2 contributes much more than water to the red line). Other possibilities involving neglected ion-molecular reactions cannot, however, be totally ruled out, although it must be pointed out that

the perfect symmetry of the spatial distribution of O(¹D) excludes a large contribution of ions or of fast electrons in the chain of reactions involving parents and grandparents. The reason for this is the strong coupling of the ions with the solar plasma, as exemplified by the H₂O⁺ behavior described in the second half of this paper; the effect of such coupling would be to distort the O(¹D) profiles.

The spatial distribution of H₂O⁺ has also been studied sunward and tailward for the same comet and the same date. Two spectra taken 20 minutes apart show recognizable wave patterns moving tailward with a velocity of 17 km s⁻¹. The tailward profiles can be explained if we observe ions constricted in a more or less cylindrical onset of the plasma tail. If ions accelerate with 100–200 cm s⁻² with a constant or slowly changing acceleration during 10⁵ km, this would imply a velocity field increasing along the tail axis; this is not observed. If they accelerate faster (~1000 cm s⁻²), in no more than 1 or 2 × 10⁴ km, to their observed terminal velocity of about 17 km s⁻¹, this latter hypothesis would require a mechanism (as, for instance, electron recombinations, or a slowly diverging tail), to diminish their density steadily, at least up to 10⁵ km.

The interaction of the H₂O⁺ ions with the solar

wind gives clues to the onset of the plasma tail. The upper limit of the Alfvén velocity gives an upper limit of 3 × 10²⁷ ions s⁻¹ in the plasma tail, that is, 15 times the production rate of H₂O⁺. This is compatible with the list of other ions observed in the tail. A characteristic time of 800 s seems to be associated with the instabilities seen at the onset of the tail; all characteristic lengths for the onset of the tail (stagnation point sunward ~10⁴ km, diameter of the tail onset 1.2 or 1.4 × 10⁴ km) seem of the same order as the size of the collision zone (10⁴ km) within the inner coma. It is therefore reasonable to believe that there is a causal link, and that ion-molecular reactions play an important role in setting the characteristic lengths and instability times of the onset of the plasma tail.

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PLATE 1

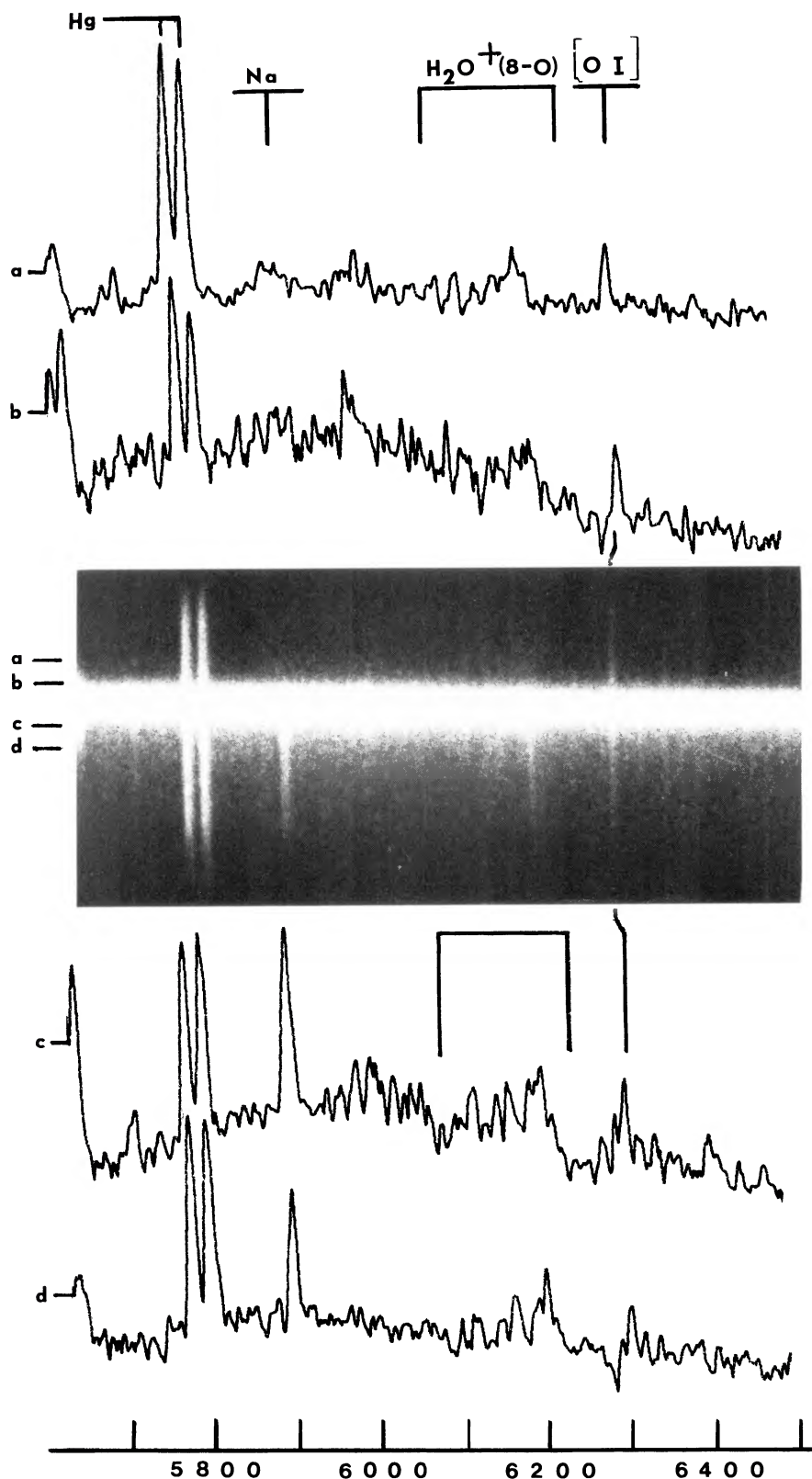


FIG. 1.—Spectrum *B* of comet Bennett taken on 1970 April 18 shown with four sample microdensitometer scans at nuclear distances: (a) 45,000 km and (b) 20,000 km sunward; and (c) 20,000 km and (d) 45,000 km antisunward. The actual brightness profiles shown in Figs. 2–5 are constructed from 70 such scans at distances up to 120,000 km from the nucleus. The wavelength scale in Å is shown at the bottom. The continuum was discounted from the measurements by averaging a 10 Å width on either side of the emission features in each scan.

DELSEMMÉ and COMBI (see page 331)