

PRODUCTION RATE AND ORIGIN OF H_2O^+ IN COMET BENNETT 1970 II

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ABSTRACT

Brightness profiles of the 8-0 band of H_2O^+ have been constructed from the spectra of comet Bennett 1970 II. The contact discontinuity, suggested by some magnetohydrodynamic (MHD) models to separate cometary ions from solar wind, is not seen, although it should flatten out the slope of the antisunward profile if the stagnation point were at a distance smaller than 10^5 km. The sunward and antisunward profiles also indicate that the major source of H_2O^+ ions is concentrated at distances of less than 10^4 km from the nucleus, that is, in the collisional zone. This suggests ionization of water by fast charge-exchange reactions, and complete uncoupling from solar wind effects for distances up to 10^5 km. In particular, the best fit to both observed profiles is given by a point-source model, with only radiation pressure taken into account. This model yields a production rate of 6×10^{26} ions s^{-1} and rather large initial ion velocities of (3.2 ± 1.2) km s^{-1} , explained by the energy balance of the proposed ionization reactions that would stem from the fast photoionization of C I (^1D) in the collision zone.

Subject headings: comets — molecular processes — Sun: solar wind

I. INTRODUCTION

Much interest over cometary ions has been generated to solve the problem of their origin and to study their interaction with the solar wind.

The long-standing argument over the place and mechanism of their formation (Wurm and Mammano 1967) has been superseded by proposals (Cherednichenko 1973; Oppenheimer 1975) for fast ion-molecule chain reactions in the inner coma (probably initiated by photoionization only, Delsemme 1976*b*) that could well be Wurm's (1966) "intrinsic cometary processes." Wurm's morphological arguments requesting short length and time scales, developed again (Wurm 1974) from the Helwan plates of P Halley, may probably be understood in terms of the small size ($\leq 10^4$ km) of the collisional zone that is needed for the propagation of chain reactions.

The magnetic collision of the ionized coma with the solar wind is described by a fluid dynamics approach. The Munich school (Biermann 1974) has developed axisymmetric models reaching Mach numbers close to 2. Wallis (1973) applies this type of model to an H_2O coma the size of Bennett, and suggests with Ong (Wallis and Ong 1976) that the assumed "contact surface" between solar wind and cometary plasma is not real. Wallis and Dryer (1976) theoretically describe the different flow regimes and the transition discontinuities.

It comes as a surprise that nobody has ever tried to check these different ideas with actual brightness profiles deduced in the monochromatic light of any ion. Since the 8-0 bands of H_2O^+ , recently identified in comet Kohoutek (Herzberg and Lew 1974; Wehinger *et al.* 1974), were clearly visible in our spectra of comet Bennett (Delsemme and Moreau 1973), we have

established these brightness profiles, with the hope that we could clarify observationally some of the questions still disputed by theorists.

Arpigny (1965) has published a single very flat profile representing both CO^+ and N_2^+ , deduced from Greenstein's (1962) spectrum of comet Humason 1961*e*. Not only was comet Humason a very peculiar comet, but the profile extends radially in one unknown direction; and since the asymmetry of the coma has not been studied, the author says "any attempt to fit the observed distributions . . . would be meaningless, for it is definitely certain that the ions do not move radially."

Apart from this early attempt, the only observational data published so far on cometary ions generally speak in terms of averaged column densities. For instance, Wyckoff and Wehinger (1976) give the observed H_2O^+ luminosities and column densities of comet Kohoutek reduced for 10^4 km from the nucleus. They also say (p. 623) that they have *arbitrarily* adopted Haser's (1966) model C. However, since they do not mention any *observed* brightness profile in the light of H_2O^+ , what they did with Haser's model C is unclear; in particular, they do not mention any of the three parameters—scale length, velocity, and acceleration—that they could have deduced by the fitting of Haser's model C. The present results are therefore the first H_2O^+ profiles ever published and the first attempt to fit a model of the inner coma to any ion.

II. ANALYSIS

The absolute brightness profile of the 8-0 band of H_2O^+ for comet Bennett on 1970 April 18 is shown in Figure 1. The details concerning the actual determination of this profile are discussed in the accompanying *Letter* (Delsemme and Combi 1976), since they are

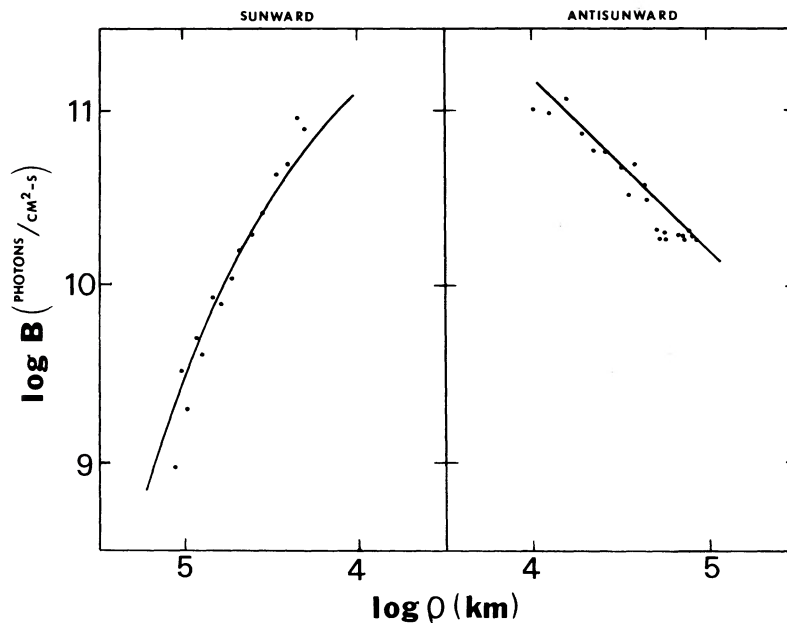


FIG. 1.—The observed brightness profile of the H_2O^+ 8-0 band (points) shown with the best-fit kinematic model. Log B (brightness) is in units of photons $\text{cm}^{-2} \text{s}^{-1}$ (or 10^{-6} rayleighs), and log ρ (projected distance) is in units of kilometers.

essentially the same as for [O I]. The asymmetry of the sunward and antisunward profiles makes obvious the existence of some mechanism accelerating the ions antisunward. Since the two brightness profiles of H_2O^+ remain smooth with a large slope, from 10^4 km to 10^5 km, the contact surface mentioned in the Introduction remains unobserved. This may mean either that it is within 10^4 or beyond 10^5 km from the nucleus (at a heliocentric distance of 0.841 AU), or that it is diffuse enough not to be observable, as suggested by Wallis and Ong (1976).

A simple kinematic model has been developed which produces brightness profiles similar to the ones observed in comet Bennett. Haser's (1966) models are approximations valid only for a slightly distorted coma, where the ions never reach the paraboloid envelope; hence they cannot really be used here.

The model considers an isotropic ejection of ions from a point source having a Maxwellian velocity distribution and subjected to a constant acceleration from the sunward direction; the line-of-sight column densities are computed in the sunward and antisunward directions, along the projection of the radius vector onto the plane of the sky.

The basic model with a single ejection velocity was developed by Wallace and Miller (1958). By superposing a standard Maxwell-Boltzmann velocity distribution and integrating over velocities (Combi 1976), the column densities as a function of projected distance in the antisunward and sunward directions are given respectively by

$$J_A(\rho) = Q/2\pi^{1/2}\rho v_m$$

$$J_S(\rho) = \frac{Q}{2\pi^{1/2}\rho v_m} \exp[-a\rho(\cos\theta + 1)/v_m^2],$$

where Q is the production rate, ρ is the projected distance, v_m is the rms velocity, a is the acceleration, and θ is the angle the radius vector makes with the plane which is perpendicular to the line of sight.

The best-fit model is shown as the solid lines in Figure 1. The shape of the sunward profile determines the parameter a/v_m^2 to be $(0.9 \pm 0.16) \times 10^{-5} \text{ km}^{-1}$. Accepting the same emission rate factor for H_2O^+ as computed by Wyckoff and Wehinger (1976), the position of the model curves on the data determines the value of the parameter Q/v_m to be $2 \times 10^{21} \text{ cm}^{-1}$.

Since we mainly deal with distances in the coma that are shorter than the position of the contact surface, it is reasonable to assume that the ions are not yet much influenced by the magnetic field of the solar wind, and therefore their acceleration is mainly due to radiation pressure only. Hence Q and v_m can also be determined. The acceleration due to radiation pressure has been calculated from the wavelengths and lifetimes of the 5-0 through 15-0 bands (Erman and Brzozowski 1973; Wyckoff and Wehinger 1976) and from the fluxes of solar radiation as a function of wavelength (Ackerman 1970). The acceleration reduced to 0.841 AU due to radiation pressure has been determined to be $9 \pm 4 \text{ cm s}^{-2}$.

Using the values of the parameters Q/v_m and a/v_m^2 from the model, the values of v_m and Q were found to be

$$v_m = 3.2 \pm 1.2 \text{ km s}^{-1},$$

$$Q(\text{H}_2\text{O}^+) = 0.6(-0.4, +0.7) \times 10^{27} \text{ ions s}^{-1}.$$

III. DISCUSSION

The large sunward distortion of the observed brightness profile, and its constant -1 slope antisunward, are two characteristic features of the point-source model

that can readily be explained by a constant acceleration antisunward, whose order of magnitude has not to be larger than that of the radiation pressure exerted by the solar light absorbed in the H₂O⁺ bands. A strong coupling with the solar wind would destroy these characteristic features of the model.

In particular, a simplified wind-sock model of the contact discontinuity with the solar wind had been developed first, but it does not fit the profiles at all; for any value of the upstream stagnation point smaller than 10⁵ km, the profile antisunward flattens rapidly to an asymptotic slope of zero. When integrating along the line of sight, if the stagnation point is beyond 10⁵ km, we have checked that the contribution of the ions deflected by the magnetic shock becomes negligible for the observed profiles.

Therefore, our results imply rather strongly that most of the observed H₂O⁺ ions are *inside* the contact discontinuity, where they do not yet feel the coupling with the solar wind.

The position of the stagnation point beyond 10⁵ km implies that the total stagnation pressure developed by all cometary ions could be almost two orders of magnitude higher than that of H₂O⁺ only. This is not too surprising, because many other cometary ions have already been observed for a long time (CO⁺, CO₂⁺, N₂⁺, OH⁺, CH⁺) or more recently (C⁺, Feldman and Brune 1976). The C⁺ radical is likely to play an important role in setting the position of the stagnation point, because the lifetime of C I against ionization is 2.6 × 10⁵ s only; therefore, a large fraction of the carbon available will be ionized before reaching this distance. A large fraction of C I is observed in the ¹D state, as discovered in comet West (Feldman and Brune 1976). This state has a shorter lifetime of 5 × 10⁴ s against ionization, and this fraction will therefore be ionized earlier in the inner coma. Many other unobserved ions are predicted to be very abundant—e.g., H₃O⁺, which should predominate in the inner coma (Aikin 1974). Many other proposed ions will depend on the presence of a suitable parent molecule (for instance, ammonia would yield NH₄⁺). By and large, many metals, in particular Na, K, and Al, have low ionization potentials and could also provide concentrated sources of ions in the inner coma.

The fitting of the brightness profiles to a point source model indicates that the source of most of the H₂O⁺ ions cannot extend to distance larger than 10⁴ km. Any model for a more extended source would flatten the profiles considerably. This suggests that the photoionization of water molecules is *not* the major producer of H₂O⁺. The scale length for water dissociation (Keller and Lillie 1974) is at least one order of magnitude, and for photoionization two orders of magnitude, larger than the profiles indicate for the size of the source(s), and this is independent of any choice of model. The rather large initial velocities (3.2 km s⁻¹) found with the model are consistent with the fact that the H₂O⁺ ions leave the nuclear region with a velocity resulting from the energy balance of the reactions producing the ions.

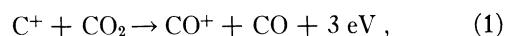
Oppenheimer (1975) has proposed the fast charge-exchange reaction OH⁺ + H₂ → H₂O⁺ + H as the

source of H₂O⁺ in the collisional region (<10⁴ km); in this reaction H₂ is supposed to come from the dissociation of methane in the collisional zone. But neither OH⁺ nor H₂ are abundant in this zone.

From the scale lengths for OH production by its parent (probably water) (Delsemme 1976a) and for OH ionization (Blamont and Festou 1974), some 10⁻⁴ of the OH atoms will be ionized before leaving the collision zone. Methane has remained undetected in comets, and its dissociation would yield only a small fraction of (also undetected) H₂ in the collision zone. Another source of ionization must be found with a scale length compatible with a large production rate in the collision zone.

We submit that the photoionization of atomic carbon already in the ¹D state is a likely candidate. Feldman and Brune (1976) have observed a production rate of 1.3 × 10²⁹ C I (¹D) per second in comet West 1975n, to be compared with 9.6 × 10²⁹ OH per second in the same comet. (Comets West and Bennett were both average bright comets of the Halley type, and we will assume hereafter that they were identical.) Since the ¹D state of atomic carbon is ionized by all wavelengths shorter than 1239 Å, the solar Lα is very effective, yielding at 1 AU an ionization lifetime τ_i = 5 × 10⁴ s (to be compared with its radiative lifetime of 3250 s, Garstang 1951). Unfortunately, the parent molecule as well as the space distribution of C (¹D) is unknown, but in the simple-minded model ignoring other ions, a sensibly large scale length of 10^{5.6} km of the C (¹D) is consistent with the observed production rate of the H₂O⁺, whereas a point source of C (¹D) would produce 39 times more C⁺ than H₂O⁺ in the collision zone. The truth probably lies between these two limiting cases.

In order to produce H₂O⁺ from C⁺, the following cascade of two exothermic charge-exchange reactions is proposed:



These reactions use only the two probable major constituents (Delsemme and Combi 1976) exchanging charges with the major ion. It is interesting to mention that, as a fringe benefit, reactions (1) and (2) yield the two major ions observed in the cometary tails. From the Langevin rate constants, the kinetics of these two reactions is consistent with the production of CO⁺ and H₂O⁺ in the collision zone at the proper rates. The energy balance of reaction (1) yields a velocity of 3.2 km s⁻¹ for CO⁺; reaction (2), 2.4 km s⁻¹ for H₂O⁺. Of course, these velocities are related to the center of mass of their respective collisions. With a radial velocity *v* = 1 km s⁻¹ for water, CO₂, and C⁺, this yields a radial component of 2.7 km s⁻¹ for H₂O⁺ which is consistent with our observed radial mean velocity of 3.2 ± 1.2 km s⁻¹.

Since collisions are needed for charge transfer reactions, it is also clear that all chemical removal processes of H₂O⁺ (like dissociative recombination) do not play any role outside the 10⁴ km radius, which explains the success of our point-source model.

The production rate of H_2O^+ found here is on the order of 0.15 percent of that found for water (Keller and Lillie 1974), to within a factor of 5 because of the compounding of the large error bars involved in both measurements. From solar ultraviolet data and laboratory photoabsorption cross sections, Wyckoff and Wehinger (1976) determined that 4 percent of all water molecules would be photoionized. But as both of their lifetimes were only accurate to within "a factor of 2 or 3," this ratio can only be taken within an order of magnitude. Therefore, because of the very large error bars (altogether, a factor of 50), these observed and theoretical ratios cannot really be used to prove or disprove any conclusion on the nature of the ionization source.

IV. CONCLUSION

Two important consequences have been deduced from our model of the H_2O^+ brightness profiles in comet Bennett.

1. No contact surface is consistent with the observations, if its upstream stagnation point were at a distance of less than 10^5 km, sunward of the nucleus.
2. Within the collisional zone ($< 10^4$ km) there probably is a strong source of ionization present which

produces the bulk of the H_2O^+ ions observed: we submit that the photoionization of the atomic carbon observed in its ^1D state is one of the best candidates.

Together these suggest that neither solar wind interaction nor photoionization produces the bulk of the H_2O^+ ions, and that a large fraction of the cometary plasma pressure comes from other ions.¹

A strictly kinematic model has been used which reproduces the observed profiles in the region from 10^4 to 10^5 km. Since ion production takes place at less than 10^4 km from the nucleus, a point source has been employed; and since MHD interactions with the solar wind are negligible inside the contact surface ($> 10^5$ km), the asymmetry of the profiles is taken into account by radiation pressure alone.

The initial velocities of the H_2O^+ , derived from the model (3.2 ± 1.2 km s⁻¹), are too large to be thermal, and most likely result from the balance of those charge-exchange reactions which produce H_2O^+ in the collisional zone. The proposed charge-exchange reactions are consistent with these velocities.²

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¹ Note 1 added in proof.—Most other ions absorb and scatter less solar flux than H_2O^+ . Because of their magnetic coupling with H_2O^+ , their large abundance implies that the plasma acceleration a and radial velocity v_m , deduced in the framework of our model, are upper limits. The error bars imply that velocities up to 40% smaller would remain consistent with the proposed charge-exchange reactions.

² Note 2 added in proof.—Since our model suggests a surprisingly large distance for the solar wind transition, MHD models should explore whether the upstream stagnation point could be brought back to shorter distances, *without flattening the observed antisunward profile*. We thank Drs. Biermann, Keller, and Schmidt for a discussion leading to this suggestion.

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