On the Solar EUV Deposition in the Inner Comae of Comets with Large Gas Production Rates

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1. Introduction

Comets are water-dominated tiny objects in our solar system. A comet exists as a bare nucleus at large heliocentric distances, but develop a huge coma and long tail when closer to the Sun (typically \( \sim 3 \) AU). The coma, which is generated by sublimation of volatile species from the nucleus, hosts most of the physical, chemical and dynamical processes for comets. One of the important parameters that govern the activity of the comet, and thus size of the coma, is the total gas production rate, \( Q \) (s\(^{-1}\)), which depends on the intrinsic properties of the comet, for example its size, and is a function of the heliocentric distance of the comet.

Comet C/1995 O1 Hale Bopp was by far the brightest comet of the last century. The very high gas production rate of Hale Bopp imposes several interesting physical effects that are related to it. Specifically, we have studied the effects of high-Q comets on radial profiles of (i) photoionization rates of \( \text{H}_2\text{O}^+ \) and its variation with solar zenith angle (SZA), and (ii) photoelectron impact ionization of \( \text{H}_2\text{O} \). In particular, we found that in the case of high-Q comets the altitude profile of photoionization rate has a double-peak structure and that the SZA-effect has a marked bearing on the ion production rate profiles in the anti-sunward direction. We have also shown that in the inner coma of high-Q comets the photoelectron impact give rise to an additional ionization peak whose magnitude is a factor of 10 or more larger than the photoionization peak. The present results will be useful in interpretation and understanding the data in higher production rate comets, like Hale Bopp, and other bright comets. The findings will have implications for the energetics and chemistry in the inner coma of high-Q comets.

2. Model Calculations

Since water is the dominant constituent in comets, the absorption of EUV photons in the coma is mainly dictated by \( \text{H}_2\text{O} \). Therefore, we have considered a pure \( \text{H}_2\text{O} \) comet at 1 AU with 4 different cases of gas production rate: (a) \( Q = 1 \times 10^{31} \text{ s}^{-1} \), (b) \( Q = 7 \times 10^{28} \text{ s}^{-1} \), (c) \( Q = 1 \times 10^{28} \text{ s}^{-1} \), and (d) \( Q = 1 \times 10^{25} \text{ s}^{-1} \). The first case is representative of C/1995 O1 Hale Bopp-type comets, the second case of IP/Halley-type comets, the third case of 46P/Wirtanen-type comets, while the fourth case is taken to assess the effects of very high Q comets. The neutral density of \( \text{H}_2\text{O} \) in the coma is calculated using Hauler’s model as described in our previous papers [Bhardwaj et al., 1990, 1996; Bhardwaj, 1999], and the coma is assumed to be spherically symmetric. All the calculations are made at standard heliocentric distance of 1 AU for solar minimum conditions, which is quite appropriate for the Halley and Hale Bopp apparitions in 1986 and 1997, respectively. The solar EUV reference spectrum is taken from Torr and Torr [1979] in 41–1025 Å range. The \( \text{H}_2\text{O} \) photoabsorption and photoionization cross...
sections are taken from Haddad and Samson [1986], which are binned into 71-wavelength intervals of Torr and Torr [1979] solar EUV flux.

[6] The ion production rate, $q(r, \theta)$, at cometary distance $r$ and solar zenith angle $\theta$ in an atmosphere due to the absorption of solar EUV radiation is given by

$$q(r, \theta) = \int n(r) \sigma^I(\lambda) I_\lambda(\lambda) \exp[-\tau(r, \theta)] d\lambda$$  

(1)

where

$$\tau(r, \theta) = \sigma^A(\lambda) \int n(r) ds$$  

(2)

Here $\sigma^A(\lambda)$ and $\sigma^I(\lambda)$ are the absorption and ionization cross sections at wavelength $\lambda$, $I_\lambda(\lambda)$ is the unattenuated solar flux at top of the atmosphere at wavelength $\lambda$, $n(r)$ is the neutral density at cometary distance $r$, and $ds$ is the element of distance along the path of radiation. Since our aim is to study the effects of SZA on photoionization rates we have used the generalized Chapman function [Green and Martin, 1966] to calculate optical depth. The use of generalized Chapman function is important as it allows for proper accounting of the optical depth effects at large SZA values.

[7] For $\theta \leq 90^\circ$ the optical depth $\tau = \sigma \int n ds$ is given by

$$\tau = \sigma \int \frac{n(y) dy \sec \theta_y}{y}$$  

(3)

where

$$\sec \theta_y = 1 \sqrt{1 - \frac{(R + Z)^2}{(R + y)^2 \sin^2 \theta}}$$  

(4)

Integration of the above equation gives

$$\tau = \sigma n(r) r(1/\sin \theta)[\pi/2 - \cos^{-1} \sin \theta]$$  

(5)

where $r = Z + R$ is the cometary distance and $R$ is the radius of the comet, which is taken as 10 km. For $\theta > 90^\circ$ the optical depth $\tau$ is given by

$$\tau = \sigma n(r) r(1/\sin \theta)[\pi/2 + \cos^{-1} \sin \theta]$$  

(6)

Ion production rate is obtained by carrying out integrations in equations (1) and (2).

3. Results and Discussion

[8] Figure 1 shows the $\text{H}_2\text{O}^+$ photoion production rates for 4 different $Q$ (gas production rate) values at SZA = 0°. At a given radial distance, as $Q$ increases the density of neutral $\text{H}_2\text{O}$ also increase resulting in a larger attenuation of solar radiation, thereby reducing the magnitude of peak production and upward shift of the ion production rate peak. However, at $Q = 1 \times 10^{31} \text{ s}^{-1}$ a second peak in ion production rate profile is observed close to the nucleus.

This lower peak is clearly seen at $Q = 10^{32} \text{ s}^{-1}$. Also observed from Figure 1 is that the altitude region in the inner cometary coma over which the major solar EUV deposition takes place extend up to ~100 km from the nucleus at $Q = 7 \times 10^{28} \text{ s}^{-1}$, to ~2000 km at $1 \times 10^{31} \text{ s}^{-1}$, and to ~$10^4$ km at $1 \times 10^{32} \text{ s}^{-1}$. Thus, in case of Halley-type comets the UV opacity effects are most important mainly within a few 100 km from the nucleus, which is consistent with the findings by earlier studies (e.g., Giguere and Huebner, 1978; Huebner, 1985, and references therein). The optical depth effects are generally neglected in data interpretation and modeling studies since most of the ion-modeling studies, which start basically with photoionization as the primary source, concentrate their efforts in doing comparison with the Giotto data that are available at radial distances $>\sim 10^3$ km [e.g., Balsiger et al., 1986; Krankowsky et al., 1986]. But in case of bright comets, like Hale Bopp, opacity effects extend to a few $10^3$ km from the nucleus, and this distance increases with increase in $Q$, and hence cannot be ignored in modeling the inner cometary coma.

[9] The reason for the occurrence of a double peak structure in photoion production profile seen in Figure 1 in higher $Q$ comets can be understood on inspecting Figure 2, where the altitudinal degradation of solar flux at 3 selected wavelengths of 303.8 Å (40.8 eV), 180–165 Å (68.9–75.2 eV), and 62–41 Å (200–300.4 eV) are plotted at SZA = 0° for 4 representative $Q$ values. In case of $Q = 1 \times 10^{28} \text{ s}^{-1}$ (low-$Q$ comets), essentially no attenuation of solar EUV flux in the coma takes place, which is reflected in a straight-line profile of its photoionization rate seen in Figure 1. Even in case of brighter comets like Halley ($Q = 7 \times 10^{29} \text{ s}^{-1}$), the neutral densities in the innermost coma are not sufficiently large to completely attenuate higher ($>\sim 60$ eV) energy solar photons, while solar soft x-ray ($>\sim 100$ eV) photons travel almost unattenuated to the nucleus. The photoionization peak observed in Figure 1 at ~30–40 km is due to the attenuation of photons of energy <50 eV in the cometary atmosphere, with larger contribution from He II Lyman-$\alpha$ line at 303.8 Å, which is the dominant line in the solar EUV spectrum. As observed from Figure 2, the maximum attenuation of this line occurs in the 20–60 km region and hence the ion production peaks around
we have taken from partially due to photoionization cross sections used, which different solar EUV flux used in different studies, and [1987], respectively. The small differences are due to impact ionization of H₂O at 4 different Q values are also /C₂⁻¹A Ui s⁴. The coma increases resulting in a larger attenuation at about 10%, with values 4.1 × 10⁻⁷ s⁻¹ and 3.8 × 10⁻⁷ s⁻¹ reported by Huebner et al. [1992] and Korosmezey et al. [1987], respectively. The small differences are due to different solar EUV flux used in different studies, and partially due to photoionization cross sections used, which we have taken from Haddad and Samson [1986], while Huebner et al. [1992] compiled them from different sources.

[10] Our calculated total photoionization rate of H₂O at 1 AU is 4.4 × 10⁻⁷ s⁻¹, which is in agreement, within about 10%, with values 4.1 × 10⁻⁷ s⁻¹ and 3.8 × 10⁻⁷ s⁻¹ reported by Huebner et al. [1992] and Korosmezey et al. [1987], respectively. The small differences are due to different solar EUV flux used in different studies, and partially due to photoionization cross sections used, which we have taken from Haddad and Samson [1986], while Huebner et al. [1992] compiled them from different sources.

[11] In the post-Halley era, the electron impact ionization in the cometary coma has drawn the attention of several workers [e.g., Boice et al., 1986; Korosmezey et al., 1987; Cravens et al., 1987; Bhardwaj et al., 1990, 1996; Wegmann et al., 1987, 1999; Haider et al., 1993; Haberli et al., 1996; Bhardwaj, 1999]. Evidences for the presence of an electron impact source in the cometary coma have been inferred from many observations made during the appearance of comet Halley, which are discussed in our earlier papers [e.g., Bhardwaj et al., 1996; Bhardwaj, 1999]. The presence of electrons in cometary comae is clearly publicized by the detection of OI 1356 Å emission in comets [e.g., McPhate et al., 1999], since this emission being a spin-forbidden transition cannot be produced by solar fluorescence.

[12] The H₂O⁺ ion production rates due to photoelectron impact ionization of H₂O at 4 different Q values are also presented in Figure 1. The photoelectrons are generated in photoionization of H₂O by solar photons whose wavelength is less than 984 Å, while at λ < 620 Å the efficiency of ionization is unity (i.e., all solar photons absorbed by H₂O in the coma create H₂O⁺ ions and photoelectrons). The photoelectron impact ionization rates are calculated using Analytical Yield Spectrum (AYS) approach and inputs as described in our previous papers [e.g., Bhardwaj et al., 1990, 1996; Haider et al., 1993; Bhardwaj, 1999; Bhardwaj and Haider, 2002 and references therein]. The AYS is generated by running the Monte Carlo model and then analytically representing the yield [e.g., Singhal and Green, 1981; Green et al., 1985; Singhal and Bhardwaj, 1991; Bhardwaj and Michael, 1999a, 1999b], and is used to calculate the photoelectron flux. The photoelectron impact ion production rate, P(r), is calculated using

\[ P(r) = n(r) \int W(E, r) \sigma(E) dE \]  

where W is the ionization threshold, \( \sigma(E) \) is the ionization cross section at energy E, n(r) is the neutral gas density at cometocentric distance r, and F(E, r) is the photoelectron flux obtained by using the AYS technique (see Bhardwaj et al., 1990, 1996; Bhardwaj, 1999 for details).

[13] From Figure 1 it is seen that photoelectron impact H₂O⁺ production rate is higher than photoionization rate at the peak. This is because longer wavelengths, which contribute to photoionization but do not contribute greatly to photoelectron flux, are attenuated more efficiently in the upper region of the atmosphere (due to larger absorption cross section at longer wavelengths) than the shorter wavelengths that actually produce energetic photoelectrons. However, in case of higher-Q comets, the photoelectron impact ionization rate at the second-lower photoionization peak is an order of magnitude greater than the photoionization rate. This can be understood from Figure 3 where we have plotted the energy spectrum of photoelectrons for the case Q = 10⁳² s⁻¹ at 4 different cometocentric distances of 60, 600, 6000, and 60,000 km. It can be noted that photoelectron energy spectrum at higher (>100 eV) energies is higher at shorter (60 and 600 km) distances compared to those at larger (>~6000 km) distances. This is because the absorption of solar soft x-rays occurs deep in the coma producing energetic (>100 eV) photoelectron which is

![Figure 2. Radial degradation profiles of solar EUV flux at 3 energies at solar zenith angle of 0° for 4 different gas production rates Q (in s⁻¹).](image)

![Figure 3. Photoelectron energy spectrum at 4 cometocentric distances in case of Q = 1 × 10³² s⁻¹, and at 2 distances in case of Q = 7 × 10²⁹ s⁻¹. Note the change in the energy scale on x-axis after break at 70 eV.](image)
capable of causing multiple ionization of H$_2$O leading to a sharp increase in the ionization rate. But in case of $Q = 7 \times 10^{29}$ s$^{-1}$, even at cometary distance of 30 km (photo-ionization peak), the $>$60-eV electrons produced are less compared to those produced at lower energies (cf. Figure 3). This is because the coma is not sufficiently dense to attenuate the solar soft x-ray flux, which is also evident from Figure 2.

[14] The effect of large Q on the ion production rates is more emphatically demonstrated when we calculated the production rates at different SZA. In Figure 4 we present the photoionization rate profiles at SZA of 30°, 120°, and 160° at 4 Q values. It is seen that at $Q = 7 \times 10^{29}$ s$^{-1}$ the peak production rate is obtained at around 40 km in the sunward direction and rises to an altitude $\sim$1000 km in the anti-sunward direction. Also to be noticed is the fact that the second peak structure starts to appear when SZA $> 130^\circ$ in case of comets with lower Q of $7 \times 10^{28}$ s$^{-1}$, since photons now travel a larger column resulting in an increased attenuation. At $Q = 1 \times 10^{28}$ s$^{-1}$ the primary (upper) peak rises from $\sim$500 km in sunward to around 10$^4$ km in anti-sunward direction, and the production rate at peak falls by 2 orders of magnitude, from $\sim$100 cm$^{-3}$ s$^{-1}$ to $\sim$1 cm$^{-3}$ s$^{-1}$. Moreover, the lower peak is roughly of the same magnitude as the upper peak. In case of $Q = 1 \times 10^{28}$ s$^{-1}$, the opacity effects are found to extend to $\sim$10$^5$ km. This has implications for deriving quantities from observations, like production rate from column brightness, particularly in higher Q-comets, because one cannot assume the coma to be uniformly sunlit: the absorption effects on the solar radiation has to be taken into account. Such sunward to anti-sunward differences may be one of the causes of asymmetry seen in the emission profiles of metastable atomic O and C emissions on comet Hale-Bopp [Morgenthaler et al., 2002; Oliverson et al., 2002]. The SZA effects will be more pronounced when the field-of-view of the instrument is relatively smaller [e.g., Oliverson et al., 2002].

[15] The double peak structure in the H$_2$O$^+$ ion production rate profile predicted by the present calculations in the inner coma of large-Q comets can be observed either by in-situ measurements, like the Giotto mission for comet Halley, or by measuring emissions induced by electrons at spatial resolution sufficient to resolve the structure, like OI 1356 A emission. Alternately, the double peak structure can be detected by observing H$_2$O$^+$ ion emissions at sufficiently high spatial resolution of a few 100 km, although in this case a model [e.g., Wegmann et al., 1999] would be required to do a better interpretation, because of the chemistry involved. It may be mentioned here that in high-Q comets the size of the nucleus could be larger (say $\sim$50 km at $Q = 10^{32}$ s$^{-1}$) than the 10-km radius assumed for all Q values in the present study.

### 4. Summary

[16] In this paper we have emphasized the need for a proper accounting of the absorption of solar EUV radiation in the inner coma of comets with large gas production rates. In higher-Q comets, a double-peak structure in photoionization rate profile is found, which results from the effective degradation of solar soft x-ray photons deep in the coma: producing energetic photoelectrons. These energetic photoelectrons create additional ionization in the coma whose magnitude at the peak is more than a factor of 10 larger than the photoionization peak. The effect of SZA on the photoionization rates is studied and is found to be important in higher-Q comets. The present study has demonstrated the importance of photoelectron impact as the ionization source relative to solar EUV radiation in the inner coma of high-Q comets.

### References


