Model for the Production of CO Cameron band emission in Comet 1P/Halley

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Abstract
The abundance of CO$_2$ in comets has been derived using CO Cameron band ($a^3\Pi \rightarrow X^1\Sigma^+$) emission assuming that photodissociative excitation of CO$_2$ is the main production process of CO($a^3\Pi$). On comet 1P/Halley the Cameron (1-0) band has been observed by International Ultraviolet Explorer (IUE) on several days in March 1986. A coupled chemistry-emission model is developed for comet 1P/Halley to assess the importance of various production and loss mechanisms of CO($a^3\Pi$) and to calculate the intensity of Cameron band emission on different days of IUE observation. Two different solar EUV flux models, EUVAC of [Richards et al. (1994)] and SOLAR2000 of [Tobiska (2004)], and different relative abundances of CO and CO$_2$, are used to evaluate the role of photon and photoelectron in producing CO molecule in $a^3\Pi$ state in the cometary coma. It is found that in comet 1P/Halley 60–70% of the total intensity of the Cameron band emission is contributed by electron impact excitation of CO and CO$_2$, while the contribution from photodissociative excitation of CO$_2$ is small (20–30%). Thus, in the comets where CO and CO$_2$ relative abundances are comparable, the Cameron band emission is largely governed by electron impact excitation of CO, and not by the photodissociative excitation of CO$_2$ as assumed earlier. Model calculated Cameron band 1-0 emission intensity (40 R) is consistent with the observed IUE slit-averaged brightness (37 ± 6 R) using EUVAC model solar flux on 13 March 1986, and also on other days of observations. Since electron impact excitation is the major production mechanism, the Cameron emission can be used to derive photoelectron density in the inner coma rather than the CO$_2$ abundance.

Keywords: CO molecule, comet 1P/Halley, Cameron band emission, UV emission, photochemistry

1. Introduction
Ejecting neutral gas and dust into space, comets create extensive and unique atmospheres in the interplanetary space. Interaction of solar extreme ultraviolet (EUV) radiation with cometary species causes spectrum of different emissions. Spectroscopic observations of comets in the UV region by space-based telescopes give information about composition, abundance, and spatial distribution of neutral species in the cometary coma (e.g., [Feldman et al. 2004]). The number densities of CO$_2$ and CO in cometary coma have been derived using emissions from the dissociative products which can be produced in metastable states. Assuming photodissociative excitation is the main production mechanism in populating the $a^3\Pi$ metastable state of CO, the Cameron band ($a^3\Pi \rightarrow X^1\Sigma^+$) emission has been used to estimate the abundance of CO$_2$ in comets ([Weaver et al. 1994], [Weaver et al. 1997], [Feldman et al. 1997]).

The observation of Cameron band of CO molecule in the coma of comet 103P/Hartley 2 ([Weaver et al. 1994]) by Hubble Space Telescope (HST) gave an incitement to re-examine the data of several comets observed by the International Ultraviolet Explorer (IUE) satellite. Cameron band (1-0) emission at 1993 Å is observed in 4 comets, including comet 1P/Halley, in the IUE spectra ([Feldman et al. 1997]). The Cameron band (0-0) and (0-1) emissions at 2063 and 2155 Å, respectively, could not be observed since they fall in the low sensitivity end of the IUE long-wavelength camera. Since the excited upper state ($a^3\Pi$) of Cameron band emission is metastable and its lifetime is very small (~3 ms, [Giljanse et al. 2007]) compared to lifetime of CO$_2$ molecule (~135 hours at 1 AU, [Huebner et al. 1992]), the CO($a^3\Pi$) molecule can travel a distance of few meters only in the cometary coma before de-exciting into ground state ($X^1\Sigma^+$) via emitting photons. Hence, the
Cameron band emission can be used to probe CO$_2$ distribution, and thus its abundance in the coma, provided it is produced only through photodissociation of CO$_2$.

Besides photons, the solar EUV-generated photoelectrons also play a significant role in driving the chemistry of cometary species in the coma. The importance of photoelectrons in excitation, dissociation, and ionization of various cometary species and subsequent effects on emissions in the inner coma are discussed in several works (e.g., Cravens and Green, 1978; In Boice et al., 1986; Körömezey et al., 1987; Bhardwaj et al., 1990, 1996; Haider et al., 1993; Härberli et al., 1996; Bhardwaj, 1999, 2003; Haider and Bhardwaj, 2005; Campbell and Brunger, 2009; Feldman et al., 2009; Bhardwaj and Raghuram, 2011a). To explain the Cameron band emission in comet 103P/Hartley 2, Weaver et al. (1994) considered five possible production mechanisms of CO(a$^3\Pi$) molecule. The modelled Cameron band emission of CO molecule by Weaver et al. (1994) suggested that 60% of total CO(a$^3\Pi$) production can be through photodissociative excitation of CO$_2$; the remaining was attributed to other excitation processes. Feldman et al. (1997) assumed that photodissociative excitation of CO$_2$ is the only source of production of Cameron band emission in comet 1P/Halley. Recent calculations of Bhardwaj and Raghuram (2011a) have demonstrated that in the comet 103P/Hartley 2, 60 to 90% of CO(a$^3\Pi$) production is through the photoelectron impact of CO$_2$ and CO and that the contribution of photodissociation of CO$_2$ is quite small. The derived rates of electron impact dissociation of CO$_2$ producing CO(a$^3\Pi$) by Feldman et al. (2009) show that photodissociation can be comparable with electron impact excitation in producing Cameron band emission. However, the comet 103P/Hartley 2 is depleted in CO (relative abundance $<$1%). But in the case of comet 1P/Halley the CO abundance is relatively higher compared to that on the 103P/Hartley 2, and hence the contribution due to direct excitation of CO by electron impact would be much larger.

There are several observations of CO in comet 1P/Halley, as well as in other comets, which suggest that CO is produced directly from the nucleus as well as having prevailed distributed sources in the cometary coma (Eberhardt et al., 1987; Eberhardt, 1999; DiSanti et al., 2003; Cottin and Fray, 2008). The measured number density of CO by neutral mass spectrometer on Giotto spacecraft, which flew through the coma of 1P/Halley, is $\leq$7% relative to water at 1000 km cometocentric distance. This relative abundance is higher ($\leq$15%) at larger distances ($2 \times 10^4$ km) in the coma (Eberhardt et al., 1987; Eberhardt, 1999; Festou, 1999). This increase in abundance can be explained by dissociation of CO-bounded species and also through heating of several refractory grains by sunlight. Other cometary species like H$_2$CO, C$_2$O$_2$, POM (polyoxymethylene, or polyformaldehyde), CH$_3$OH, and CO$_2$ can also produce CO molecules in photodissociation process (see Greenberg and Li, 1998; Cottin and Fray, 2008) and references therein. However, there are no literature reports on the production of CO(a$^3\Pi$) from CO-bearing species, like H$_2$CO, CH$_3$OH, and C$_2$O$_2$, via photodissociation or electron impact dissociative excitation.

Reanalysis of the IUE data on comet 1P/Halley showed 5 observations of the Cameron 1-0 band emission, which span over a 10-days period in March 1986; the intensity of 1-0 emission varied by a factor of about 4 from lowest value of $20 \pm 6$ to highest value of $65 \pm 9$ Rayleighs (Feldman et al., 1997). Assuming that the production of Cameron band emission is only through photodissociation of CO$_2$, Feldman et al. (1997) derived the CO$_2$ abundances of $\sim$2 to 6%, and also the CO$_2$/CO abundance ratio.

The production of CO(a$^3\Pi$) is mainly associated with spatial distribution of CO$_2$ and CO molecules in the coma. We have recently developed a model for the chemistry of CO(a$^3\Pi$) on comet 103P/Hartley 2 (Bhardwaj and Raghuram, 2011a). In the present paper this coupled chemistry model has been employed to study the production of Cameron band emissions on comet 1P/Halley. The contributions of major production and loss processes of CO(a$^3\Pi$) in comet 1P/Halley are evaluated for different relative abundances of CO and CO$_2$.

The photochemistry in the cometary coma is driven by solar UV-EUV radiation. The solar UV flux is known to vary considerably both with the 27-day solar rotation period and with the 11-year solar activity cycle. Since the continuous measurements of solar UV fluxes are not available for different cometary observations, one has to depend on the empirical solar EUV models. To assess the impact of solar EUV flux on the calculated brightness of Cameron band emission we have taken two most commonly used solar EUV flux models, namely EUVAC model of Richards et al. (1994) and SOLAR2000 v.2.3.6 (S2K) model of Tobiska (2004). The solar EUV flux from these two models for 13 March 1986 are shown in Fig. 1.

This paper will demonstrate that in comets where CO$_2$ and CO relative abundances are comparable, the photoelectron impact excitation of CO plays a major role in controlling the brightness of Cameron band, and not the photodissociation of CO$_2$ as assumed previously. Since the Cameron band emission is forbidden and electron impact is the major excitation mechanism, this
emission is suitable to track photoelectron flux in the inner cometary coma rather than the CO₂ abundance. We have also studied the sensitivity of calculations associated with variation in input solar flux and electron impact excitation cross sections of CO₂ and CO in estimating the intensity of Cameron band emission.

2. Model

The neutral parent species considered in the model are H₂O, CO₂, and CO. The density of neutral parent species in the coma is calculated using Haser’s formula, which assumes spherical distribution of gaseous environment around the nucleus. The number density nᵢ(r) of iᵗʰ species in the coma at a cometocentric distance r is given by

\[ nᵢ(r) = \frac{fᵢQᵢ}{4\pi vᵢr^2}(e^{-βᵢ/r}) \]  

(1)

Here Qᵢ is the total gas production rate of the comet, vᵢ is the average velocity of neutral species taken as 1 km s⁻¹, βᵢ is scale length (β_H₂O = 8.2 × 10⁴ km, β_CO₂ = 5.0 × 10⁵ km, and β_CO = 1.4 × 10⁷ km) and fᵢ is fractional abundance of iᵗʰ species. Calculations are made for comet 1P/Halley taking total gas production rate as 6.9 × 10²⁹ s⁻¹, which has been observed by Giotto mission (Krankowsky et al. 1986). Since cometary coma is dominated by water, 80% of total production rate is assumed to be H₂O.

The in situ gas measurements at comet 1P/Halley made by Giotto Neutral Mass Spectrometer (NMS) on the encounter date 13 March 1986 showed that CO₂ abundance is 3.5% of water (Krankowsky et al. 1986). On the same day, based on IUE observation, Feldman et al. (1997) derived CO₂ abundance of 4.3%. Eberhardt et al. (1987) suggested that below 1000 km, nuclear rate of CO production can be 7% of water. The radial profile of CO calculated by Eberhardt et al. (1987) showed almost a constant value of CO relative abundance (≤15%) above 15000 km. This increase in CO abundance is attributed to the presence of an extended source for CO in the cometary coma. The IUE-derived average production rate of CO is 4.7% (Feldman et al. 1997). We have taken 4% CO₂ and 7% CO directly coming from nucleus as the standard input for the model. We have also considered extended CO density profile directly from Giotto NMS observation (Eberhardt et al. 1987). Further, the relative abundances of CO₂ and CO are varied to assess the effect on the intensity of Cameron band emission and different production channels of CO(a²Π).

The primary photoelectron energy spectrum Q(E, r, θ), at energy E, cometocentric distance r, and solar zenith angle θ, is calculated by degrading the solar UV-EUV radiation in the cometary coma using the following equation

\[ Q(E, r, θ) = \sum_i \int \sigmaᵢ(λ) Iᵦ(λ) \exp[-τ(r, θ, λ)] dλ \]  

(2)

where

\[ τ(r, θ, λ) = \sum_i σᵢ(λ) \secθ \int_r^∞ nᵢ(r') dr' \]  

(3)

Here σᵢ(λ) and σᵢ(λ) are absorption and ionization cross sections, respectively, of iᵗʰ species at wavelength λ. nᵢ(r) is its neutral gas density calculated using the equation and τ(r, θ, λ) is optical depth of the medium. Iᵦ(λ) is unattenuated solar flux at the top of atmosphere at wavelength λ. All calculations are made at solar zenith angle 0°. The photoabsorption and photoionization cross sections of H₂O, CO₂, and CO are taken from Shunk and Nagy (2009).

The steady state photoelectron fluxes are calculated using the Analytical Yield Spectrum (AYS) approach, which is based on the Monte Carlo method. Details of the AYS approach are given in several of the previous papers (Singhal and Haider 1983, 1984, Bhardwaj et al. 1990, 1995, Singhal and Bhardwaj 1991, Singhal and Bhardwaj 1993, Bhardwaj et al. 1999, 2003, Singhal and Michael 1999a, 1999b, Haider and Bhardwaj 2005, Bhardwaj and Jain 2009). We have used two dimensional yield spectra to calculated photoelectron flux fₑ(E, r) as a function of energy E and cometocentric distance r

\[ fₑ(E, r) = \intₚ Q(E, r, θ) Uᵦ(E, Eₚ) \sum_i nᵢ(r)σᵢ(T) \]  

(4)

where Q(E, r, θ) is primary photoelectron production rate calculated using equation and σᵢ(T) is total inelastic electron impact cross section at energy E for the iᵗʰ species whose number density is nᵢ(r). The lower limit of integration w is minimum excitation energy and Uᵦ(E, Eₚ) is two dimensional composite yield spectra (Singhal and Haider 1983, Bhardwaj et al. 1990). The total inelastic electron impact cross sections for water are taken from Rao et al. (1995), and those for CO₂ and CO are taken from Jackman et al. (1977). The loss process of photoelectrons through collisions with thermal electrons is considered using the following formula

\[ nₑσₑₑ = \frac{nᵢβ(E, nₑ, T)}{E W} \]  

(5)

where nₑ is the thermal electron density, E is the energy of photoelectron, and W is the average energy lost per
collision between photoelectron and the thermal electron. The expression \( \beta \) is given by McCormick et al. (1976). More details are provided in Bhardwaj et al. (1990). The calculated photoelectron fluxes for the two solar EUV flux models at 1000 km are shown in Fig. 2.

The electron impact volume production rates of different ions from neutral species and volume excitation rates for CO(a\(^\Pi\)) state from CO\(_2\) and CO are calculated using photoelectron flux \( f_p(E, r) \) and electron impact excitation cross section \( \sigma_{ik} \) of \( i^{th} \) species and \( k^{th} \) state as

\[
V(r) = n_i(r) \int_{\text{n}}^{100} f_p(E, r) \sigma_{ik}(E) dE \tag{6}
\]

The cross sections for electron impact dissociative ionization of CO\(_2\) are taken from Hikawa and Mason (2005), for CO\(^3\) from Bhardwaj and Jain (2009), and for CO from McConkey et al. (2008). Table 1 presents the reactions involved in the production and loss of CO(a\(^\Pi\)).

The calculated production rate profiles of CO(a\(^\Pi\)) using solar EUVAC and S2K models for relative abundance of 4\% CO\(_2\) and 7\% CO are shown in Figure 4. For both solar EUV flux models, the peak production rate occurs at cometocentric distance ~20 km. The major production mechanism of CO(a\(^\Pi\)) is the photoelectron impact of CO, whose contribution is ~70\% to the total CO(a\(^\Pi\)) production. On using the S2K solar flux, the calculated total production rate is 1.5 times larger than that obtained using the EUVAC flux. This variation is mainly due to the difference in the input solar EUV flux (cf. Fig. 1) and subsequently EUV-generated photoelectron flux (cf. Fig. 2).

In comet 103P/Hartley 2 the photoelectron impact dissociative excitation of CO\(_2\) followed by photoelectron impact of CO are the major production processes of Cameron band, and not the photodissociative excitation of CO\(_2\) as suggested by Weaver et al. (1994).

Since comet 103P/Hartley 2 is CO depleted (relative abundance \( \leq 1\% \)), the contribution to Cameron band emission through dissociative excitation of CO\(_2\) by EUV-generated photoelectrons is more important. However, in case of comets where CO abundance is larger, like 1P/Halley, the contribution of CO to the Cameron band emission would be significant. The derived CO\(_3\)/CO abundance ratios for several IUE observations of comet 1P/Halley showed that the abundance of CO can be even double that of CO\(_2\) (Feldman et al. 1997).

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In the wavelength region 700–1050 Å, the S2K model solar flux is a factor of ~2.5 larger than the EUVAC model (cf. Fig. 1). As shown in Figure 3, the photodissociative excitation cross section of CO\(_2\) producing CO(a\(^\Pi\)) maximizes around 880–1000 Å. Further, the S2K solar flux in the 1000–1050 Å wavelength bin is around 20 times higher than the EUVAC flux. The average cross section value for photodissociation of CO\(_2\) producing CO(a\(^\Pi\)) in the wavelength region 1000–1050 Å is comparable with the peak value around 900 Å (cf. Figure 3).

Moreover, in the inner cometary coma, below cometocentric distance of 50 km, the optical depth for solar flux at wavelengths below 200 Å and above 1000 Å is smaller compared to other wavelengths because of smaller absorption cross sections of neutral species (mainly water). The rate of photodissociative excitation of CO\(_2\) molecule into CO(a\(^\Pi\)) mainly depends on the degradation of solar flux in the wavelength region 850–1050 Å. Hence, in the innermost coma (\( \leq 50 \) km), for a given relative abundance of CO\(_2\), the production rate of CO(a\(^\Pi\)) via photodissociation of CO\(_2\) is determined.
by the solar flux in the wavelength bin 1000–1050 Å and at wavelengths 1025.7 Å (H I) and 1031.9 Å (O VI). The calculated photodissociation rates of CO producing CO(a^1Π) at 0.9 AU are 1.66 × 10^{-7} s^{-1} and 5.28 × 10^{-7} s^{-1} using EUVAC and S2K solar fluxes, respectively, on 13 March 1986 at geocentric distance 0.96 AU. The volume emission rate for 3 transitions (0-0, 1-0, and 0-1) of the Cameron band are calculated using the following formula

\[ V_{\nu'\nu}(r) = q_{\nu\nu}(A_{\nu'\nu}/\sum_{\nu'} A_{\nu'\nu})V(r)\exp(-\tau) \]  

where \( V(r) \) is total volume excitation rate of CO(a^1Π) at a given cometary distance \( r \), given by equation \( 6 \). \( q_{\nu\nu} \) is the Franck-Condon factor for transition, \( A_{\nu'\nu} \) is the Einstein transition probability from upper state \( \nu' \) to lower state \( \nu '' \), and \( \tau \) is the optical depth. Since resonance fluorescence is not an effective excitation mechanism for the Cameron band, the cometary coma can be safely assumed to be optically thin. The Franck-Condron factors are taken from [Nicholls (1962)] and branching ratios from [Conway (1981)].

The calculated brightness profiles for each of the production processes along projected distances from nucleus are shown in Figure 7. At 100 km projected distance, the contribution due to photodissociation excitation of CO to the total Cameron band intensity is about a factor 4 higher than the dissociative excitation processes of CO\textsubscript{2}, while contributions of other production processes are around 2 orders of magnitude smaller. Around 1000 km projected distance, both photodissociative excitation and electron impact dissociative excitation of CO\textsubscript{2} are contributing equally to the total Cameron band intensity. The photodissociative excitation of CO\textsubscript{2} dominates the electron impact excitation processes above 5000 km.

The calculated relative contributions of (1-0), (0-0), and (0-1) bands to the total Cameron band are 13.9%, 10.4%, and 14.5%, respectively. The intensities of (1-0), (0-0) and (0-1) Cameron bands of CO molecule are calculated as a function of relative abundances of CO\textsubscript{2} and CO. The calculated percentage contributions of different production processes of Cameron band at three projected distances for two different solar flux models are presented in Table 2. The IUE-observed 1-0 Cameron band emission on 13 March 1986 is 37±6 Rayleighs.

Using EUVAC solar flux as input, our model calculated 1-0 Cameron band emission intensity for the relative abundance 4% CO\textsubscript{2} and extended distribution of CO is 59 Rayleighs which is higher than IUE observed intensity by a factor 1.3 to 2. Taking CO\textsubscript{2} abundance as 4% and CO abundance as 7% from nucleus, the calculated 1-0 intensity is 51 Rayleighs, which is higher than the IUE-observed value by a factor 1.2 to 1.6. The calculated intensity for 3% CO\textsubscript{2} and 7% CO
is 46 Rayleighs, which is consistent only with the upper limit of IUE-observed intensity. In all the above cases, below 1000 km projected distances, the contribution of photodissociation of CO$_2$ to the Cameron band emission is <15%, while electron impact of CO contribute 65 to 80%. We have also calculated the intensity of Cameron band taking the Feldman et al. (1997) derived abundances of 4.3% CO$_2$ and 4.7% CO. The calculated intensity of 1-0 Cameron band emission in this case is 40 R, which is consistent with the observed value of 37 ± 6 R on 13 March 1986 (cf. Table 3). The calculated 1-0 Cameron band emission intensity at various projected distances in the IUE-slit field of view is presented in the Figure 8. The circular contours and gray scale provide information on brightness variation. The calculated results using S2K solar flux model for the above discussed relative compositions of CO$_2$ and CO are also presented in Table 2. The calculated intensities are higher by a factor of ~1.5, which is mainly due to higher input solar flux and subsequently EUV-produced photoelectron’s flux (cf. Figs. 1 and 2).

Using OH 3085 Å emission observation by IUE, Tozzi et al. (1998) derived water production rates for different days of IUE observations (1986 March 9, 11, 13, 16, 18) around Giotto encounter period. The water production rate derived on 13 March 1986, the closest approach day of Giotto spacecraft, was $5.9 \times 10^{29}$ s$^{-1}$. Feldman et al. (1997) have considered these derived production rates of H$_2$O to estimate relative abundances of CO$_2$ and CO for corresponding days of observation. We have calculated the intensity of Cameron band for different days of IUE observations taking the same H$_2$O, CO$_2$, and CO production rates as quoted in Feldman et al. (1997). The solar EUV fluxes on each day of observation was obtained by using EUVAC and S2K solar flux models and scaling them according to the heliocentric distance of comet. The IUE projected field of view is calculated for IUE slit dimension used in observation, which vary according to the geocentric distance of the comet in March 1986. The calculated intensities of Cameron 1-0, 0-0, 0-1 bands and percentage contributions from different production process to the IUE slit-averaged brightness are presented Table 3. The calculated intensity of 1-0 emission is consistent with the IUE-observation for the EUVAC solar flux model, while it is higher by a factor of 1.5 on using S2K solar flux. The calculations presented in Table 3 show that for a change in the CO$_2$/CO abundance ratio by a factor of 2, the total photoelectron impact excitation contribution changes by only ~10%; it varies from 68 to 76% (60 to 69%) of the total IUE-observed intensity for EUVAC (S2K) solar flux model. The photoelectron impact excitation of CO alone contribute around 45 to 55% (40 to 60%) to the total Cameron band intensity when EUVAC (S2K) solar flux is used. The contribution of photodissociation of CO$_2$ to the IUE-observed Cameron band brightness is around 20% (30%) for EUVAC (S2K) solar flux model when the abundances of CO and CO$_2$ in the comet are almost equal. These computation show that in the IUE field of view the photoelectron is a major production source (60-75% contribution) for the Cameron band emission, whereas the contribution due to photons is small (20-35%).

The calculations presented in Tables 2 and 3 renders that in case of comets where CO$_2$/CO abundance ratio is closer to 1 or larger than 1, the emission intensity of Cameron band is mainly controlled by the abundance of CO in the inner cometary coma. The photoelectron impact excitation of CO is the main production mechanism for the production of Cameron band emission, but not the photodissociative excitation of CO$_2$ as suggested or assumed in earlier studies (Weaver et al., 1994; Weaver et al., 1997; Feldman et al., 1997). Thus, in comets that have sufficient CO abundance the electron impact excitation of CO producing CO(a$^3$Π) can be an efficient excitation mechanism for Cameron band emission. Since Cameron emission is mainly governed by electron impact excitation reactions, this emission can be used to track the photoelectron density mainly in the energy range 10 to 15 eV near the nucleus.

In the case of comet 103P/Hartley 2, which has an order of magnitude lower gas production rate and much lower CO (abundance < 1%) than comet 1P/Halley, the dissociative recombination of CO$_2$ becomes a competing production mechanism at larger (>10$^3$ km) cometocentric distances (Bhardwaj and Raghuram, 2011a). However, in comparison, on comet 1P/Halley the production rates of H$_2$O, CO$_2$, and CO are so high that the photon and photoelectron impact reactions are dominant throughout the inner cometary coma.

### 3.2. Effect of electron impact cross section

In this section we will discuss the impact of cross sections for electron impact excitation of CO(a$^3$Π) from CO$_2$ and CO. The threshold for exciting CO molecule in the metastable a$^3$Π state is 6 eV and the peak value of cross section occurs around 10 eV (cf. Fig 2). The cross section for electron impact excitation of CO producing CO(a$^3$Π) reported by Jackman et al. (1977) is theoretically fitted based on Born approximation and experimental measurements of Ajello (1971). The uncertainty associated with measurement is about 75%. However, the uncertainty in the cross section at energies less than 15 eV is 35% (Ajello, 1971), where the contribution of
electron impact excitation plays a major role (cf. Fig 2).

The cross section measurements of [Furlong and Newell (1996)] differ at the peak value of cross section by a factor of 2 (cf. Figure 2). The threshold for dissociation of CO₂ molecule into CO(λιΠ) state is 11.45 eV. [Ajello (1971)] measured Cameron band emission cross sections in the wavelength region 1950–2500 Å by exciting CO₂ molecule through electron impact. [Sawada et al. (1972)] concluded that these cross sections are comparable with cross sections of 12.6 eV and 13.6 eV states. The cross section value for CO(λιΠ) production due to electron impact of CO₂ measured at 80 eV by [Erdman and Zipf (1983)] is 2.4 × 10⁻¹⁶ cm². [Bhardwaj and Jain (2009)] modified the fitting parameters given by [Jackman et al. (1977)] for the excited states 12.6 eV and 13.6 eV of CO₂ molecule to match cross section value measured by [Erdman and Zipf (1983)] at 80 eV (for more discussion on these cross sections see [Ajello (1971); Sawada et al. (1972); Bhardwaj and Jain (2009)]. [Avakyan et al. (1998)] corrected [Ajello (1971)] reported cross sections based on measurements of [Erdman and Zipf (1983)]. The difference in the cross section of [Avakyan et al. (1998)] and [Bhardwaj and Jain (2009)] below 30 eV is about a factor of 2 (cf. Fig 2).

Using electron impact CO(λιΠ) excitation cross sections from [Furlong and Newell (1996)] for CO and from [Avakyan et al. (1998)] for CO₂, and using EUVAC solar flux, the calculated emission intensity of 1-0 Cameron band, for a given relative abundances of CO and CO₂, is larger by a factor 2. In these calculations the contribution of electron impact excitation of CO is increased from 70% to 85% at cometary distances below 10³ km and 40% to 60% at distances above 10³ km. On using these cross sections, the percentage contribution of photoelectron impact excitation of CO to the total Cameron emission in the IUE-slit-averaged intensity is found to increase by 10%, but there is no significant change in electron impact excitation of CO₂. In this case the contribution from photodissociative excitation of CO₂ is decreased by 10%.

4. Summary

Using the coupled chemistry-emission model a detailed study of Cameron band (λιΠ → Σ+) emission has been carried out on the comet IP/Halley around the Giotto encounter period. The effects of change in solar flux on the production of CO(λιΠ) and thus the Cameron band intensity have been evaluated by considering two different solar EUV flux models, viz. EUVAC model (Richards et al. 1994) and S2K (SOLAR2000) model (Tobiska 2004). Calculations are made for different days of IUE-observation of comet IP/Halley. The important results from the present model calculations can be summarized as follows:

- For the same day, the solar flux from the two models (EUVAC & S2K) are different, and the difference between them varies with wavelength.
- The production rates obtained by using S2K solar flux model are higher than that of EUVAC model. The photodissociation of CO₂ is larger by a factor of 2.5, while the photoelectron impact excitation is larger by a factor of ~1.5.
- The total production rate of CO(λιΠ) peaks around cometocentric distance of 20 km for both solar flux models.
- Throughout the inner coma the main loss mechanism of CO(λιΠ) is radiative decay. Very close to the nucleus (< 20 km) quenching by water is also significant.
- In the inner (< 5000 km) coma the major production mechanism of CO(λιΠ) is photoelectron impact excitation of CO.
- On using EUVAC solar flux, and abundances of CO and CO₂ as derived from IUE-observation, the model calculated Cameron band 1-0 emission intensity (40 R) is consistent with the IUE-observed brightness (37 ± 6 R) on 13 March 1986, and also on other days of observations. However, the calculated intensities are larger by a factor 1.5 when the S2K solar EUV flux is used.
- For EUVAC (S2K) solar flux model, around 70% (65%) of the total intensity of Cameron band observed by the IUE is contributed by electron impact excitation of CO and CO₂ molecules, while the contribution from photodissociative excitation of CO₂ is about 20–30% only.
- In comets having comparable CO and CO₂ relative abundances, the intensity of Cameron band is largely determined by the photoelectron impact excitation of CO, and not the photodissociative excitation of CO₂ as suggested by earlier studies.
- Since the emission intensity of Cameron band is mainly governed by electron impact reactions, this emission may be more useful to track the photoelectron density in 10–15 eV energy region in the inner coma, rather than the CO₂ abundance.
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Table 1: Reactions for the production and loss of CO(a^3Π).

| Reaction                                                                 | Rate(cm^3 s^{-1} or s^{-1}) | Reference            |
|-------------------------------------------------------------------------|------------------------------|----------------------|
| CO\(_2\) + h\(\nu\) → CO(a^3Π) + O(3P)                                 | Model                        | Present work         |
| CO + h\(\nu\) → CO(a^3Π)                                               | 1.69 × 10^{-9}               | Weaver et al. (1994) |
| CO\(_2\) + e\(\bar{p}\) → CO(a^3Π) + O + e^-                           | Model                        | Present work         |
| CO + e\(\bar{p}\) → CO(a^3Π) + e^-                                     | Model                        | Present work         |
| CO\(_2\) + e^- → CO(a^3Π) + O                                         | K_a^\*                      | Seiersen et al. (2003), Rosati et al. (2003) |
| HCO\(^+\) + e^- → CO(a^3Π) + H                                         | K_b^†                        | Schmidt et al. (1988), Rosati et al. (2007) |
| CO(a^3Π) + h\(\nu\) → C + O                                           | 7.2 × 10^{-5}               | Huebner et al. (1992) |
| CO(a^3Π) + h\(\nu\) → CO\(^+\) + e^-                                 | 8.58 × 10^{-6}              | Huebner et al. (1992) |
| CO(a^3Π) + h\(\nu\) → O+C\(^+\) + e^-                                | 2.45 × 10^{-8}              | Huebner et al. (1992) |
| CO(a^3Π) + h\(\nu\) → C + O\(^+\) + e^-                              | 2.06 × 10^{-8}              | Huebner et al. (1992) |
| CO(a^3Π) + H\(_2\)O → CO + H\(_2\)O                                   | 3.3 × 10^{-10}              | Wysong (2000)         |
| CO(a^3Π) + CO\(_2\) → CO + CO\(_2\)                                  | 1.0 × 10^{-11}              | Skrzypkowski et al. (1998) |
| CO(a^3Π) + CO → CO + CO                                               | 5.7 × 10^{-11}              | Wysong (2000)         |
| CO(a^3Π) + e\(\bar{p}\) → CO\(^+\) + 2e^-                           | Model                        | Present work         |
| CO(a^3Π) → CO + h\(\nu\)                                             | 1.26 × 10^{2}               | Lawrence (1972)       |

\({^*K_a}=6.5 \times 10^{-7} (300/\text{Te})^{0.8} \times 0.87 \times 0.29 \text{ cm}^3 \text{ s}^{-1}; \text{ here } 0.87 \text{ is yield of dissociative recombination of CO}_2 \text{ producing CO, and } 0.29 \text{ is yield of CO(a^3Π) produced from CO.}

\({^\dagger K_b}=2.4 \times 10^{-7} (300/\text{Te})^{0.7} \times 0.23 \text{ cm}^3 \text{ s}^{-1}; \text{ here } 0.23 \text{ is yield of dissociative recombination of HCO\(^+\) producing CO(a^3Π), e\(\bar{p}\)= photoelectron.}
Table 2: Calculated brightness of the Cameron band at comet 1P/Halley for different conditions on 13 March 1986.

| Relative abundance (%) | IUE-slit averaged brightness (R) | Percentage contribution to total Cameron band for different processes at three different projected radial distances (km) | Total Cameron band brightness (R) |
|------------------------|---------------------------------|-----------------------------------------------------------------------------------------------------------------|----------------------------------|
|                        |                                 |                                                                                                                 |                                  |
| EUVAC                  |                                 |                                                                                                                 |                                  |
| 4                      | Ext                              | 59 44 63                                                        | 9 14 52 15 15 11 74 66 25 0.5 2 5 | 430 10946                      |
| 4.7                    | 7                                | 51 38 54                                                        | 9 15 65 14 16 13 75 64 12 0.5 3 5 | 308 8836                       |
| 3                      | 7                                | 46 34 48                                                        | 7 12 63 11 13 12 80 70 15 0.5 2 5 | 331 10626                      |
| 4.3                    | 4.7                              | 45 34 48                                                        | 11 19 69 20 21 13 68 55 9 0.5 3 6 | 329 9582                       |
| S2K                    |                                 |                                                                                                                 |                                  |
| 4                      | Ext                              | 87 66 96                                                        | 14 19 61 13 13 9 71 62 20 0.5 3 4 | 638 15612                      |
| 4.7                    | 7                                | 77 58 82                                                        | 14 21 73 13 14 10 71 60 10 0.5 2 5 | 559 15841                      |
| 3                      | 7                                | 68 51 72                                                        | 11 17 71 10 12 9 77 66 11 0.5 2 5 | 490 14991                      |
| 4.3                    | 4.7                              | 67 50 70                                                        | 16 24 76 17 18 10 65 52 6 0.5 3 5 | 472 13582                      |

*The intensity of Cameron (1-0) band observed by IUE is 37±6 Raleighs on 13 March 1986.; †Ext: Extended CO distribution.; $e^{-}\text{ph}$ is photoelectron and $e^{-}$ is thermal electron.;
Table 3: Calculated brightness of the Cameron band at comet 1P/Halley on different days of IUE observations.

| Date in March 1986 (AU) | ∆(AU) | QH₂O (10²9 s⁻¹)† | Derived abundances (%) † | Ratio QCO₂/QCO | IUE-slit averaged brightness (R) | Percentage contribution to the IUE-slit averaged total Cameron band emission for different excitation processes (%) |
|------------------------|-------|------------------|--------------------------|----------------|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| 2.69                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 4.96                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 4.46                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 4.47                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 2.87                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 1.77                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 0.77                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 0.39                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 0.10                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |
| 0.00                   | 0     | 2.8             | 0.92                     | 0.84           | 18                           | 0.87                                                                       |

The value in square brackets is IUE-observed (1-0) Cameron band intensity. The production rates of H₂O and abundances of CO₂ are taken from Feldman et al. (1997). The production rates of CO₂ and abundances of CO are taken from Feldman et al. (1997).
Figure 1: Solar EUV fluxes from EUVAC model [Richards et al., 1994] and SOLAR2000 (S2K) model [Robusta, 2004] for the day 13 March 1986. Significant differences in the two model solar EUV fluxes can be noticed. (★) The value of solar flux in SOLAR2000 model for the bin 1000–1050 Å is $30 \times 10^9$ cm$^{-2}$ s$^{-1}$.

Figure 2: Cross sections for electron impact excitation of CO($a^3\Pi$) from CO and CO$_2$. Calculated photoelectron flux at cometocentric distance of 1000 km is also shown for both SOLAR2000 (S2K) and EUVAC model solar fluxes with magnitude on right side y-axis.

Figure 3: Photodissociative excitation cross section of CO$_2$ producing CO($a^3\Pi$), taken from Huebner et al. (1992).

Figure 4: Radial profiles of various production mechanisms of CO($a^3\Pi$) in comet 1P/Halley on 13 March 1986 for relative abundance of 4% CO$_2$ and 7% CO. The calculated profiles for dissociative recombination of CO$_2$ and HCO$^+$, and resonance fluorescence of CO are shown for EUVAC solar flux only. Res. flu. = resonance fluorescence of CO molecule. $e^{-}$ph = Photoelectron, hv = Solar photon, and $e^{-}$ = thermal electron.
Figure 5: Radial profiles of various loss mechanisms of CO(a^3Π) for 4% CO2 and 7% CO relative abundances using EUVAC solar flux. Photoelectron impact ionization of CO(a^3Π) is plotted after multiplying by a factor 20.

Figure 6: The calculated radial profiles of number density CO(a^3Π) for SOLAR2000 (S2K) and EUVAC solar flux models. The density of CO(a^3Π) is plotted after multiplying by a factor 10^6. The number density profiles of CO2 and CO are also shown for 4% and 7% relative abundances, respectively.

Figure 7: The integrated Cameron band brightness profiles as a function of projected distance from nucleus for different production processes of the Cameron band, using EUVAC solar flux model and relative contribution of 4% CO2 and 7% CO. The calculated brightness profiles for Cameron (1-0) band for EUVAC solar flux and total brightness for S2K solar flux are also shown.

Figure 8: The calculated (1-0) Cameron band emission brightness in the IUE projected field of view on 13 March 1986, assuming spherical symmetry, using EUVAC solar flux model, for relative contribution of 4.3% CO2 and 4.7% CO. The rectangle represent the projected field of view corresponding to IUE slit dimension of 9.07′ × 5.1′ centred on the nucleus of comet 1P/Halley, which is 11000×6600 km. The gray scale represent the calculated brightness with contours (solid lines) for 10^3, 10^6, 20, and 10 R marked in the figure. The calculated brightness averaged over IUE slit projected area (40 R) is shown by thick black contour between two dotted line contours which represent the upper and lower limits of IUE observed intensity value (37 ± 6 R).