NEGATIVE IONS IN COMETS

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Abstract. The primary negative ion sources in comets are shown to be: for the inner coma – both polar photodissociation of HCN, electron attachment of OH and collisions with alkalis; in the vicinity of the nucleus – plasma, excavated during interplanetary dust impacts on the nucleus; for both the contaminated solar wind region and sporadic discharges in the non-homogeneous inner coma plasma – dissociative electron attachment and charge inversion during keV positive ion scattering by cometary dust are also significant sources. Negative ion abundance for Halley's Comet has been estimated to be from 10^{-6} to 10^{-10} of electron densities. However, this ratio may be more due to the formation of clusters $A^-(H_2O)_n$. Some possible cometary plasma effects, caused by negative ions, have also been discussed.

1. Introduction

Such complex plasma objects as comets are, for their comprehensive description, badly in need of all 'witnesses' of relevant phenomena. Among these phenomena, negative ions may be an area of interest due to noteworthy possible consequences. However, up to the present, there have been only vague anticipation or estimations of negative ion containment in cometary plasma (e.g., Mendis, 1977). On the other hand, much theoretical and experimental work on laboratory plasmas has been published during the last few years: for various gaseous situations by Massey, (1976); for rarefaction waves after impacts by Dalman *et al.* (1977); for laser plasma by Fürstenau *et al.* (1979); and for CO_2 convectional laser discharges by Shields and Smith (1978). In the latter paper, negative ions CO_4^- and CO_3^- were found to be a cause of generation of plasma instabilities even to the point of disruption of discharge. It is conceivable that similar phenomena are significant in comet tails, if a sufficient abundance of negative ions is present. Even if they are not sufficiently dense to produce such dramatic effects, they may still be important enough in interaction with positive ions, electrons, and neutral particles so as to be additional physical parameters for the inner coma. It seems that the simplest and most correct way to analyze the roles of negative ions is to make separate estimates of all their possible sources and traps, and then to select only the most intensive one from each side. All data which have been obtained in this way are listed in Table I.

The approximation of only binary collisions was assumed here. This restriction is justified, for both generation and loss mechanisms, by the much smaller magnitude of the triple collisions in ordinary gaseous discharges (Massey, 1976). The approximation should be especially good for the rare gases of comets. Various ionic reactions besides the simplest ones are also not under discussion here.

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TABLE I

Negative ions in comets; Halley's Comet, nominal case, preperihelion 1.53 Au

Part 1. Main negative ion sources, Binary collison approximation

Negative ion source	Laboratory research	Intensities ($cm^{-3} s^{-1}$) on the distance from nucleus: 10 km	10^2 km	10^3 km	10^4 km	Notes and conclusions
1. *e*-attachment: $e + A \rightarrow A^- + h\nu$; $e + A \rightarrow A^-$	Various types of plasma (1); threshold is 1.78 eV for $OH + e \rightarrow OH^-$	10^{-4}	10^{-5}	10^{-7}	10^{-9}	Data on neutral and electron abundances from (2).
			Symmetric			
2. Dissociative *e*-attachment: $e + AB \rightarrow A + B^-$; $\rightarrow A^+ + B^- + e$	Electron beam interaction with gases (1, 12).	–	–	–	3×10^{-4}	10 to 500 eV contaminated solar wind electrons and electrons from sporadic discharges in the coma.
			Apex			
		–	10^{-2}	10^{-4}	10^{-6}	
			Tail			
3. Polar photodissociation $AB + h\nu \rightarrow A^+ + B^-$	Other reaction modes: $AB + h\nu \rightarrow A + B$; $\rightarrow A + B^+ + e$; $\rightarrow A^+ + B + e$ (1)	For $\leqslant 1$	$HCN + h\nu \rightarrow H^+ + CN^-$: 2×10^{-2}	3×10^{-4}	2×10^{-6}	HCN abundance is 10^{-2} of H_2O (5). Solar photons are in the energy range $15.2\ eV \leqslant h\nu \leqslant 19.43\ eV$
			Symmetric			
4. Reversal of charge during positive ion scattering by targets: $A^+ + T \rightarrow A^-$ and secondary negative ion emission.	Reversal was studied for: Nb, Au, Ta, and ThO_2 bombarded by 3–15 keV beams of H_1, H_2^+, D_1^+, and D_2^+ (6). Secondary emission for H^+ in (1, 7).	–	–	–	3×10^{-7}	Contaminated solar wind protons (2) and sporadic keV ions (2, 3) scattered by coma dust. Dust distribution from (8).
			Apex			
		–	3×10^{-5}	3×10^{-6}	3×10^{-8}	
			Tail			
5. Ion conservation ('freezing effect') during dense plasma expansion in vacuum.	Macroparticle impacts, laser plasma (9, 10); from 5% to 80% of negative ions in plasma flame.	5×10^{-2}	–	–	–	Interplanetary dust impacts on the front of the nucleus with $v \simeq 35\ km\,s^{-1}$.
			Apex			
6. Collisions with alkalis K, Na	$K + O_2 \rightarrow K^+ + O_2^-$ (7); $Na + H \rightarrow Na^+ + H^-$	$\geqslant 10^{-5}$	7×10^{-7}	7×10^{-8}	$\leqslant 10^{-10}$	Abundance of alkalis (5) $n(K) = 10^{-4}$ of H_2O; $n(Na) = 10^{-3}$ of H_2O.
			Symmetric			
		$\geqslant 10^{-2}$	$\geqslant 10^{-4}$	$\geqslant 10^{-5}$	$\geqslant 10^{-7}$	

TABLE I continued

Part 2. Main negative ion losses in comets, in terms of n^- ($cm^{-3}s^{-1}$)

Negative ion trap	Laboratory research	Intensities on the distance from nucleus				Notes and conclusions
		10 km	10^2 km	10^3 km	10^4 km	
1. Mutual neutralization and charge exchange: $A^- + B^+ \rightarrow AB + h\nu$; $\rightarrow A^+ + B^-$; $\rightarrow A + B$	The largest cross-section among binary collisions: $\sigma \sim 10^{-13}\,cm^2$ (1, 11)	10^{-3}	10^{-4}	10^{-5}	10^{-6}	Equal probability for each reaction has been assumed.
2. Collisions with neutral particles: $A^- + B \rightarrow A + B + e$; $\rightarrow AB + e$	Can lead to the formation of clusters: $A^- + H_2O + M \rightarrow A^-{\cdot}H_2O + M$; $A^-{\cdot}B + H_2O \rightarrow A^-{\cdot}H_2O + B$ (1)	10^{-1}	10^{-3}	10^{-5}	10^{-7}	As $A^-{\cdot}(H_2O)_n$ is also negative, the total ion concentration n^- may increase in the vicinity of the nucleus.
3. Photodetachment: $A^- + h\nu \rightarrow A + e$	$\sigma \sim 10^{-17}\,cm^2$, for photon wavelengths in the interval 4000 Å to 8000 Å for various ions, except CN^- (1).	1, 2	1, 2	1, 2	1, 2	This is the main trap which limits OH^- lifetimes to 1 s, and H^- to 0.2 s for solar photon flux at 1.53 AU.

Others (1):

4. Autodetachment $A^- \rightarrow A + e$ limits lifetime to $\lesssim 10^{-12}$ s for CO^-, N_2^-, and other ions with negative electron affinity.
5. Detachment by electron impact has high energy threshold > 10 eV ($\sigma \sim 3 \times 10^{-15}\,cm^2$); and operates in the contaminated solar wind region and during sporadic discharges in the tail.

TABLE I, Part 2, continued

		Densities (cm^{-3}) on the distance from nucleus				
		10 km	10^2 km	10^3 km	10^4 km	Notes and conclusions
Resultant densities						If negative ions formed sheets or filaments as electrons did (3), their densities might be considerably greater.
Electron densities (2):		6×10^5	6×10^4	4×10^3	2×10^2	
Negative ion densities	Apex	5×10^{-2}	5×10^{-6}	7×10^{-7}	3×10^{-7}	
	Tail	10^{-3}	10^{-2}	10^{-4}	10^{-6}	

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2. Sources

Let me start the analysis with well-known processes of negative ion production: electron attachment (1) and dissociative attachment (2), which have been discussed for various electrical discharges in gases and for electron beam interactions with gases, and which were summarized by Massey (1976) and McDaniel (1964):

$$e + A \rightarrow A^- + h\nu, \quad e + A \rightleftarrows A^-; \tag{1}$$

$$e + AB \begin{array}{l} \rightarrow A + B^-, \\ \rightarrow A^+ + B^- + e. \end{array} \tag{2}$$

The efficiency of the first process is proportional both to the energy of electron capture by the field of an atom – to the electron affinity Ea – and to the time during which the electron traverses this field. This means that the greater the electron energy, the less the probability of electron capture. The intensity of this process can be calculated with the help of the coefficient of electron attachment K_{ea} ($cm^3 s^{-1}$), and the electron and neutral particle densities n_e and n_n:

$$W = K_{ea} n_e n_n \,(cm^{-3} s^{-1}). \tag{3}$$

Since this process is the most effective for plasma, which has electron energies less than Ea, let me estimate the intensity (3) for the coolest region of comets: for the inner coma with its temperature of about 0.3 eV. In this region, the hydroxide OH is the first candidate; it has a small electron affinity of 1.73 eV (with corresponding $K_{ea} = 2 \times 10^{-15}$ $cm^3 s^{-1}$), large (after H_2O) abundance in comets, and a stable negative ion OH^-. Let us assume the case of Halley's Comet and use the latest data on both electron $n_e(R)$ and hydroxide $n_{OH}(R)$ radial distributions from Houpis and Mendis (1980). The resulting negative OH^- ion densities are listed in Table I. They are obviously symmetrical in the radial plane of the coma. The OH^- density follows the peak of the electron density between the inner shock and tangential discontinuity surfaces, where this mechanism, for temperatures of about 10 eV, is still valid. At radial distances along the sun-nucleus axis greater than that of the tangential discontinuity, i.e., $R \geqslant 3.5 \times 10^3$ km, there is a hot region of contaminated solar wind with electron temperatures in the range of 500–100 eV. Here the efficiency of another process – dissociative electron attachment (2) – exceeds that of the previous one, and is the dominant mechanism for water molecules. This is due both to its relatively small energy threshold of 6.4 eV (compared with 9.9 eV for CO_2, etc.; cf. Massey (1976)), and to the relative abundance of water. The reaction (2) has a cross-section $\sigma = 10^{-18}$ cm^2 for H_2O and results in negative ions H^- and O^-.

The intensity of this source can be estimated from a simple equation for binary collisions of electrons with neutral atoms. This is similar to Equation (3) where, instead of K_{ea}, one needs to use σv, with σ equal to the above-mentioned value for H_2O, and with v in accordance with the electron energy. The results are listed in Table I together with those for the inner coma in the tail direction. That is because this region sometimes also has keV-electrons due to sporadic discharges, which usually happen during sunbursts. As was found by Ip (1979) in such cases electric currents reach 10^8 A for a flare region of about 10^2 to 10^3 km. Corresponding electron current densities can be more than 10^{-8} A cm^{-2}, or electron fluxes $j \geqslant 10^{11}$ e $cm^{-2} s^{-1}$. These fluxes are not only sporadic, but also local phenomena, which can happen at any point from the comet tail to the nucleus.

Other binary collisions in cometary plasma, such as neutral–neutral reactions (except alkalis)

$$A + B \rightarrow A^+ + B^- \tag{4}$$

must be considered as negligible in comets because the energy threshold for the reaction is too high (e.g., about 10 keV for $H + H_2 \rightarrow H^- + H^+$; Massey, 1976). There are no such energetic neutrals in cometary plasma besides those results of charge-exchange reactions for solar wind protons at a distance greater than that of the TD. Indeed, this two-step process has a very low probability, because of the small value of the product of two cross-sections: charge exchange, $\sigma \simeq 10^{-17} cm^2$; and neutral–neutral collisions, $\sigma \simeq 3 \times 10^{-17}$ cm^2 (Massey, 1976).

Neutral–neutral reactions involving alkalis can result in the formation or negative ions similar to ones studied by Schlachter *et al.*, (1980), Hiskes (1979), Lacmann and Herschbach (1970):

$$\begin{aligned} Na + H &\rightarrow Na^+ + H^- \\ K + O_2 &\rightarrow K^+ + O_2^-. \end{aligned} \tag{5}$$

The observed value of the electron affinity for the first reaction is 0.75 ± 0.2 eV, and for the second one, 0.5 ± 0.02 eV (cross-sections for both reactions were extrapolated to their energy threshold ~ 1.3 eV, where such collisions in coma are only 10^{-2} of ordinary thermal ~ 0.3 eV collisions, accepted value of $\sigma \simeq 10^{-17} cm^2$). Apparently, negative ions like O_2^-, H_2^-; H^- are generated by this mechanism in cometary plasma. In spite of intensive competitive reactions of alkalis with water molecules, the ratio of the abundances of alkalis to water cannot be considered as insignificant: 0.1% for Na and 0.01% for K, both for Halley's Comet (Newburn and Yeomans, 1977) and Temple-2 (Nagy *et al.* 1979). However, the percentage of molecular oxygen O_2 is below 0.01% of hydrogen or water molecules. Nevertheless, the intensity of O_2^- production due to reactions (5), estimated for Halley's Comet, turned out to be only about an order of magnitude less than that for electron attachment of OH while for H^- that is about the same. (See Table I.) To make these estimates, the above-mentioned data on Halley's Comet were used, together with thermal velocities of cometary atoms, $v_t = 10^5 cm s^{-1}$, in Equation (3) for binary collisions, of the form

$$W = n(K) n(O_2) \sigma_{A1} v_t \ cm^{-3} s^{-1}. \tag{6}$$

Now let me discuss polar photodissociation (Massey, 1976)

$$AB + h\nu \rightarrow A^+ + B^-, \tag{7}$$

which is usually followed by a simple photodissociation and by photoionization

$$AB + h\nu \rightarrow A + B; \tag{8}$$

$$AB + h\nu \begin{array}{l} \to A^+ + B + e, \\ \to A + B^+ + e. \end{array} \tag{9}$$

A large variety of cometary molecules can be involved in these processes, However, polar photodissociation was studied for only a few molecules, such as HCN (Berkowitz *et al.*, 1969). HCN abundance in comets is significant: 10^{-2} of H_2O molecules for both Halley's Comet (Newburn and Yeomans, 1977) and Temple-2 (Nagy *et al.*, 1979). For HCN, this reaction resulted in the production of negative ions CN^-. Let me estimate this source for Halley's comet using a simple way of separation of channels of reactions 7, 8, and 9 for HCN.

The threshold for the polar photodissociation of HCN is 15.18 eV, while for the last two processes (9), the thresholds are 19.0 eV and 19.43 eV (Berkowitz *et al.*, 1969). Hence, solar UV radiation in the range between 15.18 eV and 19 eV may cause only polar and simple photodissociation of HCN, while photons with energies above 19 eV ionize HCN in reactions (9). Photoelectrons, ejected by these photons can be involved in electron attachment with neutral products of photoionization. This is responsible for some uncertainty in results above 19 eV, while simple photodissociation causes uncertainty below 19 eV.

If we assume that the cross-section for polar photodissociation σ_{pd} is equal to that of photoionization σ_{pi} when the photon energy $h\nu$ is very close to the threshold of the process, then in accordance with Zel'dovich and Raizer, (1967), $\sigma_{pd} \sim 10^{-18}\,\text{cm}^2$. The intensity of solar radiation I_s in the interval of photon energies 15 eV to 19 eV one can take from measurements by Heroux and Hinteregger (1978): $I_s(\Delta h\nu) = 3 \times 10^9$ photons $\text{cm}^{-2}\,\text{s}^{-1}$. The intensity of this reaction is obviously equal to

$$W(CN^-) = n(HCN)\sigma_{pd}I_s(\Delta h\nu)\ \text{cm}^{-3}\text{s}^{-1}. \tag{10}$$

The resultant profile for HCN is listed in Table I. However, it is a qualitative profile due to a few reasons: there is no accurate HCN radial density distribution for Halley's Comet, but only its vague ratio to water molecules; and there exists some uncertainty in the mechanisms of reactions 7, 8, and 9. The real values might be more for these reactions, if they are valid for other molecules like H_2O etc. But there are no available data.

Since there are no other efficeint candidates for polar photodissociation in comets, except maybe some water molecules, let me discuss the next possible source of negative ions, which was also experimentally studied: the inversion of electric charge during the scattering of energetic (keV) positive ions by dust grains and simultaneous secondary negative ion emission.

Let us start this analysis for solar wind protons. Solar wind protons can only reach radial distances up to the tangential discontinuity surface, where they are deflected by the magnetic field which steeply increases from 5γ to 100γ in this region. The radial distance from this region to the nucleus for Halley's Comet is normally from 5×10^3 to 10^4 km (Houpis and Mendis, 1980). Only protons with energies $E \geqslant 10$ keV can penetrate to the nucleus, but their content in solar wind is very small (i.e., Formizano, 1979). Apparently, this mechanism is not valid for cool thermal ions of the inner coma because of incident energies for real scattering, which must be at least a few times greater than normal absorption–emission energies, equal to about 5 eV. This leads to the conclusion that for thermal positive ions ($E \sim 0.3$ eV) there is a very high probability of absorption during collision with grains. Nevertheless, the situation for the inner coma can be different during sun bursts, which causes extreme non-homogeneity of the cometary plasma, with electrical currents localized into sheets of filaments (Ip, 1979). For such discharges, the voltage drop across the whole comet tail reaches 10^6 V and forms a high internal cometary electric field. This field accelerates positive ions up to the keV range with intensities of $6 \times 10^7 \text{cm}^{-2} \text{s}^{-1}$ (Houpis and Mendis, 1980). These sporadic fluxes can be formed at any point from the tail to the nucleus and can also be scattered by cometary dust.

According to Verbeek *et al.* (1976, 1975), the positive hydrogen ions H_1^+, H_2^+, H_3^+, D_1^+, D_2^+, and D_3^+ with incident energies from 3 to 15 keV inverted their electric potentials during scattering by Au, Ta, and ThO_2 targets. The number of negative ions in reflected beams $K_R = N^-/N^+$ increased proportionally with increasing bombardment energies, and much more with a decrease in the work function ϕ of the targets. For example, in the case of the Ta target ($\phi = 4.8$ eV), N^-/N^+ varied from 0.1 to 0.3 for 5–15 keV H_1^+ beams, and from 1.2 to 3.50 in the case of the ThO_2 target ($\phi = 2$ eV) for the same beams. This phenomenon does not change significantly with changes in angles of beam incidence. Such processes have been studied only in connection with recycling in high-temperature plasma experiments; other types of positive ion scattering have not been measured. The reflection coefficient for positive ions was $\sim 20\%$, and it was emphasized that this scattering differed from well-known ion sputtering and secondary ion emission. These were summarized by McDaniel (1964). For our purposes it seems reasonable to use the last two effects for comparative analysis of the reflection coefficient.

For sputtering another parameter is usually used – yield, the number of ejected atoms per incident ion. This parameter was found to increase with the mass and energy of the incident ions, and could exceed 10 (for 10 keV Kr^+ and Xe^+ on metal targets), while for H^+ beams with the same energy the yield was about 10 or 20 times less (McDaniel, 1964). In these cases only about 1% of the ejected particles were charged. But in later investigations of backscattering by Behrisch (1975), this quantity exceeded 30%. Apparently, the backscattering (or reflection) was followed by sputtering, which included secondary positive and negative ion emission. However, the yield of this process was much less: $K_s \lesssim 10^{-4}$ (Benninghoven, 1973). Since grains can be considered to be dirty icy targets, for which there is no similar data available, the following rough estimate for the reflection coefficient may be proposed: that there is a similar tendency for the yield in comets. Thus, the reflection coefficient for H^+ has to be about 10% and $\sim 30\%$ for the case in which the incident ion is an OH^+.

Obviously, the above-mentioned energetic cometary ions belong to the low limit of beam energies in the Verbeek *et al.* (1976, 1975) experiments. Hence, such data can be used with just a little linear extrapolation along an energy scale. This has been done with data on the ThO_2 target, since its work function is closer to those of silicate or icy dust grains than to pure, heavy-metal targets.

To continue with the case of Halley's Comet, one can use the distribution of dust grains, calculated by Newburn (1979) for the comet when positioned at 1.53 AU. He found a radial distribution of cometary dust to be proportional to $N(R_0)/R^2$, with nominal dust abundance at the radial distance $R_0 = 10^3$ km equal to $n_{d1} = 1.29 \times 10^{-5}$ cm^{-3} for grain diameter $d_1 = 1.125 \times 10^{-4}$ cm; $n_{d2} = 8.93 \times 10^{-6}$ cm^{-3} for $d_2 = 1.5 \times 10^{-4}$ cm; and $n_{d3} = 6.04 \times 10^{-6}$ cm^{-3} for $d_3 = 2.175 \times 10^{-4}$ cm. As scattering is produced by all grains, their effective surfaces must be integrated. The contribution from surfaces of other grains in this integral besides those specified above is small.

Thus, all data for the estimation of negative ion production during positive ion scattering by cometary dust have now been summarized here. The results were estimated with the aid of a simple equation, similar to Equation (10) for binary colisions in gas, of the form

$$W = (K_n K_R + K_s) F_i^+ \Sigma(n_g \sigma_g), \tag{11}$$

where $K_R = 10^{-1}$ is the reflection coefficient for scattering for H^+; $K_n = 0.3$, the proportion of negative ions among the scattered ions; K_s, the coefficient of secondary negative ion emission; F_i^+, the flux of positive ions, which can be either solar wind protons in the contaminated solar wind region or sporadic ions from the tail; n_g, the normal comet dust abundance at a distance R from the nucleus; and σ_g, the cross-section of the dust grains.

Next let me outline both positive and negative ion sources, which have been described for planets without atmospheres by Wekhof (1979) and for Io by Coradini and Wekhof (1979): the plasma phase in rarefaction waves after micrometeorite impacts. As the comet moves in space, its nucleus is also bombarded by micrometeorites. Two factors can decrease this effect. The first one is the possible ablation of micrometeorites on their way through the inner coma before their collisions with the nucleus or with grains in the vicinity of the nucleus. According to Ip and Mendis (1976) the column density of the coma's ionosphere in Haley's Comet is about 10^{17} cm^{-2} (or 3×10^{-6} g cm^{-2}). This is 10^2 times less than Io's ionosphere, through which a large quantity of micrometeorites can pass without significant ablation (Coradini and Wekhof, 1979); such is also the case in the coma. The second obstacle to interplanetary dust penetration to the comet nucleus is their possible deflection by the Lorentz force resulting from the 100γ magnetic field in the TD regions. This case is similar to one of interstellar grains considered by Levy and Jokipi (1977) for the solar system. Here they used an electrical charge for dust grains equal to $q = 3 \times 10^{-8}$ esu. Assuming the same charge for micrometeorites, their Larmor radius was found to be much greater than the coma radius.

Thus, there are not any obstacles to micrometeorite penetration through the coma, and hence none for plasma generation on the surface of the nucleus. The last one is conglomerate of dirty icy rocks: 90% ice and 10% silicates (Axford, 1979).

Ion conservation during plasma expansion is caused by the effects of a local disturbance of thermodynamic equilibrium. Here, according to the Sacha correlation, collisions in plasma cannot stabilize the degree of ionization (Zel'dovich and Raizer, 1966). A similar effect was used by Dietzel *et al.* (1973) in the design of a micrometeorite detector. With this detector Hoffman *et al.* (1975) and later Fechtig *et al.* (1979) measured micrometeorite swarms on the HEOS-2 satellite. Their data on charge ($Q\pm$) dependence from parameters of both incident particle and interplanetary dust fluxes can be used with some approximations for our estimations. In fact, the comet moves in space far from the Earth where data on HEOS-2 is valid. However, these values of micrometeorite fluxes are of the same order of magnitude as for fluxes in deep space, measured by McDonnell *et al.* (1975) on Pioneer 8 and 9. For our case, all these data can be used with some corrections on impact velocities. Meteorite flux data were corresponded to micrometeorite velocities $v_m = 8 \text{ km s}^{-1}$, and charge generation was measured for impact velocities v_m from 2.5 km s^{-1} to 10 km s^{-1}. Impact velocities in the case fo the comet were $\mathbf{v}_i = \mathbf{v}_c + \mathbf{v}_m$, where $v_c \simeq 32 \text{ km s}^{-1}$ was the comet velocity at a distance of 1.53 AU. Hence, in this instance, the impact velocities on the comet nucleus were as much as a few times greater than the micrometeorite velocities.

In order to estimate corresponding ion flux, one needs to integrate the contribution of each incident mass m_i because of the charge generation during impact $Q_i \sim m_i v_i^{3/2}$ (Hoffman *et al.*, 1975; Dalmann *et al*, 1977). This plasma-charge, and hence, ion flux, was definitely measured for masses ranging from 10^{-10} g to 10^{-7} g and for incident velocities from 1 km s^{-1} to 20 km s^{-1}. Apparently, the only way is to extrapolate these experimental data. Since in our case masses of about 10^{-7} g compose the major part of the ion flux, one can find the corresponding plasma-charge $Q \sim 10^{-6}$ C, or number of ions $N_i \sim 2 \times 10^{13}$. In order to calculate the full ion flux one needs to increase these value proportionally by the ratio between impact velocities on Halley's comet and on the detectors of HEOS-2. After all the above-mentioned procedures, including integration over the range of incident masses, one can find that the ion flux $F_i \sim 5 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$, or that the ion density near the comet nucleus $n_i \sim 0.05 \text{ cm}^{-3}$ (if ions expand with velocities of about 10^6 cm s^{-1}; Eichhorn, 1978).

This value is about an order of magnitude less than for ion fluxes from the Moon, calculated by Wekhof (1979) on the basis of a phase distribution model and impact modeling by laser irradiation. It is due to some differences in all these models. To complete this estimation, one needs the ratio of positive to negative ions in impact plasma. For incident velocities from 2 km s^{-1} to 10 km s^{-1}, Dalmann *et al.* (1977) found this ratio to be between 3 and 6%. For our range of impact velocities similar data are not available; however, they can be modeled by laser irradiation of the targets (Chernjak and Wekhof, 1979). For the case of incident photon flux from a ruby laser equal to $\sim 10^8 \text{ W cm}^{-2}$, this ratio is a hundred times more than for the above-mentioned impact data. Let us assume the mean value of these results – i.e., about 50%. Then the negative ion flux from the comet nucleus is about $3 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$. The corresponding negative ion density $n^- \sim 0.03$ cm^{-3} falls steeply with radial distance due to loss mechanisms.

Ions ejected after micrometeorite impacts on the comet's nucleus are obviously composed of the same elements as micrometeorites and dirty comet ice: O^+, O^-, Si^+, Si^-, H^+, H^-, OH^+, OH^-, etc. The level of these fluxes is measurable only in the vicinity of the cometary nucleus. Apparently, another type of micrometeorite collisions – those with cometary dust – result in negligible ion production.

3. Losses

As any losses of negative ions are proportional to their abundance n^-, which one needs to find, let us estimate each possible loss in terms of the n^- factor, in order to correlate it later with the primary source.

The strongest binary atom collisions in plasma – those of positive ions with negative ones – have two modes of further reaction: charge exchange and mutual neutralization (Massey, 1976; Mosely *et al.*, 1975)

$$A^+ + B^- \rightarrow A^- + B^+; \tag{12}$$

$$A^+ + B^- \begin{matrix} \rightarrow A + B, \\ \rightarrow AB + h\nu. \end{matrix} \tag{13}$$

The cross-sections for these processes are $\sigma_b = (10. \pm 0.3) \times 10^{-13}\,\text{cm}^2$. As two of these three modes (i.e., Equation (13)) lead to a trap for incident negative ions, it seems reasonable simply to accept equal probability on each side and to estimate loss intensity in accordance with the equation for binary collisions in gas, given by

$$W = n_i^- n_i^+ v_t \sigma_b\,\text{cm}^{-3}\,\text{s}^{-1}, \tag{14}$$

where n_i^- and n_i^+ are the negative and positive ion densities; and v_t is the thermal ion velocity (for the inner coma $v_t = 10^5\,\text{cm}\,\text{s}^{-1}$). The results are listed in Table I.

Collisions with neutrals may also lead to a trap (Massey, 1976)

$$A^- + B \begin{matrix} \rightarrow A + B + e, \\ \rightarrow AB + e. \end{matrix} \tag{15}$$

The intensity of this loss can be estimated in a similar way using equation (14), where one needs to take the cross-section from Massey's 1976 data. This cross-section is equal to $10^{-16}\,\text{cm}^2$ over a wide range of energies. Densities of the major neutral molecules H_2O, OH, CO_2, CO, and N_2 in the coma for the case of Halley's Comet decrease from $10^{10}\,\text{cm}^{-3}$ to $5 \times 10^4\,\text{cm}^{-3}$ at radial distances ranging from 10 to 10^4 km (Houpis and Mendis, 1980). However, since water molecules are prevalent, the reaction (15) is likely to follow one of those in Equation (16): namely,

$$\begin{aligned} &A^- + H_2O + M \rightarrow (A^-H_2O) + M, \\ &(A^-B) + H_2O \rightarrow (A^-H_2O) + B, \end{aligned} \tag{16}$$

which result in the formation of clusters $A^-(H_2O)_n$, whose characteristics are far from those of the original ions. These clusters are also negative ions, but they are traps for the simple negative ions. Results are listed in Table I and the consequences of such a possible conservation of the negative ions will be discussed further.

The other possible cause of negative ion loss due to binary collisions is their scattering by inner-coma dust grains – i.e., the reverse process of negative ion generation. It could result in a trap, if the physical conditions for scattering were similar to those for positive ions. But they are different, and this leads to a low intensity for the process. First of all, one can easily be convinced that the travel time of negative ions between possible collisions with cometary dust is of a few orders of magnitude more than their lifetimes, and is limited by any other loss collision or photo-detachment. Hence, the role of such collisions is negligible.

New, let us consider photodetachment

$$A^- + h\nu \rightarrow A + e, \tag{17}$$

which was studied during the last decade by various authors and whose data was also summarized by Massey in 1976. In the case of rare cometary plasma, any negative ions in any position in a comet are irradiated by solar photons and, hence, have a chance to follow reaction (17). The lifetime of any definite negative ions, if limited only by photodetachment, depends on the solar photon flux intensity in the interval where the cross-section σ_{pd} of the reaction (17) is sufficient. This interval for the negative hydrogen ion H^- is from 4000 Å to 12 000 Å, where $\sigma_{pd} = (4 \pm 2) \times 10^{-17}\,cm^2$; and for the negative hydroxide ion OH^- it is from 4000 Å to 6500 Å with $\sigma_{pd} = (1.0 \pm 0.2) \times 10^{-17}\,cm^2$. The corresponding solar photon flux in these intervals is for a radial distance of 1.53 AU. $F_{sp} \sim 10^{17}\,cm^{-2}\,s^{-1}$ (Allen, 1973). The loss-intensity for H^- and OH^- ions, which are mong the most abundant in comets, can be estimated in terms of n^-, using an equation similar to (10): $W_{ph}(H^-) = 4 \times n^-\,(cm^{-3}\,s^{-1})$ and $W_{ph}(OH^-) = 1 \times n^-\,(cm^{-3}\,s^{-1})$. Most of the other atomic and simple molecular negative ions have photodetachment parameters of the same order of magnitude (Massey, 1976). However, one of the major negative ions in comets, CN^-, has the largest detachment energy $E_d = 3.6 \pm 0.2$ eV (or the shortest photon wavelength $\lambda_d = 3440$ Å; Berkowitz *et al.*, 1970). Unfortunately, there is no obvious cross-section data for this process in their paper. For other negative ions such as O_2^-, CO_3^-, and clusters $A^-(H_2O)_n$, which can be a subject of interest for cometary applications, only the rate coefficients are available, having been measured in connection with low earth atmospheric problems. For our qualitative estimates, based primarily on only three kinds of major negative ions, H^-, OH^-, and CN^-, one can accept the efficiency of photodetachment as equal to that of one of them (OH^-): $W = 1 \times n^-$.

Finally, we need to consider losses due to autodetachment (Massey, 1976)

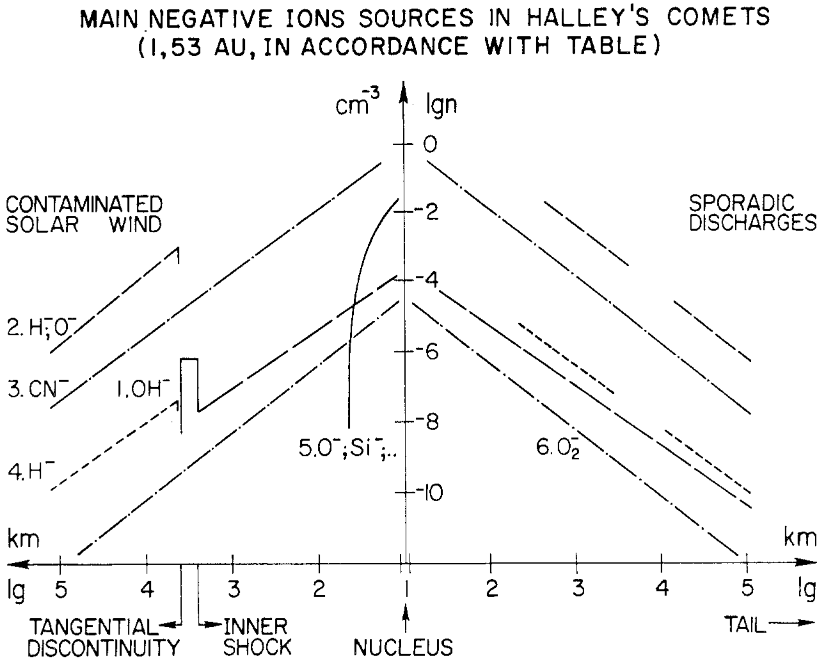
$$A^- \rightarrow A + e. \tag{18}$$

For ground states, the lifetimes τ of negative ions and, hence, attainable radial distances, may well be long enough for them to reach the comet tail from the nucleus. But they can be trapped before that due to phtotdetachment. What is really important is that some of the negative ions like CO^-, N^-, and others, with a very small or negative electron affinity, may decay immediately ($\tau < 10^{-12}$ s) after their generation (Massey, 1974; McDaniel, 1964).

In order to select the main loss mechanism, one needs to be convinced that the greater the coefficient in front of the n^- factor in Table I, the stronger the trap. In fact, a low coefficient leads to the accumulation of negative ions within each elementary volume and to an increase in their instantaneous density – effective traps decrease them. The resultant negative ion densities can be estimated in accordance with our initial assumptions by way of a simple relation between the main source and the main trap, from

$$\frac{dn^-}{dt} = W_s - W_t, \tag{19}$$

where W_t represents the photodetachment. The results for equilibrium ($dn^-/dt = 0$) radial negative ion densities are listed in Table I and are drawn in Figure 1.



4. Discussion

As can be seen from Table I and Figure 1, there are a few regions along the comet axes, each with different dominant negative ion sources.

In front of the inner coma, just up to the tangential discontinuity surface TD., it is dissociative electron attachment by solar wind electrons and polar photodissociation of HCN which generate the most negative ions. Negative ion abundance can reach 10^{-6} of electron densities in this region.

Between the tangential discontinuity surface TD and the inner shock IS another source becomes important also: electron attachment resulting in the formation of OH^- increases steeply following a peak in the electron density, the ratio of these two being about 10^{-9}.

Just behind the inner shock IS, the temperature is expected to decrease from a few eV to ~ 0.3 eV in the inner coma plasma and even lower in the vicinity of the nucleus. For this inner coma polar photodissociation of HCN becomes a major source of negative ions. The density of this source depends only on the radial distance from the nucleus, and is symmetrical with respect to the comet apex or the tail. The magnitude of this source is difficult to estimate, due to uncertainty in the mechanisms of reactions (7), (8), and (9). Any measurements of CN^- or OH^- here may give information about the source, because the magnitude of electron attachment here is less than that of polar photodissociation. At this point, the ratio of negative ion abundance to that of electrons can also be greater than 10^{-6}.

Just a few tens of km in front of the nucleus there is a region where an intense flux of negative and positive ions and electrons is generated by interplanetary dust collisions with the nucleus. The negative ion density n_i, according to this model, may be about 0.05 cm^{-3} in the vicinity of the surface of the nucleus. In order to estimate the ratio of ion to electron density one needs to compare data on inner coma electrons with those for electrons generated during impact. Assuming that these last ones have densities roughly equal to negative ion densities in impact plasma, the total ratio was found to be $n_e/n_i \sim 10^{-7}$. These negative ions, together with positive ones, can give information about components of the nucleus, because they are expelled directly from the nucleus after micrometeorite impacts. This region is too thin to be measured during the fly-by of Halley's Comet, but it may be large enough for Temple-2 rendezvous experiments. The maximum radial distance from the nucleus which negative ions can reach after expanding from the impact plasma is proportional both to the maximum value of the velocity ($v_R \simeq 3 \times 10^6$ cm s^{-1}; Eichhorn, 1978) and to ion lifetimes, which are limited by photodetachment; this distance turns out to be from 50 km to 100 km.

This negative ion density might be an order of magnitude more, if one were to accept the model of ion generation based on laser plasma modeling by Wekhof (1979). However, it seems to be more accurate to follow the present model, based on plasma-charge, which gives nominal values of negative ion fluxes.

Let me now discuss the case of non-homogeneous cometary plasma, when dissociative electron attachment by sporadic energetic electron currents and keV ion scattering by cometary dust grains become important. These are not only sporadic, but partially local phenomena, which are the consequence of electrical discharges in cometary tail and ionosphere. However, one cannot neglect these phenomena, which can be the primary ones present during sun-bursts and can increase the ratio of negative ions to electrons to more than 10^{-6}. Even this value might be exceeded if negative ions could form filaments like the electrons did.

The ratio of negative ion to electron abundance anywhere in the comet is much less than would be sufficient to cause specific negative ion instabilities in accordance with Nighan's 1977 results. He obtained them for convectional discharges and labelled them "attachment" and "thermal" instabilities. They were discovered by Shields *et al.* (1978) in convectional CO_2 laser plasma with electron pumping. These instabilities even disturbed normal electron pumping and then caused discharge disruption. No doubt, cometary plasma is very different from the above-mentioned type, but it has the same tendency toward density fluctuations because of localization of cometary electric currents into sheets of filaments (Ip, 1979). There are no reasons why a similar phenomenon could not also be valid for negative ions, such as might form tearing modes of instability. If such a phenomenon occurs, the situation during solar wind enhancement might be more complex for cometary plasma than was described before.

Apparently, even for steady homogeneous cometary plasma the abundance of negative ions seems to be sufficient to cause similar instabilities due to the underestimated role of reactions with alkalis or polar photodissociation of H_2O. In fact, the last processes might be major ones, but there is no available data exactly for our cases.

Nevertheless, water molecules have another opportunity to increase the concentration of negative ions, forming clusters $A^-(H_2O)$, $A^-(CO_2)$, etc., in reaction (16). This process is effective in the earth's ionosphere at a height of about 100 km, for which case Reid (1970) found the ratio of negative clusters to electrons to be unity. Although the concentration of molecules (or atoms) n_a at this altitude is 10^{13}–10^{11} cm^{-3}, with corresponding electron densities $n_e \sim 10^4$–10^5 cm^{-3} (Allen, 1973), are much like cometary parameters in the vicinity of the nucleus ($n_a \sim 10^{10}$–10^8 cm^{-3}, $n_e \sim 10^5$ cm^{-3}; Houpis and Mendis, 1980), there is no simple way to estimate the similar processes in cometary gas. Furthermore, these processes also take place for both positive and negative ions during three-body collisions (16), which have not been discussed here. Let us mention a few negative clusters which may be expected – such as $OH^-(H_2O)_{1,2}$–H_2O (binding energy $\epsilon_b =$ 0.98 eV); $O_2^-(H_2O)_{1,2}$ ($\epsilon_b = 0.8$ eV); OH^-–CO_2 ($\epsilon_b = 2.5$ eV); etc., which can be formed during negative ion collisions with the neutrals H_2O, CO_2, and CO (Smirnov, 1977). It is obvious that the time τ_s between such collisions of negative ions must be less than their lifetimes, limited by photodetachment ($\tau_s < \tau_{pd}$). This is also a restriction on the possible location of negative clusters to the vicinity of the cometary nucleus, with its maximum abundance of neutral atoms.

5. Conclusion

Thus, in spite of the complexity and variety of phenomena in comets, and our insufficient knowledge of the objects, some ways have been found here to understand one of the most intriguing and curious effects, that of negative ions formation in comets. The data presented here make it possible to anticipate and plan ion mass-spectrometer experiments *in situ* during the coming cometary mission. The detection of negative ions such as OH^-, CN^-, H^-, O_2^-, etc. along with their abundances, which were evaluated here, is within the range of present experimental techniques, and can be done simultaneously with measurements of electron abundances *in situ* during the mission to Halley's Comet and possible to Temple-2. The results will contribute a significant amount to our understanding of processes in cometary plasma. Moreover, if the ratio of negative ion abundance greatly exceeds 10^{-6} when evaluated for the homogeneous case, then the negative ion filaments discussed here earlier might acutally exist and may cause some spectacular cometary plasma instabilities. However, it is too early to discuss these aspects until experimental data are obtained.

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