PLASMA PHENOMENA IN THE VICINITY OF THE CLOSEST APPROACH OF VEGA-1,2 SPACECRAFT TO THE COMET HALLEY NUCLEUS

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ABSTRACT

The plasma phenomena observed on board VEGA-1,2 spacecraft inside the cometary plasma region are summarized and their nature is discussed. The observed quasi-periodic modulation of the heavy ion density in this region could be explained by the development of the large-scale instability connected with the cyclotron resonance of ions with Alfven oscillations. The occurence of ≈1 KeV electrons during VEGA-2 flyby could be a signature of sporadic "magnetospheric substorm" in the cometary atmosphere. Plasma and magnetic field observations near VEGA-1 closest approach to the nucleus give evidences of superalfvenic cometary plasma acceleration initiated by interaction of two portions of different polarity magnetic fields.

Plasma measurements performed by the PLASMAG-1 scientific package in the vicinity of comet Halley nucleus (Gringauz et al., 1982, 1986a; Apathy et al., 1986) revealed the existence of relatively sharp, yet unexpected boundary - cometopause at a cometocentric distance of $R \approx 1.6.10^5$ km (Gringauz et al., 1986 b,c,d). This boundary separates the cometosheath region, which is controlled by the solar wind proton flow, from the cometary plasma region which is dominated by heavy ions of increasing in the approach to the nucleus densities.

However the increase of cometary plasma density was neither monotonic nor stationary. In the present paper after the brief review of the instrumentation used, the plasma phenomena observed on board VEGA-1,2 spacecraft inside the cometary plasma region are summarized and their nature is discussed.

PLASMAG-1 package for cometary plasma studies included five different sensors. Two electrostatic analyzers for measuring the E/Q spectra of ions arriving from the spacecraft-comet relative velocity direction (the Cometary Ram Analyzer CRA) and from the solar direction (the Solar Direction Analyzer SDA). The CRA had a field of view (FOV) of $14^o x 32^o$, and it detected ions in the $15 < E/Q < 3500$ V range within 120 logarithmically spaced energy intervals. The SDA had the FOV of $30^o x 38^o$ and registered ions in the $50 < E/Q < 25000$ V energy range, within 60 logarithmically spaced energy intervals.

Electron electrostatic analyzer (EA) with the FOV of $7^o x 7^o$ was oriented perpendicularly to the ecliptic plane and measured electron fluxes in the $3 < E < 10000$ eV energy range, with 30 energy intervals.

PLASMAG-1 also included two Faraday cups. The Solar Direction Faraday Cup (SDFC) with the FOV of $84^o x 84^o$ measured the solar wind ion fluxes. The Ram Faraday Cup (RFC) with the FOV of $25^o x 25^o$ recorded the ion flux from the ram direction.

During the encounter of VEGA-1,2 with comet Halley the following sensors were in operation:

Sensor	SDA	CRA	EA	SDFC	RFC
VEGA-1	+	-	-	+	+
VEGA-2	+	+	+	-	+

Well inside the cometary plasma region both the thermal and the bulk velocities of ions become small compared to the spacecraft relative velocity of ≈ 80 km/s so that the E/Q spectra measured by CRA can be transformed into M/Q scale.

Figure 1 shows the sequence of 4 sec-averaged ion spectra measured at $R \approx \approx (1.4 - 1.7).10^4$ km (Gringauz et al., 1986e). The first broad left-hand peak at $E/Q \approx 30$ eV, which is certainly originated from protons (M = 1), indicates that their velocity is close to the spacecraft relative velocity.

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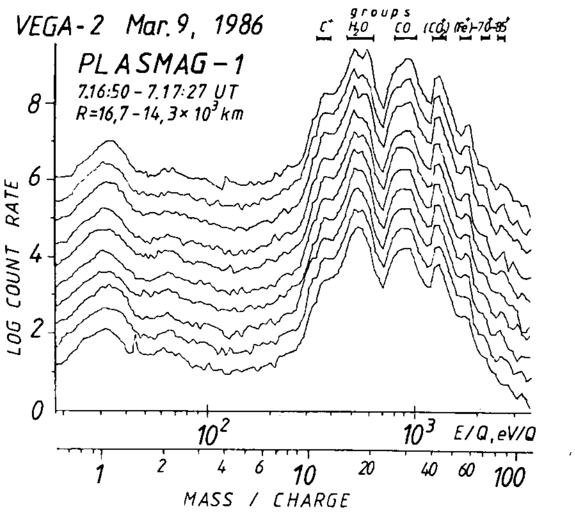

Figure 1.

On the basis of Figure 1 we can suggest the presence of H^+, C^+, CO_2^+ and Fe^+ ions in the cometary plasma region. The structured peak at $14 < M/Q < 20$ may originate from H_2O parent molecules (O^+, OH^+, H_2O^+, H_3O^+), while the peak at $24 < M/Q < 34$ may be due to CO/CO_2 parent molecules. Several minor peaks at $M/Q \approx 2, 8, 70$ and 85 could stem from H_2^+, O^{++}, some heavier not identified yet organic ions or ion-water clusters. Different groups of cometary ions are marked at the top of Figure 1.

For these groups we have evaluated their densities at different R by summing the respective count rates. For slowly moving and cold cometary ions this sum is proportional to the number densities while respective coefficient was determined from simultaneous RFC data. The result is shown in Figure 2. For the total sum $n_i(R)$ of all ions the $R^{-2.4}$ dependence is valid in $3 \cdot 10^4 < R < 1.5\ 10^4$ km cometocentric range. This CRA result is consistent with the IMS (Balsiger et al., 1986) and PICCA (Korth et al., 1986) observations on board Giotto.

Close to R^{-2} dependence of $n_i(R)$ is evidently due to the R^{-2} decrease of neutral molecules density $n_n(R)$ (Gringauz et al., 1986 b,c,d ; Remizov et al.,1986; Grard et al.,1986; Krankowsky et al., 1986). Somewhat faster decrease of the ion density could be associated with the increasing convective outflow of the cometary ions. Really, for a characteristic ionization time of $\tau_i \approx 10^6$ sec and $n_n \approx 1.5 . 10^5$ cm^{-3} at $R \simeq 2 \cdot 10^4$ km (Remizov et al., 1986), the local ion production rate is $Q_1 \approx n_n/\tau_i \simeq 0.15$ cm^{-3} s^{-1}. In order to obtain $n_i \approx 10^3$cm^{-3} at these distances (see Figure 2), the conventive outflow velocity of $v_i \approx Q_i R/n_i \approx 3$ km/s would be sufficient. This v_i value is in reasonable agreement with the water group ion velocity determined from the IMS measurements onboard Giotto (Balsiger et al., 1986).

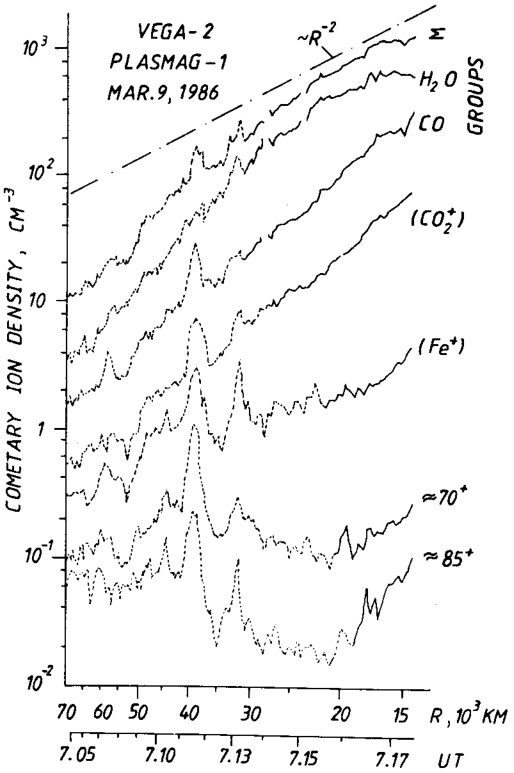

Figure 2.

It is obvious from the data presented in Figure 2 that general increase of n_i with decreasing of R is not monotonic. An example of non-stationary character of cometary plasma region was the observed at $R \simeq 4 \cdot 10^4$ km and $\simeq 3 \cdot 10^4$ km fast increasings of n_i was followed by proper decreasings (Figure 2). In this so called "hot spots" (Gringauz et al., 1986c) the growth of plasma waves intensity at low hybrid frequency was also observed. The phenomena mentioned are interpreted by Galeev et al. (1986) in terms of Alfven critical ionization velocity.

Lower scale ingomogeneities in cometary plasma region appear as quasi-periodic modulation of ion fluxes (Gringauz et al., 1986b,d). This is shown in Figure 3 exhibiting two high-resolution spectrograms as observed by CRA on board VEGA-2 at cometocentric distances $R \approx 8 \times 10^4$ and $\approx 5 . 10^4$ km. The count rates corresponding to the outermost isolines f_0 and the count-rate increments df_0 for each spectrogram are shown in the Figure. The typical amplitude of the water group ion flux modulation $A \approx (f_{max} - f_{min})/(f_{max} +$

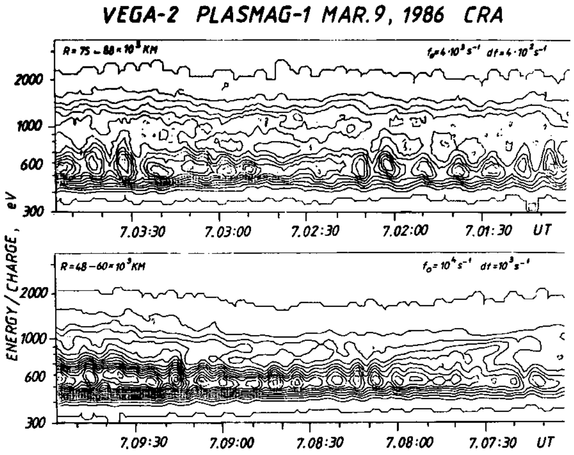

Figure 3.

+ $f_{min}) \approx 0.05 - 0.1$. Moreover, the modulation period T decreases when approaching the nucleus from about $T = 10$ sec at $R = 8x10^4$ km to about $T \approx 8$ sec at $R \approx$ $\approx 5x10^4$ km, possibly reflecting the magnetic field intensity increase from $\approx 40\gamma$ to $\approx 50\gamma$ (Schwingenschuh et al., 1986).

The observed quasi-periodic modulation in the heavy ion density in the cometary plasma region could be explained by the development of the large-scale instability caused by the anisotropic velocity distributions of cometary ions. This instability is connected with the cyclotron resonance of ions by Alfven oscillations and therefore, the wave length of these oscillations can be estimated as $\lambda \approx v_{\parallel}/f_{ci}$ where f_{ci} is the cyclotron frequency of the ions and $v_{\parallel}$ is their velocity along the magnetic field. Taking the magnetic field of $B \approx 50\gamma$ and the spatial dimensions of the plasma flow fluctuations as ≈ 8 sec x x 80 km/sec ≈ 640 km into account, the field-aligned velocity can be estimated as $v_{\parallel} \approx 30$ km/sec which seems to be reasonable.

The VEGA-2 registration of energetic electron fluxes at $R \approx (1.5 - 2) \cdot 10^4$ km can also be considered as an example of unsteady processes in the cometary region. Figure 4a presents two typical electron spectra as measured by the EA in the solar wind (a) and near the closest approach of VEGA-2 to the cometary nucleus (b). The main difference between these spectra is the appearance of the energetic cometary electron component, which could serve as as additional source of ionization of cometary neutrals.

The presence of ~ 1 keV electrons during VEGA-2 fly-by and absence of similar electrons during Giotto flyby (Gringauz et al., 1986b,d) could either be due to instrumental effect, or due to the sporadic occurence of these particles. The possible instrumental effect was discussed by Gringauz et al. (1986f). The electrons with

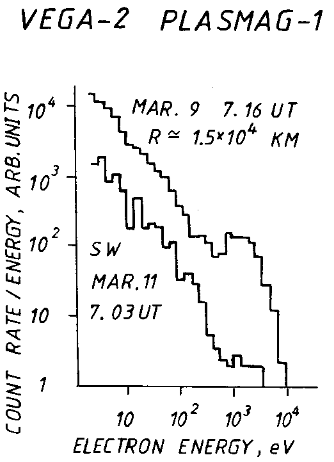

Figure 4a

energies about 1 keV could be generated by a "magnetospheric substorm" similar to the events occuring in the terrestrial substorm" similar to the events occuring in the terrestrial magnetosphere. The occurence of such events in the cometary magnetotail has been proposed by Ip and Mendis (1976) and by Ip (1986). A schematic representation of a "cometary substorm", as suggested by Ip and Axford (1982) and by Mendis et al. (1985) is shown in Figure 4b. In the steady-state the cometary tail electric current adopts the usual θ-shape configuration. If the cross-trail current gets partially disrupted, the induced tail-aligned currents can discharge through the cometary coma (Figure 4b). Such a process can accelerate electrons to some few keV energies, as in case of auroral electrons in the terrestrial upper atmosphere. VEGA-2 might have observed such substorm generated energetic electrons, while Giotto have not.

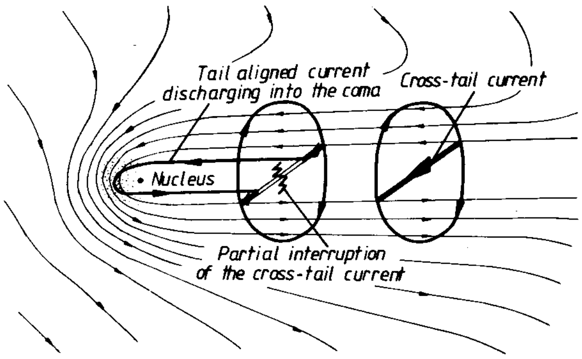

Figure 4b

Finally let us consider an example of large scale inhomogeneity formed in the cometary plasma region by the solar wind IMF parameters change (Verigin et al., 1987). The general feature of the plasma measurements on board both VEGAs is the absence of any plasma registration by SDA analysers inside the cometopause. However, in case of VEGA-1 this sensor observed a burst, lasting for about 5 min, of ions with energies E_i = 100 - 1000 eV approximately near the closest approach to comet Halley (Figure 5). For roughly the same time interval as in Figure 5, the SDFC sensor observed ion flux coming from the solar direction (Figure 6), which was evaluated as $(5\text{-}8)\times10^9$ $cm^{-2}\cdot s^{-1}$ (Verigin et al. 1987). The density of cometary ions by RFC data could only be estimated to a few thousands per cc.

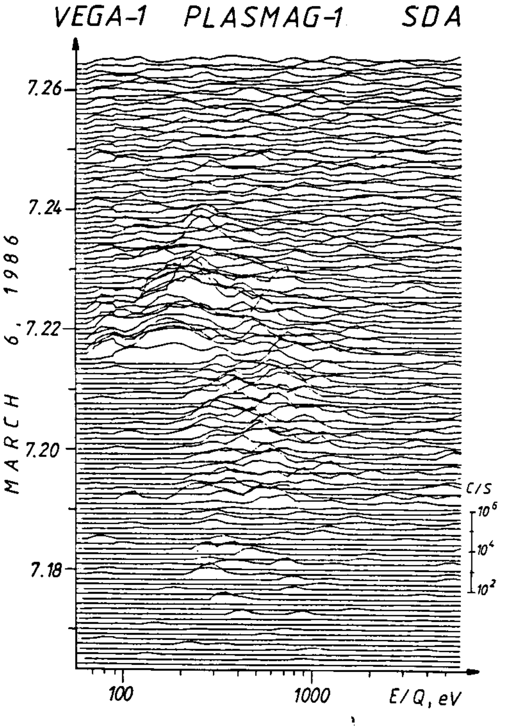

Figure 5

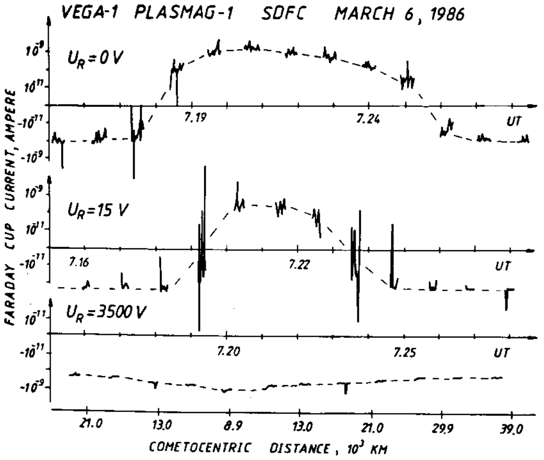

Figure 6

Inspecting the evolution of the magnetic field direction along the VEGA-1 trajectory Riedler et al., (1986) and Schwingenshuh et al. (1986) concluded that in addition to the global drapping of the magnetic field lines around the comet, the portion of the MF observed near closest approach is a remnant of the IMF of the previous polarity.

When interacting near the closest approach, two portions of magnetic fields of opposite polarities will lead to an X-type reconnection pattern of the magnetic field lines (Figure 7a). The region in which the SDA and SDEC sensors observed the enhanced flux of ions is indicated by dots in this Figure. It seems quite reasonable to suggest that these ions were accelerated by the non-stationary process of magnetic field reconnection near closest approach (Verigin et al., 1987).

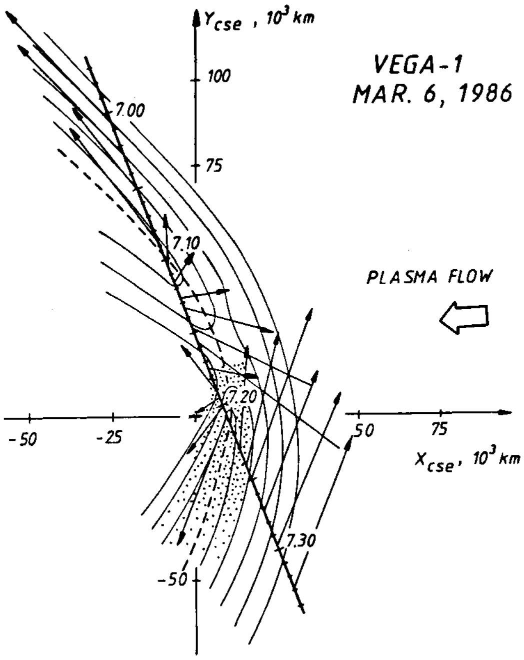

Figure 7a

Why are these ions then observed by SDA/SDFC sensor only on the outbound leg of the VEGA-1 trajectory but not on the inbound leg? The answer is provided by Figure 7b,c. Here together with look-directions and the angular FOV's of the SDA, SDFC and RFC sensors (Figure 7b), the possible diagramm of the velocity vectors $\bar{V}_s$, $\bar{V}_i$ and $\bar{V}$ is shown. Here V_s is the velocity of ions being in rest in the cometary frame of reference, $\tilde{V}_i$ is the velocity of accelerated ions in the same frame, and $\vec{V} = \vec{V}_i + \vec{V}_s$ is their velocity in the VEGA-1 frame of reference. This diagram holds for the outbound situation (the $\vec{V}_i$ is supposed to be parallel to the surface separating magnetic fields of oppo-

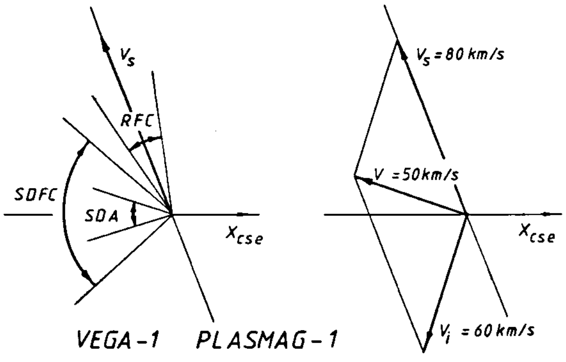

Figure 7b,c

site direction which marked by dashed curve in Figure 7a). For the inbound case the direction of $\vec{V}_i$ is close to the direction of $\vec{V}_s$ and hence the direction of $\vec{V}$ is close to the same direction (and out of the FOV of SDA/SDFC).

The ion composition measurements (Gringauz et al.,1986e; Balsiger et al., 1986) indicate that cometary ions are predominantly the water-group ions with a M = 16-18. At their velocity relative to the VEGA-1 about 50 km/sec (see Figure 7c), they will be observed at energies $E_i > 100$ eV by SDA analyzer. This is in agreement with the actual measurements shown in Figure 5. From the SDFC measurements we estimated the total ion flux as $(5\text{-}8)\cdot 10^9$ cm^{-2}sec^{-1}. Taking now their velocity V into account, we may estimate their density as $n_i >$ $>(1\text{-}2)\cdot 10^3$ cm^{-3}. This value agrees, at least qualitatively, with the number density estimated from the RFC observations.

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