COMETARY PLASMA REGION IN THE COMA OF COMET HALLEY: VEGA-2 MEASUREMENTS

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ABSTRACT

Based on the measurements of the CRA electrostatic analyzer of the PLASMAG-1 instrument, which was oriented along the spacecraft-comet relative velocity direction, we present the observations of (1) the cometopause, (2) of quasi-periodic features occurring in the ion intensity inside the cometopause, (3) of the mass composition of cometary ions between 1 and 100 amu in the cold and slowly moving plasma, and (4) of the radial dependence of the density of certain groups of cometary ions. The ion measurements are corrected for the nonlinear effects in the channeltron counting rates close to the encounter.

Keywords: VEGA, Cometopause, Cometary Ions, Mass Composition

1. INTRODUCTION

The VEGA-2 plasma measurements in the vicinity of Halley's comet revealed the existence of a relatively sharp boundary at a distance of about 1.6x10^5 km from the nucleus, the cometopause, which separates the outer region or cometosheath region, which is controlled by the solar wind, from the inner region of cometary plasma, where the number of heavy cometary ions is increasing (Refs. 1-3). These measurements were performed by the PLASMAG-1 instrument package (Refs. 4-6). In this paper we will present additional observations and discuss certain features of the cometary plasma region.

2. OBSERVATIONS

The basic data obtained by VEGA-2 in the cometary plasma region were provided by the Cometary Ram Analyzer (CRA) of the PLASMAG-1 instrument package. This electrostatic analyzer had a wide acceptance angle of 14°x32°, and it was oriented along the velocity vector of the spacecraft relative to the comet. This CRA sensor measured energy spectra of ions every second and in 120 logarithmically spaced intervals in the energy range of 15-3500 eV/q (q is the charge state) with an energy resolution of $\Delta E/E$ = 0.055. At the same time, ion flows were also observed by the electrostatic analyzer SDA oriented into the solar direction, and the energy spectra of electrons were measured by the electron electrostatic analyzer EA.

It was mentioned earlier (Ref. 1 and 3) that due to the enhanced flux of cometary ions in the inner part of the cometary plasma region during closest approach, the channeltrons of the CRA operated in a non-linear regime where significant increases in the ion fluxes correspond to small changes in the counting rates. This effect will now be taken into account based on the calibration data and on the simultaneous measurements of the Ram Faraday Cup RFC.

Figure 1 presents the colour coded results of the plasma measurements performed by the PLASMAG-1 instrument on board VEGA-2 ranging from 6.30 to 7.17 UT. During the time interval shown in Figure 1, VEGA-2 approached the nucleus from a cometocentric distance of ι 2.3x10^5 km to 1.4x10^4 km. In this figure the time scale runs from the left to the right. Each time interval between the tick-marks corresponds to 10 minutes. The energy spectra of electrons registered by the EA sensor is shown in the upper panel, and the energy spectra of ions measured by the CRA and the SDA are shown in the middle and in the lower panel, respectively. In each panel energy is increased from the bottom to the top. The colour code is changing from dark blue corresponding to the smallest fluxes to red representing the largest fluxes (the scale of colours is given on the left-hand side of Figure 1).

At a distance of 2.3x10^5 km from the nucleus (6.30 UT), i.e., in the cometosheath region, the velocity of the solar wind, being mass-loaded by heavy cometary ions, had decreased to about 230 km/sec and its temperature was estimated as ι 2x10^5 °K. The proton flow is further decelerated to about 190 km/sec when approaching the cometopause, which was observed between 6.43 and 6.45 UT (at 1.7-1.6x10^5 km, see Figure 1). At this time VEGA-2 crossed a sharp (ι 10^4 km thick) boundary separating two plasma regions of different chemical composition (see middle panel) and entered the cometary plasma region.

As the spacecraft was penetrating deeper into the cometary plasma region, the fluxes and densities of heavy ions were increasing and the temperature was decreasing, so that from 7.10 UT (ι 5x10^4 km from the nucleus) onwards rather

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distinct peaks were observed in the energy distributions of ions, measured by the CRA, which are associated with the presence of ions of their corresponding mass over charge values (middle panel).

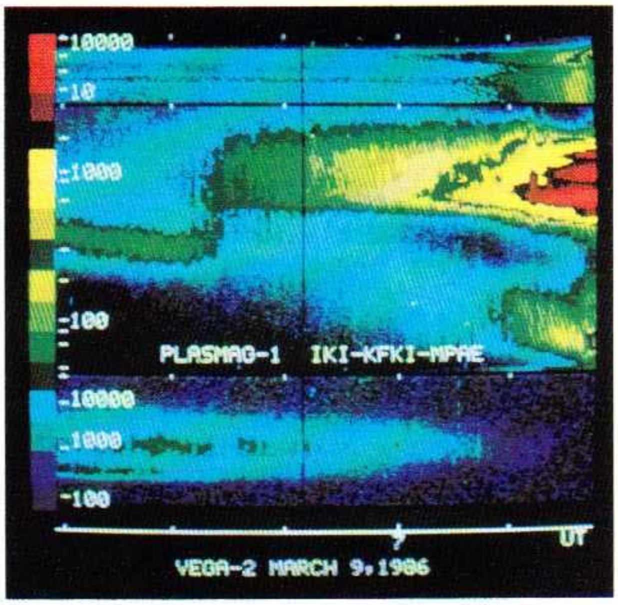

Figure 1. Colour coded results of plasma measurements around the cometopause and in the cometary plasma region provided by the PLASMAG-1 instrument on board the VEGA-2 spacecraft. The dependence on energy (vertical axis) and on time (horizontal axis) is presented for the electron flow measured by EA (upper panel), for the ion flow measured by CRA (middle panel) and by SDA (lower panel).

As shown in the lower panel of Figure 1, the SDA did not observe protons in the cometary plasma region, and the proton fluxes registered by the CRA up to a cometocentric distance of about ~ $5x10^4$ km (7.10 UT on the middle panel) were also significantly smaller than the proton fluxes in the cometosheath.

It has to be mentioned here that the widening of the proton energy spectra at the cometpause provides evidence for some heating processes occurring at this boundary (Ref. 2). Heavy ions were registered by the SDA to a cometocentric distance of $5x10^4$ km. Afterwards they disappeared from the acceptance angle of this sensor. The peak of these ions occurred at an energy of ~ 1000 eV, as shown on the lower panel of Figure 1.

The electron spectra and consequently the plasma density showed no sudden change at the cometopause (upper panel). However, deep in the cometary plasma region an increase was observed in the electron flow at an energy of about 1 keV (Ref. 1 and 3).

It is obvious from the CRA data presented in Figure 1 that the general increase in the density of heavy ions was not monotonous as the spacecraft was penetrating deeper into the cometary plasma region. Figure 2 shows the spectrograms of ions registered by the CRA during the time intervals 7.00-7.04 UT and 7.06-7.10 UT, i.e., at distances ~ $8x10^4$ km and ~ $5x10^4$ km from the nucleus, respectively. The counting rate of the CRA corresponding to the outermost isoline is given by f_o, and the difference in counting rates between the inner and adjacent isolines is df. The most characteristic features of the data presented in Figure 2 seems to be the quasi-periodic modulation in the intensity of the ion flow (Ref. 1 and 3). The typical amplitude of the modulation in the ion flow of the water group ($E/q = 500-600$ eV) is $A = (f_{max}-f_{min})/(f_{max}+f_{min}) \approx 0.05-0.1$. Moreover, it should be noticed that the "modulation period" T is decreasing when approaching the nucleus from $T \approx 10$ sec at $R \approx 8x10^4$ km to $T \approx 8$ sec at $R \approx 5x10^4$ km.

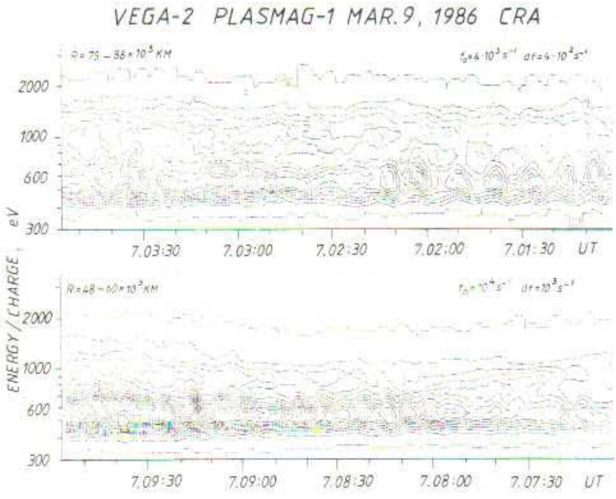

Figure 2. Spectrograms of the ion flows in the cometary plasma region at distances ~ $8x10^4$ km and ~ $5x10^4$ km from the nucleus. A quasiperiodic modulation of the ion flow is observed in this region.

While penetrating deeper into the cometary plasma region, there is also another observation indicating that the increase in the density n_i of heavy ions is not monotonous. So called "hot spots" occur where n_i first suddenly increases and then decreases, as being registered by the CRA on board VEGA-2 at cometocentric distances ~ $4x10^4$ km and ~ $3x10^4$ km, i.e., at 7.11:30-7.12:10 UT and at 7.13:00-7.13:30 UT, respectively (Ref. 2). In connection with these "hot spots" also plasma wave bursts in the lower hybrid frequency range were observed. These events were explained by the critical ionization velocity effects of Alfvén (Ref. 7).

Besides the increase in the ion density in the cometary plasma region, we also observe a decrease in the ion temperature, as the ion distributions become narrower with decreasing distance from the nucleus. This can be seen on the right-hand side of Figure 1, where the band of heavy ions ($E \approx 500$-2000 eV) which was wider after crossing the cometopause brakes up into a system of narrow bands of high intensity (red). The peak energy (light blue) of the proton band located below the heavy ion band is very quickly decreasing with decreasing distance as a result of the fast deceleration of protons. At the end of the time interval shown in Figure 1 (at $R \approx 1.5$-2.5×10^4 km), the proton energy is close to the value of ı 30 eV which would be the energy of protons practically stagnating relative to the comet and hitting the CRA sensor at a velocity of 76.78 km/sec, i.e., with the velocity of the VEGA-2 spacecraft relative to Halley's comet.

In contrast to the protons the heavy ions are practically not decelerated in the cometary plasma region (see Figure 1), since in this region almost stagnating heavy ions are predominant (their bulk velocity is much smaller than the spacecraft relative velocity V).

Around closest approach when both the thermal and the bulk velocities of the ions are small compared to V, i.e., all ions hit the CRA sensor with a velocity close to V, the E/q spectra can be transformed into M/q spectra. Figure 3 shows the 4 sec averages of the ion energy spectra measured by the CRA sensor at distances 1.4-1.7×10^4 km from the nucleus. The counting rates were corrected for the non-linear effect mentioned above. The data presented in Figure 3 suggest the presence of H^+, C^+, CO_2^+ and Fe^+ ions in the cometary plasma region. The peak at $14 < M/q < 20$ most probably originates from H_2O parent molecules and the contributing ions are mainly O^+, OH^+, H_3O^+. The peak at $24 < M/q < 34$ might originate from the parent molecules of CO/CO_2 or other molecules containing N or S and the contibuting ions might be CO^+, N_2^+, H_2CO^+, HCO^+, CN^+, HCN^+ or O_2^+, or atomic ions like Mg^+, Al^+, Si^+, P^+ or S^+. The minor peaks at $M/q \approx 2$, 8, 70 and 85 might be due to H_2^+, O^{++} and some heavy organic ions or ionized clusters, respectively.

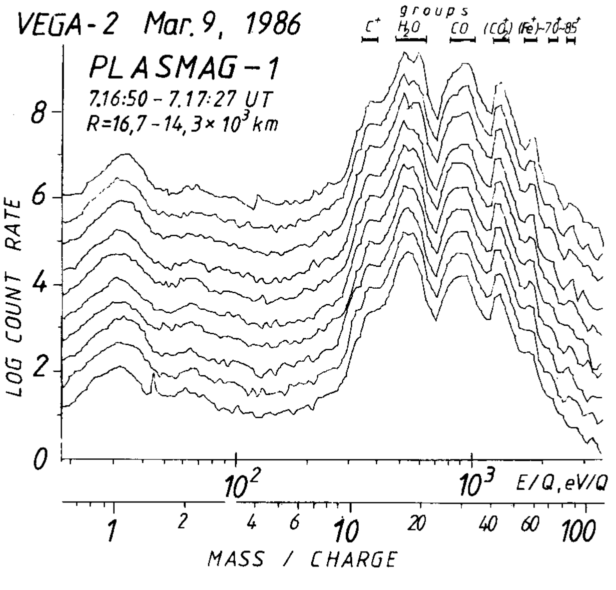

Figure 3. Spectra of cometary ions observed on board VEGA-2 at distances 1.4-1.7×10^3 km from the nucleus (4 sec averages). The upper limit of the counting rates was taken into account (see text).

In order to show how the density of the heavy ions depend on the cometocentric distance R in the cometary plasma region, we present in Figure 4 the dependence of ion densities on R as registered by the CRA in the individual E/q (M/q) intervals marked at the top of Figure 3 and also on the basis of the sum of all ions in the interval 0.3 keV $< E/q <$ 3 keV. For cold cometary ions, which are stagnating relative to the comet, the flux is proportional to their density. When moving away from the nucleus, these conditions are not satisfied in general. Therefore at larger distances, the data shown in Figure 4 can be interpreted as cometocentric density profiles of ions only with a lower accuracy.

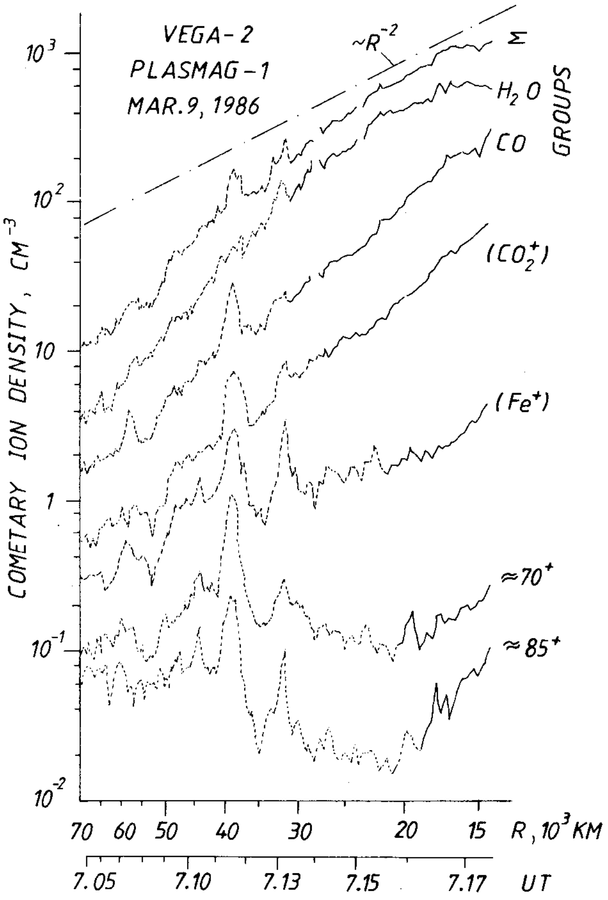

Figure 4. Cometocentric dependence of the density of some groups of cometary ions estimated from the ion spectra measured by the CRA (see Figure 3).

At the top of Figure 4, a dashed-dotted straight line shows the R^{-2} dependence. When comparing this dependence with the sum $\sum$ of all cometary ion densities it can be seen that the latter curve is declining faster than R^{-2}. We find $\sum n_i \sim R^{-2.4}$ at distances $3 \times 10^4 < R < 1.5 \times 10^4$ km.

3. DISCUSSIONS

The not expected and hence the most interesting results provided by the CRA on board VEGA-2 were the discovery of the cometopause, the significant difference between the velocity of the protons and the heavy ions in the cometary plasma region, and the existence of a quasiperiodic modulation in the density of cometary ions in this region. The origin of these features have not yet been understood completely.

The data of other experiments indicate a phenomena which might be associated with the crossing of the cometopause. The low-frequency plasma wave detector APV-V registered an increase in the oscillation of the electric field in a wide frequency range around 6.45 UT ($R \approx 1.6 \times 10^5$ km) (Ref. 14), and according to the data measured by the magnetometer MISCHA, some changes were observed in the magnetic field components B_y and B_z (Ref. 15).

Based on the observation of the PICCA instrument on board the GIOTTO spacecraft, the cometopause was clearly observed, when the fluxes of heavy ions increased at $R \approx 1.5 \times 10^5$ km (Ref. 18). Even the expression 'cometopause' was used when explaining this phenomenon. According to other experiments on board GIOTTO, some boundary was registered at $R \approx 1.35 \times 10^5$ km where the magnitude of the magnetic field suddenly increased (Ref. 16), or at $R \approx 1.5 \times 10^5$ km where the density of heavy ions began to increase (Ref. 8), or at $R \approx 1.4 \times 10^5$ km where the density of electrons of energies larger than 10 eV suddenly decreased (Ref. 17).

The velocity of protons can differ from the velocity of heavy ions in the cometary plasma region in the presence of a strong magnetic field $B > 35$ nT (Ref. 15), if the proton velocity is more or less parallel to the magnetic field direction. The velocity of the heavy ions is small in the cometary plasma region, and they are cooled continuously since the resonant charge exchange with cometary neutrals couples the heavy ions to the neutrals. On the other hand, as the density of neutral hydrogen in the cometary plasma region is rather small, the resonant charge exchange between these particles and the protons is not important, so that the protons are cooled and decelerated mainly by elastic collisions with heavy neutrals. This process has a relatively small cross-section and therefore the protons are not as strongly coupled to the neutrals as the heavy ions are. This fact probably explains the difference between the proton and heavy ion velocities in the cometary plasma region (Ref. 2).

Next we will discuss the possible reasons for the occurrence of the quasiperiodic modulations in the density of heavy ions observed in the cometary plasma region with a period of 10 sec (see Figure 2). The observed fluctuations in the flow of heavy cometary ions could be explained either by the strongly non-stationary process of the ionization of the gas or by the development of large-scale instabilities caused by the anisotropic velocity distributions of the cometary ions. The first effect will occur as a result of a very fast ionization of the atomic gas at a characteristic time scale shorter than the gyroperiod of the ions or comparable to it. Then the ions get condensed forming bunches in the phase of the cyclotron rotation. In this case the observed decrease of the fluctuation period from $T = 10$ sec at $R \approx 8 \times 10^4$ km to $T \approx 8$ sec at $R \approx 5 \times 10^4$ km could be associated with the increase of the magnetic field from $B \approx 40$ nT to $B \approx 50$ nT as observed on board VEGA-2 (Ref. 15). The characteristic frequency of the fluctuations in the plasma flow, however, is a few times higher than the cyclotron frequency for the water group ions, which dominate the plasma. Therefore it is more likely that the observed fluctuations are associated with MHD waves originating from the instabilities of the anisotropic velocity distribution of newly formed ions, in a similar way as in the solar wind upstream of the cometary bow shock. This instability is connected with the cyclotron resonance of ions by Alfvénic 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 $v_{\parallel}$ their velocity parallel to the magnetic field. Taking the magnetic field of $B \approx 50$ nT (Ref. 15) and the spatial dimensions of the fluctuations in the plasma flow as $\sim$ 8 sec x 80 km/sec = 640 km into account, the parallel velocity can be estimated as $v_{\parallel} \approx 30$ km/sec, which seems to be a reasonable value.

The detection of a well defined peak around $M/q \approx 56$ in the CRA spectra (see Figure 3) seems to be a rather unexpected result. The reasons for the existence of a significant amount of metallic ions, such as Fe^+, in the vicinity of comets were discussed by Ip and Axford (Ref. 19).

At cometocentric distances of $1.5\text{-}3 \times 10^4$ km the decrease in the density of cometary ions is somewhat faster than R^{-2} (see Figure 4). These observations can be compared with the measurements obtained by the HIS sensor of the IMS instrument on board GIOTTO (Ref. 8). The counting rates measured by HIS in the H-mode also indicate a somewhat faster decrease than R^{-2} (see Figure 4 in Ref. 8). Although the neutral gas density decreases as R^{-2} (Refs. 1,3,9-11), the somewhat faster decrease in the density of cometary ions is probably connected to the fact that the loss rate of ions is increasing with increasing distance due to an increase in the convective outflow of ions. According to the data measured by the RFC on board VEGA-2 the neutral density was $n_n \approx 1.5 \times 10^5$ cm^{-3} at $R \approx 2 \times 10^4$ km (Ref. 9). With the value of $\tau_i \approx 10^6$ sec for the characteristic time of ionization, the local production rate of ions is $Q \approx n_n/\tau_i \approx 0.15$ cm^{-3} sec^{-1}. In order to obtain $n_i \approx 10^3$ cm^{-3} for the ion density at these distances, a value of the velocity of the convective outflow of $v_i \approx QR/n_i \approx 3$ km/sec would be sufficient, which is in reasonable agreement with the velocity measured by the HIS spectrometer of the IMS instrument on board GIOTTO (Ref. 8).

According to the CRA measurements at a distance of a few times ten thousand km from the nucleus, 70-80 % of the ion content belongs to the water group, 15-20 % stems from the CO/CO_2 group, and 2-5 % has a mass of ≈ 44 (CO_2^+) (see Figure 4). These ratios are in reasonable agreement with those measured by the PICCA (Ref. 12) and by the IMS (Ref. 8) instruments on board GIOTTO.

If the main mechanism for ion loss is the convective outflow (and the ionization potentials of the initial molecules are close to each other), the ratios of the densities of the different ions and of the parent neutral molecules have to be close to each other. The value of 5 % for the CO_2 content relative to the H_2O content (Ref. 11) seems to be in reasonable agreement with the relative content of ions of $M \approx 44$ (CO_2^+) compared to the water group ions as measured by the CRA. In this way we can estimate the relative content of the parent molecules H_2O and CO/CO_2 based on the CRA data of the PLASMAG-1 instrument as 70-80 % and 15-20 %, respectively. This agrees with the production rates of H_2O and CO, as determined by the UV measurements of the IUE spacecraft (Ref. 13).

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