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Quasi-periodic features and the radial distribution of cometary ions in the cometary plasma region of comet P/Halley

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Summary. Based on the measurements of the ion electrostatic analyzer CRA of the Plasmag-1 instrument on board Vega-2, which was oriented along the spacecraft–comet relative velocity direction, we present observations (1) of quasi-periodic features in the intensity of cometry ions occurring inside the cometopause, (2) of the mass composition of the cometary ions in the mass range of 1 to 100 atomic mass units (amu), and (3) of the radial dependence of the density of certain, well-defined groups of cometary ions.

Key words: cometary ions – mass composition – radial dependence – Vega-2

1. Introduction

Plasma measurements performed by the Plasmag-1 experiment on board Vega-2 during its approach of Halley's comet revealed the existence of a relatively sharp, yet unexpected boundary within the cometary coma at a cometocentric distance of about 1.6 10^5 km (Gringauz et al., 1986a, 1986b, 1985). This boundary, the so-called cometopause, separates the cometosheath region, which is controlled by the solar wind crossing the cometary bow shock and flowing around the cometary nucleus, from the cometary plasma region in the direct vicinity of the nucleus, which is dominated by heavy cometary ions of fastly increasing densities. Based on the plasma measurements deep inside this cometary plasma region, we will present two new classes of observation: the occurrence of a quasi-periodic structure in the intensity of heavy cometary ions, and the radial dependence of certain, well-defined mass-groups of cometary ions. These observations are compared with other ones and with theoretical suggestions.

2. Observations

The data presented in this communication were obtained by the ion electrostatic analyzer of the Plasmag-1 experiment on board Vega-2, which was oriented along the spacecraft–comet relative velocity direction. This Cometary Ram Analyzer (CRA) provided a rather wide angular field-of-view of 14° × 32°, and it measured the energy spectra of ions in the energy-over-charge range of 15 to 3500 eV/Q in 120 logarithmically spaced energy channels every one second and with an energy resolution of $\Delta E/E = 0.055$. The CRA observations were supported by the simultaneous and independent measurements of the Ram Faraday Cup (RFC). A detailed description of these sensors can be found in the papers by Gringauz et al. (1982, 1986c) and Apáthy et al. (1986).

It was mentioned earlier (see Gringauz et al., 1985 and 1986a) that due to the enhanced fluxes of certain cometary ions, especially of the ions of the water-group, the channeltrons of the CRA started to operate in a non-linear regime in the innermost part of the cometary ion region, when significant increases in the ion flux correspond to small changes in the measured counting rates only. However, this effect will now be taken into account based on calibration data and on the measurements of the RFC sensor, and the counting rates will be transformed into density values.

As described earlier (see Gringauz et al., 1985, Fig. 3, and Gringauz et al., 1986b, Fig. 1), the CRA measurements deep inside the cometary ion region revealed the following overall scenario: the flow of heavy cometary ions was almost stagnating, i.e., their velocities were much smaller than the spacecraft relative velocity; their intensities increased towards closest approach; their temperatures were decreasing, so that from 7:10 UT or about 5 10^4 km onwards rather distinct peaks could be identified in their energy spectra being associated with the different populations of cometary ions; and that the proton fluxes being registered up to a cometocentric distance of about 5 10^4 km were significantly smaller than in the cometosheath region.

2.1. *Quasi-periodic cometary ion enhancements*

While penetrating deeper into the cometary plasma region, the CRA sensor observed regions of a non-steady, patchy increase in the counting rates of heavy cometary ions. This is shown in Fig. 1 exhibiting two high-resolution spectrograms, as observed during 7:00–7:04 UT and during 7:06–7:10 UT or at distances of about 8 10^4 km and 5 10^4 km, respectively (time runs from right to left). The counting rates corresponding to the outermost isolines are given by $f_0 = 4\,10^3\,\mathrm{s}^{-1}$ and $f_0 = 10^4\,\mathrm{s}^{-1}$, respectively. The increase in the counting rates is characterized in steps of df between two adjacent isolines with $df = 4\,10^2\,\mathrm{s}^{-1}$ and $df = 10^3\,\mathrm{s}^{-}$,

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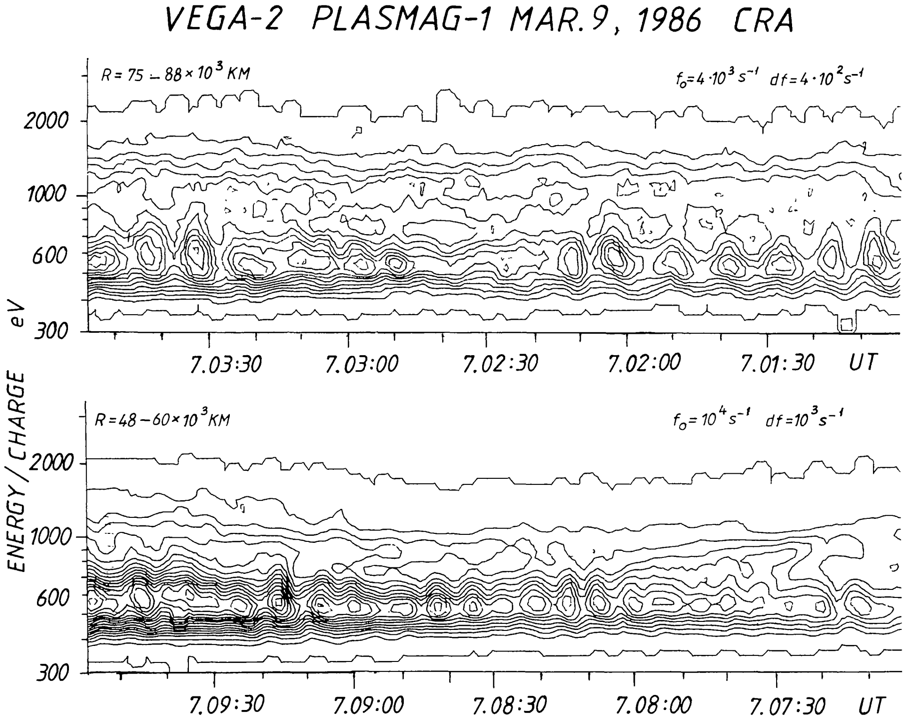

Fig. 1. Contour plots of the ion intensity vs. energy/charge and time, as measured by the Cometary Ram Analyzer (CRA) on board Vega-2 in the cometary plasma region at distances of $8\,10^4$ km and $5\,10^4$ km from the nucleus

respectively. From these figures it readily follows that a quasi-periodic modulation in the intensity of cometary ions exists. This modulation is most pronounced in the energy-over-charge range around 500–600, which (see Fig. 2) corresponds to the ions of the water group. The typical normalized amplitude in the modulation of these latter ions is about

$$A = (f_{\rm Max} - f_{\rm Min})/(f_{\rm Max} + f_{\rm Min}) \approx 0.05 - 0.1$$

Moreover, we find that the modulation period $\tau_{\rm M}$ decreases when approaching the nucleus from about $\tau_{\rm M} \approx 10$ s at $8\,10^4$ km to about $\tau_{\rm M} \approx 8$ s at $5\,10^4$ km.

It should be noted that this type of modulation differs from the sporadic, burst-type density enhancements, which have been observed by Vega-2 at about $4\,10^4$ km and $3\,10^4$ km (Gringauz et al., 1985, Fig. 4). These bursts were associated with enhancements in the plasma wave intentity around the lower hybrid frequency, and their occurrence was therefore explained by the "critical ionization velocity effect" of Alfvén (Galeev et al., 1986).

2.2. *Radial dependence of cometary ions*

Well inside the cometary plasma region both the thermal and the bulk velocities of ions become small compared to the spacecraft relative velocity of 76.78 km s^{-1}. The energy-over-charge spectra break up in several well-defined sub-distributions with their maximum intensity being located at distinct E/Q values. This situation is depicted in Fig. 2, showing a sequence of 4 s averaged ion energy spectra as obtained by the CRA sensor at a distance of 1.4–1.7 10^4 km from the nucleus. Here the counting rates have been corrected for the non-linear effect mentioned above. From the first left-hand distribution it readily follows that the bulk velocity of the protons is close to the spacecraft relative velocity. Thus, the energy-over-charge (E/Q) spectra can be transformed into mass-over-charge (M/Q) spectra. In this way Fig. 2 suggests the presence of H^+, C^+, $CO_2{}^+$, and Fe^+ ions in the cometary plasma region. The peak at $14 \leq M/Q \leq 20$ may originate from the H_2O parent molecules, such as O^+, OH^+, H_2O^+, and H_3O^+, while the peak at $24 \leq M/Q \leq 34$ may be due to parent molecules of CO/CO_2 or to molecules containing N/S, such as CO^+, $N_2{}^+$, H_2CO^+, HCO^+, CN^+, HCN^+, or $O_2{}^+$, or to atomic ions like Mg^+, Al^+, Si^+, P^+, or S^+. Finally, the minor peaks at $M/Q = 2$, 8, 70, and 85 might stem from $H_2{}^+$ and O^{++} and from some heavier, not yet identified organic ions. We have marked these different groups of cometary ions at the top of Fig. 2.

For these groups we have determined their densities at different cometocentric radial distances by summing the respective

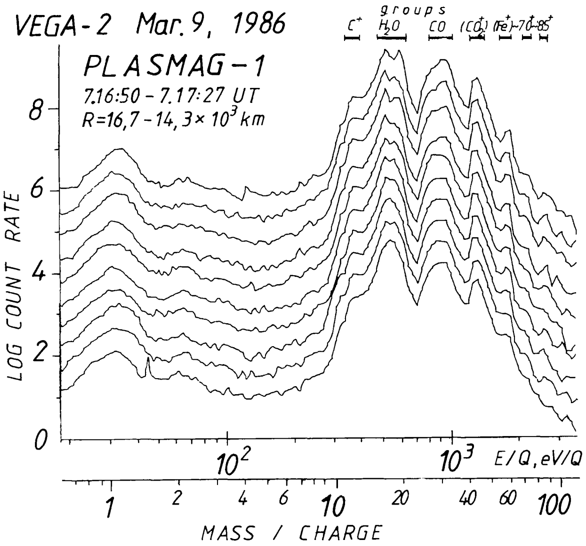

Fig. 2. Time sequence of 4 s averaged ion energy/charge (mass/charge) spectra, as observed by the CRA sensor on board Vega-2 at a cometocentric distance of (1.4–1.7) 10^4 km

count rates. The result is shown in Fig. 3 together with the total sum $\sum$ of all ions and with the anticipated R^{-2} slope. Straight lines correspond to the regions where the densities could be determined more accurately. From Fig. 3 it readily follows that, in principle, really none of the curves, except may-be the curve of mass-group 70^+, can be approximated by a pure R^{-2} dependence. For the total sum we find a dependence of $R^{-2.4}$ for $3\,10^4 \leq R \leq 1.5\,10^4$ km.

3. Discussion

At present we do not know whether the observed quasi-periodic modulation in the intensity of heavier ions in the cometary plasma region is due to density variations or to fluctuations in velocity space. However, this modulation could be explained either by a strongly non-stationary ionization process of the cometary neutral gas, mainly consisting of water at these distances, 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 neutral gas at a characteristic time scale shorter than the gyro-period of the ions or comparable to it. If this is the case, the ions get condensed forming bunches in the phase of the cyclotron rotation. In this case the observed decrease of the fluctuation period from $\tau_M = 10$ s at $8\,10^4$ km to $\tau_M \approx 8$ s at $5\,10^4$ km could be associated with the increase of the magnetic field from $B \approx 40nT$ to $B \approx 50nT$ as observed on board Vega-2 (Schwingenschuh et al., 1986). 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 streaming velocity parallel to the magnetic field. Taking the magnetic field of $B \approx 50nT$ and the spatial dimensions of the fluctuations in the plasma flow as $\sim 8\,\mathrm{s}\,80\,\mathrm{km\,s^{-1}} = 640$ km into account, the parallel velocity can be estimated as $v_{\parallel} \approx 30\,\mathrm{km\,s^{-1}}$, which seems to be a reasonable value.

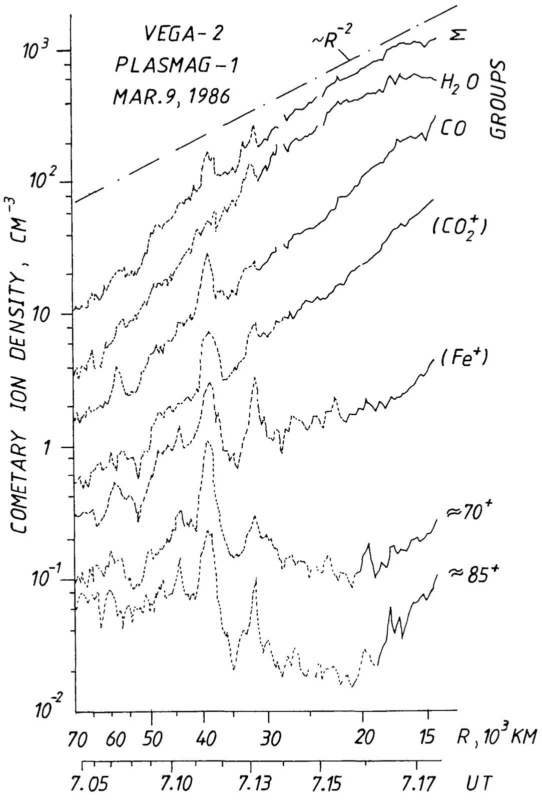

Fig. 3. Cometocentric radial dependence of the densities of certain groups of cometary ions, as defined in Fig. 2, and of the total sum $\sum$ of all ions. For comparison the R^{-2} slope is inserted

A somewhat unexpected result is the observed well defined peak at $M/Q = 56$ in the CRA ion spectra. This peak was also identified in the IMS (Balsiger et al., 1986) and NMS (Krankowsky et al., 1986) measurements on board Giotto, however, it has not been observed by the Giotto-PICCA instrument (Korth et al., 1986), although otherwise this sensor is quite similar to the CRA sensor on board Vega-2. It seems quite natural to identify this peak with the occurrence of Fe^+ ions in the innermost part of the cometary plasma region, although it should be noticed that, due to the energy resolution of the CRA sensor of 5.5%, there is an uncertainty of about 3 amu in the mass resolution. From the observed mass composition of cometary dust particles iron has been identified in most of the mass spectra analysed (Kissel et al., 1986). Thus, sputtering at dust grains with large metallic cores and no layer of ice could account for the release of metallic ions in the cometary coma (Ip and Axford, 1986), although also other processes discussed by Geiss et al. (1986) could account for the occurrence of metal ions.

As indicated in Fig. 3, the density of cometary ions decreases somewhat faster than R^{-2}. This result is consistent with the observations of the IMS (Balsiger et al., 1986) and the PICCA instrument (Korth et al., 1987) on board Giotto. The neutral gas density, however, decreases as R^{-2}, as observed both by Vega (Gringauz et al., 1986a; Gringauz et al., 1985; Remizov et al., 1986; and Grard et al., 1986) and by Giotto (Krankowsky et al., 1986). This somewhat faster decrease in the ion density could be associated with the fact, that the loss rate of ions increases with increasing distances from the nucleus due to an increasing convective outflow of the cometary ions. Vega-2 observed a neutral gas density of $N_n \approx 1.5\,10^5\,\mathrm{cm^{-3}}$ at $2\,10^4$ km (Remizov et al., 1986). For a characteristic time of ionization of $\tau_i \approx 10^6$ s, the local production rate for ions is $Q_i \approx N_n/\tau_i \approx 0.15\,\mathrm{cm^{-3}\,s^{-1}}$. In order to obtain an ion density of $N_i \approx 10^3\,\mathrm{cm^{-3}}$ at these distances, a value for the velocity of the convective outflow of $V_i \approx Q_i R/N_i \approx 3\,\mathrm{km\,s^{-1}}$ would be sufficient. This value for V_i is in reasonable agreement with the velocity determined for the water group ions from the IMS measurement on board Giotto (Balsiger et al., 1986).

On the other hand, if the loss of cometary ions is mainly caused by the convective outflow, then the ratios in the densities of the ions and of their parent molecules must be close to each other. Krankowsky et al. (1986) estimated a value of 5% for the CO_2 content relative to the content of H_2O. From our CRA measurements we find that 70–80% of the total ion content belongs to the water group ions and 2–5% to the ions with $M/Q \approx 44$ $(CO_2{}^+)$. In turn, as we find 15–20% for the content of the CO/CO_2 group ions, we can estimate the content of the parent molecules H_2O and CO/CO_2 based on our CRA data to be 70–80% and 15–20%, respectively. This agrees with the production rates of H_2O and CO, as determined from the UV measurements on board the IUE spacecraft (Festou et al., 1986).

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