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CRITICAL IONIZATION VELOCITY EFFECTS IN THE INNER COMA OF COMET HALLEY: MEASUREMENTS BY VEGA-2

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Abstract. Plasma density and plasma wave measurements aboard the "Vega-2" spacecraft discovered two plasma density enhancements in the inner coma of comet Halley that are accompanied by bursts of plasma waves in the lower-hybrid frequency range. These events are explained by the critical ionization velocity (CIV) effects of Alfvén. The persistent bursty plasma wave activity and the intermittent plasma density growth toward the cometary nucleus indicate that the CIV effect contributes to the ionization of the cometary gas.

Introduction

Fast spatial and time variations of the plasma density observed by Wurm (1963) in the inner comae of some comets on scales of $\sim 10^3$ to 10^4 km and $\sim 10^3$ to 10^4 s, respectively, posed a long standing problem of anomalous ionization of the cometary gas. Among the different mechanisms proposed (see recent reviews by Ip (1985) and Mendis et al. (1985)) the critical ionization velocity (CIV) effect of Alfvén (1954) is the most natural one for the case of the magnetized solar wind flowing through the cometary atmosphere. Actually, this has been suggested a long time ago by Danielson and Kasai (1968). The theory of this effect was developed much later by Formisano et al. (1982) and was applied to the problem of anomalous ionization of cometary atmospheres. The collisionless transfer of part of the kinetic energy of the flow across the magnetic field to the plasma electrons is the most crucial process of the whole phenomenon. The efficiency, η, of this energy transfer controls the critical velocity value

$$V_c = \eta^{-1/2}\sqrt{\frac{2e\phi_I}{m_a}} \qquad (1)$$

where ϕ_I is the ionization potential of an atom with mass m_a. Formisano et al. (1982) have shown that the efficiency of energy transfer in a rarefied gas turns out to be very low (η = 0.025) and reaches the relatively high value, $\eta = 2/3$, only in a sufficiently dense gas when the condition

$$\nu_{ion}\frac{n_{Te}}{n_i} = \frac{\langle\sigma_{ion} v_e\rangle}{4\pi v_g r^2}\frac{n_{Te}}{n_i}\omega_{ci} \qquad (2)$$

is satisfied. Here ν_{ion} n_{Te} / n_i is the characteristic rate of plasma density growth due to ionization by electron impact; σ_{ion} is the cross-section of ionization, v_e and n_{Te} are characteristic velocity and density of suprathermal electrons; n_i is the ion density; Q the production rate of cometary gas, v_g the velocity of expansion of the cometary gas; $\omega_{ci} = e_i B_o/m_i c$ is the cyclotron frequency of ions with charge e_i and mass m_i in the magnetic field B_o ; c is the speed of light.

On the other hand, the Townsend condition for avalanche ionization of a gas (Formisano et al., 1982)

$$\nu_{ion} > \frac{V_e}{r} K^{-1}, \text{ i.e. } r < \frac{\sigma_{ion} QK}{4\pi V_g} \qquad (3)$$

restricts the region of anomalous ionization of cometary gas to the inner part of the coma ($\sim 10^5$ km for the gas production rate of comet Halley, where the plasma velocity drops to the very low value of a few tens of km/s due to strong solar wind loading (see, for instance, Schmidt and Wegmann, 1982; Galeev et al., 1985). In Equation 3, the coefficient K varies from 1 to $\sqrt{m_a/m_e}$ depending on the details of the process of replacement of ionizing suprathermal electrons by cold electrons from external regions. In case of water molecules as the main gas species, the efficiency of energy transfer from newly born ions to electrons has to reach the maximum possible value of $\eta = 2/3$ in order to fall below the flow velocity in the inner coma. However, condition (2) can be satisfied only in the innermost part of the coma, where ion-neutral collisions may entirely stop the plasma flow. Thus it was unclear what role the CIV effects play for comet Halley (Galeev and Lipatov, 1984). Nevertheless, plasma density enhancements accompanied by bursts of high intensity plasma waves in the lower hybrid frequency range were observed during the "Vega-2" passage through the coma of comet Halley (Gringauz et al., 1986, 1986; Klimov et al., 1986). In the present paper we discuss the plasma and wave measurements aboard "Vega-2" relevant to this effect and then show that condition (2) should be corrected, following a suggestion by Haerendel (1986). Finally, we show that these abrupt increases of plsma density could be explained by the CIV effect.

Plasma Density and Wave Measurements

Measurements of the energy spectra of cometary ions aboard "Vega-2" were performed by the cometary ram analyser (CRA) that is one of six

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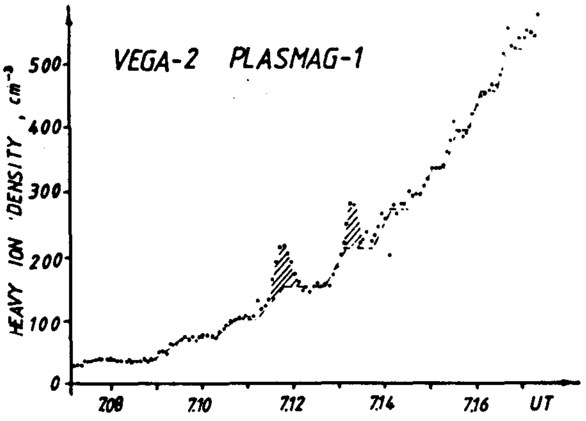

Fig. 1. Cometary ion density along the "Vega-2" trajectory.

different sensors of a plasma instrument package (PLASMAG-1). It is a hemispherical electrostatic analyser with an acceptance angle of 10^{o} x 32^{o} and an energy/charge range from 15 to 3,500 eV/q (where the charge state q is assumed to be equal to q = 1 for most of the ions) (see details in Gringauz et al., 1986). Figure 1 shows the cometary ion density along the "Vega-2" trajectory obtained by the integration of ion flux over the energy range from 300 to 3,000 eV, assuming that the directed and thermal velocities of these ions are much smaller than the velocity of the "Vega-2" spacecraft ($v_{s/c}$ = 77 km/s relative to the comet). We clearly see two plasma density enhancements: at 7:11:20 - 7:12:10 UT and at 7:12:50 - 7:13:30 UT at distances of 39,000 km and 32,000 km from the nucleus, respectively. These two events are very similar. We discuss only the first one in detail.

The energy spectra of cometary ions obtained by the CRA in this event are shown in Figure 2. We see that prior to the beginning of a sharp density increase at 7:11:20 UT the spectra are smooth and featureless, but a weak CO^+ peak (indicated by arrow) becomes clearly visible on the background of a wide energy distribution of the water group ions, when plasma the density is increasing. This can be explained by the plasma velocity decrease from a value u > 15 km/s to values below 15 km/s, when the gyromotion of the newly ionized atoms smoothens the peaks of the energy distribution. This estimate of plasma velocity is consistent with the value of the average velocity of protons of 20 km/s in the ram direction calculated from the proton energy spectra obtained by the RPA, as well as with model calculations by Galeev et al. (1985).

As was pointed out earlier (Klimov et al., 1986), the sharp plasma density increase at 7:11:20 is accompanied by plasma wave bursts in a frequency range around 15 Hz. During a 2000 s-period of measurements (6:59:30 - 7:32:50 UT) near the closest approach (7:20 UT) a burst of plasma wave emission at 7:11:20 - 7:11:40 UT is followed by a gap in the wave activity over the whole frequency range analysed. The Fourier spectra of the electric field oscillations in this burst and immediately after are shown in Figure 3. The spectrum in the burst has a maximum (E_f ≈ 7 mV/m $Hz^{1/2}$ at f ≈ 14 Hz, and in the gap the maximum shifts to f ≈ 4 Hz). In spite of the averaging over 20-s time intervals, the spectra are quite noisy. It should also be pointed out that the intensity of plasma waves decreases below 2 Hz.

The second plasma enhancement at 7:12:50 UT is also accompanied by a plasma wave burst followed by a less pronounced gap. The overall wave activity was characterized by a continuous increase of the intensity of plasma waves, while the spacecraft approached the nucleus of the comet. At the same time the frequency of the most intense waves grows up to a distance of ~ 15,000 km and then suddenly drops to a fraction of 1 Hertz. Let us note that wave emission is persisting in the whole inner coma and even where the plasma velocity value is certainly below the critical one. The wave activity has a bursty character which is reflected by the very unsteady growth of plasma density. The rapid density increase is interrupted by periods of much slower growth. On the average the density grows as $n_i \propto r^{-2}$.

Discussion of Measurements

The plasma density enhancements accompanied by the plasma wave bursts are the signatures of the operation of the CIV phenomenon in the coma of comet Halley. The plasma waves were identified earlier (Klimov et al., 1986) as the oblique Langmuir/high frequency magnetosonic waves with the dispersion relation

$$1 + \frac{\omega^2_{pe}}{\omega^2_{ce}} \left(1 + \frac{\omega^2_{pe}}{k^2c^2(1+\beta_e)} - \frac{\omega^2_{pp}}{\omega^2} - \frac{\omega^2_{pe}}{\omega^2}\frac{k^2_{\parallel}}{k^2}\right.$$

$$\left.\left(1 + \frac{\omega^2_{pe}}{k^2c^2}\right)^{-1} + \frac{\omega^2_{pi}}{k^2} \int \frac{\vec{k}\,\partial f_i/\partial\vec{v}}{\omega - \vec{k}\cdot\vec{v} + i\sigma}\, d^3\vec{v} = 0 \qquad (4)$$

where $\omega_{pj} = \sqrt{4\pi e^2 n_j/m_j}$ is the Langmuir frequency of the j-species of plasma k and $k_{\parallel}$

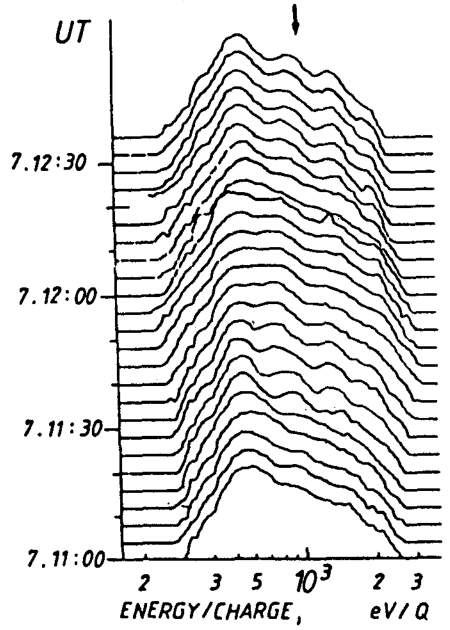

Fig. 2. The energy spectra of cometary ions (5-sec averages) measured by the "Vega-1" cometary ram analyser during the first density enhancement.

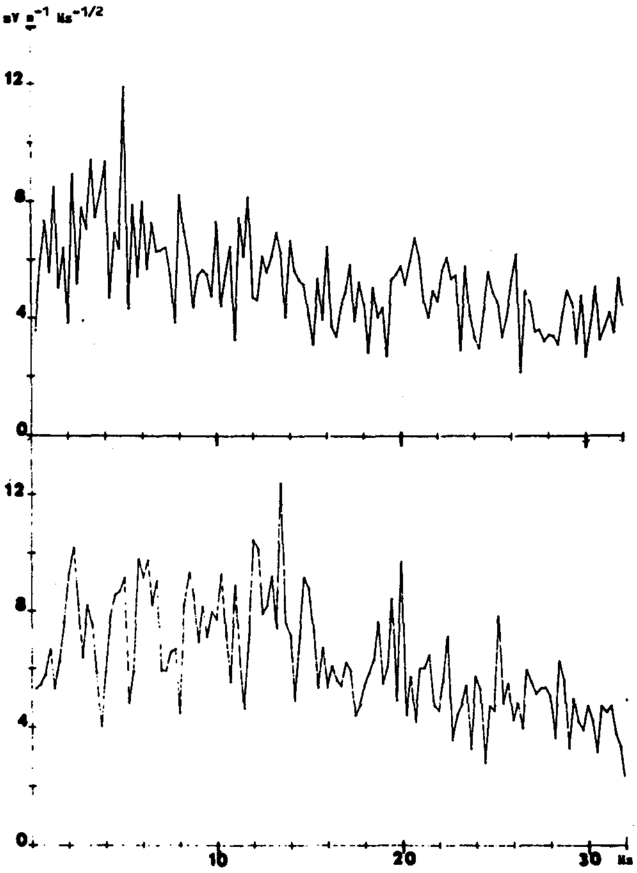

Fig. 3. Electric field spectrum averaged over two 20-s intervals at the beginning of the plasma density increase (a) and immediately after it (b).

are the wave vector and its component along the magnetic field direction, ω is the frequency of the plasma wave, and $f_i(v)$ is the velocity distribution function of cometary ions. In contrast to Formisano et al. (1982), we have taken into account electromagnetic corrections to the dispersion relation that are important in the finite β-plasma ($\beta_e = 8\pi n_e T_e/B^2$, T_e is the electron temperature).

Now we can correct condition (2) for a high efficiency of energy transfer to the electrons, as obtained by Formisano et al. (1982). They assumed quasi-stationary ionization and a characteristic time of quasi-linear relaxation of the beam of newly ionized atoms equal to the time constant of plasma density increase by ionization. Let us now consider a situation where this relaxation proceeds faster than the gyration of ions owing to a high growth rate of the instability, i.e. (compare with Haerendel, 1986)

$$\gamma \cong \frac{\pi\omega_{LH}^2}{2\omega}\frac{n_{new}}{n_i} > \ell n\Lambda\ \omega_{ci} \qquad (5)$$

where $\ell n\Lambda$ is the Coulomb logarithm, $\omega_{LH} \cong \sqrt{\omega_{ci}\omega_{ce}}$ is the lower-hybrid resonance frequency, $n_{new} \cong \nu_{ion}\ n_{Te}/\omega_{ci}$ is the density of atoms ionized in less than one gyroperiod. In the above ansatz for the growth rate, γ , we assume a warm ion beam. The wave frequency can be estimated from (Klimov et al., 1986)

$$\omega \cong \omega_{ce}\ k_{\parallel}/k\ (1+\omega^2_{pe}/k^2c^2) \cong \omega_{pe}\ u/c \qquad (6)$$

Here we have taken into account that the waves are excited by a Cherenkov resonance ($\omega \cong ku$) with the newly ionized atoms moving relative to the background plasma with velocity $-u$. Besides that we used the condition that the electron Landau damping should not affect waves with sufficiently high phase velocities:

$$\frac{\omega}{k_{\parallel}v_{Te}} \cong \left(\frac{2}{\beta_e}\right)^{1/2} \frac{\omega_{pe}}{kc(1+\omega^2_{pe}/k^2c^2)} > 1 \qquad (7)$$

That is why we put $k \cong \omega_{pe}/c$.

Condition (5) can be now rewritten in a form similar to (2):

$$\frac{\nu_{ion}\ n_{Te}}{n_i} > \frac{\ell n\Lambda}{\pi}\ \frac{u}{V_{Ae}}\ \omega_{ci} \quad , \qquad (8)$$

where $V_{Ae} \cong B/\sqrt{4\pi n_e m_e}$ is the electron Alfvén velocity. For plasma and magnetic field parameters measured aboard the "Vega-2" spacecraft at the moment of the first density enhancement (i.e., $n_e \cong 250\ cm^{-3}$, $B \cong 50$ nT (Riedler et al., 1986) and a plasma velocity estimated as ∿ 20 km/s), we see that the rate of density increase of ∿ $10^{-2}\ s^{-1}$ derived from the observations shown in Figure 1 is just sufficient to satisfy this criterium. This means that the efficiency of energy transfer $\eta \cong 2/3$ is reached here and the estimated plasma velocity exceeds the critical velocity v_c = 15 km/s for an H_2O gas. Therefore the CIV effect leads to a rapid density increase.

One of the crucial signatures of the CIV effect, the suprathermal electrons, have not been measured aboard "Vega-2" due to interference problems at close distances (r < 70,000 km) to the nucleus of the comet. We only mention here that energy balance equations for waves and particles provide rough estimates of their energy and density (see details in Galeev and Sagdeev, 1983):

$$m_e V^2_{oe}/2 \cong m_i u^2/2\ ;\ n_{Te} \cong n_i \qquad (9)$$

Suprathermal electrons should have very anisotropic distributions elongated in the magnetic field direction. this is a source for the excitation of oblique Langmuir waves with frequencies $f \cong (1/5 - 1/3)\ f_{ce}$ (Galeev, Khabibrakhmanov, 1985). Therefore we suggest that the electric field oscillations with frequencies from 200 to 400 Hz detected by the high frequency plasma wave analyser (APV-V) aboard "Vega-2" (Grard et al., 1986) could probably be explained as the manifestation of the above-mentioned process.

Finally, we should note that the position of the maximum in the wave spectra and the width of the spectra (see Fig. 3) are well described by Equations (6) and (7). The intensity of the excited waves agrees well with the theoretical estimate based on the assumption that the rate of quasi-linear relaxation of newly ionized atoms is of the order of the ionization rate, i.e. (Formisano et al., 1982)

$$\int \frac{e^2 E^2_f \, df}{2\pi m^2_i f u^2} \sim \nu_{ion} \frac{n_{Te}}{n_i} + \frac{Q}{4\pi v_g r^2 n_i \tau} \qquad (10)$$

where $\tau \cong 10^6$ s is the time of cometary gas photoionization.

In conclusion we should say that two density enhancements discovered by the "Vega-2" in the inner coma of comet Halley are remarkable manifestation of CIV effect in operation here. This kind of events can explain so-called receding envelopes seen in several comets (Ip, 1985, and the references therein). CIV effects manifest themselves also in the anomalously fast plasma density growth towards the nucleus of comet Halley interrupted by periods of much slower density growth that could be explained by the photoionization by sunlight. On the average the plasma density grows towards the nucleus as $n_i \propto r^{-2}$ which requires faster braking of plasma ($u \propto r$) than the models of Galeev et al. (1985) and Schmidt and Wegman (1982) predict ($u \propto \sqrt{r}$).

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