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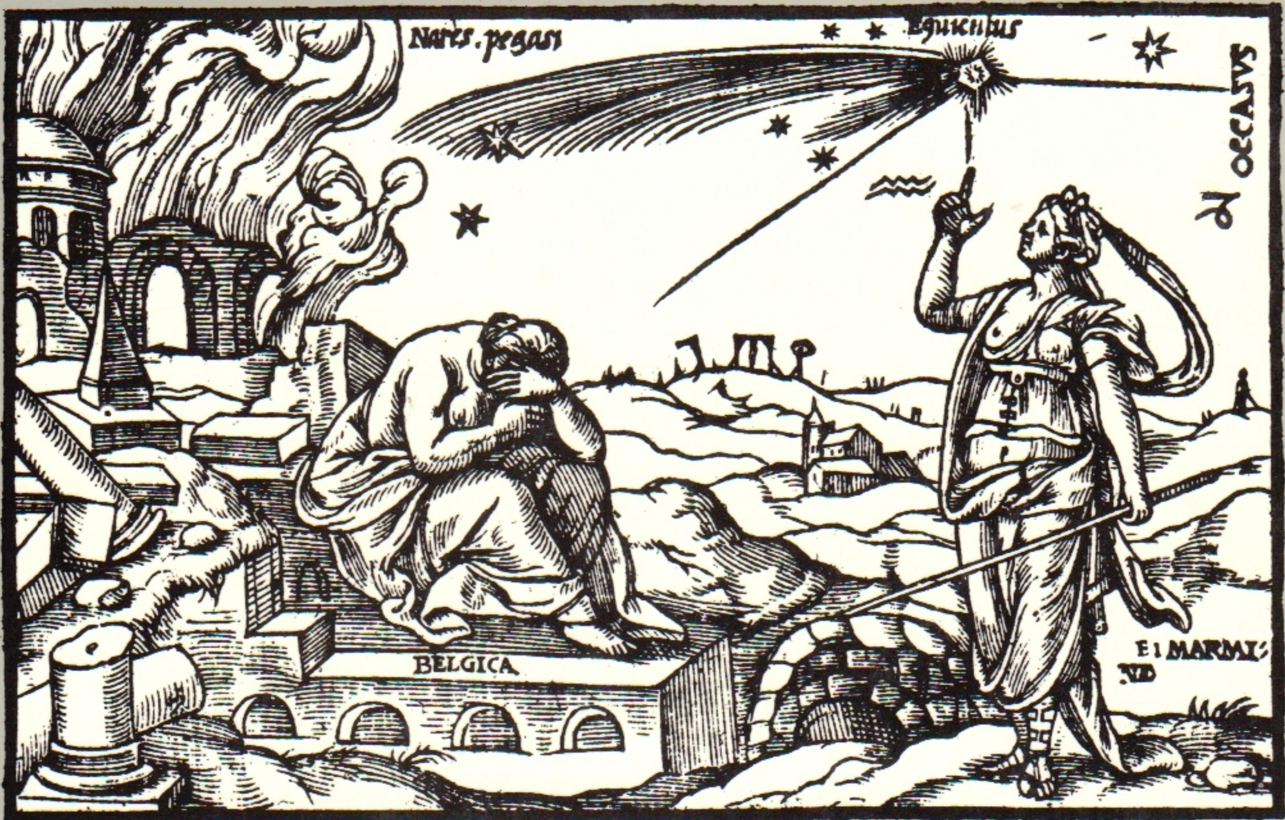

Comet over Belgium in 1577 A.D. Antverpiae, ex officina – Christophori Plantini, 1578

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PHYSICAL PROCESSES IN THE VICINITY OF THE COMETOPAUSE INTERPRETED ON THE BASIS OF PLASMA, MAGNETIC FIELD AND PLASMA WAVE DATA MEASURED ON BOARD THE VEGA-2 SPACECRAFT

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ABSTRACT

This paper presents the first step towards a comprehensive interpretation of the plasma, electric and magnetic field data measurements performed by four different instruments near the cometopause of Halley's comet. No flow parameter displays any drastic variation at this boundary which separates two environments with different chemical composition. Fire-hose instability is possibly developing near the cometopause where the number of cometary ions significantly increases. The waves at the lower hybrid frequency and in the whistler range have similar amplitudes.

Keywords: Cometopause, Fire-Hose Instability, Plasma Wave Oscillations, Solar Wind Protons, Cometary Ions.

1. INTRODUCTION

The plasma data collected by the instrument PLASMAG-1 on board both VEGA spacecraft led to the discovery of a thin boundary downstream of the bow shock of Halley's comet at a distance of about 1.6×10^5 km from the nucleus. This boundary separates the region controlled by the solar wind proton flow from the inner cometary plasma region dominated by slowly moving heavy cometary ions (Ref. 1-4). The existence of this boundary was confirmed by the plasma wave experiment APV-N on board the VEGA s/c (Ref. 5) and by the instruments PICCA and JPA on board GIOTTO (Ref. 6-7).

In spite of the fact that the characteristics of plasma and field parameters near the cometopause have been independently reported elsewhere, no discussion of this phenomenon has been based on simultaneous analysis of plasma, magnetic field and plasma wave measurements. The physical processes responsible for the existence of the cometopause have not been investigated either. In this work we shall attempt to give a complex approach to the phenomena occuring at the cometopause on the basis of plasma, magnetic field and plasma wave data simultaneously recorded on board the VEGA-2 spacecraft.

2. EXPERIMENTAL DATA

Ion and electron energy spectra were measured by different sensors of the PLASMAG-1 instrument package on board the VEGA-2 s/c (Ref. 1-2). The Cometary Ram Analyzer (CRA) which was oriented along the velocity vector of the spacecraft relative to the comet, detected ions in the energy/charge range 15-3500 eV/Q. The Solar Direction Analyzer measured ions in the range 50-25,000 eV/Q. An electrostatic Electron Analyzer (EA) was oriented perpendicular to the ecliptic plane and detected electrons in the energy range 3-10,000 eV.

The magnetic field was measured by the triaxial fluxgate magnetometer MISCHA in the range $\pm 100\gamma$ for all components with a resolution of 0.05γ (Ref. 8). The intensity of plasma waves was observed by the instruments APV-N (Ref. 9) and APV-V (Ref. 10). The first instrument recorded the electric field oscillations and the fluctuations of ion fluxes in the direction of the spacecraft velocity relative to the comet in the frequency range 0.01-1000 Hz. APV-V measured the same electric field component in the frequency range 0-300 kHz.

The top panel of Fig. 1 shows the ion spectrogram measured by the CRA of the PLASMAG-1 instrument in the vicinity of the cometopause. The outermost isolines correspond to a count rate of 10^3 s^{-1} and the ratio between count rates represented by adjacent isolines is equal to 2. The two vertical dashed lines indicate the time interval 6.43-6.45 UT when VEGA-2 crossed the cometopause (Ref. 3).

As shown by the spectrogram of Fig. 1, the typical energy/charge ratio of ions detected by the CRA significantly increases at the cometopause from ~170 eV to ~900 eV. This feature is due to changes in the distribution function and ion composition of the plasma; protons (m_p=1 amu) are most abundant in the cometosheath, while water group ions (m_i=16-18 amu) dominate inside the cometopause. Proton fluxes detected by the CRA significantly decrease after crossing the cometopause, though their energy spectra become wider (Refs. 1,3) and their typical energy increases to ~250 eV.

Before crossing the cometopause, the ion energy spectra observed by the Solar Direction Analyzer show two maxima (see Fig. 1 in Ref. 3 and Figs. 2 and 3 in Ref. 1). The first maximum which is es-

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sentially due to protons is typically ~300 eV; the heavy water group ions produce a second maximum at ~900 eV. After crossing the cometopause, protons practically disappear from the acceptance angle of the SDA, while the energy of heavy ions is hardly changed (Refs. 1,3).

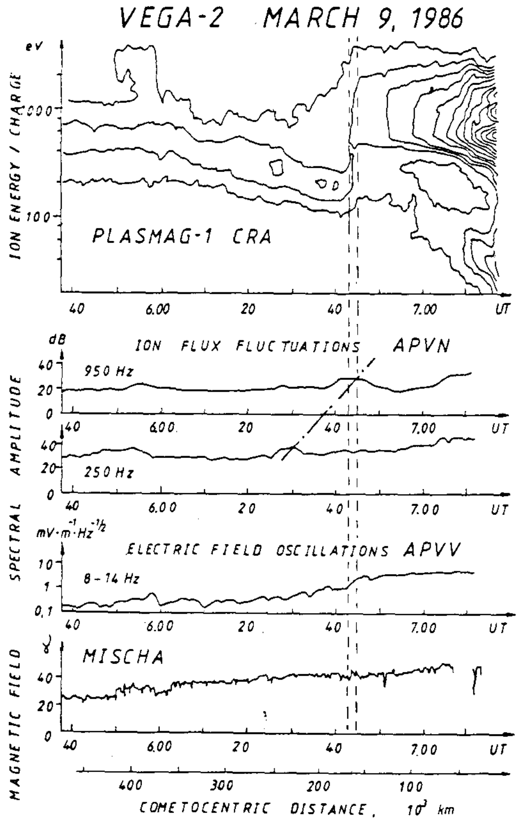

Figure 1. Plasma and field data collected by four different instruments during the last 100 min before closest approach. From top to bottom: spectrogram of ion flux in the ram direction, plasma wave activity in three different frequency ranges, total magnetic field. The cometopause is indicated by dashed lines.

Electron spectra measured by the Electron Analyzer and hence the density and temperature of the electrons do not show any characteristic variation when the cometopause is crossed (Refs. 1,3).

Magnetic field measurements performed by the magnetometer MISCHA on board VEGA-2 are also consistent with the conclusion that the plasma density does not change significantly at the cometopause. As seen from the bottom panel of Fig. 1, the magnitude of the total magnetic field is practically constant in this region. Only minor changes are observed in the B_y and B_z components (Refs. 4,8).

The middle part of Fig. 1 shows the plasma wave activity measured by the instruments APV-N and APV-V on board VEGA-2. In general, the filter channels shown in this figure (and also other channels not shown here) are characterized by an increase of the average amplitude of plasma and electric field oscillations from a cometocentric distance of 1.5-2x10^5 km when the VEGA-2 spacecraft approaches the nucleus. In the vicinity of the cometopause (around 6.30-6.50 UT), plasma wave oscillations are observed in the whistler frequency range (0.2-1 kHz) and the amplitude of the electric field suddenly increases in the lower hybrid frequency range (8-14 Hz) during a 2 min interval when the s/c crosses the cometopause.

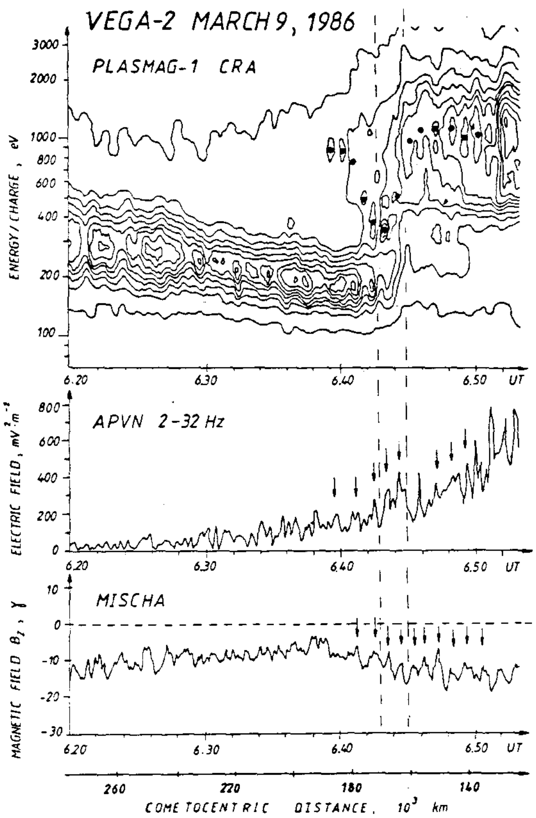

Figure 2. Fluctuations of ion flux, electric field and B_z component (pointing towards the north pole of the ecliptic) of the magnetic field around the cometopause (indicated by dashed lines). Maxima are shown by dots and arrows.

The wave activity in the lower frequency range can be seen in Fig. 2 where more detailed measurements of plasma, magnetic field and waves are presented. The top panel shows the ion spectrogram measured by the CRA. Here the difference between count rates represented by adjacent isolines is 440 s^{-1} and the outermost isolines correspond to a count rate of 10^3 s^{-1}. Dots on the spectrogram mark the maxima of ion flux in an interval of 10 min around the cometopause. A comparison between the spectrograms simultaneously measured by the CRA and SDA (see Fig. 1 in Ref. 3 where the spectrograms are color coded) shows that the fluctuations of ion fluxes measured by the two sensors are in anticorrelation. This is an indication of the existence of large-scale MHD variations in the direction and/or in the velocity of the plasma flow with a characteristic period $T \approx 1$ min.

These large-scale MHD waves at the cometopause are reflected in the electric field by oscillations at the lower hybrid frequency (2-32 Hz) and in the B_z component of the magnetic field by fluctuations with the same characteristic period ($T \approx 1$ min). The correspondence between the maxima of electric field, magnetic field and ion fluxes is indicated by arrows in Fig. 2.

3. DISCUSSION

The sudden decrease of proton fluxes within a ~2 min interval (corresponding to $\Delta \approx 10^4$ km along the trajectory of the VEGA-2 s/c) in the ram and solar direction cannot be explained without taking into account collisionless deceleration processes and/or isotropization of the proton distribution function; this phenomenon may be caused by an instability due to the relative motion of solar wind protons and cometary ions. We shall therefore estimate the velocity of the protons and ions observed by PLASMAG-1.

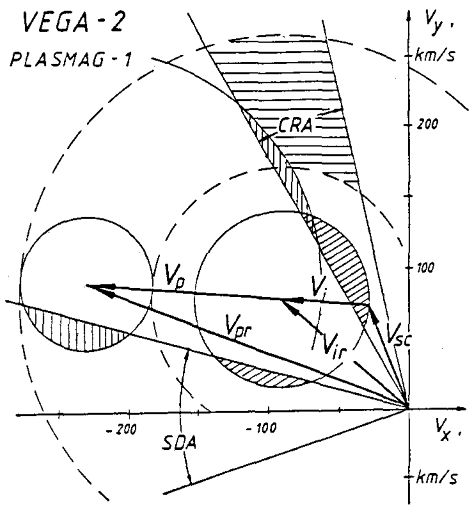

Figure 3. Possible proton and ion velocity vector diagrams and the acceptance angles of the SDA and CRA ion analyzers in the s/c reference frame. Particles from the shaded areas can be observed by the analyzers (sloping lines: cometary ions, vertical lines: protons outside the cometopause, horizontal lines: protons inside the cometopause).

Outside the cometopause, the typical energy of solar wind protons is ~170 eV in the ram direction and ~300 eV in the solar direction. Their estimated bulk velocity relative to the spacecraft is $v_{pr} \approx 250$ km/s. The velocity of the protons relative to the comet $v_p \approx 200$ km/s is given by a possible vector diagram shown by Fig. 3 where the s/c velocity relative to the comet $v_{sc} \approx 80$ km/s is taken into account. This figure also shows the acceptance angles of the CRA and SDA sensors and the regions of velocity space in which protons can be observed by these analyzers (areas shaded with vertical lines). In a similar way, the velocity of heavy cometary ions can be estimated; $v_{ir} \approx 120$ km/s relative to the spacecraft and $v_i \approx 60$ km/s relative to the comet.

The measured magnetic field direction is not far from parallel to the plasma flow and a fire-hose instability might develop. Outside the cometopause, when the proton number density is $n_p \approx 10\text{-}20$ cm^{-3} and the magnitude of the magnetic field is $B \approx 40\gamma$, the condition for a fire-hose instability caused by the solar wind flow through the cometary plasma is not fulfilled. On the other side of this boundary, when the number density of heavy ions is $n_i \approx 10$ cm^{-3} and the velocity is $v_i \approx 60$ km/s relative to the comet, the increasing ionization of cometary neutrals leads to an instability caused by the flow of solar wind protons and picked-up cometary ions relative to the newly ionized cometary gas. As a consequence, protons get decelerated and pitch angle scattering takes place; the intensity of proton fluxes detected by both CRA and SDA is therefore decreasing.

A clear indication of the instability which develops near the cometopause is the large-scale variation of the plasma flow correlated with the oscillations of the perpendicular magnetic field component (relative to the main field direction) as seen in Fig. 2. The characteristic scale of these oscillations is $v_{sc}T \approx 5000$ km along the spacecraft trajectory which is comparable with the thickness of the cometopause Δ, but it is much larger than the Larmor radius of cometary ions $\rho_{ci} = v_i/\omega_{ci} \approx$ ≈ 300 km ($\omega_{ci} \approx 0.2$ s^{-1} is the cyclotron frequency of water group ions). The plasma velocity vector was not measured on board the VEGA s/c, and it is not possible to determine the mode of oscillation excited by the instability. Since the magnitude of the magnetic field is almost constant there, the oscillations seem to be perpendicular. The amplitude of the velocity perturbation $\delta v_\perp$ can be estimated from the oscillation of the perpendicular magnetic field component $\delta B_\perp$

$$\delta v_\perp \approx (\delta B_\perp/B)v_A \approx 10 \text{ km/s} \qquad (1)$$

where $v_A \approx 60$ km/sec is the Alfven velocity. This effect can induce strong modulations in the ion flows observed by both analyzers. The large scale of these oscillations compared to the ion Larmor radius indicates that these waves are certainly not caused by cyclotron resonance. In other words we possibly observe the development of a fire-hose instability with a significantly larger growth rate than in the case of a resonance instability. The source of energy of such an instability is the kinetic energy of the newly born cometary ions relative to the plasma flow; the density of this flow is much larger than the density of the original solar wind proton flow.

The significant decrease of the proton flux at the cometopause and in the cometary plasma region shows that the dominant mechanism for producing cometary ions is the charge exchange between protons and cometary gas. The characteristic time for charge exchange is

$$\tau_{ct} \approx (\sigma_{ct} v_p n_n)^{-1} \approx 6\times10^3 \text{ s} \qquad (2)$$

where $\sigma_{ct} \approx 2\times10^{-15}$ cm^2 is the cross-section for charge exchange, $n_n \approx 4\times10^3$ cm^{-3} is the number density of neutral gas in the vicinity of the cometopause at a cometocentric distance $R \approx 1.6\times10^5$ km (Ref. 11) and $v_p \approx 200$ km/s is the velocity of the proton flow outside the cometopause which is of the same order of magnitude as the proton gyrovelocity inside the cometopause after pitch angle scattering. Since the above estimated τ_{ct} is comparable to the characteristic time of the plasma flow around the comet (of the order of $2R/v_i \approx 5\times10^3$ s in the vicinity of the cometopause for a flow velocity $v_i \approx 60$ km/s), charge exchange is effective in this region.

As a consequence of the existence of a cometary ion beam in the plasma flow, the intensity of plasma waves is increasing in the lower hybrid frequency range at the cometopause (see Figs. 1 and 2). The growth of this wave is limited by the quasi-linear relaxation of the ion beam to a steady state when the wave intensity reaches (Ref. 12)

$$E_f^2 \approx (n_n m_i^2 v_p^2)/(\tau_i n_p e^2) \approx 1 \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1} \qquad (3)$$

where $E_f^2/8\pi$ is the spectral energy density of the lower hybrid electric field oscillation, m_i is the mass of ions and $\tau_i \approx 5\text{x}10^5$ sec is the characteristic ionization time of the neutral gas taking into account the increased efficiency of charge exchange in the vicinity of the cometopause. The wave intensity in the lower hybrid range measured by the instruments APV-V (see Fig. 1) and APV-N (see Fig. 2) is in reasonable agreement with the theoretical estimation given by Eq. (3).

The excited lower hybrid waves accelerate the suprathermal electrons which are in Cherenkov resonance (Refs. 13-14). If the lifetime of the suprathermal electrons were significantly larger than the time of acceleration, their maximum density would be determined by the condition that the electron Landau damping be small compared to the growth rate of the instability. In this case the efficiency of energy transfer from the ion beam of density $n_b \approx \eta n_i$ (where $\eta \approx 7.5\%$ is the efficiency of energy transfer to electrons) is around unity, therefore the density n_{Te} and the energy ε_e of the suprathermal electrons can be estimated (Ref. 13)

$$n_{Te} \approx n_b \approx 1 \text{ cm}^{-3} \quad \text{and} \quad \varepsilon_e \approx m_i v_i^2/2 \approx 300 \text{ eV}. \qquad (4)$$

The density of suprathermal electrons estimated by the relation (4) is in agreement with direct measurements (Ref. 15) but it is not sufficiently high to explain the observed increase of cometary ion density by electron impacts.

The acceleration of suprathermal electrons along the magnetic field lines leads to the excitation of oblique Langmuir waves (whistlers in high β plasma) due to the growing anisotropy in the velocity distribution of electrons. These waves reach their maximum intensity around the frequency (Ref. 13)

$$\bar{\omega} \approx \omega_{ce} v_{Te}/(\varepsilon_e/m_e)^{1/2} \approx 2.3\text{x}10^3 \text{ s}^{-1} \qquad (5)$$

where $\omega_{pe} \approx 7\text{x}10^3 \text{ s}^{-1}$ is the electron cyclotron frequency and $v_{Te} \approx 2.5\text{x}10^8$ cm/s is the thermal velocity corresponding to a temperature of $\sim 2\text{x}10^5$ K around the cometopause (Ref. 16). The maximum amplitude of the high frequency oblique Langmuir waves can be estimated from the limit imposed by the non-linear theory (Vaisberg et al., 1983):

$$E^2 \approx 4\pi n_{Te} \varepsilon_e (\omega_{ce}^2/\omega_{pe}^2)(\bar{\omega}/\omega_{ce})^5 \approx 20 \text{ mV}^2 \text{ m}^{-2} \qquad (6)$$

where $\omega_{pe} \approx 2\text{x}10^5 \text{ s}^{-1}$ is the electron plasma frequency. From the estimations given by Eqs. (3) and (6) and in agreement with the measurements, it is seen that the spectral energy densities of the electric field oscillations in the oblique Langmuir mode and in the lower hybrid range have the same order of magnitude. It has to be mentioned here that the excitation of lower hybrid and whistler modes (in low β plasma oblique Langmuir mode) with similar energies is typical when a plasma flow interacts with a gas as discussed elsewhere in the case of the Io plasma torus (Ref. 17).

In agreement with Eq. (5), the frequency of high frequency Langmuir waves increases as the plasma is decelerating in the vicinity of the cometopause because the energy of suprathermal electrons is decreasing in Eq. (4). This effect is marked by a dashed-dotted line in Fig. 1. The increase in the level of lower hybrid and whistler mode plasma oscillations is the consequence of the rapid mass-loading and deceleration of the solar wind by cometary ions in the vicinity of the cometopause, it is not responsible for the mass-loading process.

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