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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 toward a comprehensive interpretation of the plasma, electric, and magnetic field 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. A 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.

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 [Gringauz et al., 1985, 1986a,b,c]. The existence of this boundary was confirmed by the low-frequency plasma wave analyzer (APV-N) on board the VEGA spacecraft [Savin et al., 1986] and by the positive-ion cluster composition analyzer (PICCA) and the Johnstone plasma analyzer (JPA) on board Giotto [Korth et al., 1985; Amata et al., 1986]. However, some observations showed differences. The Giotto magnetometer observed a sudden field increase at a cometocentric distance of $\sim1.35\times10^5$ km [Neubauer et al., 1986], while the magnetic field slowly increased around the cometopause as measured on board both VEGA spacecraft [Riedler et al., 1986]. Besides, plasma detectors which were not oriented parallel to the ram direction observed a broader transition in this region [Balsiger et al., 1986; Amata et al., 1986].

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 occurring at the cometopause on the basis of plasma, magnetic field, and plasma wave data simultaneously recorded on board the VEGA 2 spacecraft.

Experimental Data

Ion and electron energy spectra were measured by different sensors of the Plasmag 1 instrument package on board the VEGA 2 spacecraft [Gringauz et al., 1985, 1986a]. 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 (SDA) 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 flux gate magnetometer MISCHA (magnetic fields in interplanetary space during comet Halley's approach) in the range $\pm100\ \gamma$ for all components with a resolution of $0.05\ \gamma$ [Riedler et al., 1986]. The intensity of plasma waves was observed by the instruments APV-N [Klimov et al., 1986] and APV-V [Grard et al., 1986]. 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 (high-frequency plasma wave analyzer) measured the same electric field component in the frequency range 0-300 kHz.

The top panel of Figure 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 0643-0645 UT when VEGA 2 crossed the cometopause [Gringauz et al., 1986b].

As shown by the spectrogram of Figure 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;

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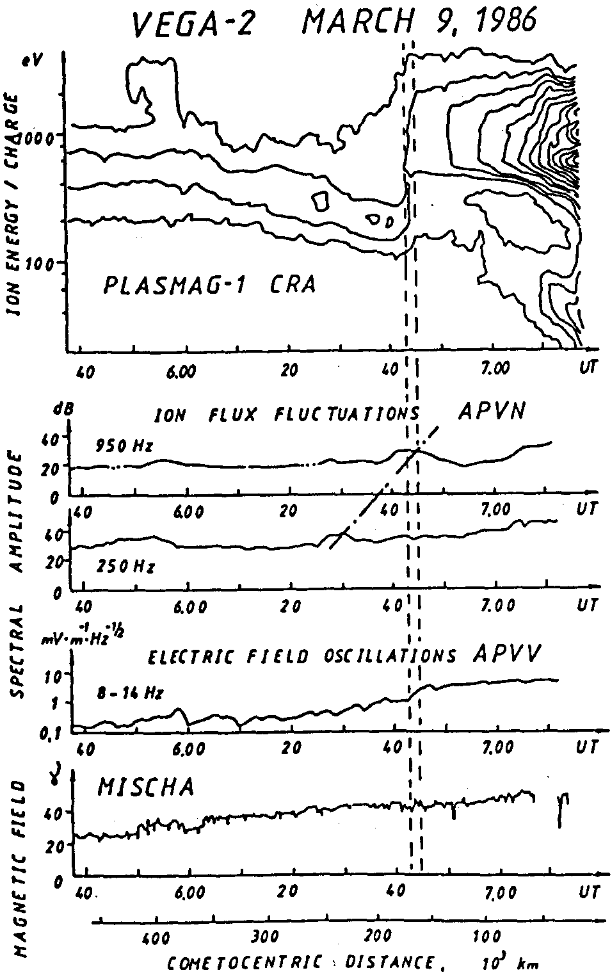

Fig. 1. Plasma and field data collected by four different instruments during the last 100 min before closest approach. From top to bottom: spectrogram of ion flux in the ram direction, plasma wave activity in three different frequency ranges, and total magnetic field. The cometopause is indicated by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

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 [Gringauz et al., 1985, 1986b] and their typical energy increases to ~250 eV.

Before crossing the cometopause, the ion energy spectra observed by the SDA show two maxima [see Gringauz et al., 1986b, Figure 1; Gringauz et al., 1985, Figures 2 and 3]. The first maximum, which is essentially due to protons, is ~300 eV; the heavy water group ions produce the 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 [Gringauz et al., 1985, 1986b].

Electron spectra measured by the electron analyzer and hence the density and temperature of the electrons do not show any characteristic change when the cometopause is crossed [Gringauz et al., 1985, 1986b].

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 Figure 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 [Riedler et al., 1986; Gringauz et al., 1986c].

The middle part of Figure 1 shows the plasma wave activity measured by the instruments APV-N and APV-V on board VEGA 2. In the selected frequency bands shown in this figure (and also at other frequencies not shown here), the average amplitudes of plasma and electric field oscillations are generally increasing at a distance of 1.5-2x10^5 km from the nucleus. In the vicinity of the cometopause (around 0630-0650 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 the 2-min interval when the spacecraft crosses the cometopause.

The wave activity in the lower frequency range can be seen in Figure 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 Gringauz et al.'s [1986b] Figure 1, where the spectrograms are color coded) shows that the fluctuations in ion fluxes measured by the two sensors are in anticorrelation. This is an indication of the large-scale MHD variations in the direction and/or in the velocity of the plasma flow with a characteristic period T~1 min.

These large-scale MHD variations around the cometopause are reflected in the electric field oscillations of 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~1 min). The correspondence between the maxima of electric field, magnetic field, and ion fluxes is indicated by arrows in Figure 2.

Discussion

The sudden decrease of proton fluxes within a ~2-min interval (corresponding to Δ~10^4 km along the trajectory of VEGA 2) 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 protons and ions observed by Plasmag 1.

Outside the cometopause, the typical energy

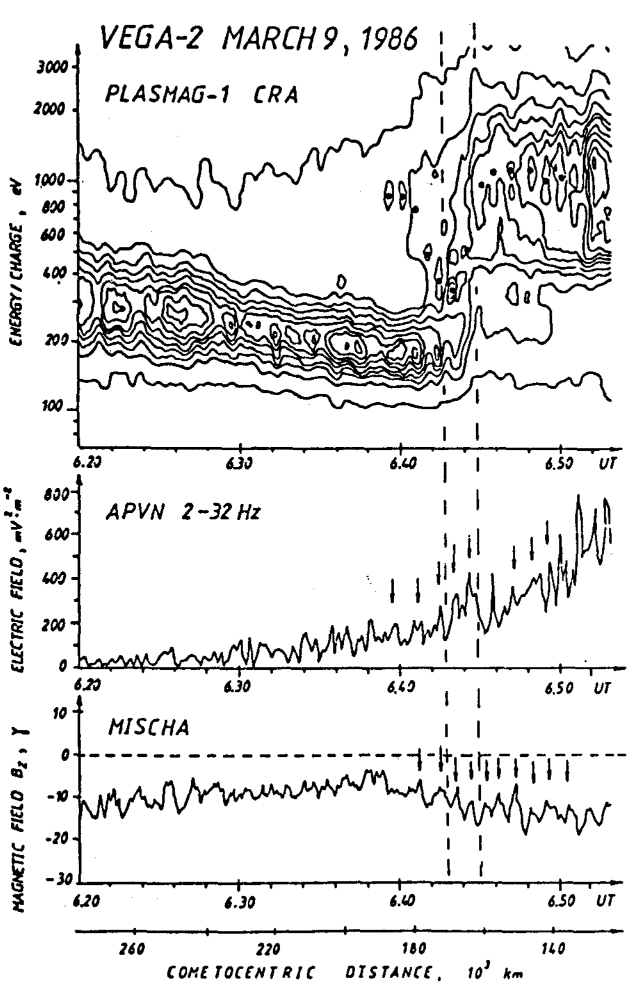

Fig. 2. Fluctuating ion flux, electric field, and B_z component (pointing toward the north pole of the ecliptic) of the magnetic field around the cometopause (indicated by dashed lines). Maxima are shown by dots and arrows.

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. Then the velocity of the protons relative to the comet $v_p \approx 200$ km/s is given by a possible vector diagram shown in Figure 3, where the spacecraft 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 nearly 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 $B \approx 40$ γ, the condition for the 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 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 Figure 2. The characteristic wavelength 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 $\rho_{ci} \approx v_i/\omega_{ci} \approx 300$ km ($\omega_{ci} \approx 0.2$ s^{-1} is the cyclotron frequency of water group ions). The direction of the plasma flow was not measured exactly on board the VEGA spacecraft, 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/s is the Alfven velocity. The spatial scale (defined as the inverse wave

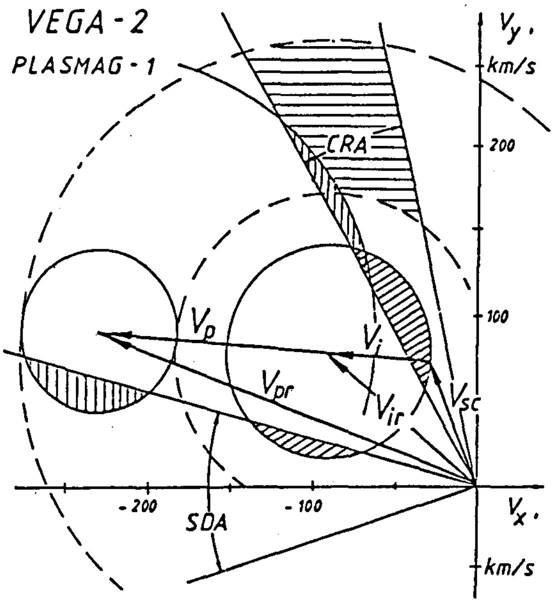

Fig. 3. Possible proton and ion velocity vector diagrams and the acceptance angles of the SDA and CRA ion analyzers in the spacecraft reference frame. Particles from shaded areas can be observed by the analyzers (sloping lines: cometary ions; vertical lines: protons outside the cometopause; horizontal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

number) of these oscillations is twice as large as the cometary ion Larmor radius. There are two instabilities excited by the newly born cometary ions: the resonant cyclotron instability and the nonresonant fire hose instability. The fastest growing modes of both types have a spatial scale comparable to the ion Larmor radius, and it is not possible to separate these modes on the basis of our limited data. However, the resonantly excited MHD waves can be accompanied by whistler waves as observed at comet Giacobini-Zinner [Tsurutani and Smith, 1986]. Such whistler waves are absent in our case with a time resolution of 10 magnetic field vectors per second. On the other hand, the plasma flows nearly parallel to the magnetic field in the vicinity of the cometopause ($\cos\theta_{BV}\approx0.7$), and the condition for the fire hose instability is satisfied if we assume that the pickup of cometary ions is inefficient along the magnetic field: the growth rate of the fire hose instability is of the order of the cometary ion cyclotron frequency, explaining the fast onset of the instability.

The isotropization of the proton distribution function in the vicinity of the cometopause, resulting in a significant decrease of the proton flux at this boundary, leads to the increasing importance of charge exchange as a mechanism producing cometary ions.

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 $\sigma_{ct}\approx2\times10^{-15}$ cm^2 is the cross section for charge exchange, $n_n\approx4\times10^3$ cm^{-3} is the number density of neutral gas in the vicinity of the cometopause at a cometocentric distance $R\approx1.6\times10^5$ km [Remizov et al., 1986], and $v_p\approx200$ 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 (it is of the order of $2R/v_i\approx5\times10^3$ s in the vicinity of the cometopause for a flow velocity $v_i\approx60$ 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 Figures 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 [Formisano et al., 1982]

$$E_f^2\approx(n_n\, m_i^2\, v_p^2)/(\tau_i\, n_p\, e^2)\approx1 \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1} \qquad (3)$$

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 $\tau_i\approx5\times10^5$ s 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 Figure 1) and APV-N (see Figure 2) is in reasonable agreement with the theoretical estimation given by equation (3).

The excited lower hybrid waves accelerate the suprathermal electrons which are in Cherenkov resonance [Vaisberg et al., 1983; Galeev and Khabibrachmanov, 1985]. 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 $\eta\approx7.5\%$) to electrons is around unity; therefore the density n_{Te} and the energy ϵ_e of the suprathermal electrons can be estimated [Vaisberg et al., 1983; Galeev and Sagdeev, 1983]:

$$\begin{aligned} n_{Te} &\approx n_b \approx 1 \text{ cm}^{-3} \\ \epsilon_e &\approx m_i\, v_i^2/2 \approx 300 \text{ eV} \end{aligned} \qquad (4)$$

The density of suprathermal electrons estimated by relation (4) is in agreement with direct measurements [d'Uston et al., 1986], 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 [Vaisberg et al., 1983]

$$\bar{\omega} \approx \omega_{ce}\, v_{Te}/(\epsilon_e/m_e)^{1/2} \approx 2.3\times10^3 \text{ s}^{-1} \qquad (5)$$

where $\omega_{ce}\approx7\times10^3$ s^{-1} is the electron cyclotron frequency, and $v_{Te}\approx2.5\times10^8$ cm/s is the thermal velocity corresponding to a temperature of 2×10^5K around the cometopause [Gringauz et al., 1986d]. The maximum amplitude of the high-frequency oblique Langmuir waves can be estimated from the limit imposed by the nonlinear theory [Vaisberg et al., 1983]:

$$E^2\approx4\pi n_{Te}\epsilon_e(\omega_{ce}^2/\omega_{pe}^2)(\bar{\omega}/\omega_{ce})^5\approx20 \text{ mV}^2 \text{ m}^{-2} \qquad (6)$$

where $\omega_{pe}\approx2\times10^5$ s^{-1} is the electron plasma frequency. From the estimations given by equations (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 mode (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 [Galeev and Khabibrachmanov, 1983].

In agreement with equation (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 equation (4). This effect is marked by a dashed-dotted line in Figure 1 connecting the enhancements of the whistler wave intensities at the frequencies 250 Hz and 950 Hz (ion flux fluctuations were measured in a frequency range up to 1 kHz [Klimov et al., 1986]). Both of these enhancements have the same nature; i.e., these waves were excited by the tail electrons generated at the beginning of the fast solar wind mass loading by cometary ions and at the cometopause, respectively. 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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References

Amata, E., et al., The cometopause region at comet Halley, Exploration of Halley's Comet, vol. I, edited by R. Reinhard, Eur. Space Agency Spec. Publ., ESA SP-250, 213, 1986.

Balsiger, H., et al., The composition and dynamics of cometary ions in the outer coma of comet Halley, Exploration of Halley's Comet, vol. I, edited by R. Reinhard, Eur. Space Agency Spec. Publ., ESA SP-250, 99, 1986.

d'Uston, C., et al., Description of the main boundaries seen by the Giotto electron experiment inside the comet Halley-solar wind interaction regions, Exploration of Halley's comet, vol. I, edited by R. Reinhard, Eur. Space Agency Spec. Publ., ESA SP-250, 77, 1986.

Formisano, V., A. A. Galeev, and R. Z. Sagdeev, The role of the critical ionization velocity phenomena in the production of inner coma cometary plasma, Planet. Space Sci., 30, 491, 1982.

Galeev, A. A., and I. Kh. Khabibrachmanov, Origin and energetics of the Io torus, in Giant Planets and Their Satellites, edited by M. G. Kivelson, p. 71, Pergamon, New York, 1983.

Galeev, A. A., and I. Kh. Khabibrachmanov, On the nature of plasma waves in the Io torus (in Russian), Pisma Astron. Zh., 11, 292, 1985.

Galeev, A. A., and R. Z. Sagdeev, The theory of critical ionization phenomenon, Sov. Phys. Plasma Phys., 9, 209, 1983.

Grard, R., A. Pedersen, J.-G. Trotignon, C. Beghin, M. Mogilevsky, Y. Mikhalov, O. Molchanov, and V. Formisano, Observations of waves and plasma in the environment of comet Halley, Nature, 321, 290, 1986.

Gringauz, K. I., et al., First results of plasma and neutral gas measurements from VEGA 1/2 near comet Halley, Adv. Space Res., 5(12), 165, 1985.

Gringauz, K. I., et al., First in-situ plasma and neutral gas measurements at comet Halley, Nature, 321, 282, 1986a.

Gringauz, K. I., et al., Detection of a new "chemical" boundary at comet Halley, Geophys. Res. Lett., 13, 613, 1986b.

Gringauz, K. I., M. I. Verigin, A. K. Richter, T. I. Gombosi, K. Szego, M. Tatrallyay, A. P. Remizov, and I. Apathy, Cometary plasma region in the coma of comet Halley: VEGA 2 measurements, Exploration of Halley's Comet, vol. I, edited by R. Reinhard, Eur. Space Agency Spec. Publ., ESA SP-250, 93, 1986c.

Gringauz, K. I., A. P. Remizov, M. I. Verigin, A. K. Richter, M. Tatrallyay, K. Szego, I. N. Klimenko, I. Apathy, T. I. Gombosi, and T. Szemerey, Electron component of the plasma around Halley's comet measured by the electrostatic analyzer of Plasmag 1 on board VEGA 2, Exploration of Halley's Comet, vol. I., edited by R. Reinhard, Eur. Space Agency Spec. Publ., ESA SP-250, 195, 1986d.

Klimov, S., et al., Extremely-low-frequency plasma waves in the environment of comet Halley, Nature, 321, 292, 1986.

Korth, A., et al., Cometary ion observations at and within the cometopause-region of comet Halley, Adv. Space Res., 5(12), 221, 1985.

Neubauer, F. M., et al., First results from the Giotto magnetometer experiment at comet Halley, Nature, 321, 352, 1986.

Remizov, A. P., M. I. Verigin, K. I. Gringauz, I. Apathy, I. Szemerey, T. I. Gombosi, and A. K. Richter, Measurements of neutral particle density in the vicinity of comet Halley by Plasmag 1 on board VEGA 1 and VEGA 2, Exploration of Halley's Comet, vol. I., edited by R. Reinhard, Eur. Space Agency Spec. Publ., ESA SP-250, 387, 1986.

Riedler, W., K. Schwingenschuh, Ye. G. Yeroshenko, V. A. Styashkin, and C. T. Russell, Magnetic field observations in comet Halley's coma, Nature, 321, 288, 1986.

Savin, S., G. Avanesova, M. Balikhin, S. Klimov, A. Sokolov, P. Oberc, D. Orlowski, and Z. Krawczyk, ELF waves in the plasma regions near the comet, Exploration of Halley's Comet, vol. III, edited by R. Reinhard, Eur. Space Agency Spec. Publ., ESA SP-250, 433, 1986.

Tsurutani, B. T., and E. J. Smith, Hydromagnetic waves and instabilities associated with cometary ion pickup: ICE observations, Geophys. Res. Lett., 13, 263, 1986.

Vaisberg, O. L., A. A. Galeev, G. N. Zastenker, S. I. Klimov, M. N. Nozdrachev, R. Z. Sagdeev, A. Yu. Sololov, and V. D. Shapiro, Electron acceleration at the front of strong collisionless shock waves (in Russian), Zh. Eksp. Teor. Fiz., 85, 1232, 1983.

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