The inner zone has another interesting property: near the closest approach of Vega 1 to the nucleus (07^{h}20^{m} UT in Fig. 2), a set of closely spaced, narrow peaks are evident at all energies. Remarkably enough, this feature coincides with the occurrence of maximum magnetic field intensity and rapid changes in field direction.[15]

Finally, the flux of 160-300-keV electrons detected by the Tünde-M experiment increases very rapidly from the background counting rate at close-approach to the cometary nucleus, and stays high for ≈ 4 h afterward. No significant variation in this flux had been observed for several days preceding closest approach.

The Vega 1 Tünde-M experiment has therefore shown that the behavior of the high-energy ions is at least phenomenologically related to the interaction between the solar wind and Comet Halley. In order to ascertain what processes are chiefly at work here, we plan to carry out a more comprehensive analysis of these unique data.

*Reprinted by permission, without substantive change, from Nature 321, 285-288 (May 15, 1986). The first five letters in this issue continue the series of Vega-Halley communications presented in the last issue of Soviet Astronomy Letters.

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First *in situ* plasma and neutral-gas measurements near Comet Halley: preliminary *Vega* results*

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The first *in situ* plasma measurements near Comet Halley are presented, and the large-scale behavior of the cometary plasma environment is described. The Plasmag-1 experiments aboard the two *Vega* spacecraft were designed: a) to study how the plasma parameters depend on distance from the comet nucleus; b) to investigate the position and structure of the bow shock; c) to determine the change in chemical composition of the heavily mass-loaded plasma as the spacecraft approached the comet; d) to measure the neutral-gas distribution along the trajectory. The total gas-production rate is estimated to have been 1.3×10^{30} molecules sec.

To meet the scientific objectives listed in the abstract, each Vega spacecraft carried a Plasmag-1 package comprising six different sensors.

Two hemispherical electrostatic analyzers observed the energy spectra of ions arriving from the spacecraft–comet relative-velocity direction and from the direction of the sun. These sensors will be referred to as the cometary ram analyzer (CRA) and solar-direction analyzer (SDA), respectively. Since the solar-wind direction can vary by ± 10°, using conventional electrostatic analyzers with their small angular aperture might have introduced error (such as an apparent decrease in ion flux due to a change in the direction of flow) into the measurements aboard these spacecraft, which were stabilized about three axes. Accordingly, electrostatic lenses were installed at the entrance slits of both ion analyzers in order to widen the acceptance angle without decreasing the energy resolution. The CRA had an acceptance angle of 14° × 32° and detected ions in the energy/charge range (15-3,500 eV)/q (where q is the charge state),

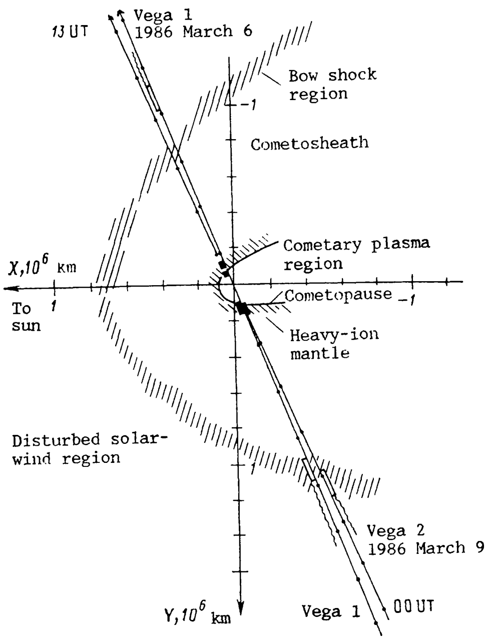

FIG. 1. The plasma environment of Comet Halley, as observed in the Vega 1 and Vega 2 Plasmag-1 experiments, mapped in projection on the spacecraft orbit planes. Each trajectory carries hourly UT dots. Wavy lines, disturbances in the solar-wind plasma; open boxes, the heavily structured bow-shock region; filled boxes, the heavy-ion mantle.

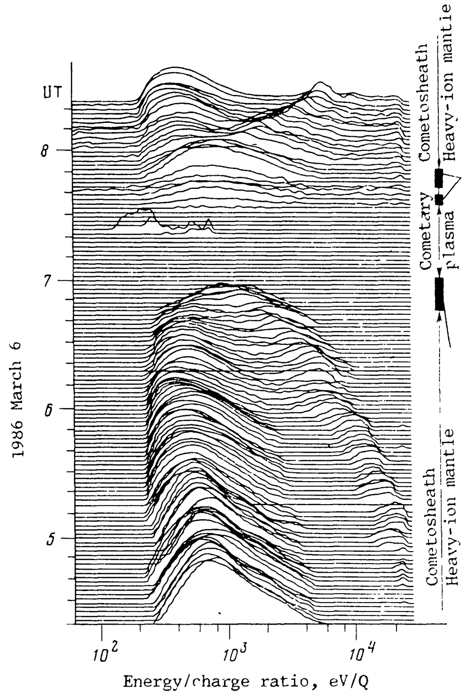

FIG. 2. High-resolution (1 sec) ion energy spectra measured by the Vega 1 solar-direction analyzer (SDA) during the 4-h interval (2-min averages) of high-speed telemetry in the neighborbood of Comet Halley.

in 120 intervals spaced uniformly on a logarithmic scale, providing a complete coverage of this range without any gaps. The SDA had a 38° × 30° acceptance angle and measured ions in the range (50-25,000 eV)/q in 60 logarithmically spaced energy intervals. All acceptance-angle data presented refer to the 10% level; for the same level, the energy resolutions of both the CRA and SDA were $\Delta E/E = 0.055$.

A cylindrical electrostatic electron analyzer with an acceptance angle of 7° × 7° was oriented perpendicular to the ecliptic plane. It had 30 logarithmically spaced intervals with $\Delta E/E = 0.075$ in the energy range 3-10,000 eV.

The energy spectra of the ions and electrons were continuously measured once per second for ≈4 h, beginning 3 h before closest approach to the nucleus. During the 2 days before the 1 day after closest approach, spectra were continuously measured at a rate of 0.35 per min.

Plasmag-1 also included two Faraday cups (charged-particle traps). The solar-direction Faraday cup, with an acceptance angle of 84° × 84°, measured the solar-wind ion flux. The ram Faraday cup (RFC), with a 25° × 25° acceptance angle had four periodically changed modes of operation. Two of these modes provided information on the neutral-particle flux from the comet, by detecting the secondary electrons produced by neutrals striking the metallic emitter; the other two modes measured the total charged-particle flux.

The final sensor included in the Plasmag-1 package was an impact plasma detector, for measuring neutral-particle flux. This detector was similar to the one developed by R. Grard at ESTEC for the Giotto mission, and its results will not be discussed here.

We have given elsewhere[1,2] a more comprehensive description of the Plasmag-1 experiment.

Figure 1 schematically indicates the various plasma regions observed during the Vega 1 and Vega 2 encounters. On the inbound legs both SDAs measured a relatively fast and warm solar wind: $(2\text{-}3)\cdot 10^6$ km from the comet Vega 1 found that the proton velocity, number density, and temperature were $V \approx 580$ km/sec, $n \approx 12$ cm^{-3}, $T \approx 1.2\cdot 10^5$ °K, while Vega 2 measured $V \approx 620$ km/sec, $n \approx 11$ cm^{-3}, $T \approx 3\cdot 10^5$ °K. The proton-flux parameters given here are, however, only preliminary estimates and are subject to later refinement.

The first sign of the comet was detected by the CRA, which observed ions of cometary origin as far as $5\cdot 10^6$ km from the nucleus. As the spacecraft approached the bow-shock region, disturbances starte to appear in the solar-wind plasma distributions (wavy lines in Fig. 1). At a distance of $\approx (1.1\text{-}1.2)\cdot 10^6$ km from the nucleus, both Vega spacecraft encountered a broad (~10^5 km), heavily structured bow-shock region and then entered a region of decelerated solar plasma, the "cometosheath," where the proton distribution broadened significantly, so that the α-particle peak in the energy spectrum became indistinguishable. The direction of the plasma stream was no longer anti-sunward, as the Vega 2 CRA and SDA detected proton fluxes of approximately the same energy. In the cometosheath Vega 2 also observed some oscillations in the direction of the plasma flow, protons sometimes disappearing from the SDA spectra and appearing in the CRA spectra, and vice versa.

On the outbound leg Vega 1 observed a broad, eroded bow-shock region at a distance of $\approx 1.1\cdot 10^6$

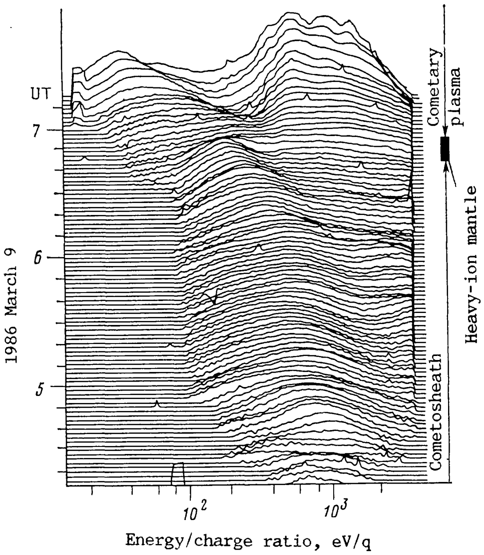

FIG. 3. High-resolution (1 sec) ion energy spectra measured by the Vega 2 cometary ram analyzer (CRA; 2-min averages) during the encounter with Comet Halley.

km from the nucleus. Once this region was crossed, the solar wind became slower and cooler than on approach to the comet: V ≈ 380 km/sec, n ≈ 17 cm^{-3}, T ≈ $4\cdot10^4$ K.

Figure 2 presents 2-min averages of the high-resolution SDA spectra measured by Vega 1 during the 4 h of high-speed data transmission near closest approach. At a distance of ≈ $8\cdot10^5$ km from the nucleus (4^h20^m UT), a single broad peak dominates the spectra, corresponding to a shocked (thermalized) solar-wind proton and α-particle flow with a velocity of ≈350-400 $km\cdot s^{-1}$. Closer to the nucleus the solar wind gradually slows further and a second peak appears in the SDA spectra corresponding to a much higher energy than that of the solar-wind protons. This second peak must be produced by cometary ions (probably of the H_2O group), because solar-wind ions never have such a high energy.

At a distance of ≈ $3\cdot10^5$ km from the nucleus (6^h15^mUT), the solar-wind proton population becomes comparable to the cometary implanted ions. From Fig. 2 and the Vega 2 data, one may conclude that at ≈ $1.5\cdot10^5$ km from the nucleus (6^h45^m UT) the original solar-wind population effectively disappears from the solar direction; instead, the SDA observed merely a broad distribution of slow cometary ions. This region can be called the "heavy-ion mantle," where the plasma is moving slowly around the cometary obstacle. Shortly afterward, at ≈ $1\cdot10^5$ km (7^h00^m UT), the SDA stopped detecting particles. On the outbound pass, the cometary ions reappeared in the SDA at ≈ $7\cdot10^4$ km from the nucleus (7^h35^m UT), after which the shocked solar-wind protons could again be observed.

Figure 3 shows 2-min averages of the high-resolution spectra obtained by the Vega 2 CRA, starting at ≈ $8\cdot10^5$ km from the nucleus (4^h20^m UT); that is, well downstream of the bow-shock region. Between $8\cdot10^5$ and ≈ $1.5\cdot10^5$ km (6^h45^m UT), the CRA observed a broad energy distribution of decelerated protons. These particles are probably solar-wind protons diverted from their original direction, observed simultaneously by the SDA. Signatures of heavy cometary ions can be seen in the upper part of the measured energy range, and the simultaneous SDA data (not shown here) indicate that at ≈ $1.5\cdot10^5$ km from the nucleus, the solar-wind proton population virtually disappears from the SDA direction. Closer to the comet, up to ≈ $1\cdot10^5$ km, the SDA recorded chiefly the slowly moving layer of heavy cometary ions in the heavy-ion mantle observed by Vega 1.

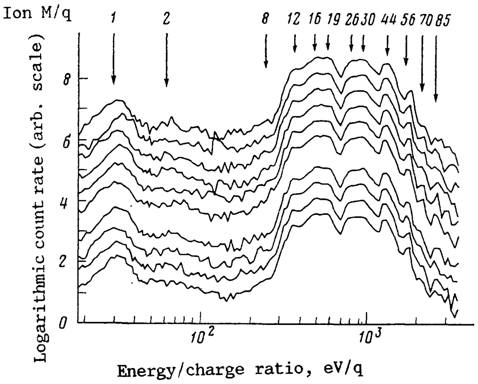

FIG. 4. Successive 1-sec ion energy spectra measured by the Vega 2 CRA in the cometary plasma region 15,000 km from the nucleus of Comet Halley.

At ≈ $1\cdot10^5$ km (6^h55^m UT), Vega 2 entered the cold, almost stagnantly or only very slowly moving cometary-ion region, which was characterized by increasing ion fluxes in the (300-3,000 eV)/q range (Fig. 3). This region is inhomogeneous, comprising extended stratified zones with layers of quasiregularly varying ion density (the ≈10-sec time scale of variation is equivalent to a ≈800-km characteristic length along the trajectory). When 15,000 km from the nucleus the CRA detected only cold cometary ions and it is possible to carry out a mass analysis of these heavy ions. Unfortunately, not long afterward the plasma instrument became temporarily disabled by exposure to the harsh cometary environment.

Figure 4 shows enlarged versions of several successive 1-sec spectra measured by the CRA in the cometary plasma region. The first peak, definitely due to H^+ ions, occurs at ≈ 30 eV, indicating a proton velocity nearly equal to the spacecraft—comet relative velocity, v_R = 76.78 km/sec. This property indicates that the cometary plasma is relatively "cold"; that is, both the bulk and thermal velocities of these ions are much smaller than v_R. The peaks of the other ions then correspond to E/q = 30.55 M/q, where M is the ion mass in AMU. For several values M/q = 1, 2, ..., 85, the arrows in

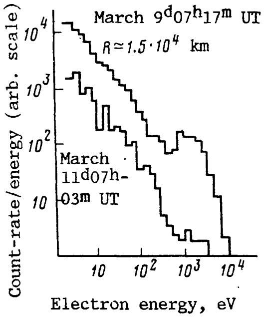

FIG. 5. Electron energy spectra measured by Vega 2, both near closest approach to the comet and 2 days later in the solar wind.

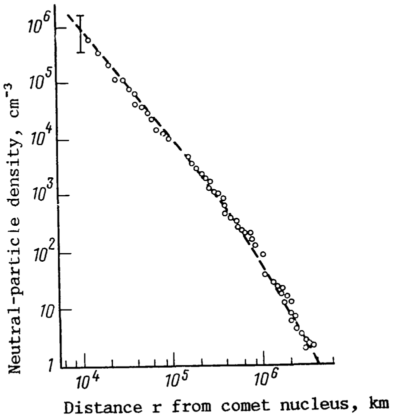

FIG. 6. Neutral-gas density profile in the vicinity of Comet Halley, as derived from the Vega 1 ram Faraday cup (RFC) measurements of the secondary-electron flux along the spacecraft relative-velocity vector.

Fig. 4 indicate the corresponding E/q (lower axis). Assuming that these ions are predominantly singly charged, the CRA energy spectra shown in Fig. 4 can be used for mass spectrometry of the cometary plasma.

In the spectra of Fig. 4, H^+, C^+, CO_2^+, and Fe^+ ions can be identified with confidence. The peak at $14 \le M/q \le 20$ most probably originates from H_2O parent molecules, with some possible contribution of CH_4 and NH_3. There are two secondary peaks at $M/q = 16\text{-}17$ and $M/q = 19$, possibly corresponding to O^+, OH^+ and H_3O^+ ions, respectively. The identity of the $24 \le M/q \le 34$ peak is less certain; it probably originates from several parent molecules, such as CO, CO_2, and N- or S-bearing molecules.

Figure 4 is based on channeltron count rates, which reach the level of $\approx 8 \cdot 10^5$ counts/sec at the major peaks. At such rates the channeltrons which were used operate in a nonlinear regime: significant flux increases result in only small changes in count rate. This effect will be taken into account in later publications.

Figure 5 displays two typical electron spectra: one was measured deep in the cometary plasma region and the other was obtained 2 days later in interplanetary space. A major difference between the two spectra is the appearance of a very energetic (few keV) electron population. These electrons might be an additional effective source of ionization in the coma.

Finally, Fig. 6 shows a typical neutral-gas density profile with respect to distance from the comet. These density estimates assume that collisions of ≈ 80 km/sec incident neutral particles will have a secondary-electron yield of ≈ 0.3. The dashed curve in Fig. 6 represents a simple $r^{-2} \exp(-r/\lambda)$ fit to the density profile (r is the distance from the nucleus). The ionization scale length λ was estimated to be $2 \cdot 10^6$ km, and a value of $1.3 \cdot 10^{30}$ molecules/sec was obtained for the total gas-production rate $Q = 4\pi r_0^2 n_0 v_g$, assuming a neutral-gas velocity of 1 km/sec.

The data shown in Fig. 6 were obtained during the inbound pass of the Vega 1 flyby. On the outbound leg a more complicated neutral-gas density distribution was observed, indicating significant spatial and temporal deviations from a simple r^{-2} dependence. We estimate the uncertainty of our preliminary analysis to be a factor of 2-3.

As anticipated, both Vega spacecraft crossed a wide and structured bow-shock region at $\approx 1.1 \cdot 10^6$ km from the nucleus. This bow-shock is not the result of a dynamic compression of the solar wind at a "hard" obstacle, but is produced by the continuous mass loading of the solar wind by newly created cometary ions.[3-7]

On the other hand, the large-scale plasma structure downstream of the bow shock proves to be more complex than expected. It has been found that the plasma flow mass-loaded by cometary ions is controlled dynamically by the solar wind only in the region between the bow shock and the "cometopause" (observed $1 \cdot 10^5$ km from the nucleus) which separates the solar-wind—controlled cometosheath and heavy-ion mantle from the magnetized[8] cometary plasma region. This magnetized region behaves as an obstacle to the mass-loaded solar-wind flow, and its volume, which is controlled by the comet, is much larger than was theoretically predicted (see the review by Mendis et al.[4]). According to previous calculations only the plasma region inside the contact surface is dynamically detached from the solar wind. The relative contributions of the magnetic field and the various plasma components to the pressure balance across the cometopause will be the subject of a future study.

*A slightly modified version of the report in Nature 321, 282-285 (May 15, 1986), reprinted by permission.

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