First *in situ* observations of energetic particles near Comet Halley*

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The Tünde-*M* energetic-particle detector aboard *Vega 1* recorded an intense flux of high-energy ($\gtrsim$40 keV) ions near Comet Halley, starting $\approx 10^7$ km prior to closest approach. Three regions have been identified, differing in their ion characteristics: An outer zone, extending several million kilometers, contains heavy cometary ions picked up by the solar wind. A region inside the bow shock (scale length, a few hundred thousand kilometers) contributes the most intensive ion flux. In the inner zone (extending tens of thousands of kilometers from the comet nucleus) the energetic ions are depleted, but sharp spikes in the ion intensity were observed near closest approach.

Cometary ions are created from cometary neutrals by photoionization and charge exchange with solar-wind particles. The newly formed cometary ions are practically at rest; they are then accelerated by the solar-wind electric field, **E**, resulting at first in a cycloidal electric drift in the $\mathbf{E}\times\mathbf{B}$ direction, where B is the interplanetary magnetic field (Refs. 1, 2). The cometary-ion distribution function forms a ring in velocity space,[2,3] drifting parallel to **B**. This type of distribution is highly unstable and generates magnetic fluctuations which can scatter the ions in pitch angle, and thereby make the distribution nearly isotropic.[1,4] The traversal of the bow shock by ions created upstream is expected to lead to further acceleration and energization of these ions (Refs. 2, 4, 5), either by gradient drift and/or Fermi acceleration or by adiabatic compression. Further acceleration of cometary ions downstream of the bow shock could be caused by first- and second-order Fermi processes, adiabatic compression (most important in the magnetic barrier region close to the comet nucleus), and by magnetic reconnection up- and down downstream of the nucleus. The result of these processes is that H_2O^+ ions, for example, can be accelerated up to energies of several hundred keV or even up to MeV energies.[5,6]

The Vega mission and spacecraft trajectories are described elsewhere.[7] The trajectories form an angle of $\approx 110°$ to the sun–comet axis, and the Tünde-M telescope points normal to this axis in the ecliptic plane, in a direction roughly opposite to the spacecraft motion.[8,9]

The Tünde-M telescope measures ions;, within a cone of half-angle 25°, in 10-keV bins for energies ranging from 40 to 490 keV, and in 20-keV bins for 490 to 630 keV. Other channels for higher-energy electrons, protons, and ions are not discussed here. Tünde-M is not able to distinguish the mass of an incident ion at a given energy; however, only heavy ions picked up by the solar wind and further accelerated by the processes outlined above are expected to have sufficient energy to be detected.

Figure 1 shows the records obtained in the two lowest-energy channels of the Vega 1 Tünde-M telescope, while Fig. 2 gives several time-histograms for the flux observed near closest approach. The energies indicated in Figs. 1-3 are those deposited as ionization energy in the silicon layer of the topmost detector of the Tünde-M telescope, by incident ions that were totally absorbed in that layer. For protons, these energies are very close to the incident energies, but for a heavy ion the energy deposited in the silicon layer may be considerably less than the incident energy (for details, see Ipavich et al.[10]).

We would further point out that contamination by electrons may be neglected when the ion flux is measured under normal conditions (as predominated during the observations discussed here): a deflecting magnet was applied to the top detector, and in addition an anticoincidence scheme was used in recording particles with that detector.

Three regions can be distinguished in Figs. 1 and 2: (1) An outer region well outside of the in- and outbound shock crossings, which took place at distances of ~10^6 km from the nucleus.[11] Energetic ions were detected as far as ~10^7 km from the nucleus; the scale length of this region is several million kilometers. (2) A region containing the most intense fluxes, including the shock and large part of the transition zone (or cometosheath). The extent of this region is several hundred thousand kilometers. (3) An inner region characterized by a reduced flux level and by superimposed flux enhancements. The scale length of this region is several tens of thousands of kilometers.

Near closest approach, several distinct intensity spikes were observed over a region of several thousand kilometers. Similar regions have been identified from energetic-particle measurements near Comet Giacobini–Zinner.[12,13]

The outer region is characterized by an overall increase of the 50-60 keV flux with decreasing distance from the bow shock; this increase is steepest

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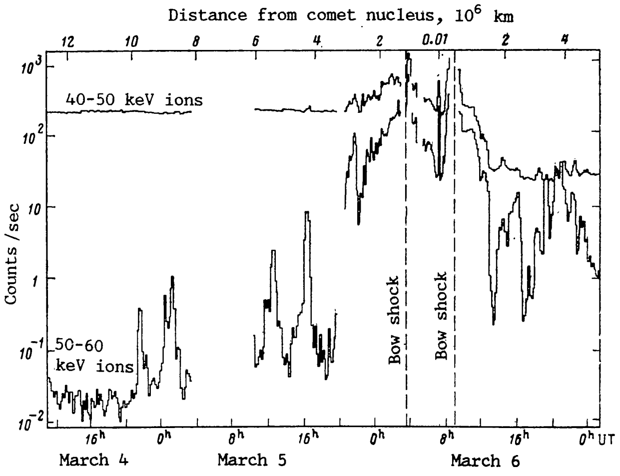

FIG. 1. Time profiles of the ion flux recorded in the two lowest-energy Tünde-M channels along the Vega 1 Comet Halley flyby.

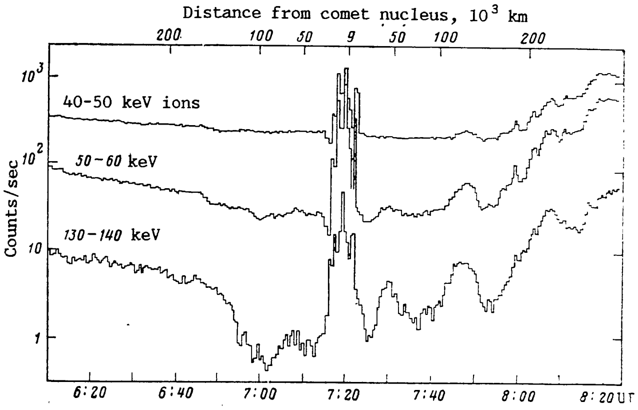

FIG. 2. Time profiles of the ion flux recorded in three Tünde-M channels near Vega 1 closest approach to the nucleus. The time scale is much magnified relative to Fig. 1.

within $\approx 3 \cdot 10^6$ km. Superimposed on this general trend are a number of discrete flux enhancements of one or two orders of magnitude, exhibiting a quasi-periodicity of ~ 4 h. The presence of these enhancements is related to the prevailing solar-wind and interplanetary magnetic field conditions. From the ion energy spectra a "temperature" of ≈ 5 keV can be estimated.

The ion fluxes (Fig. 1) begin to increase more rapidly as the shock is aproached. The flux at higher energy increases faster; that is, the spectrum hardens. This effect is most probably due to acceleration at or near the bow shock or to adiabatic compression in the bow-wave region. From the energy spectrum (Fig. 3) we estimate an effective temperature of 20-40 keV near the shock. The maxima of the ion-flux enhancements are found near the in- and outbound bow shock; the flux levels behind the shock in the cometosheath region (except for the heavy-ion depletion zone discussed below) experience only a moderate decrease. As the solar-wind velocity decreases gradually here,[11] this observation indicates a further acceleration of cometary ions after pick-up, perhaps by turbulences in this region (first- and second-order Fermi processes[5,6]). Other processes, such as better isotropization of ion velocities due to enhanced magnetic turbulence, may also contribute to the observed effect.

In addition, more ions may gain access to Tünde-M here than in the outer-region, because of the possibly greater isotropy of the ion distributions in the inner region, presumably due to the enhanced level of turbulence observed by the wave experiments on Vega-1.[14] These matters warrant a special investigation.

Now let us turn to the innermost region, extending from about March $6^{\mathrm{d}}06^{\mathrm{h}}50^{\mathrm{m}}$ to $08^{\mathrm{h}}05^{\mathrm{m}}$ UT (Fig. 2). Here the energetic-ion fluxes are much less intense, especially at higher energies, so that the energy spectrum softens (Fig. 3). This zone of energetic-ion depletion seems to correspond closely to the cometary-plasma region observed by the Plasmag instruments[11] — a region in which solar-wind protons disappear, and which is also associated with the magnetic barrier regime. Two processes can probably explain these observations.

First, energetic ions will be depleted by charge-exchange collisions with neutrals.[1] For a production rate $Q \approx 10^{30}$ molecules/sec the charge-exchange time near the edge of the depletion zone ($R \lesssim 10^5$ km) is estimated to be 10^3 sec, which is indeed comparable to the transport or convection time for an almost stagnated solar wind ($u \lesssim 30$ km/sec). Second, energetic ions can escape from this region along magnetic field lines, because their parallel velocity for most pitch angles is much greater than the bulk velocity. In fact, "conic ion" distributions might well exist.

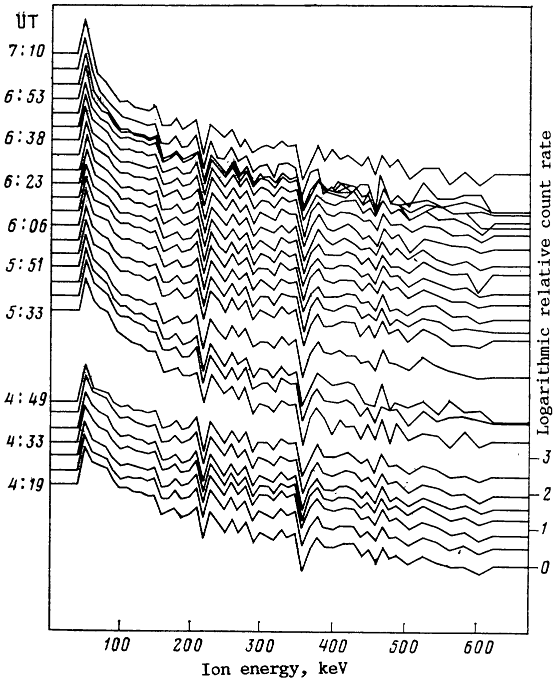

FIG. 3. Successive ion-flux energy spectra measured by the Vega 1 Tünde-M during the 3 h prior to closest approach. The sharp dips in count rate at 210 and 350 keV result from differences in the energy-channels widths; suitable corrections have not yet been made.

The inner zone has another interesting property: near the closest approach of Vega 1 to the nucleus (07^h20^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.

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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),