76.78 km s^{-1}. This indicates that the cometary plasma is '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 $E/q = 30.55M/q$, where M is the mass in AMU. Some M/q values are indicated in Fig. 4. Assuming that these ions are predominantly singly charged, the CRA energy spectra shown in Fig. 4 can be used for mass spectrometry.

From Fig. 4, H^+, C^+, CO_2^+ and Fe^+ ions can be identified with confidence. The peak at $14 \leq M/q \leq 20$ most probably originates from H_2O parent molecules with some possible contribution of CH_4 and NH_3. There are two secondary peaks at $M/q = 16$-17 and $M/q = 19$, possibly corresponding to O^+, OH^+ and H_3O^+ ions, respectively. The identity of the $24 \leq M/q \leq 34$ peak is less certain, and 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 $\sim 8 \times 10^5$ counts s^{-1} 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 shows 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.

Figure 6 shows a preliminary neutral gas density profile determined from the RFC data. When estimating the neutral density values, a secondary electron yield of 0.3 was assumed for incident neutral particles with a velocity of ~80 km s^{-1}. The dashed line in Fig. 6 represents a simple fit to the data assuming an $r^{-2} \exp(-r/\lambda)$ neutral density dependence on the distance r from the nucleus. The ionization scale length λ was estimated to be 2×10^6 km, and a value of 1.3×10^{30} molecules s^{-1} was obtained for the total gas production rate, assuming a neutral gas velocity of 1 km s^{-1}.

The data shown in Fig. 6 were obtained during the inbound pass of the Vega 1 fly-by. 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.

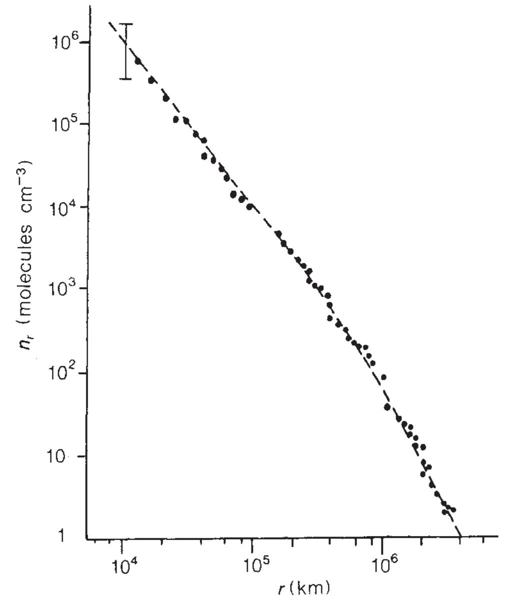

Fig. 6 Neutral gas density profile determined from the ram Faraday cup (RFC) data. The data are fitted to a curve of the form $n_r = n_0(r_0/r)^2 \exp(-r/\lambda)$, where n_r is the neutral gas density at distance r from the nucleus, $r_0 = 10^5$ km, and the ionization scale length $\lambda = 2 \times 10^6$ km. The gas production rate Q was estimated as $Q = 4\pi r_0^2 n_0 v_g$, where the neutral gas velocity v_g was assumed to be 1 km s^{-1}.

As discussed above, both Vega spacecraft crossed a wide and structured bow shock region at $\sim 1.1 \times 10^6$ 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[4-8]. It was found that the mass-loaded, shocked plasma flow is dynamically controlled by the solar wind between the bow shock and the 'cometopause', observed at a distance of 1×10^5 km from the nucleus, which separates the solar-wind-controlled cometosheath and heavy-ion mantle from the magnetized[9] cometary plasma region. This magnetized cometary plasma 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[4,5]. According to previous theoretical 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.

Received 6 April; accepted 16 April 1986.

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First observations of energetic particles near comet Halley

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The TÜNDE-M energetic particle instrument aboard the Vega 1 spacecraft detected intense fluxes of energetic (≥40 keV) ions in the vicinity of comet Halley, starting at a distance of 10^7 km from closest approach. Three regions of differing ion characteristics have been identified. An outer region, several million kilometres

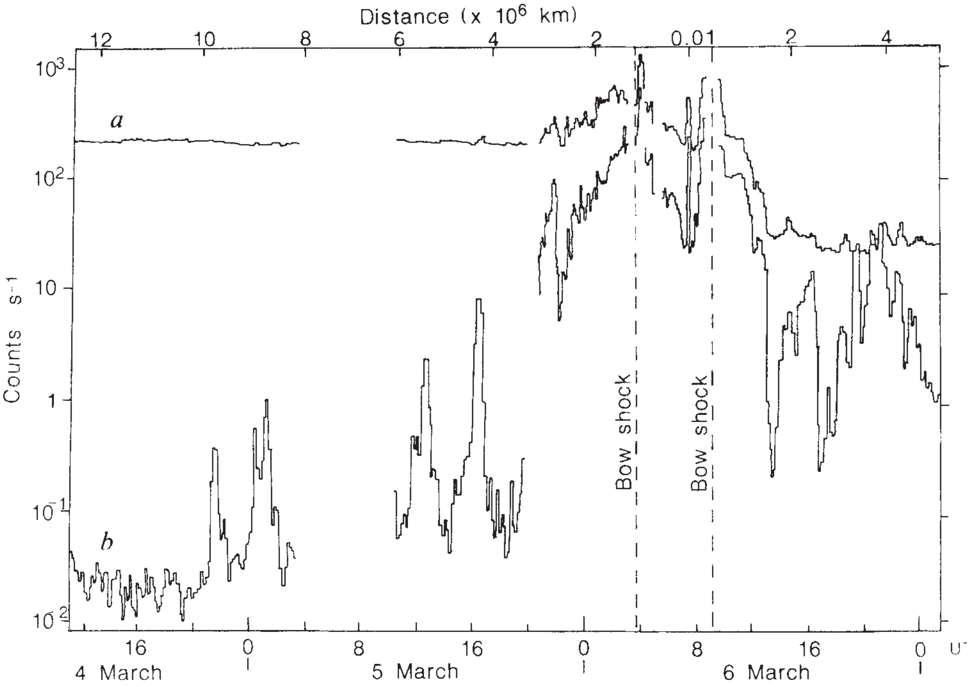

Fig. 1 Ion flux recorded on 4-6 March 1986 by the two lowest-energy channels of the Vega 1 TÜNDE-M. *a*, 40-50 keV; *b*, 50-60 keV. The upper horizontal scale is the distance of the spacecraft from the comet nucleus. The high level of flux seen in the lowest-energy channel (curve *a*) until 20:00 on 5 March is probably due to temporarily increased instrumental background. The outbound shock cannot be located unequivocally: the position indicated is a possible location deduced from our measurements, combined with magnetic observations[15].

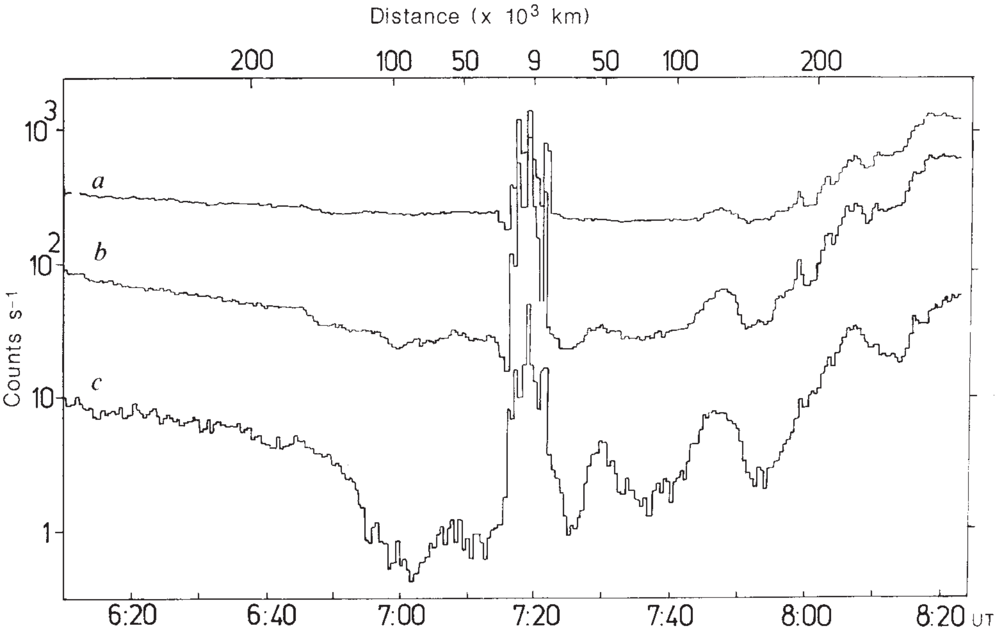

Fig. 2 An expanded version of the region of Fig. 1 near the time of closest approach to the nucleus (07:20 UT on 6 March).

in extent, contains pick-up ions in the solar wind. A second region, inside the bow shock (several hundred thousand kilometres in extent), contains the most intense fluxes, whereas the innermost region (several tens of thousands of kilometres) is characterized by lower intensities and sharp spikes near closest approach (~8,900 km from the nucleus).

Cometary ions are created from cometary neutrals by photoionization and charge exchange with solar-wind particles. The newly created cometary ions are approximately at rest; they are then accelerated by the solar-wind electric field, **E**, resulting at first in cycloidal motion in the **E** × **B** direction, where **B** is the interplanetary magnetic field[1,2]. The cometary ion distribution function forms a ring in velocity space, drifting parallel to **B** (refs 2, 3). This type of distribution is highly unstable and generates magnetic fluctuations which 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[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 nucleus), and by magnetic reconnection up- and 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 ~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 two typical TÜNDE-M records; expanded plots of the fluxes observed near the time of closest approach are shown in Fig. 2. 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 ref. 10). The contamination of the measured ionic fluxes by electrons was negligible during the period of observation discussed here, partly because of a deflecting magnet applied to the top detector, and partly because of the anti-coincidence condition requiring total absorption of the particles in the top detector[8,9].

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 $\sim 10^6$ km (refs 11, 15) and $\sim 5\times 10^5$ km (see Fig. 1 legend), respectively, from the nucleus. Energetic ions are detected as far as 10^7 km from the nucleus; the scale length of this region is $\sim 10^6$ km. (2) A region containing the most intense fluxes, including the shock[15] and most of the cometosheath[11]. The extent of this region is several hundred thousand kilometres. (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 kilometres. Near closest approach, several distinct intensity spikes are observed over a region of several thousand kilometres. 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 within $\sim 3\times 10^6$ km. Superimposed on this general trend are a number of discrete flux enhancements of 1 to 2 orders of magnitude, exhibiting a quasi-periodicity of $\sim$4 h. The presence of these enhancements is related to the prevailing solar-wind and magnetic field conditions. From the energy spectra a 'temperature' of $\sim$5 keV can be estimated.

The ion fluxes (Fig. 1) begin to increase more rapidly as the shock is approached. The flux at higher energy increases faster; thus, the spectrum hardens. This 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 depletion zone discussed below) remain approximately the same with only a moderate decrease. As the solar wind velocity decreases considerably in this region[11], this observation indicates further acceleration of cometary ions after pick-up, by turbulences in this region (first- and second-order Fermi processes[5,6]). Other processes, such as 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, which is probably due to the enhanced level of turbulence observed by the wave experiments on Vega-1[14].

In the innermost region, which extends from $\sim$06:50 to $\sim$08:05 UT (Fig. 2), the energetic ion fluxes are much lower, 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[11] instruments 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 are depleted by charge-exchange collisions with neutrals[1]. For a production rate $Q \simeq 10^{30}$ molecules s^{-1}, the charge-exchange time near the edge of the depletion zone ($R \lesssim 10^5$ km) is estimated as 10^3 s, which is indeed comparable to the transport or convection time for an almost stagnated solar wind ($u \lesssim$ 30 km s^{-1}). 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' distributions should exist.

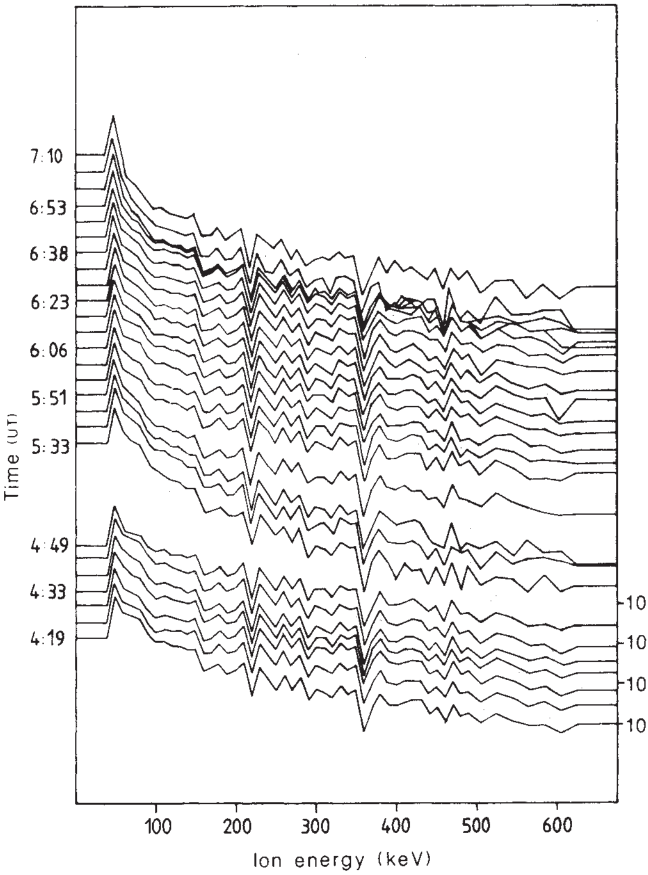

Fig. 3 Time series of ion flux versus energy profiles measured by the Vega 1 TÜNDE-M during the 3 h preceding closest approach. Points represent 5-min averages of count rate (per s), multiplied (for ease of display) by $(t/5)\times 10^{0.4}$, where t is time (min) measured from 04:19 UT on 6 March 1986. The sharp decreases in count rate at 210 and 350 keV are caused by differences in the energy-channel widths, for which correction has not yet been made.

Near the closest approach of Vega 1 to the nucleus (07:20 UT in Fig. 2), a set of closely spaced, narrow peaks are evident at all energies. We note that 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, as detected by the TÜNDE-M experiment, increases very rapidly from the background counting rate at closest approach to the cometary nucleus, and stays high for $\sim$4 h afterwards. No significant variation in this flux had been observed for several days preceding closest approach.

Received 4 April; accepted 16 April 1986.

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Magnetic field observations in comet Halley's coma

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During the encounter with comet Halley, the magnetometer (MISCHA) aboard the Vega 1 spacecraft observed an increased level of magnetic field turbulence, resulting from an upstream bow wave. Both Vega spacecraft measured a peak field strength of 70–80 nT and observed draping of magnetic field lines around the cometary obstacle. An unexpected rotation of the magnetic field vector was observed, which may reflect either penetration of magnetic field lines into a diffuse layer related to the contact surface separating the solar-wind and cometary plasma, or the persistence of pre-existing interplanetary field structures.

Our present understanding of the interaction of the solar wind with the ionized gas cloud surrounding a comet derives from the pioneering work of Alfvén[1] and Biermann *et al.*[2] The deceleration of the solar-wind plasma in the vicinity of the comet due to mass loading bends the magnetic field lines around the inner parts of the coma and stretches the magnetic field in the anti-solar direction. The resulting configuration can be modelled by modern computer simulations[3] in three dimensions; however, these simulations do not reveal where the plasma will be unstable to the production of magnetohydrodynamic plasma waves. Thus, the ICE (International Cometary Explorer) spacecraft observations of strong turbulence in the vicinity of comet Giacobini-Zinner[4] were somewhat unexpected, but are now much better understood[5].

The magnetic field experiments MISCHA (Magnetic field in interplanetary space during comet Halley's approach) carried by Vega 1 and Vega 2 use four sensor fluxgate systems, with three sensors mounted on a boom at the end of the solar panels and a gradiometer sensor mounted one metre closer in. The instruments have a dynamic range of ±100 nT and a sensitivity of 0.05 nT. Spectral analysis of magnetic field fluctuations in the frequency range 0–10 Hz is performed on board the spacecraft. A more detailed description can be found in ref. 6.

On 6 March 1986 (7:20:06 UT), Vega 1 passed the nucleus of comet Halley at a distance of 8,890 km with a relative velocity of 79 km s^{-1}. Vega 2 passed Halley on 9 March 1986 (07:20:00 UT) at a distance of 8,030 km and with a relative velocity of 76 km s^{-1}. Two days before the encounters the magnetometers were switched from the cruise-phase mode (TRASSA-1 mode: 1 vector per 2.5 min) to the TRASSA-2 mode (1 vector per min and 1 spectrum per 5 min). From 3 h before until 1 h after closest approach the DT-mode (direct transmission, 10 vectors per s) was switched on.

At a distance of 1.1×10^6 km the spectral channels of the Vega 1 magnetometer showed a significant increase of the turbulence in the frequency range 0.05–2 Hz (Fig. 1). During the encounter

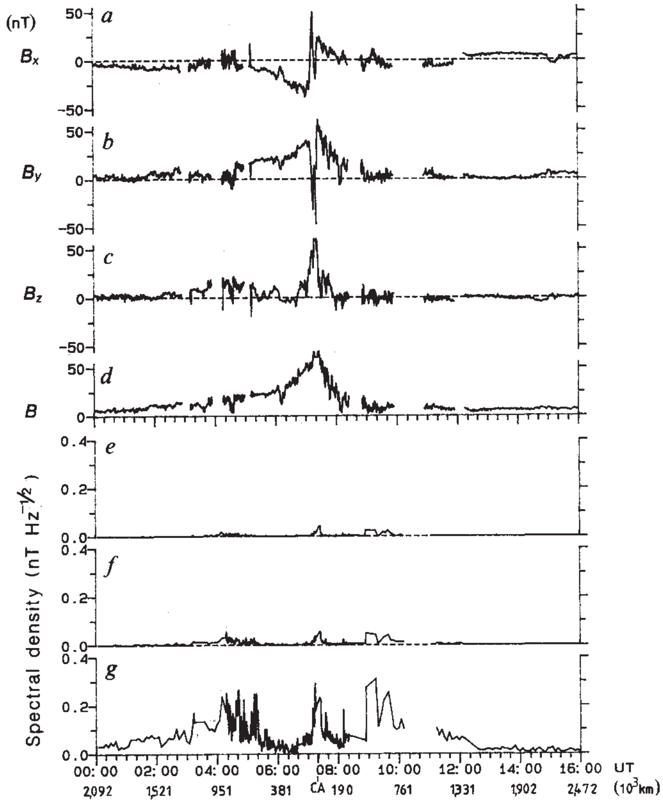

Fig. 1 Components (a–c), magnitude (d) and power spectral density (e–g) of the B_x component during the Vega 1 encounter on 6 March 1986. The spectral densities shown are for the frequency ranges 1.367–1.992 (e), 0.703–1.328 (f) and 0.039–0.664 (g) Hz. The increase of turbulence at 03:10 UT and the decay of turbulence at 12:05 can be interpreted as an inbound and outbound bow wave. The lower horizontal scale is the distance of the spacecraft from the nucleus; 'CA' denotes the closest approach to the nucleus at 07:20:06 UT (8,980 km). x, y and z are cometary solar ecliptic, (CSE) coordinates: z points towards the north pole of the ecliptic, x points from the comet towards the Sun (but parallel to the ecliptic), and y completes the right-handed coordinate system.

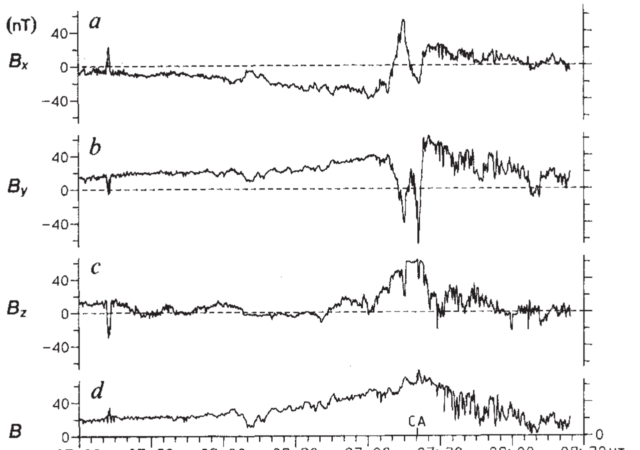

Fig. 2 High-resolution (10 vectors per s) magnetic field data from the Vega 1 encounter. CA, closest approach.