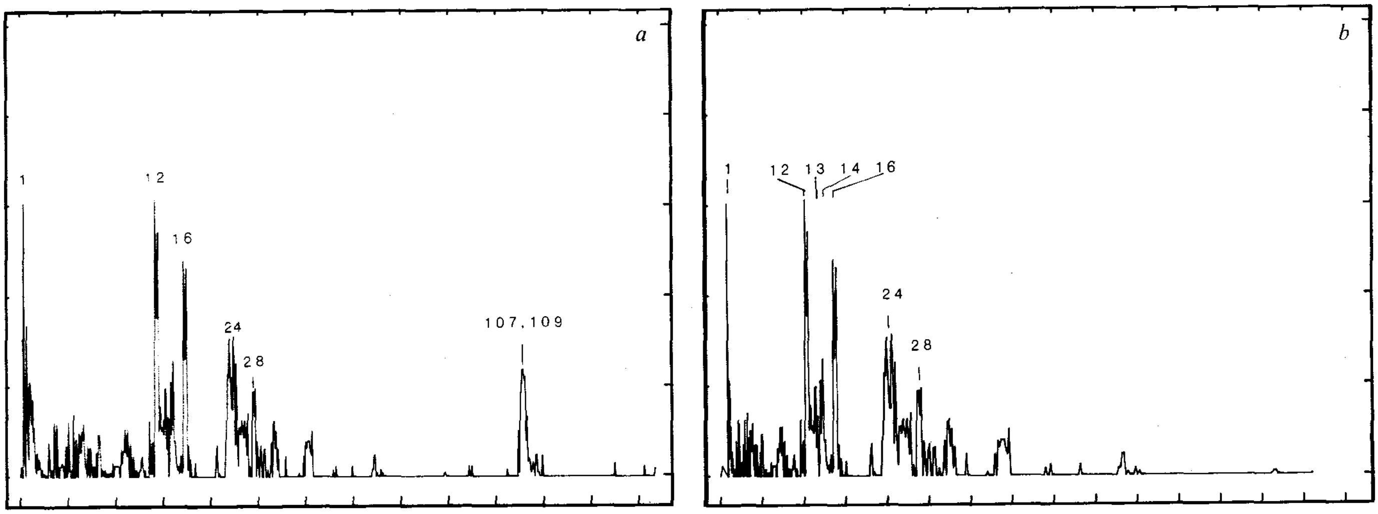

Fig. 3 Mass spectrum of a cometary particle measured by PUMA-1, aboard Vega 1 (internal reference no. 51445). See Fig. 1 legend. This mass spectrum may be regarded as typical for particulates composed predominantly of light elements. See text for further explanation.

unprocessed spectra, from which the effects of instrument characteristics have not been removed. The validity of the small peaks will have to be proved by summing several spectra. Each spectrum is plotted both as a mass spectrum (upper part of each figure), and as a time-of-flight spectrum (lower part), as originally measured. The logarithmic intensity scale shows only the expected sensitivity. The figures are used to illustrate the important features of the data; they are by no means suited to a more detailed interpretation.

The mass spectrum in Fig. 1 is characterized by its dominant mass lines, which are—apart from the contribution of the target material Ag at 107 and 109 AMU—the peaks at 12, 16, 23, 24, 28, 40 and 56 AMU, indicating the presence of C, O, Na, Mg, Si, Ca and Fe. (No peaks were observed at half the atomic mass of Ag; we therefore assume that all ions are singly charged.) These particles may be closest in composition to the C1 carbonaceous chondrites, which was expected. The mass spectrum in Fig. 2 differs from that in Fig. 1 mainly in having peaks at 1, 12, 13, 14 and 32 AMU, indicating a material richer in carbon, nitrogen, and sulphur.

The mass spectrum in Fig. 3 shows dominant peaks at 1, 12 and 16 AMU, with almost no contributions at 24, 28 and higher values. These may be particles with only a small or perhaps no mineral core. Examining all the mass spectra, including those taken in modes with higher data compression, it is striking that ~80% of all spectra seem to be of the type shown in Figs 2 and 3; the remainder are similar to that in Fig. 1. The apparent high content of carbon and nitrogen makes it difficult to accept type C1 carbonaceous chondrites as the sole chemical model for cometary dust particles.

The mass spectra of the type shown in Fig. 3 may indicate that some of the cometary material released may be ice-processed by ionizing radiation as proposed in ref. 8, and thereby converted to a non-volatile compound. The composition of other particles may support the formation model proposed in ref. 9, in which comets are aggregates of interstellar dust particles, consisting of a silicate core embedded into a non-volatile organic mantle, produced from ices by ultraviolet radiation before solar nebular condensation. Gross isotopic anomalies have not been detected as yet.

Received 9 April; accepted 11 April 1986.

1. Divine, N. *Eur. Space Ag. spec. Publ.* **174**, 25-30 (1981).
2. Mamyrin, B. A., Karatyev, V. I., Shmikk, D. V. & Zagulin, V. A. *Zh. éksp. teor. Fiz.* **64**, 82 (1973).
3. Sagdeev, R. Z. *et al. Venus-Halley Mission* (Louis-Jean, Gap, 1985).
4. Kissel, J. *Eur. Space Ag. spec. Publ.* **1077**, 67-68 (1986).
5. Brownlee, D. E. *A. Rev. Earth Planet. Sci.* **13**, 147-173 (1985).
6. Drapatz, S. & Lichel, K. W. *Z. Naturf.* **29A**, 870 (1974).
7. Krueger, F. R. *Z. Naturf.* **38A**, 385 (1983).
8. Brown, W. L., Lamerotti, L. J. & Johnson, R. E. *Science* **218**, 528 (1982).
9. Greenberg, J. M. in *Comets* (ed. Wilkening, L. L.) 131-163 (University of Arizona Press, Tucson, 1982).

First *in situ* plasma and neutral gas measurements at comet Halley

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We present the first *in situ* observations and a description of the large-scale behaviour of comet Halley's plasma environment. The PLASMAG-1 experiment, carried aboard the spacecraft Vega 1 and Vega 2, had the following aims: (1) to study the change of plasma parameters and distributions as a function of distance from the nucleus; (2) to investigate the existence and structure of the cometary bow shock; (3) to determine the change in chemical composition of the heavily mass-loaded plasma as the spacecraft approached the comet; and (4) to measure the neutral gas distribution along the spacecraft trajectory. We observe a discontinuity (the 'cometopause') between the solar-wind-controlled cometosheath and heavy-ion mantle and the magnetized cometary plasma region. From the measured neutral gas density distribution we estimate a total gas production rate of 1.3×10^{30} molecules s^{-1}.

Each Vega spacecraft carried a plasma instrument package (PLASMAG-1) comprising six different sensors[1,2]. Two hemispherical electrostatic analysers 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

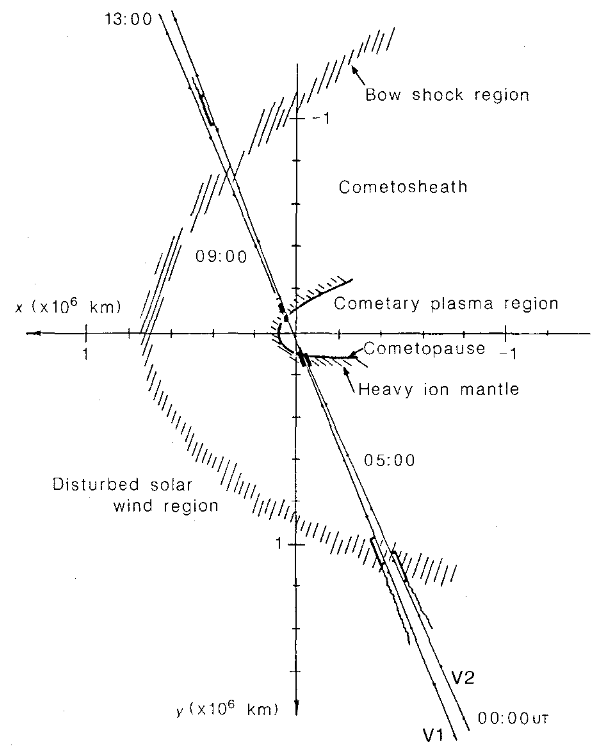

Fig. 1 The plasma environment of comet Halley, as observed by Vega 1 and Vega 2, projected on the spacecraft orbital plane. The x-axis points from the comet nucleus to the Sun. Features of the PLASMAG-1 data are marked with symbols along the spacecraft trajectories (V1, V2), which are marked at 1-h intervals of Universal Time. Wavy lines, region of disturbances in the solar-wind plasma distribution; open rectangles, heavily structured bow shock region; solid rectangles, heavy-ion mantle (see Figs 2, 3).

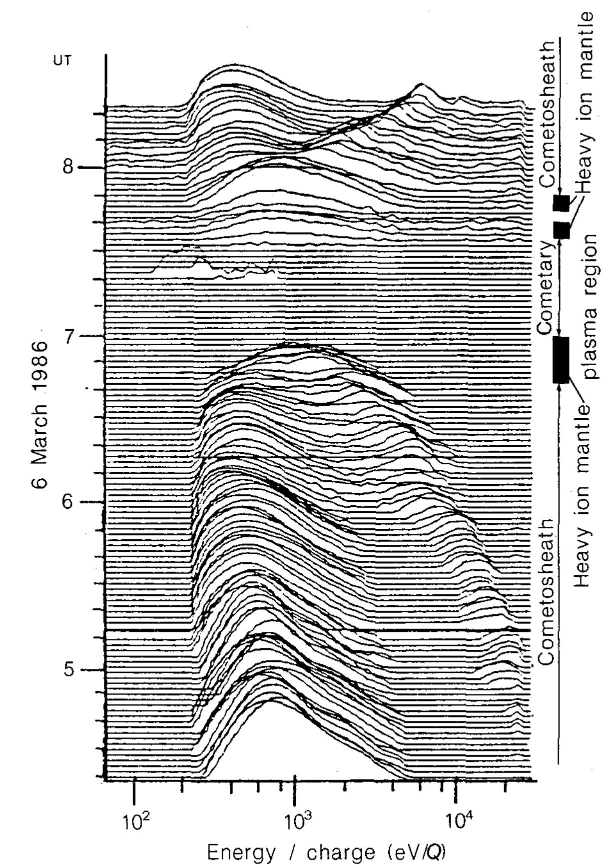

Fig. 2 High-time-resolution ion energy spectra (2-min averages) measured by the Vega 1 solar direction analyser (SDA) during encounter. Annotations refer to the regions shown in Fig. 1.

referred to as the cometary ram analyser (CRA) and solar direction analyser (SDA), respectively. Because of the three-axis stabilization of the spacecraft, electrostatic lenses were installed at the entrance slits of both ion analysers in order to widen the acceptance angle without decreasing the energy resolution. The CRA had an acceptance angle of $14° \times 32°$ and detected ions in the energy/charge range 15-3,500 eV/q (where q is the charge state), in 120 logarithmically spaced intervals which provided a complete coverage of this range without any gaps. The SDA had an acceptance angle of $38° \times 30°$ 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 analyser with an acceptance angle of $7° \times 7°$ 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 at a rate of 1 per s for ~4 h, beginning 3 h before the time of closest approach to the nucleus. During the 2 days before and 1 day after closest approach, spectra were continuously measured at a rate of 0.35 per min.

PLASMAG-1 also included two Faraday cups. The solar direction Faraday cup, with an acceptance angle of $84° \times 84°$, measured the solar-wind ion flux. The ram Faraday cup (RFC), with an acceptance angle of $25° \times 25°$, has 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.

Figure 1 shows a schematic representation of the various plasma regions observed during the Vega 1 and Vega 2 encounters. On the inbound legs both SDAs measured a relatively fast solar wind (velocity $u \simeq 510$ and 620 km s^{-1}, respectively). The first sign of the comet was detected by the CRA, which observed ions of cometary origin as far as 5×10^6 km from the nucleus.

As the spacecraft approached the bow shock region, disturbances started to appear in the solar-wind plasma distributions (wavy lines in Fig. 1). At a distance of ~1.1-1.2 $\times 10^6$ 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 plasma, the 'cometosheath', where the proton distribution broadened significantly, so that the peak of α-particles became indistinguishable in the energy spectrum. (The width of the transition region between the solar wind and the cometosheath is small compared with its distance from the nucleus: for this reason we use the term 'bow shock', rather than 'bow wave', which was applied to the transition region at comet Giacobini-Zinner[3].) The direction of the plasma stream was no longer anti-sunward, as the CRA and SDA detected proton fluxes of approximately the same energy. Vega 2 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.

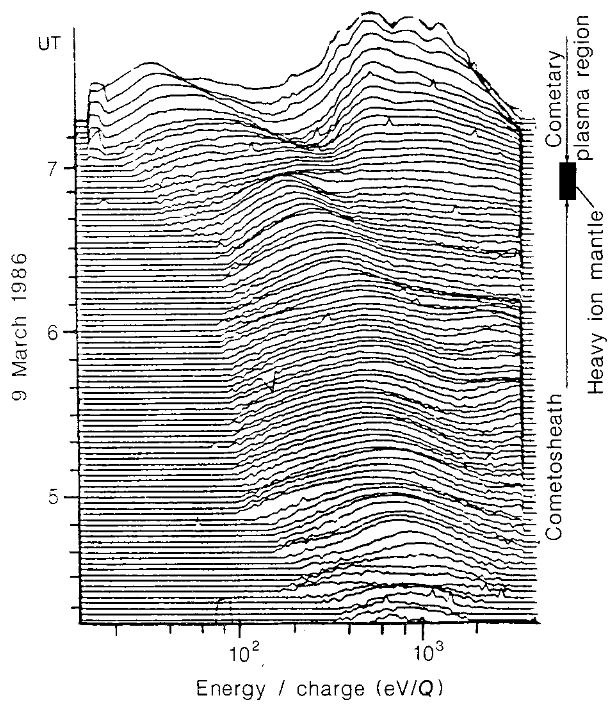

Fig. 3 High-time-resolution ion energy spectra (2-min averages) measured by the Vega 2 cometary ram analyser (CRA) during encounter. Annotations refer to the regions shown in Fig. 1.

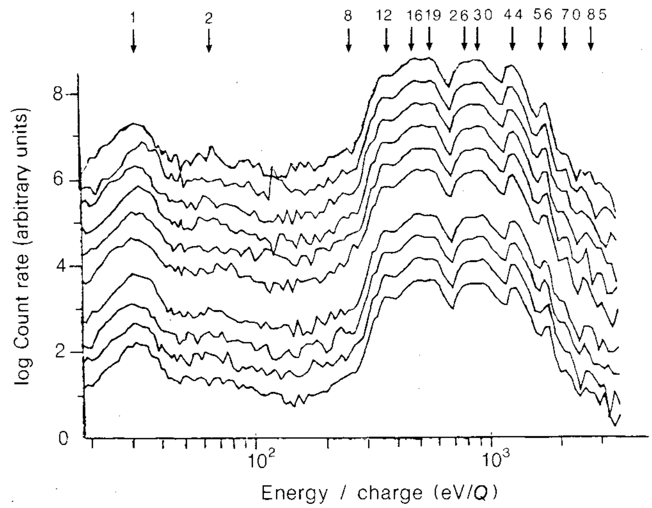

Fig. 4 Ion energy spectra (1-s averages) measured by the Vega 2 CRA at a distance of 1.5×10^4 km from the nucleus. Some of the mass/charge (M/q) peaks are identified in the text.

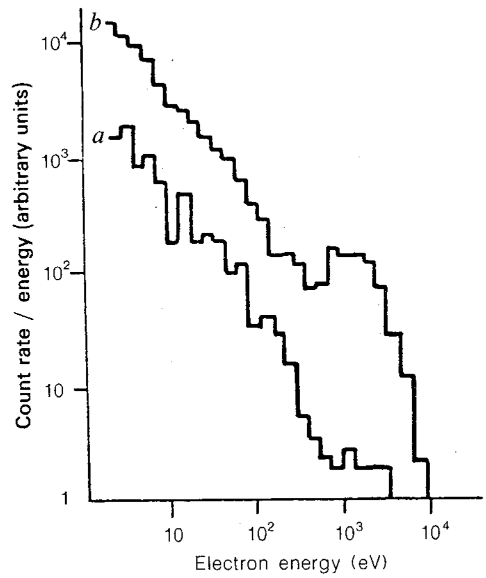

Fig. 5 Electron energy spectra measured in the solar wind (*a*, 07:03 UT, 11 March) and at a distance of 1.5×10^4 km from the nucleus (*b*, 07:17:29 UT, 9 March).

On the outbound leg Vega 1 observed a broad, eroded bow shock region at a distance of $\sim1.1\times10^6$ km from the nucleus before re-entering the solar wind ($u\simeq380$ km s^{-1}).

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 $\sim8\times10^5$ km from the nucleus (04:20 UT), a single broad peak dominates the spectra, corresponding to a shocked solar-wind proton flow with a velocity of $\sim$350–400 km s^{-1}. Closer to the nucleus a second peak appears in the SDA spectra which corresponds 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 $\sim3\times10^5$ km from the nucleus (06:15 UT), 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 $\sim1.5\times10^5$ km from the nucleus (06:45 UT), the original solar-wind population effectively disappears from the solar direction; instead, the SDA observes mainly a broad distributon of slow cometary ions. This region can be called the 'heavy ion mantle', where the plasma is moving slowly around the cometary obstacle. Shortly afterwards, at $\sim1\times10^5$ km (07:00 UT), the SDA stops detecting particles. On the outbound pass, the cometary ions reappear in the SDA at $\sim7\times10^4$ km from the nucleus (07:35 UT), after which the shocked solar-wind protons can again be observed.

Figure 3 shows 2-min averages of the high-resolution spectra obtained by the Vega 2 CRA, starting at $\sim8\times10^5$ km from the nucleus (04:20 UT); that is, well downstream of the bow shock region. Between 8×10^5 and $\sim1.5\times10^5$ km (06:45 UT), the CRA observes a broad distribution of decelerated protons. These particles are probably diverted solar-wind protons with largely randomized velocities which were observed simultaneously by the SDA. Signatures of heavy cometary ions can be seen in the upper part of the measured energy range, and simultaneous SDA data (not shown here) indicate that at $\sim1.5\times10^5$ km from the nucleus, the solar-wind proton population is replaced by a slowly moving layer of heavy cometary ions (the heavy ion mantle observed by Vega 1).

At $\sim1\times10^5$ km (06:55 UT), the spacecraft entered the cold, almost stagnant or only very slowly moving cometary ion region which is characterized by increasing ion fluxes in the 300–3,000 eV/q range. This region is inhomogeneous, comprising extended stratified zones with layers of regularly varying density (corresponding to a characteristic length along the orbit of $\sim$800 km). At $\sim1.5\times10^4$ km the CRA detected only cold cometary ions and it is possible to carry out a mass analysis of these heavy ions. Unfortunately, not long afterwards the plasma instrument became temporarily disabled by exposure to the harsh cometary environment.

Figure 4 shows expanded versions of several successive 1-s spectra measured by the CRA in the cometary plasma region. The first peak is due to H^+ ions, $\simeq$30 eV, indicating a velocity nearly equal to the spacecraft-comet relative velocity, $v_R=$

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.

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.

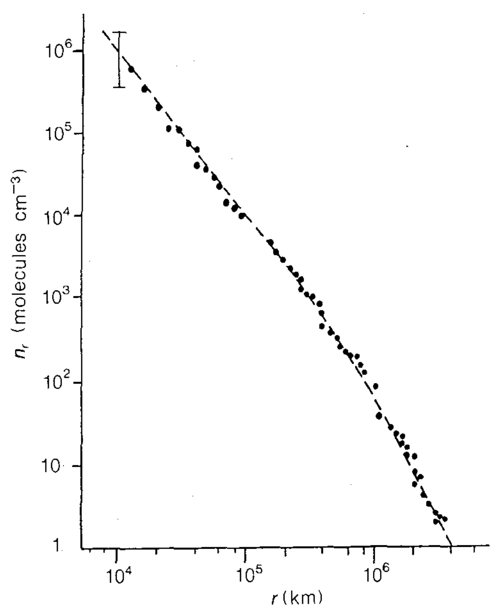

Fig. 6 Neutral gas density profile determined from the ram Faraday cup (RFC) data. The data are fitted to a curve of the form $n_r = n_0(r_0/r)^2 \exp(-r/\lambda)$, where n_r is the neutral gas density at distance r from the nucleus, $r_0 = 10^5$ km, and the ionization scale length $\lambda = 2 \times 10^6$ 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}.

Received 6 April; accepted 16 April 1986.

1. Gringauz, K. I. *et al.* in *Cometary Exploration* Vol. 3 (ed. Gombosi, T. I.) 333-349 (Central Research Institute for Physics, Budapest, 1983).
2. Gringauz, K. I. *et al.* in *Field-, Particle- and Wave-Experiments on Cometary Missions* (eds Schwingenschuh, K. & Riedler, W.) 157-171 (Austrian Academy of Sciences, Graz, 1985).
3. Jones, D. E. *et al. Geophys. Res. Lett.* **13**, 243-246 (1986).
4. Ip, W.-H. & Axford, W. I. in *Comets* (ed. Wilkening, L. L.) 588-634 (University of Arizona Press, Tucson, 1982).
5. Mendis, D. A., Houpis, H. L. F. & Marconi, M. L. *Fundam. cosmic Phys.* **10**, 1-380 (1985).
6. Sagdeev, R. Z., Shapiro, V. B., Shevchenko, V. I. & Szegő, K. *Geophys. Res. Lett.* **13**, 85-88 (1986).
7. Galeev, A. A., Cravens, T. E. & Gombosi, T. I. *Astrophys. J.* **289**, 807-819 (1985).
8. Sagdeev, R. Z. *et al.* Hungarian cent. Res. Inst. Phys. Preprint No. KFKI-1985-100 (1985).
9. Riedler, W., Schwingenschuh, K., Yeroshenko, Ye. G., Styashkin, V. A. & Russell, C. T. *Nature* **321**, 288-289 (1986).

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