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ACCELERATION OF COMETARY PLASMA IN THE VICINITY OF COMET HALLEY ASSOCIATED WITH AN INTERPLANETARY MAGNETIC FIELD POLARITY CHANGE

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Abstract. Based on the ion plasma and magnetic field observations of Vega-1 near its closest approach to comet Halley a self-consistent scenario is developed according to which the observed magnetic field topology, the observed burst of ions at energies 200 - 600 eV, and the observed directional dependence of the flow of these ions leads to the conclusion that these burst-particles are cometary ions which have been accelerated by the process of merging of magnetic field lines of opposite polarity.

Introduction

In order to ensure the simultaneous observation of solar wind and cometary ion plasma throughout the encounter with comet Halley, two pairs of sensors with wide fields-of-view (FOV) were incorporated into the Plasmag-1 experiment package on board Vega-1 and Vega-2 (Gringauz et al., 1983 and 1986a). Each pair consisted of a hemispherical ion electrostatic analyzer and an ion Faraday Cup. One pair pointed towards the solar direction (the SDA and the SDFC sensor, respectively) while the other pair pointed into the spacecraft-comet relative velocity or ram direction (the CRA and the RFC sensor, respectively).

Based on the measurements of these sensors the existence of a cometary bow shock at about 10^6 km from the nucleus, the effect of continuous mass-loading by cometary ions causing deceleration of the solar wind in the upstream and cometosheath region, the existence of a theoretically unexpected boundary (cometopause) at about 1.6×10^5 km, and the existence of a region dominated by cometary ions (cometary plasma region), together with the composition of the cometary ions in these regions were determined (Gringauz et al., 1986b, 1986c, 1986d, and 1986e; Verigin et al., 1986).

In particular, it was found that throughout the cometary plasma region (bounded by the in- and outbound cometopause) the SDA sensor practically ceased to detect any ions coming from the solar direction. However, in the case of the Vega-1 encounter, the SDA sensor observed a burst of ions with energies $E_i \approx 100 - 1000$ eV near to closest approach with comet Halley which lasted for about 5 min. The purpose of this communication is to discuss the observations of this event, and, by comparison of plasma and magnetic field measurements, to propose an explanation for its origin.

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Observations

During the encounter of Vega-1 with comet Halley only three of the four aforementioned sensors were operating: the Solar Direction Analyzer SDA with a FOV of $30^\circ \times 38^\circ$, providing ion spectra in the energy range 50 - 25000 eV/Q in 60 logarithmically spaced intervals, the Solar Direction Faraday Cup (SDFC) and the Ram Faraday Cup (RFC) with FOV's of $84^\circ \times 84^\circ$ and $25^\circ \times 25^\circ$ respectively, providing measurements of the total ion flux from the solar direction and from the spacecraft-comet ram direction, respectively.

Figure 1a shows the sequence of ion spectra (intensity vs. energy/charge) obtained by the SDA sensor on the inbound and outbound leg of Vega-1 within the cometosheath, the cometary plasma, and the cometsheath regions of comet Halley, respectively. During its passage through the cometary plasma region the SDA sensor practically ceased to detect any ions coming from the solar direction, with the exception of a burst-like enhancement (marked in black) observed near closest approach (CA) of Vega-1 relative to the nucleus of comet Halley; CA occured at 7:20:06 UT and at a cometocentric distance of 8889 km. A detailed sequence of 5 sec averaged ion spectra associated with this event is shown in Figure 1b. Here the spectra were smoothed by taking a running average over three adjacent energy intervals, and the counting rates are plotted on a logarithmic scale (see scale at right). From this figure we find (1) that a well-defined flux of ions coming from the solar direction was observed between 7:19 and 7:24 UT, (2) that the region of this enhanced ion flux was not symmetric with respect to the time of closest approach, and (3) that the mean energy of these ions was about 600 eV before 7:21:30 UT but about 200 eV afterwards, i.e., that a sudden shift of the maximum energy towards the lower end occurred at that time.

For roughly the same time interval as in Figure 1b, we show in Figure 2 the 1 second averaged measurements of the collector currents of the SDFC sensor at its retarding voltages of U_R = 0, 15 and 3500 V. We find that during the interval when the SDA sensor observed the ion burst the collector currents for U_R = 0 and 15 V became positive and increased to about 10^{-9} A. For U_R = 3500 V, however, the collector current remained negative and even decreased slightly to about $(0.5 - 1) \times 10^{-9}$ A. By subtracting the values of the first from the second current and by taking the effective area of the SDFC sensor of 1.6 cm^2 into account, we can estimate the total ion flux coming from the solar direction as $(5 - 8) \times 10^9$ cm^{-2} sec^{-1}.

During most of this event the current amplifier of the RFC sensor was saturated as a consequence of the very large flux of neutrals. The density of cometary ions coming from the ram direction could therefore only be estimated to be a few thousands cm^{-3}, roughly consistent with

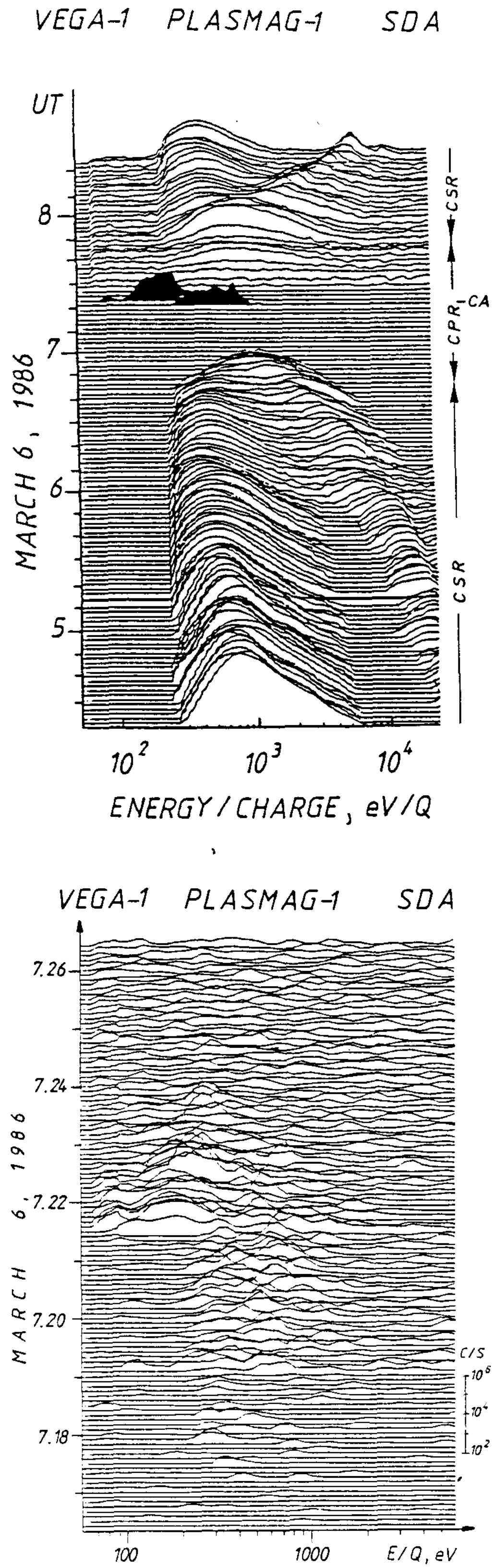

Fig. 1: Sequence of energy-per-charge spectra observed by the solar-direction ion electrostatic analyzer SDA on board of Vega-1: (a) on the in- and outbound leg in the cometosheath regions (CSR) and in the cometary plasma region (CPR) (Gringauz et al., 1986b); (b) around closest approach (CA) of comet Halley (CA at 7:20:06 UT).

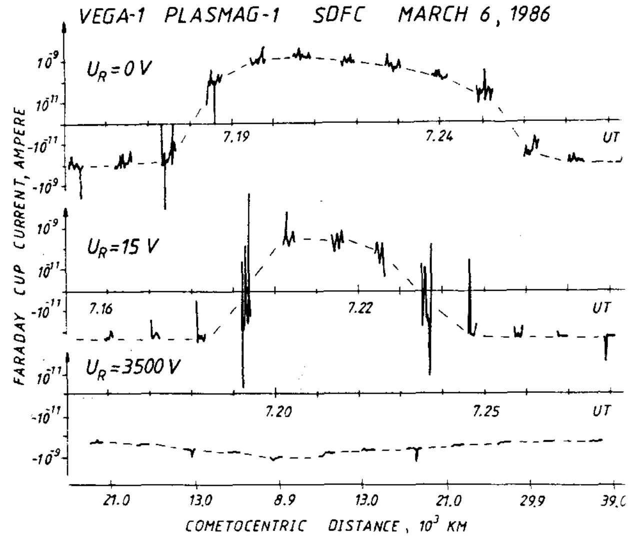

Fig. 2: The collector currents measured by the solar-direction ion Faraday cup SDFC on Vega-1 at the reflection voltages U_R indicated.

Giotto measurements at a similar distance from the nucleus (Balsiger et al., 1986).

Discussion

The rather short duration and asymmetric position relative to the point of closest approach suggests that this burst-like event originated from some non-stationary or localized process. Inspecting the evolution of the magnetic field direction along the spacecraft trajectory, we find, on a global scale, the signature of magnetic field line draping around the comet near closest approach. The field points in the anti-solar direction on the inbound leg and in the solar direction on the outbound leg of the Vega-1 trajectory (Riedler et al., 1986; Schwingenschuh et al., 1986), indicating the draping of an interplanetary magnetic field of positive polarity. Between 7:11 and 7:24 UT, however, the magnetic field topology is exactly the opposite, pointing first in the solar and shortly before closest approach in the anti-solar direction (see Riedler et al., 1986, Figure 4). Thus, over this short period of time the magnetic field exhibits the signature of magnetic field line draping which has the opposite (negative) polarity compared with the adjacent, global field. It should be mentioned that some hours prior to the encounter of Vega-1 with comet Halley the B_x component of the IMF changed its sign. It was therefore suggested by Schwingenschuh et al. (1986) that the portion of the IMF observed near closest approach is a remnant of the IMF of the previous polarity being convected towards the nucleus by the steadily decelerated plasma flow and therefore arriving at the nucleus at a delayed time (see Figure 3a).

Certainly, the interaction of the two portions of magnetic fields of opposite polarities will lead, when interacting and reconnecting near closest approach, to an X-type magnetic field pattern as assumed in the explanation of disconnection events proposed by Niedner and Brandt (1978). The overall scenario of the

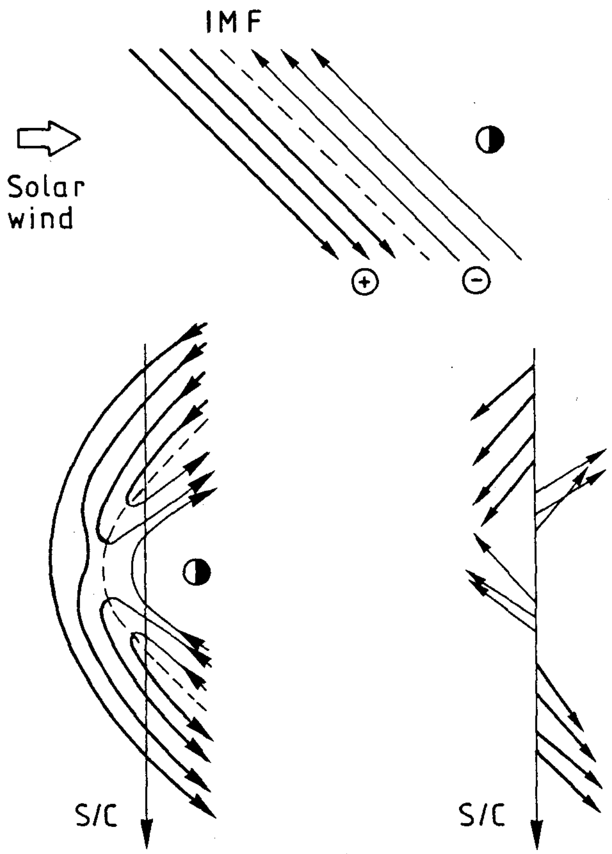

Fig. 3a: Overall picture of the interaction and reconnection of interplanetary magnetic fields (IMF) of opposite polarity near the cometary nucleus and the resulting changes in the magnetic field direction along the spacecraft (S/C) trajectory.

process leading to this type of magnetic field topology is sketched in Figure 3a. Here we also include the anticipated changes in the magnetic field direction along the trajectory of a spacecraft (S/C) passing through such a magnetic field structure. The Vega-1 magnetic field observations are shown in Figure 3b in terms of a cometocentric solar ecliptic coordinate system; the topology is obviously similar to that shown in Figure 3a. The trajectory of Vega-1 is also shown in the diagram (tick-marks correspond to 1 min.), together with the observed directions of the magnetic field, given by the arrows. The region in which the SDA and SDFC sensors observed the enhanced flux of ions from the solar direction is indicated by dots. From this figure it seems quite reasonable to suggest that these ions were accelerated by the process of magnetic field line reconnection near closest approach. If so, then these accelerated cometary ions would have left the merging region at some velocity V_i along the surface separating the magnetic fields of different directions. The question then arises as to why these particles are then observed by the SDA/SDFC sensor, and why only on the outbound leg near 7:20 UT but not on the inbound leg near 7:14 UT?

The answer is provided by Figure 4. Here in spacecraft-centered velocity coordinates V_x, V_y ($V_x || X_{CSE}$), the velocity vector $\underline{V}_s$ of the ions which are at rest in the cometocentric coordinate system is shown on the left-hand side (Figure 4a) together with the look-directions and the angular FOV's of the SDA, SDFC and RFC sensors. In Figure 4b a possible diagram of the velocity vectors $\underline{V}_s$, $\underline{V}_i$ and $\underline{V} = \underline{V}_i + \underline{V}_s$ is shown, where $\underline{V}_i$ is the (to be determined) velocity of the accelerated cometary ions in the comet frame of reference and $\underline{V}$ their velocity in the Vega-1 frame of reference. This diagram holds for the outbound situation. For the inbound case the direction of the magnetic field (and therefore of $\underline{V}_i$) is close to the direction of $\underline{V}_s$, and hence so is the direction of $\underline{V} = \underline{V}_i + \underline{V}_s$.

As the vector $\underline{V}_s$ is fixed, both in direction and magnitude ($V_s \approx 80$ km sec^{-1}), we find from Figures 4a and b that, in order to be detected by the SDFC/SDA sensor the accelerated cometary ion velocity V_i relative to the comet must exceed about 35 km sec^{-1} on the outbound leg and will never be detected by these sensors on the inbound leg.

However, inbound the RFC sensor would have been in a favourable position to detect these accelerated particles. But, as has been mentioned before, its current amplifier was saturated during that time which makes it impossible to clearly identify any burst-like enhancement.

On the other hand, we know from ion composition measurements (Gringauz et al., 1986e; Balsiger et al., 1986) that cometary ions are predominantly water-group ions with a mass of 16 - 18 atomic mass units. With a velocity

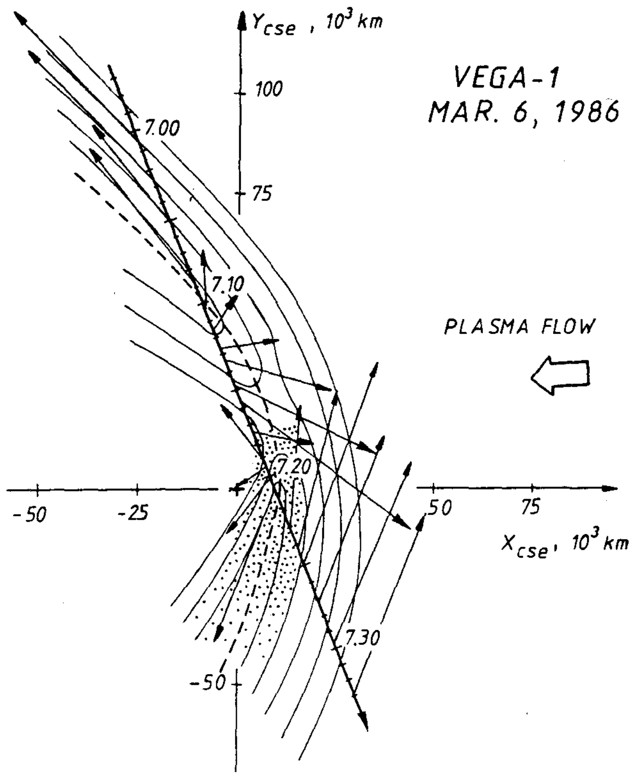

Fig. 3b: Overall topology of the magnetic field around closest approach as deduced from the measurements of the magnetic field direction (arrows) along the Vega-1 trajectory. The dotted area represents the region in which the burst of accelerated ions (see Figure 1 and 2) was observed.

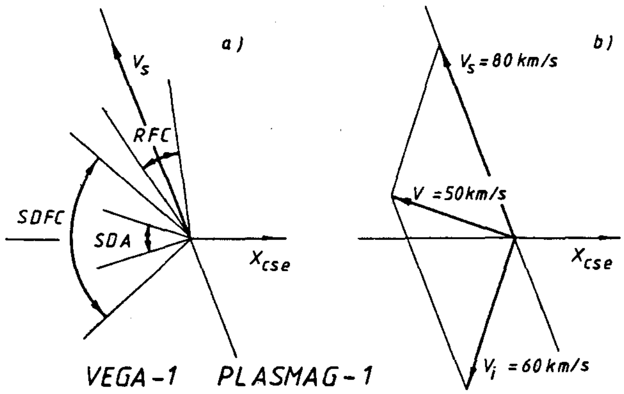

Fig. 4a: Schematic representation of the look-directions and the fields of view of the SDA, SDFC and RFC sensors on board Vega-1 relative to the cometary nucleus and to the spacecraft velocity direction $\underline{V}_s$.
Fig. 4b: Vector diagram of the spacecraft velocity $\underline{V}_s$ and of the ion velocities $\underline{V}_i$ and $\underline{V}$ in the cometary frame and in the spacecraft frame of reference, respectively. $\underline{V}_i$ is presumed to be roughly parallel to the magnetic field lines. Only for large values of $V_i \gtrsim 35$ km sec^{-1} will ions be detected by the SDFC/SDA sensors, as in this case $\underline{V}$ will fall into the field-of-view of the SDA/SDFC sensors.

relative to the Vega spacecraft of about 50 km sec^{-1} (see Figure 4), they will be observed at energies $E_i \gtrsim 200$ eV by the SDA analyzer. This is in agreement with the actual measurements shown in Figure 1. From the SDFC measurements we estimated the total ion flux as $(5 - 8) \times 10^9$ cm^{-2} sec^{-1}. Taking now their velocity V relative to the spacecraft into account, we are able to estimate their density as $N_i \gtrsim (1 - 2) \times 10^3$ cm^{-3}. This value agrees roughly with the number density estimated from the RFC observations.

Based on these different, yet self-consistent observations we may in summary conclude that the burst of cometary ions observed by the SDA and SDFC sensors on board Vega-1 near closest approach to comet Halley was produced by the motion of cometary ions of the water-group accelerated up to some tens of km sec^{-1}. This acceleration could be caused by merging of interplanetary magnetic field lines of opposite polarity retarded by the presence of cometary plasma and neutrals. At this stage it is not clear whether these accelerated particles are part of the higher-energy tail or represent the bulk motion of the plasma.

Finally, we may compare the velocity of these accelerated cometary ions with the average speed of the cometary plasma and with the Alfvén velocity: Taking the intensity of the magnetic field of ≈ 60 nT (Schwingenschuh et al., 1986) and the ion density as estimated above into account, we find an Alfvén velocity of 7 - 10 km sec^{-1}. In comparison, the speed of the cometary plasma within the cometopause is generally less than 3 km sec^{-1} (Balsiger et al., 1986). Thus the general flow of cometary plasma is subalfvénic, whereas the motion of the accelerated cometary ions discussed here is superalfvénic. The physical consequences and associated phenomena of such a superalfvénic flow in the cometary plasma region will be consider elsewhere.

Finally, we would like to mention that the Tünde-M experiment on board Vega-1 also detect a well-defined intensity enhancement of ions > 40 keV between ≈ 7:17 - 7:24 UT (Somogyi et al., 1986). From Figure 4b we find that $\underline{V}$ is practically parallel to $\underline{V}_i$, as $V_i >> V_s$ for these particles, and that $\underline{V}$ is pointing direct into the FOV of the Tünde-M sensors. We may th conclude that reconnection of magnetic field lines of opposite polarity near to closest approach caused an acceleration of cometary io up to energies greater than 40 keV.

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