

# Plasma properties from the upstream region to the cometopause of comet P/Halley: Vega observations

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**Summary.** Based on the Plasmag-1 plasma measurements on board Vega-1 and -2, evidence is provided for the deceleration upstream, for the heating at and for the thermalization and deceleration behind the bow shock of comet Halley. In the cometsheath region two separate ion populations are observed: the first one consists of cometary ions being picked up in the vicinity of the point of observation; the energy of these ions coming from the solar direction decreases much faster than the energy of the solar wind ions. The second one consists of cometary ions being picked up by the solar wind far away from the point of observation. Considerable oscillations in the plasma flow direction occur in the cometsheath region.

**Key words:** Vega – cometsheath plasma observations

## 1. Introduction

The plasma observations on board Vega-1 and Vega-2 revealed the existence of a bow shock at a distance of about  $10^6$  km from the nucleus of comet P/Halley and of a new boundary, called the cometopause, at a distance of about  $1.6 \cdot 10^5$  km, respectively (Gringauz et al., 1986b–d).

The purpose of this communication is to summarize certain well-defined properties of the plasma flow and of its thermalization, deceleration and mass-loading by heavy ions originating from cometary neutrals in the region from upstream of the bow shock into the cometsheath outside of the cometopause. These properties are then discussed qualitatively.

## 2. Plasma observations

The plasma observations in the vicinity of comet Halley presented in this communication were obtained by the two hemispherical ion electrostatic analyzers of the Plasmag-1 experiment on board the two Vega spacecraft: the SDA and the CRA, looking into the solar direction and into the spacecraft-comet relative velocity direction, respectively. These sensors had rather wide acceptance geometries of  $30^\circ \times 38^\circ$  and of  $14^\circ \times 32^\circ$ , and they measured ions in the range

of 50–25 000 eV/ $Q$  in 60 and of 15–3500 eV/ $Q$  in 120 logarithmically spaced energy intervals. A detailed description of these sensors is given by Gringauz et al. (1983, 1986a) and by Apáthy et al. (1986).

### 2.1. Up-stream deceleration and bow shock crossings

In Fig. 1 the decrease in the solar wind proton velocities with cometocentric distance  $R$  is shown, as measured by the SDA on both Vega-1 and Vega-2 during their inbound legs. At this time the SDA sensor provided seven complete ion energy-over-charge spectra per twenty minutes. The location of the bow shock, which was determined from simultaneous measurements of the plasma, the plasma waves and of the magnetic field (Galeev et al., 1986), is marked by S. As one can see, the decrease of the solar wind velocity due to mass loading by heavy cometary ions started already at a distance of  $2\text{--}3 \cdot 10^6$  km from the nucleus, i.e.  $1\text{--}2 \cdot 10^6$  km upstream of the bow shock.

Figure 2 presents the energy spectra measured by the SDA on board Vega-1 when crossing the bow shock on the inbound leg and on the outbound leg, respectively. Besides the gradual slowing down of protons, a gradual widening of the energy spectra can be observed when approaching the comet, i.e. the ion temperature is increasing several hours before reaching the bow shock. After a data gap of 20 min around 3.00 UT, the ion temperature is already so high that the proton distribution overlaps the  $\alpha$  particle peak in the spectrum. The gradient of the velocity is increasing significantly when crossing the bow shock at a distance of  $1.02 \cdot 10^6$  km from the nucleus ( $\sim 3.46$  UT). It was shown by Galeev et al. (1986) that Vega-1 crossed a quasiperpendicular and Vega-2 a quasi-parallel bow shock on their inbound legs, respectively.

The situation is more complicated when crossing the bow shock on the outbound leg of Vega-1. The highest gradient in the plasma velocity was observed between 9.00 and 9.30 UT at a distance of about  $5.5 \cdot 10^5$  km from the nucleus. At the same time the ion temperature stayed high so that the  $\alpha$  peak could not be distinguished from the proton distribution until 11.30 UT ( $R \approx 1.2 \cdot 10^6$  km). Thus, on the outbound leg the bow shock was crossed at a distance of  $5.5 \pm 1 \cdot 10^5$  km (Galeev et al., 1986), and the high ion temperature which can be observed until 12.20 UT for another about  $8 \cdot 10^5$  km is associated with the high level of MHD activity in the foreshock region upstream of a quasiparallel cometary bow shock (Schwingschuh et al., 1986).

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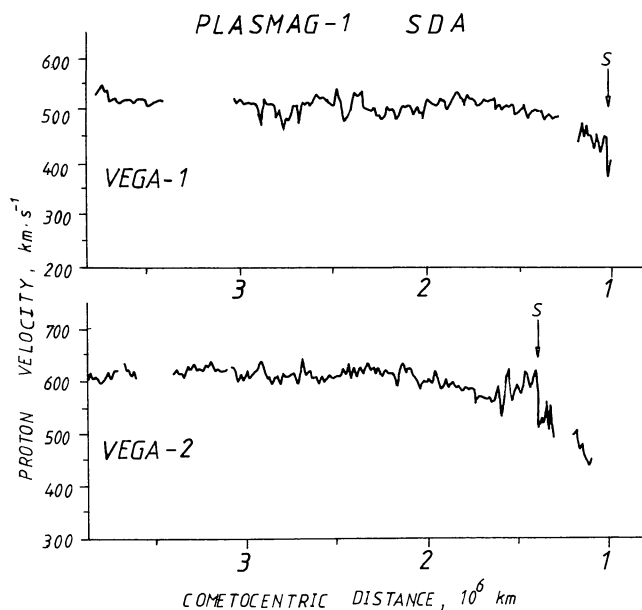


Fig. 1. Radial dependence of the solar wind bulk velocity, as observed by Vega-1 and Vega-2 on their inbound trajectories upstream of the bow shock of comet Halley (marked by S), respectively

### VEGA-1 PLASMAG-1 BOW SHOCK CROSSINGS

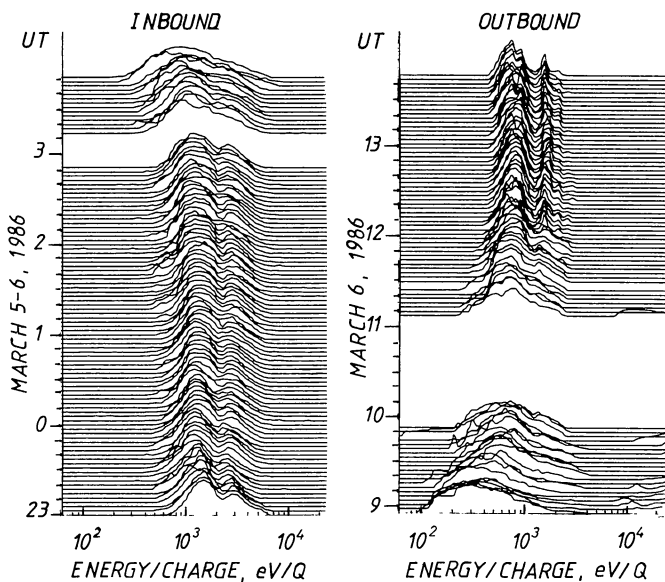


Fig. 2. Two sequences of ion energy-over-charge ( $E/Q$ ) spectra measured by Vega-1 on its inbound and outbound leg in the vicinity of the bow shock of Halley's comet, respectively

### 2.2. Cometosheath observations

Downstream of the inbound bow shock both Vega spacecraft entered the region which was called cometosheath (Gringauz et al., 1986b). In Fig. 3 the ion spectrogram (intensity vs. energy-over-charge vs. time) is shown, as observed by the SDA on board Vega-1 from a cometocentric distance of  $\sim 8 \cdot 10^5$  km inbound to  $\sim 3 \cdot 10^5$  km outbound. The closest approach to comet Halley

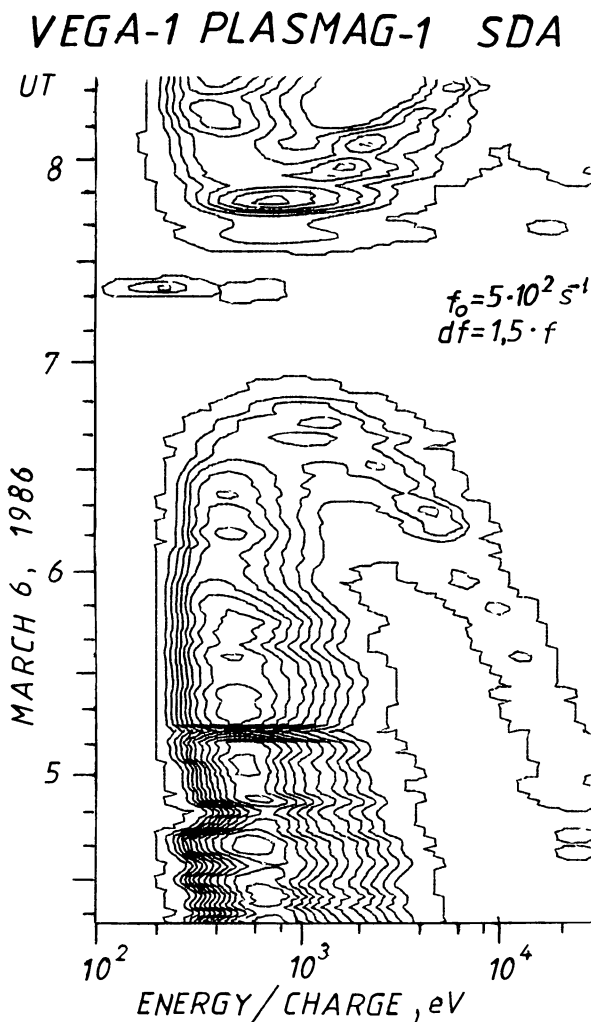
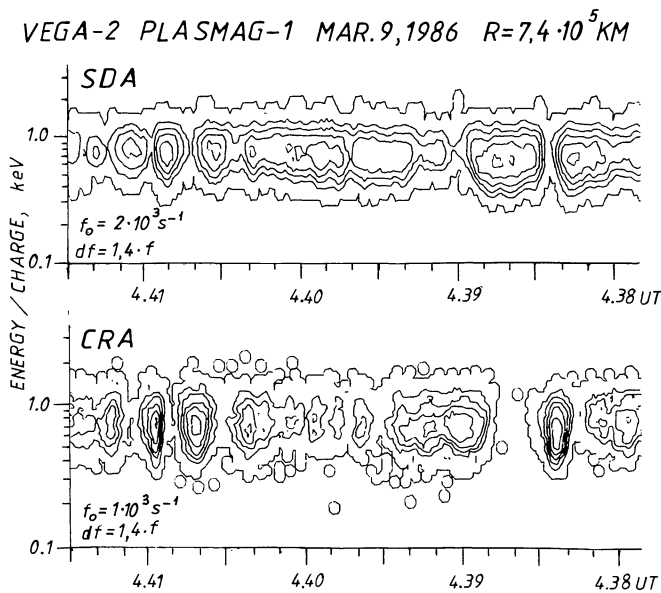


Fig. 3. Spectrogram (count rates vs.  $E/Q$  vs. time) of the ion flux throughout the cometosheath region measured by Vega-1. Closest approach at 7:20:06 UT. Normalization of iso-count rate lines: outermost line  $f_0$ ; increase for any adjacent line by  $df$

occurred at 7:20:06 UT or at a distance of 8889 km. In this spectrogram the outermost isoline corresponds to a counting rate of  $f_0 = 5 \cdot 10^2 \text{ s}^{-1}$ . Each following isoline represents a counting rate which is of a factor of 1.5 higher than its adjacent outer line, i.e.,  $f_{n+1} = f_n + df$  with  $df = 0.5 f_n$ ,  $n = 0, 1, 2, \dots$

The main feature in this spectrogram is the occurrence of two branches in the energy distribution of ions lasting until about 6.40 UT. The left hand-side branch corresponding to the lower energy obviously describes the solar wind protons and  $\alpha$  particles which were thermalized and slowed down at the cometary bow shock. The more energetic branch on the right hand-side must represent the cometary ions, since ions of such a high energy were never observed by the SDA in the solar wind. When extrapolating the energy peak corresponding to these cometary ions to larger distances from the nucleus, where it exceeds the upper limit of the energy range of 25 keV of the SDA, one can conclude that these cometary ions belong to the water group (e.g.  $\text{O}^+$ ,  $\text{OH}^+$ ,  $\text{H}_2\text{O}^+$ , or  $\text{H}_3\text{O}^+$ ), since their extrapolated energy is 60–80 times higher than the proton energy. This energy then corresponds to the energy of picked-up ions of the water group moving with a



**Fig. 4.** Spectrograms of the ion fluxes as observed by the sun-directed (SDA) and ram-directed (CRA) ion electrostatic analyzer on board Vega-2 simultaneously in the cometsheath. Note the variations in the direction of the plasma flow of cometary ions

velocity twice the solar wind velocity. These findings have been directly verified by the JPA-IIS measurements on board Giotto (Johnstone et al., 1986).

When proceeding deeper into the cometsheath, the proton energy gradually decreases. The energy of the cometary ions observed in the SDA decreases faster, so that the ratio of the energy of heavy ions to the energy of protons is also decreasing. At distances of  $3\text{--}4 \cdot 10^5$  km from the nucleus (6.00–6.15 UT) the velocity of cometary ions from the solar direction decreases to the value of the proton velocity due to some collective process, which is not quite understood. Also the fluxes of these two populations become comparable. Afterwards the rate of the energy decrease is further increasing for the heavy ions, while the energy of the protons practically does not change any more.

Around the cometopause ( $\sim 6.45$  UT), which separates the cometsheath from the cometary plasma region, solar wind protons disappear from the acceptance angle of the SDA and cometary ions produce a peak around 1 keV in the energy spectrum. When the velocity of Vega-1 relative to the comet ( $79.2 \text{ km s}^{-1}$ ) is taken into account, then the velocity of the heavy ions relative to the comet can be estimated to be a few times ten  $\text{km s}^{-1}$  in the vicinity of the cometopause, while the proton velocity is still around  $200 \text{ km s}^{-1}$  in this region.

After closest approach, these characteristic changes in the cometsheath plasma occur again on the outbound leg but in a reverse order.

### 2.3. Variations in the plasma flow

Besides these large-scale changes in the plasma flow in the cometsheath, which determine the global picture of the solar wind flowing around the comet, a high level of MHD turbulence with a wide frequency range is characteristic for this region.

In the spectrogram presented in Fig. 3, large-scale variations can be observed in the intensity of the ion flow with a period of about 15 minutes.

An example for the variations in the direction of the plasma flow within the cometsheath is presented in Fig. 4. In these spectrograms, registered by the CRA and the SDA at a distance of about  $R \approx 7.4 \cdot 10^5$  km from the nucleus, the characteristic time scale for these variations is 20–30 seconds. The variations in the flow intensity observed by both analyzers are caused by the variations in the direction of the ion flow. When the intensity of the ion flow decreases in the direction of the CRA analyzer, the counting rates observed by the SDA increase simultaneously and vice versa. The approximate value of the deviation of the proton flow from its original direction can be estimated as

$$\delta\alpha \approx \frac{2kT}{mV^2} \ln \frac{N_{\max}}{N_{\min}} \approx 5^\circ,$$

where the proton temperature is  $T \approx 3 \cdot 10^5$  K and the velocity  $V \approx 350 \text{ km s}^{-1}$ , and where the ratio of the maximum to the minimum counting rates is  $N_{\max}/N_{\min} \approx 3\text{--}5$ .

### 3. Discussion

Already the first hydrodynamic models describing the interaction of cometary with solar wind plasma discussed the effect of mass-loading and deceleration of the solar wind by cometary ions occurring even upstream of the bow shock (e.g. Wallis, 1973). From the Vega observations we find that the deceleration length at least qualitatively corresponds to the effective ionization scale length of cometary neutrals mainly of the water-group of about  $2 \cdot 10^6$  km (Gringauz et al., 1986b, c; Remizov et al., 1986).

The ions originating from these cometary neutrals first form a ring distribution in velocity space. The Alfvén wave turbulence being excited by the ion-cyclotron instability of such a distribution isotropizes the newly formed ions in the coordinate system moving with the solar wind (Sagdeev et al., 1986). In this way and after a few cyclotron periods the newly created ions are arriving from the solar direction with a maximum energy  $4 M_i$ -times higher than the proton energy ( $M_i$  is the ion mass number), independently of the angle between the solar wind flow and the magnetic field direction.

In the solar wind upstream of the bow shock, the energy of these heavy ions exceeds the upper limit of the energy range of the SDA ( $E/Q \leq 25 \text{ keV}$ ). But in the outer regions of the cometsheath, where the solar wind flow is already decelerated by the shock and by the mass-loading process, the SDA measurements can be regarded as being in accordance with the above discussed process of the implantation of cometary ions into the plasma flow at large distances from the comet.

The energy spectra of cometary ions as measured by Plasmag-1 in the inner region of the cometsheath might be interpreted in two different ways. Here the ratio of the energy of cometary ions  $E_i^1$  to the proton energy  $E_p$  measured by the SDA is smaller than  $4 M_i$  ( $\approx 60\text{--}80$ ), and it gradually decreases with decreasing cometary distances  $R$ . The IIS sensor of the JPA instrument on board Giotto was able to measure ions up to energies of  $E_i/Q \leq 90 \text{ keV}$  and to estimate the mass of the ions (Johnston et al., 1986). According to the measurements of IIS there is another, more energetic branch in the energy spectrum corresponding to water group ions with an energy of  $E_i^2 \approx 4 M_i E_p$  beside the branch which was also observed by the SDA. If the ratio  $E_i^2/E_p \approx 4 M_i$  is constant in the cometsheath, the ions with energies  $E_i^2$  might have been locally ionized and picked up by the process discussed above. In this case, the ions observed by the SDA with energies  $E_i^1 < E_i^2$  might have been ionized further

upstream of the population with energies  $E_i^2$ , and they might have lost their energy due to some collective processes afterwards (Gringauz et al., 1986c).

However, there is also another explanation for the existence of these two different cometary ion populations: the ions with the energy  $E_i^2$  were actually created far upstream from the point of observation, but the proton energy slightly changes in the cometosheath as observed by the SDA. Hence the ratio  $E_i^2/E_p$  does not change much or stays almost constant, as in the first case. The ions registered with energies  $E_i^1$  were created in the vicinity of the spacecraft. First these ions are only partially involved into the solar wind flow, however, when approaching the cometopause, these ions are not a minor population any more. In the beginning of this process there is no complete isotropization in the coordinate system moving with the solar wind. But when approaching the cometopause, the density of these ions (Fig. 3) is increasing and thus the energy of the solar wind flow will not be large enough to increase the velocity of all the newly created heavy ions. In the vicinity of the cometopause these ions are accelerated only to a velocity of a few times ten  $\text{km s}^{-1}$ . Since the spacecraft has a velocity of  $79.2 \text{ km s}^{-1}$  relative to the comet, the slowly moving newly created cometary ions will be observed by the SDA with an energy of about 1 keV around the cometopause. There is an additional fact in favour of the possibility that the cometary ions belonging to the less energetic branch  $E_i^1$  were created not very far from the spacecraft: the flux of these ions is increasing with decreasing  $R$  (see Fig. 3), corresponding to the increase of the neutral gas density. The fluxes of heavy ions, however, belonging to the high-energy branch do not increase significantly when approaching the nucleus (see Thomsen et al., 1987).

The characteristic time for the variations in the direction of the plasma flow observed by Vega-2 in the cometosheath is about 20–30 s, as shown in Fig. 4. It seems that these variations are connected with the strong turbulence of the plasma flow in this region caused by the newly created heavy ions. Associated with this process, strong MHD turbulence with a maximum at  $10^{-2}$  Hz was observed in the magnetic field (Tsurutani and Smith, 1986) and in the electron component of the plasma (Gosling et al., 1986) in the cometosheath of comet Giacobini-Zinner as measured by ICE.

In the cometosheath the variations of the plasma flow with very long periods (approximately 15 min as seen in Fig. 3) could be caused by large-scale MHD turbulence. The observed period of these variations, however, is comparable with the characteristic time of the solar wind flow in the cometosheath. As  $\tau \approx R/V \approx 10^3$  s for  $R \approx 3 \cdot 10^5$  km and  $V \approx 300 \text{ km s}^{-1}$ , their dimension along the spacecraft trajectory is of the order of  $\approx 10^5$  km and thus comparable with the overall dimension of the cometosheath itself. It is therefore suggested that the plasma flow variations with a characteristic period of about 15 min observed on board Vega-2 in the cometosheath can be associated with MHD turbulence at the eigen-frequencies of the cometosheath-solar wind system.

Finally we want to propose an explanation for why the dimension (along the spacecraft trajectory) of the region of heated

solar wind upstream of the bow shock on the inbound leg differs from that on the outbound leg of Vega-1. As can be seen from Fig. 2, a significant heating of protons and  $\alpha$  particles began at about 2.30 UT ( $R \approx 1.3 \cdot 10^6$  km) as Vega-1 was approaching the comet, and hot protons and  $\alpha$  particles (compared to the solar wind) were also registered up to almost the same cometocentric distance (to  $\approx 12.20$  UT) on the outbound leg. The cometary bow shock, on the other hand, was crossed at a distance of  $1.02 \cdot 10^6$  km inbound and  $5.5 \pm 1.1 \cdot 10^5$  km outbound indicating that the region of heated upstream solar wind had a length of about  $3 \cdot 10^5$  km inbound and of about  $7 \cdot 10^5$  km outbound. One explanation for this difference could be the following one: as the inbound (outbound) bow shock is quasiperpendicular (quasiparallel), upstream, bow shock associated turbulence will extend and heat the solar wind further out outbound than inbound. Another, yet different explanation is the following one: the onset of large-amplitude turbulence is triggered by the ionization and the pick-up process of cometary neutrals exceeding some critical density value and is, therefore, symmetric as a function of cometocentric distance with respect to the inbound and outbound trajectory of Vega-1. From the neutral gas measurements on board Vega-1 (Remizov et al., 1986) we find a gradual increase in density to about 30 particles per  $\text{cm}^3$  at a distance of about  $1.3 \cdot 10^6$  km. This value seems to be sufficient for the onset of a turbulent heating of the solar wind ions caused by the unstable beam-like distribution of the freshly ionized cometary particles. On the other hand, the difference in the location of the bow shock is simply due to the fact that this discontinuity was crossed around the flanks on the inbound leg and much closer to the subsolar point on the outbound leg.

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