CHARACTERISTIC FEATURES OF THE COMETOSHEATH OF COMET HALLEY: VEGA-1 AND VEGA-2 OBSERVATIONS

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ABSTRACT

Based on the PLASMAG-1 measurements on board VEGA-1 and -2 it is shown that besides the deceleration and thermalisation of the solar wind plasma behind the bow shock, two clearly separated populations of cometary ions are observed in the cometosheath region: the first one consists of 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 cometosheath region.

Keywords: VEGA, Cometosheath Plasma Observations

1. INTRODUCTION

Plasma observations performed by the PLASMAG-1 instrument package on board VEGA-1 and VEGA-2 (Refs. 1-3) revealed the existence of a bow shock formed by the increasing mass loading of the solar wind by heavy cometary ions at a distance of about 10^6 km from the nucleus of Halley's comet (Refs. 4-5). In addition, this mass loading process gave rise to a number of features both upstream and downstream of the bow shock (in the cometosheath)which were previously never observed around planets. This paper presents additional experimental data obtained by VEGA-1 and VEGA-2 in the solar wind being disturbed by cometary neutrals, around the bow shock region, and in the cometosheath. The physical properties of the plasma in these regions will be discussed.

2. OBSERVATIONS

The key information of the plasma properties in the outermost regions of interaction of the solar wind with Halley's comet was obtained by the two electrostatic ion analyzers of the PLASMAG-1 instrument package on board of the two VEGA spacecraft. These sensors were measuring the energy spectra of ions, one by looking into the solar direction (SDA), the other by being oriented along the spacecraft-comet relative velocity vector (CRA). SDA had an acceptance angle of 30° x 38°, and it measured ions in the range of 50-25,000 eV/q in 60 logarithmically spaced intervals. CRA detected ions with an acceptance angle of 14° x 32° in the energy range of 15-3500 eV/q in 120 logarithmically spaced intervals. A more detailed description of the instrument is given in Ref. 3.

Figure 1 shows the decrease in the solar wind proton velocities with cometocentric distance R as measured by the SDA on both VEGA-1 and VEGA-2 during their inbound legs. The location of the bow shock, which was determined from simultaneous measurements of the plasma, the plasma waves and of the magnetic field (Ref. 6), 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 $2\text{-}3 \times 10^6$ km from the nucleus, i.e. $1\text{-}2 \times 10^6$ km upstream of the bow shock.

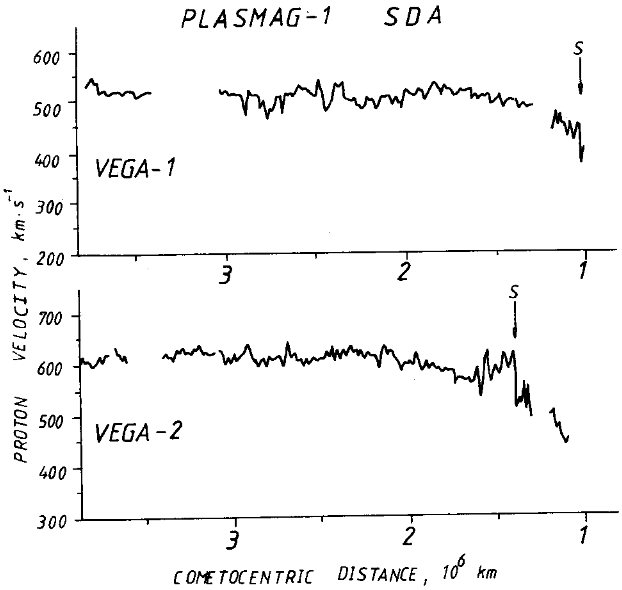

Figure 1 Dependence of the solar wind proton velocity on cometocentric distance upstream of the cometary bow shock (marked with S) on the inbound leg of both VEGA-1 and -2.

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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 outbund leg, respectively. Besides the gradual slowing down of protons, a gradual widening of the energy spectra can be observed when approching the comet, i.e. the ion temperature is increasing several hours before reaching the bow shock. After a data gap of 20 minutes around 3.00 UT, the ion temperature is already so high that the proton distribution overlaps the α particle peak in the spectrum. The gradient of the velocity is increasing significantly when crossing the bow shock at a distance of 1.02x10^{6} km from the nucleus (~ 3.46 UT).

The variation of the plasma parameters seems to be more complicated when crossing the bow shock on the outbund 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 5.5x10^{5} km from the nucleus. At the same time the ion temperature stayed high so that the α peak could not be distinguished from the proton distribution until 11.30 UT (R ≈ 1.2x10^{6} km). Thus, on the outbund leg the bow shock was crossed at a distance of 5.5 ± 1x10^{5} km (Ref. 6), and the high ion temperature which can be observed until 12.20 UT for another about 8x10^{5} km is associated with the high level of MHD activity in the foreshock region upstream of a quasiparallel cometary bow shock (Ref. 7).

Downstream of the inbound bow shock crossing both VEGA spacecraft entered a region which was called the cometosheath (Ref. 4), in order to underline that the physical processes in this region differ from the processes in the magnetosheath of planets having intrinsic magnetic fields or from the processes in the ionosheath of planets having a stronger gravity compared to comets.

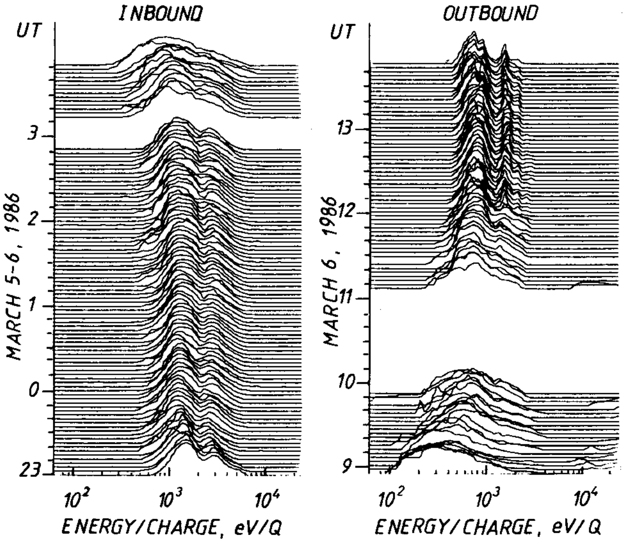

Figure 2 Ion energy spectra measured by VEGA-1 on the inbound leg and on the outbound leg around the bow shock of Halley's comet.

Figure 3 shows the ion spectrogram registered by the SDA on board VEGA-1 in this cometosheath region ranging from a cometocentric distance of ~ 8x10^{5} km on the inbound leg to 3x10^{5} km on the outbound leg. At 7.20:06 UT VEGA-1 was at a distance of 8,889 km from the nucleus which was the closest approach. The outermost isolines correspond to a counting rate of $f_o = 5\mathrm{x}10^2$ sec^{-1}. Each isoline represents a counting rate which is 1.5 times higher than the corresponding value of the adjacent outer line, respectively.

The main feature of the spectrogram presented in Figure 3 is the occurence 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 α particles which were thermalized and slowed down at the cometary bow shock. The more energetic branch on the right-hand side represents 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 the cometary ions to larger distances from the nucleus where it would exceed the 25 keV (the upper limit of the energy range of the SDA), one can con-

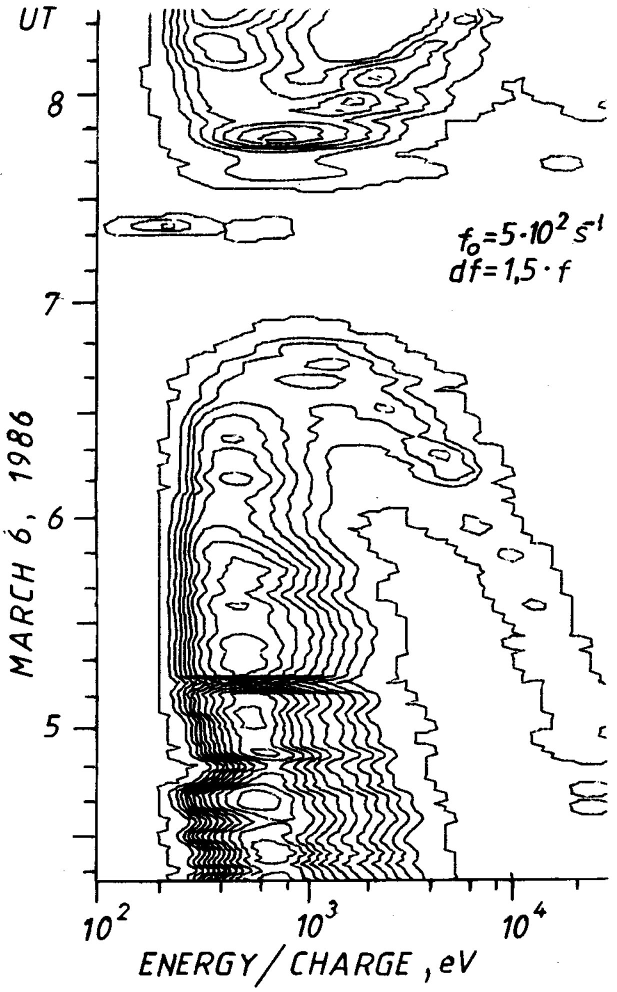

Figure 3 Spectrogram of ion fluxes in the cometosheath measured by the SDA on board VEGA-1.

clude that these cometary ions belong to the water group (e.g. O^+, OH^+, H_2O^+, or H_3O^+) 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 velocity twice the solar wind velocity.

When proceeding deeper into the cometosheath, the proton energy gradually decreases. The energy of the cometary ions observed by 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 3-4x10^5 km from the nucleus (6.00-6.15 UT) the velocity of comeatary ions from the solar direction decreases to the value of the proton velocity due to a 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 (see Figure 3).

Around the cometopause (~6.45 UT), which separates the cometosheath 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 km/sec) is taken into account, then the velocity of the heavy ions relative to the comet can be estimated to be a few times ten km/sec in the vicinity of the cometopause, while the proton velocity is still around 200 km/sec in this region.

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

Besides these large-scale changes in the plasma flow in the cometosheath, 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.

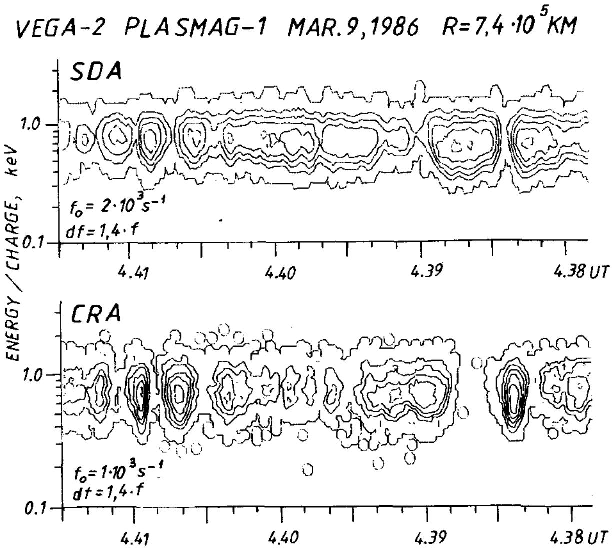

Figure 4 An example for the variation in the direction of the plasma flow around the comet in the cometosheath region.

In the spectrogram presented in Figure 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 cometosheath is presented in Figure 4. In these spectrograms, registered by the CRA and the SDA at a distance of about R ≈ 7.4x10^5 km from the nucleus, the characteristic time scale for these variations is 20-30 sec. 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 this declination of the proton flow from the original direction can be estimated as

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

where the proton temperature is $T \approx 3x10^5$ °K and their velocity V ≈ 350 km/sec, and where the ratio of the maximum to the minimum counting rates is $N_{max}/N_{min} \approx 3-5$.

3. DISCUSSION

The first hydrodynamic models of the interaction of the cometary plasma with the solar wind already discussed how cometary ions can mass-load and decelerate the solar wind even upstream of the bow shock (see e.g. Ref. 9). The scale length of the deceleration observed corresponds qualitatively to the characteristic ionization scale length of neutrals of about 2x10^6 km, as determined by the Ram Faraday Cup RFC of the PLASMAG-1 instrument package (Refs. 4-5, 10).

The ions originating from these cometary neutrals first form a ring 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 (Ref. 11). In this way and after a few cyclotron periods the newly created ions are arriving from the solar direction with an energy $4M_i$-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_i/q < 25 keV). But in the outer regions of the cometosheath, 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 cometary ions being implanted into the plasma flow at large distances from the comet (see Figure 3 and the discussion of the energetic branch).

The energy spectra of cometary ions as measured by PLASMAG-1 in the inner regions of the cometosheath might be interpreted in two different ways. Here the ratio of the energy of cometary ions E_{i1} to the proton energy E_p measured by the SDA is smaller than $4M_i$ (≈ 60-80), and it gradually decreases with decreasing cometocentric distances R. The IIS sensor of the JPA instrument package on board Giotto was able to measure ions up to energies of E_i/q < 90 keV and to estimate the mass of the ions. According to the measurements of IIS there is another more energetic branch in the energy spectrum of water group ions with an energy of $E_{i2} \approx 4M_i \cdot E_p$ (Ref. 12) beside the branch which was also observed by the SDA.

If the ratio $E_{i2}/E_p \approx 4M_i$ is constant in the cometosheath which does not contradict the IIS observations on the inbound leg but which cannot be identified on the outbound leg from Figure 2 of (Ref. 12), the ions with energies E_{i2} might have been locally ionized and picked up by the process discussed above. In this case, the ions observed by the SDA with energies $E_{i1} < E_{i2}$ might have been ionized further upstream of the population with energies E_{i2}, and they might have lost their energy due to some collective processes (Ref. 5).

However, there is also another explanation for the existence of these two different cometary ion populations: the ions with the energy E_{i2} 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_{i2}/E_p does not change much or stays almost constant, as in the first case. The ions registered with energies E_{i1} 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 cometosheath these ions are accelerated only to a velocity of a few times ten km/sec. Since the spaceraft has a velocity of 79.2 km/sec 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 of the less energetic branch E_{i1} were created not very far from the spacecraft, namely the flux of these ions is increasing with decreasing R (see Fig. 2 of (Ref. 12) and Fig. 3 here) corresponding to the increase of the neutral gas density. The fluxes of heavy ions of the branch of higher energy do not increase when approaching the nucleus, as seen in Figure 2 of (Ref. 12).

The characteristic time for variations in the direction of the plasma flow observed by VEGA-2 in the cometosheath is about 20-30 sec, as shown in Figure 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 frequency peak at 10^{-2} Hz was observed in the magnetic field (Ref. 13) and in the electron component of the plasma (Ref. 14) 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 $\tau \approx r/V \approx 10^3$ sec for $R \approx 3x10^5$ km and $V \approx 300$ km/sec, and their dimension along the spacecraft trajectory $\approx 10^5$ km can be compared with the size of the cometosheath. On this basis it can be supposed 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 an excitation by MHD turbulences of the eigen frequencies of the cometosheath-solar wind system.

Finally will be discussed the reasons why the dimension (along the spacecraft trajectory) of the region of hot solar wind upstream of the bow shock on the inbound leg differs from that on the outbound leg of the VEGA-1 trajectory. As can be seen from Figure 2, a significant heating of protons and α particles began at about 2.30 UT ($R \approx 1.3x10^6$ km) when VEGA-1 was approaching the comet; and also on the outbound leg hot protons and α particles (compared to the solar wind) were registered up to the same cometocentric distance (to ≈ 12.20 UT). This distance seems to be determined only by the distribution of the neutral gas density n_n around Halley's comet. The increase of n_n to 30 cm^{-3} at a distance of $1.3x10^6$ km from the nucleus (Ref. 10) is enough to assure a turbulent heating of the solar wind ions caused by the unstable beam-like distribution of ions of cometary origin. The location of the bow shock and the gradient of the ion velocity related to the shock is naturally different on the inbound leg ($R \approx 1.02x10^6$ km) as compared to the outbound leg ($R \approx 5.5 \pm 1x10^5$) of the VEGA-1 trajectory as seen in Fig. 2, since the bow shock was crossed around the flanks on the inbound leg and closer to the subsolar point on the outbound leg. This is the reason why there is a difference between the dimensions of both regions of hot solar wind observed inbound and outbound around the bow shock.

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