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# Interpretation of Vega Observations at Comet Halley Applying Three-Dimensional MHD Simulations

**M. Tátrallyay[1], M. I. Verigin[2], K. Szegö[1], T. I. Gombosi[3], K. C. Hansen[3], D. L. De Zeeuw[3], K. Schwingenschuh[4], M. Delva[4], A. P. Remizov[2], I. Apáthy[5] and T. Szemerey[5]**

[1]KFKI Research Institute for Particle and Nuclear Physics, 1525 Budapest P.O.B. 49, Hungary
[2]Space Research Institute, Profsoyuznaya 84/32, 117810 Moscow, Russia
[3]Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109, U.S.A.
[4]Space Research Institute, Inffeldgasse 12, 8010 Graz, Austria
[5]KFKI Atomic Energy Research Institute, 1525 Budapest P.O.B. 49, Hungary

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**Abstract.** In this work the velocity and density of the plasma flow were determined from Vega-1 and Vega-2 ion energy spectra at distances $> 0.5$ million km from the nucleus of comet Halley. Since the Solar Direction Analyser and the Cometary Ram Analyser of the PLASMAG instrument could observe the distribution of ions only in two limited sections of velocity space (and only the SDA worked aboard Vega-1), the predictions of a three-dimensional MHD simulation developed by Gombosi et al. (1996) were taken into account in order to find the best combination of the adjustable plasma parameters downstream of the bow shock. It was found that the density of the plasma flow was much higher when Vega-1 passed through the cometosheath compared to the Vega-2 flyby. The comparison of simulated and measured magnetic field profiles showed that there was a major disturbance in the interplanetary field after Vega-2 crossed the bow shock.



## 1 Introduction

Neutral particles can travel far away from the nucleus of a comet before they get ionized. The newly born cometary ions will be picked up by the solar wind, i.e. the slow heavy ions are accelerated while the plasma flow is decelerated. First Biermann et al. (1967) published a comprehensive study on the process of continuous ion pickup in cometary atmospheres called the mass loading effect. After this one-dimensional single-fluid hydrodynamic treatment, several more advanced (large-scale, multidimensional) magnetohydrodynamic models were developed in order to understand the interaction of the solar wind with cometary plasma (cf. Schmidt and Wegmann, 1982; Schmidt-Voigt, 1989; Lindgren and Cravens, 1993).

Gombosi et al. (1994) presented the first step in developing a new generation of global MHD models which solved the governing equations on an adaptively refined unstructured Cartesian grid. In this axisymmetric model the major weaknesses of earlier calculations were successfully addressed: the investigated volume was large enough to include the entire upstream mass loading region while the resolution was fine enough in the most interesting high gradient regions, e.g. around the bow shock. In order to describe also non-parallel geometries, a fully three-dimensional multiscale MHD model was developed by Gombosi et al. (1996) using the MAUS-MHD method (Multiscale Adaptive Upwind Scheme for MHD). In the presented simulation the basic physical parameters were chosen to approximate the physical conditions during the Giotto flyby. The calculated plasma and magnetic field parameters were found to be in good agreement with Giotto observations in the inner coma of comet Halley where the cometary ions of the water group dominated the plasma flow.

The Vega spacecraft did not provide three-dimensional plasma observations, therefore model calculations are especially important for the interpretation of ion energy spectra measured around and downstream of the bow shock of comet Halley where the different ion populations could not be easily separated. This paper presents a comparison of plasma and magnetic field measurements performed aboard the Vega space probes with parameters determined by the three-dimensional MHD model developed by Gombosi et al. (1996) when the upstream parameters are taken as observed by Vega-1 and Vega-2, respectively.

## 2 Observations

The PLASMAG instrument package had two spherical electrostatic ion analysers aboard the three axis stabilized twin spacecraft Vega-1 and Vega-2. There was no selection for mass. The Cometary Ram Analyser (CRA)

*Correspondence to:* M. Tátrallyay

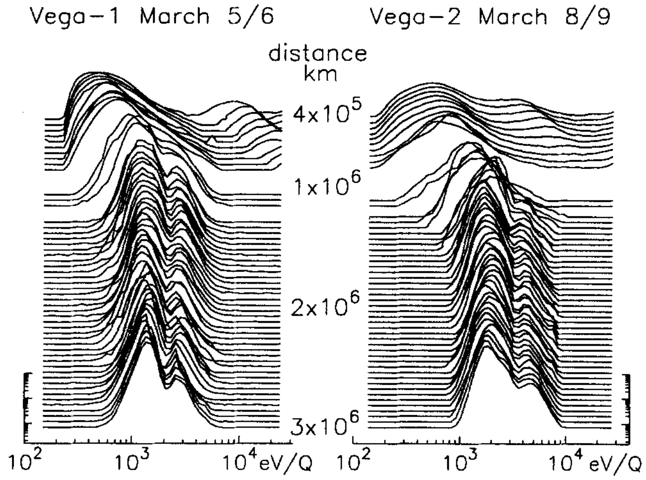


**Fig. 1.** 10 min averaged ion energy spectra taken by the SDA of Vega-1 and Vega-2 during the inbound pass at cometocentric distances between 3 million and 0.4 million km.

had an acceptance angle of 14°×32° centred on the ram direction, while the Solar Direction Analyser (SDA) had an acceptance angle of 38°×30° centred on the solar direction (Gringauz et al., 1986). The CRA worked only aboard Vega-2 at the time of the encounter with comet Halley.

Figure 1 shows 10 min averaged ion energy spectra collected by the SDA of Vega-1 and Vega-2 along the inbound trajectory. Aboard both space probes, one complete spectrum was taken in every ~2.8 min at cometocentric distances 3 - 1 million km, high time resolution (1 spectrum/sec) data sampling began at ~0.85 million km from the nucleus. As reported by Schwingenschuh et al. (1986) and Verigin et al. (1987), the bow shock was observed at a cometocentric distance of ~1 million km by Vega-1 (just before the data gap between the lower and the high resolution session) and at ~1.35 million km by Vega-2. When approaching the shock the proton peak is gradually shifted to lower energies indicating the deceleration of the solar wind caused by the mass loading effect of heavy cometary ions. Just upstream of the shock Vega-2 observed a sudden increase in velocity, the deviation from Maxwellian distribution indicates interplanetary disturbance. Around the shock proton and alpha particle peaks get broader as temperature increases. Downstream of the shock further deceleration of the solar wind component can be observed and a peak caused by cometary pick-up ions appears at higher energies.

A simple model calculation was performed for determining the plasma parameters of the different components by Tátrallyay et al. (1998). The distribution of solar wind protons and alpha particles was approximated by Maxwellians in velocity space while pickup ions were described by a bispherical shell distribution. Tátrallyay et al. (1998) presented all plasma parameters provided by the best fits for some selected spectra in the upstream region, around the bow shock, and in the outer cometosheath. In this work, plasma parameters were determined for protons and alpha particles during the whole inbound trajectory of both Vega spacecraft between 3 million and 0.5 million km from the nucleus.

## 3 Comparison with the predictions of a three-dimensional MHD model

### 3.1 Plasma parameters

Tátrallyay et al. (1997) published a preliminary comparison between proton velocities measured by the SDA of Vega-2 when approaching comet Halley and the plasma flow velocity profile provided by the MHD simulation of Gombosi et al. (1996) applying upstream conditions based on Giotto measurements. In the present study the basic parameters of the MHD simulation were chosen to approximate the upstream conditions observed by Vega-1 and Vega-2 during the inbound pass. Since the interplanetary field was very disturbed in both cases (Tátrallyay et al., 1993), the upstream conditions were different after the flyby.

In Figure 2 continuous lines show model predictions for the flow velocity, direction, and number density in Cometocentric Solar Ecliptic system where the solar wind aberration is not taken into account. Crosses present the parameters calculated from measured spectra by finding the best fit Maxwellians with adjustable parameters as discussed by Tátrallyay et al. (1998). In the middle panels, $V_\Phi$ is the azimuthal angle measured from the solar direction in the ecliptic plane. Here, the dashed lines show the deflection of the flow relative to the spacecraft. Alpha particles and cometary ions of the water group are taken into account in the number density $N = N_p + 4N_\alpha + 18N_i$. From upstream spectra, $N_\alpha = 0.08N_p$ was determined for Vega-1 and $N_\alpha < 0.05N_p$ for Vega-2. In the cometosheath, $N_i = 0.5$ cm$^{-3}$ was applied as an upper limit for the number density of cometary ions.

For both Vega encounters, the gas production rate applied in the MHD model was $Q = 1.1 \times 10^{30}$ s$^{-1}$ which is higher than the value used for Giotto, but lower than suggested by Vega measurements (Gringauz et al., 1986). The velocity of the upstream flow was 500 km/s for Vega-1 and 590 km/s for Vega-2 (371 km/s was applied for Giotto by Gombosi et al., 1996), plasma temperature was $2 \times 10^5$K and $3 \times 10^5$K ($10^5$K), and the number density was 15 cm$^{-3}$ and 8 cm$^{-3}$ (8 cm$^{-3}$), respectively. The difference in the value of the upstream sonic Mach number was negligible in the three cases. The solar wind dynamic pressure, however, was about 2.5 times larger in case of Vega-2 and more than 6 times larger in case of Vega-1 compared to Giotto conditions. Therefore, the bow shock formed much closer to the nucleus, in spite of the larger gas production rate.

The upstream $V_\Phi$ values were arbitrarily chosen as

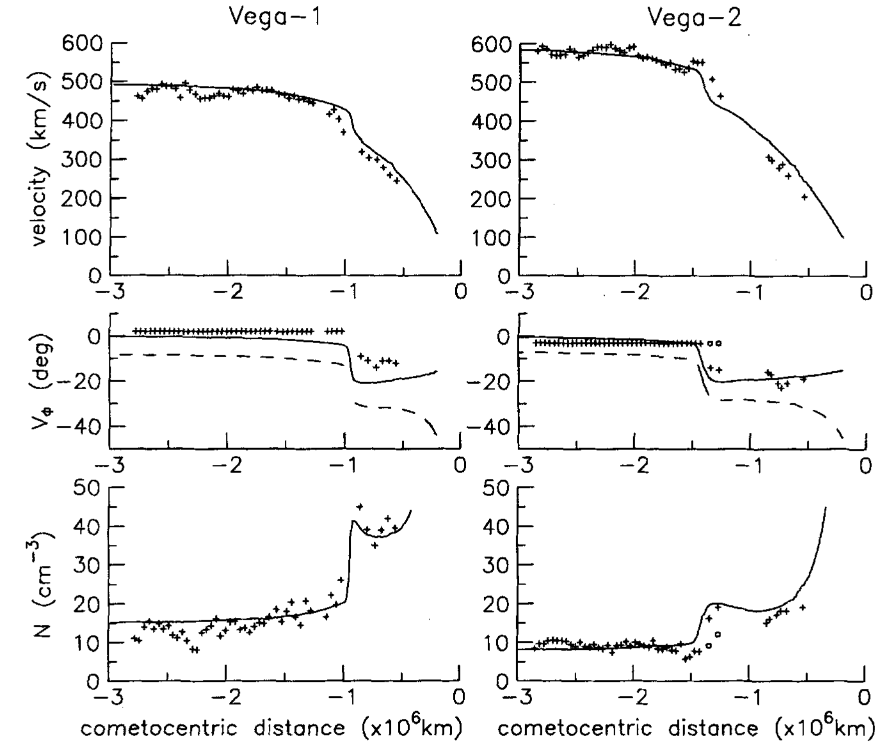


**Fig. 2.** Observed (crosses) and simulated (solid lines) velocity and density profiles along the Vega-1 and Vega-2 inbound trajectory in CSE system. Dashed line: flow deflection from solar direction in spacecraft system.

$V_\Phi = +2°$ for Vega-1 and $V_\Phi = -2°$ for Vega-2 in order to get a similar change between the upstream and downstream direction ($\Delta V_\Phi = 15°-20°$). These values were within the limits permitted by the parameter fitting procedure since the difference in the Maxwellian fits was negligible when the deflection was small ($|V_\Phi| < 3°$) in the upstream region.

At the bow shock simulations predict a sudden change in the direction of the flow which was not detected by the PLASMAG instrument since 1) in case of Vega-1 there was a gap in the observation just after crossing the shock and only the SDA was taking spectra; 2) in case of Vega-2 the temperature was around $5 \times 10^5$K just downstream of the shock and therefore the solar wind population was not seen by the CRA. Here the adjustable Maxwellian parameters $V_\Phi$ and $N$ were chosen as suggested by the MHD simulations. In Figure 2 circles show other possible $V_\Phi$ and $N$ data pairs which would provide good Maxwellian fits, but they do not agree with model predictions.

In the cometosheath the direction of the flow was determined directly from SDA and CRA measurements for Vega-2. Spectra taken around 1 million km from the nucleus (before and after the data gap) indicated an interplanetary disturbance and they could not be fitted by Maxwellian distributions. In case of Vega-1 only SDA spectra were available, therefore the $V_\Phi$ values were approximated by using the model predictions for $N$ and taking into account that larger deflection would be accompanied by too high density. In the outer cometosheath, the temperature of the proton component provided by the Maxwellian fits was more than two times higher in case of Vega-2 than in case of Vega-1.

### 3.2 Magnetic field data

Figure 3 illustrates how this three-dimensional MHD simulation can describe the draping of the non-parallel magnetic field and indicate the presence of non-cometary effects. The three models presented here used slightly different gas production rate values, therefore there is a minor difference in the location of the bow shock. The applied change in the magnetic field direction, however, resulted in a major change in the draping geometry. The simulation could not provide the correct draping of the magnetic field when components observed at ~2 million km from the nucleus were applied (model 1, dashed line). Using negative upstream $B_y$, model 2 (solid line) provided the best approximation for the change of $B_x$ and $B_y$ components close to the nucleus suggesting that the field changed significantly in the outer cometosheath. Beyond the measured $B_y$ values, the irregular shape of ion energy spectra observed by SDA also indicates interplanetary disturbance here as mentioned in the previous section. Model 3 (dotted line) used the $B_x$ value observed just upstream of the shock. The magnetometer was damaged just before closest approach therefore the magnetic field direction could not be measured along the outbound trajectory of Vega-2.

In case of Vega-1, magnetic field draping could be easily reproduced, i.e. simulated magnetic field profiles were in good agreement with observations along the whole trajectory (both inbound and outbound) when components measured upstream of the bow shock were

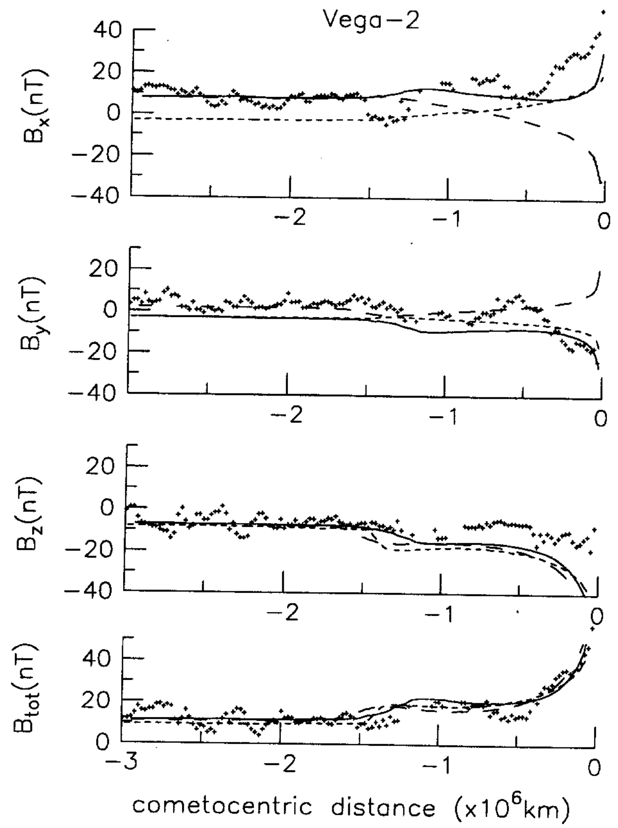


**Fig. 3.** Observed (shown by crosses) and simulated magnetic field profiles along the Vega-2 inbound trajectory in CSE system. Different parameters for model 1: $Q = 0.9 \times 10^{30}$ s$^{-1}$, $B_x = 8$ nT, $B_y = 2$ nT (dashed line); model 2: $Q = 1.3 \times 10^{30}$ s$^{-1}$, $B_x = 8$ nT, $B_y = -3$ nT (solid line); model 3: $Q = 1.1 \times 10^{30}$ s$^{-1}$, $B_x = -3$ nT, $B_y = -3$ nT (dotted line).

applied. It seems that there was no major change in the interplanetary field during the encounter while solar wind parameters changed significantly.

## 4 Summary

The SDA and CRA of the PLASMAG instrument could observe the distribution of ions only in two limited sections of velocity space. In the ecliptic plane, there was a gap of about 40° which was not covered by the viewing angle of either analyser. MHD simulations predicted that the flow is significantly deflected from the solar direction in the cometosheath. Therefore the ion energy spectra measured by PLASMAG could be interpreted when the results of the three-dimensional MHD simulation were taken into account. In this work the velocity and density of the plasma flow were determined from Vega-1 and Vega-2 ion energy spectra at cometocentric distances > 0.5 million km by finding the appropriate combination of the adjustable plasma parameters which were provided by Maxwellians fitting the observed spectra and also agreeing with the predictions of the MHD simulation. It was found that the density of the plasma flow was much larger (while temperature was lower as shown by Tátrallyay et al., 1998) when Vega-1 passed through the cometosheath compared to the Vega-2 flyby. The separation of the solar wind component from cometary ions was impossible closer to the nucleus.

The comparison of simulated and measured magnetic field profiles clearly showed that there was a significant change in the direction of the field when Vega-2 was at a cometocentric distance of 1.0 – 0.8 million km.

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