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PLASMA FLOW IN THE COMETOSHEATH OF COMET HALLEY

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ABSTRACT

Plasma parameters are investigated in the regions upstream and downstream of the bow shock of comet Halley based on the ion spectra measured by the Plasmag-1 instrument aboard the Vega-2 spacecraft. Proton velocities observed by the Solar Direction Analyser and by the Cometary Ram Analyser are compared with the simulated bulk velocity profile provided by a three-dimensional multiscale MHD model (Gombosi *et al.*, 1996). Disregarding the effects of presumably interplanetary disturbances, the simulated and measured values are in good agreement at cometocentric distances larger than about 0.5 million km.

INTRODUCTION

Since the first in-situ measurements were performed in the vicinity of a comet in 1985, several large-scale multi-dimensional models have been developed in order to interpret the observations and to understand the solar wind interaction with an expanding cometary atmosphere in more details. Within the limits of the different numerical approaches, model predictions based on the 'undisturbed' upstream plasma parameters as measured by the Giotto spacecraft were found to be in relatively good agreement with in-situ observations in the different plasma regions of comet Halley from several million km upstream of the bow shock to the inner magnetic cavity (cf. Schmidt-Voigt, 1989; Schmidt and Wegmann, 1991; Gombosi *et al.*, 1994). The Vega spacecraft did not provide three-dimensional plasma observations, therefore model predictions are especially important for the interpretation of ion energy spectra measured downstream of the bow shock of comet Halley. This paper presents the first comparison of Vega-2 plasma measurements with simulated parameters which were determined from the three-dimensional multiscale MHD model developed by Gombosi *et al.* (1996).

OBSERVATIONS

The Plasmag-1 instrument package had two spherical electrostatic ion analysers aboard the three axis stabilized twin spacecraft Vega-1 and Vega-2. The Cometary Ram Analyser (CRA) 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 was damaged during the cruise phase of the Vega-1 mission, therefore only Vega-2 could observe low energy ions outside of the solar direction at the time of the encounter with comet Halley.

Aboard the Vega spacecraft, continuous high time resolution data were taken only downstream of the bow shock. When Vega-2 passed through the bow shock, one complete spectrum was taken by both analysers in every ~2.8 min. As reported by Schwingenschuh *et al.* (1986) and Verigin *et al.* (1987), Vega-2 observed the bow shock at a cometocentric distance of ~1.35 million km. Just after crossing the bow shock, there were two data gaps in plasma and field observations before high time resolution (1 spectrum/sec) data sampling began at a cometocentric distance of 0.85 million km from the nucleus. Figure 1 shows 10 min averaged ion energy spectra taken by the SDA and CRA aboard Vega-2. Count rates are in arbitrary units, adjusted for the difference between the exposure time of the lower resolution and that of the high time resolution data collection session. Also, the ratio of the effective apertures of the two analysers is taken into account so that the displayed count rates should be more comparable.

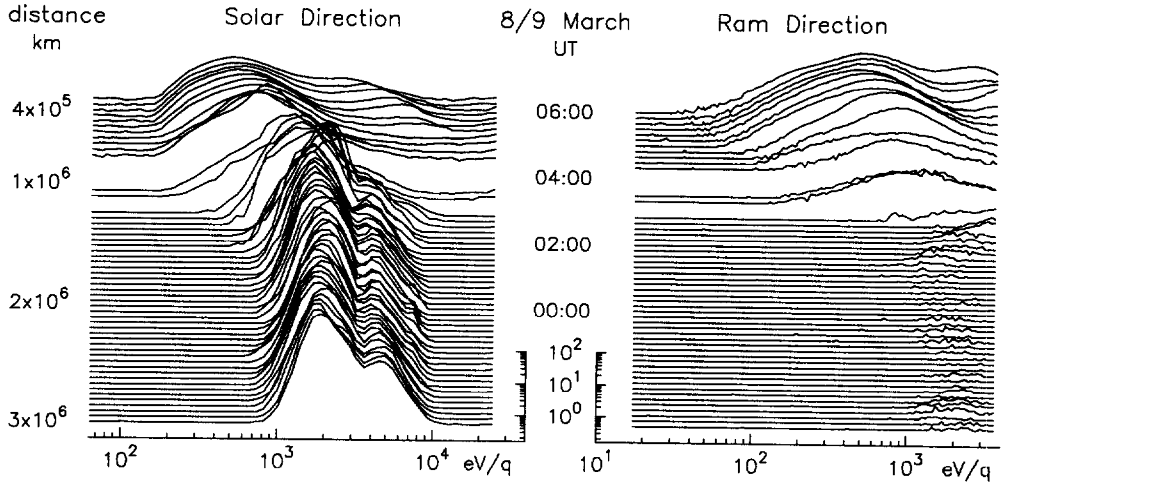

Fig. 1. 10 min averaged ion energy spectra taken by the SDA and CRA from a cometocentric distance of 3 million to 0.4 million km during the inbound pass of Vega-2.

At cometocentric distances of 2 – 1.5 million km, a gradual shifting of the proton peak to lower energies can be observed in the SDA spectra indicating the deceleration of the solar wind caused by the mass-loading effect of heavy cometary ions. On the other hand, count rates of the CRA slightly exceed the noise level around the same energy where the proton peak is seen in the solar direction. The SDA observations indicate some (probably interplanetary) disturbance just after 02:00 UT (~1.5 million km) and a sudden change of the spectra when the bow shock is crossed at ~02:30 UT. At the shock, SDA spectra show that velocity decreases and temperature increases. At the same time, the number of ions observed by the CRA suddenly increases around the upper energy limit. Downstream of the shock, the peak of alpha particles cannot be distinguished from the proton peak, both analysers observe a broad flat distribution in about the same energy interval.

The first two SDA spectra of the high time resolution session (taken around 0.8 million km between 04:10 and 04:30 UT) show an irregularly increased peak, while the CRA observes relatively lower count rates at the same time. This simultaneous change in both directions indicates some interplanetary disturbance. When moving closer to the nucleus, the maximum of the flat distribution observed by both analysers moves slowly to lower energies. While the CRA is observing higher and higher count rates, the number of protons is gradually diminishing in the field of view of the SDA. Also, a second peak produced by heavy cometary ions appears in the spectra at higher energies.

DISCUSSION

It is difficult to interpret the two time series of ion spectra shown in Figure 1 if there is no additional information about the three-dimensional nature of the pick-up process of heavy cometary ions decelerating the solar wind flow upstream and downstream of the bow shock. The global behaviour of plasma parameters has been determined by different model calculations as mentioned in the introduction. For this study, plasma velocity along the Vega-2 trajectory was determined from the three-dimensional MHD model using the Multiscale Adaptive Upwind Scheme developed by Gombosi *et al.* (1996). In this model, MHD equations were numerically solved in a dimensionless form and plasma parameters were normalized with the help of values measured by Giotto in the undisturbed interplanetary field far upstream of the bow shock: $T_{sw} = 10^5$ K was taken for the temperature, $u_{sw} = 371$ km/s $= 10 \times a_\infty$ for the velocity (where a_∞ is the sound speed in the solar wind), and $n_{sw} = 8$ cm^{-3} for the number density. For the Vega-2 encounter, it is difficult to estimate the plasma parameters far away ($> 3 \times 10^6$ km) from the nucleus since the interplanetary field was very disturbed (Tátrallyay *et al.*, 1993). At cometocentric distances of 3 – 2 million km, the mean values of the measured parameters were $T_{sw} \approx 3 \times 10^5$ K, $u_{sw} \approx 590$ km/s (relative to the comet), and $n_{sw} \approx 9 - 10$ cm^{-3}. Therefore the value of the normalized solar wind velocity u_{sw}/a_∞ is relatively close to 10 as used in the model. The major difference is in the gas production rate. Gringauz *et al.* (1986) reported $Q = 1.3 \times 10^{30}$ s^{-1} for the Vega-1 and Vega-2 encounters, while $Q = 7 \times 10^{29}$ s^{-1} was applied in the model suggesting a less extended cometary atmosphere.

In Figure 2 continuous line shows the bulk plasma velocity determined from the dimensionless parameter u_{sw}/a_∞ of the model using $u_{sw} = 590$ km/s as observed by Vega-2. Dots present proton velocities measured by the SDA. The model predicts the location of the shock at a cometocentric distance of 1.5 – 1.4 million km. According to the model calculation, the deflection of the flow is less than 20° along the Vega-2 trajectory, therefore the component measured in the solar direction is an acceptable approximation of the total value. Downstream of the bow shock, the measured velocity values were determined by fitting a single fluid Maxwellian to the peak of the observed broad distribution where it was possible, or by taking the velocity corresponding to the peak of the distribution. The simulated velocity values are slightly smaller than the measured data at distances 1.5 – 0.5 million km (the fluctuations around 1.5 and 0.8 million km must be of interplanetary origin as discussed earlier). The deviation between model calculations and SDA measurements is getting larger at cometocentric distances smaller than ~0.5 million km.

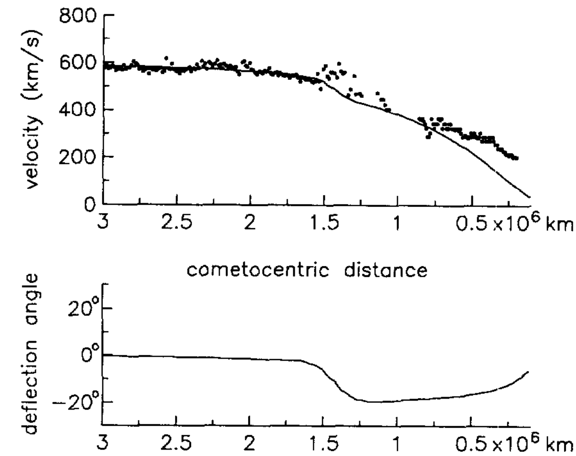

Fig. 2. Plasma velocity and the deflection of the streamline from the solar direction along the Vega-2 inbound trajectory. Continuous line: model calculations; dots: proton velocities measured by the SDA.

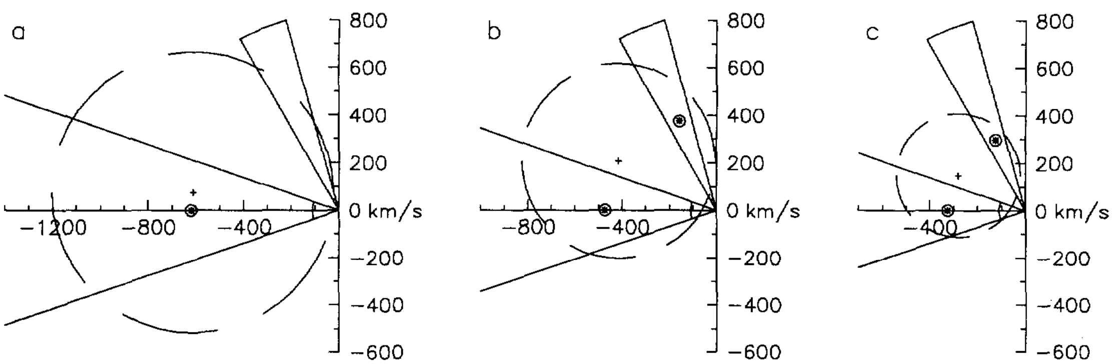

Fig. 3. Phase space diagrams of the simulated bulk velocity (cross), approximated pick-up shell (dashed circle), and the observed proton velocity (encircled star) in the spacecraft reference frame at different cometocentric distances (a: 3×10^6 km; b: 1.1×10^6 km; c: 6×10^5 km).

Figure 3 presents a comparison of model calculations with observations in velocity space at different cometocentric distances. The acceptance angles together with the velocity ranges of the two analysers are shown in the spacecraft reference frame. The SDA could detect protons in the velocity range of 110 – 2280 km/s, while the CRA could observe protons of velocities between 55 km/s and 830 km/s (relative to the comet). A cross shows the simulated bulk plasma velocity. Since the absolute value of this bulk velocity only slightly deviates from the measured velocity peak of the proton component at distances larger than 0.5 million km (see Figure 2), the location of the local pick-up shell was approximated by the dashed circle centred on the cross. The measured velocity is presented by an encircled star in the middle of the acceptance angle range of both analysers since the real direction of the flow could not determined.

As shown in Figure 1, traces of pick-up protons were observed upstream of the bow shock in the energy range of 1 – 3 keV. The corresponding velocity range (400 – 750 km/s) covers the section of the pick-up shell which is within the acceptance angle range of the CRA as shown by Figure 3a. Closer to the nucleus, we similarly expect that the majority of pick-up protons should be detected in those velocity ranges where the pick-up shell is in the acceptance angle range of the analysers. According to Figures 3b and 3c, however, this possible pick-up proton population does not seem to influence the location of the measured velocity peak in either directions. The distribution of heated solar wind protons appears to extend to a large velocity range, so that the flanks reach the acceptance regions of both analysers. The majority of protons detected by both SDA and CRA must be of solar origin at distances shown in Figure 3.

There are several limitations of the above presented simple comparison. 1) The aberration of the solar wind was not taken into account by the model, i.e. the deflection angle of the undisturbed plasma flow is zero in the cometary frame of reference. Therefore, the angle between the direction of the simulated plasma flow (marked by cross) and the supposed direction of the observed solar wind (central direction of the SDA) is $\sim 7^{\circ}$ in Figure 3a. 2) The interplanetary field was very disturbed at the time of the Vega-2 encounter and the deceleration of the solar wind was not as smooth as the model predicts. 3) The above presented simulated velocity profiles were determined from a model based on parameters measured by Giotto. 4) This model is presenting the bulk plasma velocity, therefore special care should be taken when comparing simulated values with measured parameters of a single component.

CONCLUSION

Ion energy spectra observed by the Solar Direction Analyser and the Cometary Ram Analyser of the Plasmag-1 instrument package have been analysed from a cometocentric distance of 3 million km during the inbound pass of the Vega-2 spacecraft. Proton velocities determined from these ion energy spectra were compared with the simulated bulk velocity provided by the three-dimensional multiscale MHD model developed by Gombosi *et al.* (1996). Since the interplanetary field was very disturbed at the time of the Vega-2 encounter, sometimes irregular changes could be observed in the spectra. In spite of the limitations of both observation and simulation, the global characteristic behaviour of the mass-loaded decelerating plasma flow could easily be interpreted by the comparison in the region where solar wind protons present the dominating component. The simulated plasma velocity values were found to be in good agreement with measured proton velocities at cometocentric distances larger than ~0.5 million km.

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