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ON THE DISTRIBUTION OF PICKUP IONS AS OBSERVED BY THE VEGA SPACECRAFT AT COMET HALLEY

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ABSTRACT

Two electrostatic analysers of the PLASMAG-1 plasma instrument package detected energy/charge spectra of ions (without mass separation) aboard the Vega spacecraft when encountering comet Halley. They could observe only two relatively small sections of velocity space showing a mixed effect of decelerated solar wind particles and cometary pickup ions downstream of the bow shock. The separation of the different ion components was attempted by comparing the energy spectra with simple plasma distributions. The effect of cometary pickup ions observed by Vega-1 was different from that observed by Vega-2 at cometocentric distances >0.5 million km. These differences could be interpreted when using the bispherical shell distribution based on magnetic field vectors measured by the magnetometer. © 2000 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Up to now, three comets have been visited by different space probes studying the interaction of the solar wind with cometary plasma. The most detailed observations were performed by Giotto when encountering comet Halley. The Ion Mass Spectrometer and the Johnstone Plasma Analyser (JPA) were able to characterize the proton and heavy ion populations in full since three dimensional distributions were measured separately for ions of different masses upstream and downstream of the bow shock. Coates *et al.* (1990a) discovered that the measured distributions of newly injected cometary ions can be better explained by the assumption of Galeev and Sagdeev (1988), i.e. pickup ions will spread in velocity space from the initially formed ring over the lower energy portions of two shells defined by the equation $\mathbf{V}_\perp^2 + (\mathbf{V}_\parallel \pm \mathbf{V}_A)^2 = \mathbf{const}$ instead of a single shell of radius $|\mathbf{V}_{inj}|$ (cf. Fig. 3 in Coates *et al.*, 1990a). Here $\mathbf{V}_\parallel$ is the field-aligned component and $\mathbf{V}_\perp$ is the perpendicular component of the velocity of injected ions $\mathbf{V}_{inj}$ in the solar wind frame while $\pm\mathbf{V}_A$ is the velocity of Alfvén waves propagating parallel or antiparallel to the magnetic field.

The Vega spacecraft did not provide three-dimensional plasma observations, therefore model calculations are especially important for the interpretation of ion energy spectra measured downstream of the bow shock of comet Halley where the different ion populations could not be easily separated. This paper presents an attempt to describe the possible distributions of solar wind and cometary ions at the time of the encounter of both Vega spacecraft using magnetic field observations, simple calculations of plasma distribution functions, and the results of a 3D multiscale MHD model developed by Gombosi *et al.* (1996).

OBSERVATIONS AND CALCULATED PLASMA DISTRIBUTIONS

The PLASMAG-1 plasma 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). Unfortunately, the CRA of Vega-1 did not work when the spacecraft encountered comet Halley.

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 and at ~1.3 million km by Vega-2. Ion energy spectra taken downstream of the shock show the joint effect of solar wind particles and cometary pickup ions since there was no selection for mass (Tátrallyay *et al.*, 1997; 1999). A simple model calculation was performed for the separation of the different components. The distribution of solar wind protons and alpha particles was approximated by Maxwellians

$$f_p(\mathbf{v}) + f_\alpha(\mathbf{v}) = N_p C_p exp\{-M_p(\mathbf{v}-\mathbf{V}_p)^2/2kT_p\} + N_\alpha C_\alpha exp\{-M_\alpha(\mathbf{v}-\mathbf{V}_\alpha)^2/2kT_\alpha\} \qquad (1)$$

while pickup ions were described by a bispherical shell distribution as suggested by Coates *et al.* (1990a)

$$f_i(\mathbf{v}) = N_i C_i exp\{\left(|\mathbf{v}-\mathbf{V}_{sw} \pm \mathbf{V}_A| - \sqrt{\mathbf{V}_\perp^2 + [\mathbf{V}_\parallel \pm \mathbf{V}_A]^2}\right)^2/\delta V^2\} \qquad (2)$$

where the number densities N_p, N_α, N_i, the velocities $\mathbf{V}_p$, $\mathbf{V}_\alpha$, $\mathbf{V}_{sw}$, the temperatures T_p, T_α of the actual components, and the width of the pickup shell δV are free adjustable parameters. $\mathbf{V}_\perp$, $\mathbf{V}_\parallel$, and $\mathbf{V}_A$ were defined above while C_p, C_α, and C_i are normalization constants. Observed total fluxes were approximated by the numerical integration of the solar wind and pickup ion distributions in the three dimensional velocity space taking into account the angular characteristics and transmission energy ranges of the analysers. The free parameters of Equations (1) and (2) were adjusted in order to fit the measurements.

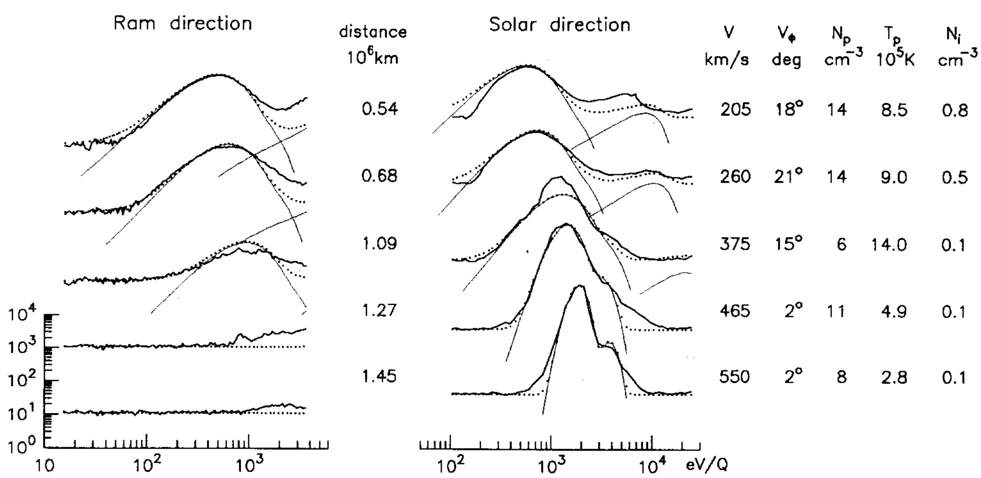

Figure 1. Ion energy spectra (relative count rates) taken by the CRA and SDA at different cometocentric distances during the inbound pass of Vega-2. Heavy lines: measured fluxes; thin lines: calculated distributions using the given best fit parameters V, V_ϕ, N_p, T_p, and N_i for 1) solar wind protons and alphas, 2) pickup ions; dotted lines: sum of 1), 2), and measured background.

Some selected spectra taken upstream and downstream of comet Halley's bow shock are shown in Figures 1 and 2. Spectra measured at cometocentric distances larger than 1 million km represent 10 min averages (covered distance is ~47000 km) while spectra observed closer to the nucleus are 5 min averages. The best fit parameters of the proton population are presented for each spectrum (determined together for CRA and SDA on Vega-2, only for SDA on Vega-1). Based on upstream spectra, $T_\alpha = 4T_p$ and $\mathbf{V}_p = \mathbf{V}_\alpha = \mathbf{V}_{sw}$ was taken in all cases. The velocity components of $\mathbf{V}_{sw}(V, V_\phi, V_\theta)$ are given in cometocentric coordinates: V_ϕ is the azimuthal angle measured from the solar direction in the ecliptic plane, and $V_\theta = 2°$ is the polar angle. $N_\alpha = 0.03 - 0.05N_p$ was used for Vega-2 and $N_\alpha = 0.08N_p$ for Vega-1 as suggested by the upstream conditions. The pickup ions were supposed to have a mass of $M_i = 18M_p$ (representing the water group) and a number density of $N_i = 0.1 - 0.8$ cm^{-3} corresponding to the observations of JPA aboard Giotto (cf. Fig. 4 in Coates *et al.*, 1990b). Together with the best fit plasma parameters, magnetic field values observed by the magnetometer (Riedler *et al.*, 1986) were used for determining the distribution of pickup ions spread over the bispherical shell. For the width of the pickup shell $\delta V = 0.2V$ was taken in all cases.

DISCUSSION

The bottom spectra of Figures 1 and 2 were taken upstream of the bow shock. The density of the solar wind (including alpha particles) was about 2.5 times higher when measured by Vega-1. In spite of the fact that Vega-2 observed higher plasma velocity, solar wind dynamic pressure was about 1.6 times higher at the time of the Vega-1 encounter providing an obvious explanation for the observation of the shock closer to the nucleus. The second set of spectra was taken around the bow shock. In this region, plasma velocity is decreasing while density and temperature is increasing as predicted by model calculations (cf. Schmidt and Wegmann, 1991; Gombosi *et al.*, 1994) and observed by plasma instruments aboard Giotto (cf. Coates *et al.*, 1990b; Goldstein *et al.*, 1992). MHD model calculations predicted a significant deflection of the plasma flow from the solar direction around the bow shock. Also, the JPA of Giotto detected a gradual change of about 15° in the direction of solar wind flow within a distance of about 0.2 million km around the shock (Coates *et al.*, 1990b). A deflection of about the same scale can be seen in Figures 1 and 2 downstream of the bow shock, namely $\Delta V_\phi \approx 15°$ is the difference between the second and third set of spectra (cf. Fig. 2 of Tátrallyay *et al.*, 1999). For the spectra taken around 1.09 million km by Vega-2, only the parameters of the hot proton population are given which could be observed by both analysers. Colder protons detected only in the solar direction indicate some solar wind disturbance of interplanetary origin as discussed by Tátrallyay *et al.* (1997; 1999).

The two upper sets of spectra presented in Figures 1 and 2 were taken at cometocentric distances of 0.7−0.5 million km where the rapidly decelerating solar wind protons are still dominating the flow, but the effect of the cometary ion population is getting more significant. The energies where the measured pickup ion peaks can be seen by the SDA of Vega-2 are about half of those observed by Vega-1 when the injection velocities $|\mathbf{V}_{inj}| = V$ are almost the same. This difference can be explained when supposing that the pickup ions are distributed along a bispherical shell as illustrated by Figure 3. Isolines (given here in the ecliptic plane) represent the observable fluxes summed up in the polar direction. The applied plasma parameters are those which produced the best fit of the measured spectrum at the given cometocentric distance. Observed magnetic field values were used for determining the location of the pickup shell. The projection of the centre of the upstream shell and that of the downstream shell is marked by + and ×, respectively. The distance between them in the ecliptic plane is $2|\mathbf{V}_A|cosB_\theta$ along the magnetic field direction. It is obvious that the bulk velocity of pickup ions seen by the SDA is larger in case of Vega-1 than for Vega-2 corresponding to the observations. The pickup ion peak measured by SDA of Vega-2 at 0.54×10^6 km (top spectra in Fig. 1) could not be completely reproduced by model calculations when using the locally measured magnetic field values which showed a sudden change certainly caused by some interplanetary disturbance (cf. Fig. 3 in Tátrallyay *et al.*, 1999). Probably, this effect was accompanied by an irregular change in the plasma flow velocity which could not be detected by PLASMAG-1.

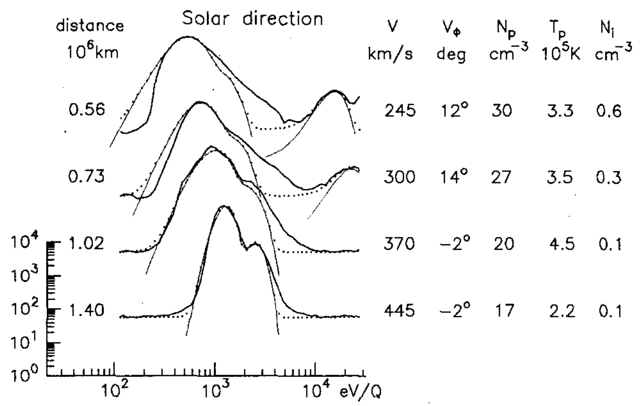

Figure 2. Ion energy spectra (relative count rates) taken by the SDA at different cometocentric distances during the inbound pass of Vega-1. Marking is the same as in Fig. 1.

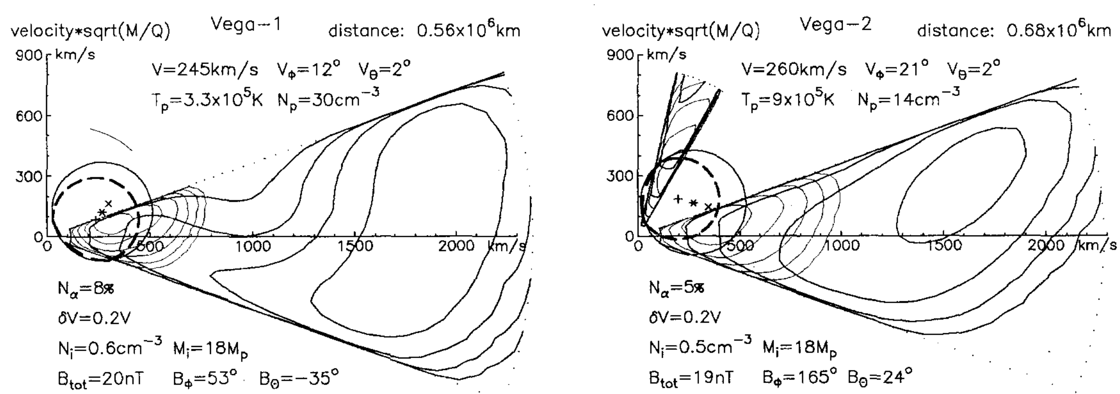

Figure 3. Calculated distribution of solar wind particles (thin isolines) and pickup ions (heavier isolines) in velocity space ($V\sqrt{M/Q}$ where M/Q=1 for protons, M/Q=2 for alphas, and M/Q=18 for cometary ions) as seen by the SDA of Vega-1 and by the CRA and SDA of Vega-2 in spacecraft reference frame. Dotted lines mark the viewing angle and energy range of the analysers in the ecliptic plane ($\theta = 0°$), horizontal is the solar direction ($\phi = 0°$). Solid circle shows the section of the pickup shell of radius V (centre marked by $*$), the dashed heavy curve presents the sections of the upstream and downstream shell (centres marked by + and ×, respectively).

As shown in Figure 1, model calculations provide lower fluxes at E>1 keV than measured by the CRA for all spectra. Cometary ions distributed along the original pickup ring are expected to be seen at these energies. The excess count rates might be indicative of a not quite uniformly populated shell. It should be mentioned here that there are some other minor disagreements between calculated and measured spectra. Our model calculations cannot reproduce the high energy tail of the solar wind population. Possible explanations: 1) the density and temperature of the alpha particles is higher in the cometosheath than it was in the upstream region, 2) the distributions are not regular Maxwellians, probably not even in the upstream region. Also, there is a significant deviation between calculated and measured fluxes at E<200 eV since the SDA-s did not detect particles of lower energies for some instrumental reason.

CONCLUSION

Ion energy spectra observed by the Solar Direction Analyser and the Cometary Ram Analyser of the PLASMAG-1 plasma instrument package have been analysed at cometocentric distances of 1.5 - 0.5 million km during the inbound pass of both Vega spacecraft (CRA data available only for Vega-2). Three ion components of different masses were separated applying simple model calculations. Maxwellian distributions provided an acceptable approximation for solar wind protons and alpha particles except for the high energy tails. The parameters of the decelerating solar wind plasma are in good agreement with the predictions of a large-scale three-dimensional MHD model as discussed by Tátrallyay *et al.* (1999). The differences in density and temperature values observed by the two Vega spacecraft originate from the different upstream conditions. The high energy part of the spectra can be interpreted by cometary ions distributed on a bispherical shell. The difference between the magnetic field values measured along the Vega-1 and Vega-2 trajectory sufficiently explains the different location of the bispherical shell at the time of the two encounters. Pickup ions spread over a spherical shell of radius $|\mathbf{V}_{inj}|$ would produce a peak at higher energies than those observed by the SDA-s of both Vega spacecraft.

ACKNOWLEDGMENTS

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