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POSITION AND STRUCTURE OF THE COMET HALLEY BOW SHOCK: VEGA-1 AND VEGA-2 MEASUREMENTS

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Abstract. The effect of solar wind loading by cometary ions on the position and structure of the comet Halley bow shock is discussed on the basis of simultaneous measurements of plasma, magnetic field and plasma waves aboard the "Vega-1" and "Vega-2" spacecraft. Data from the inbound crossings of the bow shock show that both quasiperpendiuclar ("Vega-1") and quasiparallel ("Vega-2") shocks were observed. The thickness of these shocks is greater than that of the Earth's bow shock at least by the ratio of the masses of cometary ions and protons. The bow shock position is reasonably well described by the kinetic model of solar wind loading by cometary ions.

The process of solar wind mass-loading by cometary ions implanted in the supersonic solar wind flow due to the photoionization of gas evaporated from the cometary nucleus is well known and included in gasdynamic models of the solar wind interaction with comets (Schmidt and Wegmann, 1982). However, one striking feature of this interaction, that is the development of strong magnetohydrodynamic turbulence which accompanies the mass-loading, has become clear only after first in-situ measurements of the magnetic field by the ICE spacecraft near comet Giacobini-Zinner (Tsurutani and Smith, 1986). Later, the magnetic field measurements made from the Vega spacecraft have shown the presence of strong MHD turbulene in the neighborhood of comet Halley (Riedler et al., 1986). The intensity of magnetic field fluctuations in the frequency range 10^{-2} - 10^{-3} Hz measured during the "Vega-1" encounter with comet Halley is shown in Figure 1. The excitation of the turbulence is a consequence of the collective interaction between two plasmas: of solar and cometary origin. The cometary ions that are born in the solar wind start to drift across the magnetic field lines under the action of a self-consistent electric field with the velocity component of the solar wind perpendicular to the magnetic field. Their initial velocity along the field lines is of the order of the velocity of cometary gas expansion (∿ 1 km/s) and is therefore extremely small in comparison with the solar wind velocity. Thus these ions form a beam in the solar wind plasma that excites Alfvén waves due to an ion-cyclotron instability (Sagdeev et al., 1986; Winske et al., 1985). According to the weak-turbulence theory of this phenomenon developed by Sagdeev et al. (1986), the characteristic frequency of the excited waves is of the order of the heavy ion gyrofrequency $\omega_{ci} = eB/m_i c \sim 10^{-2}$ Hz (for H_2O^+ ions) in agreement with the observations near comets Giacobini-Zinner and Halley (Tsurutani and Smith, 1986; Riedler et al., 1986).

The dependence of the wave energy density $W = \Sigma|B_k|^2$ on the distance r from the cometary nucleus is described by the following equation

$$\frac{dW}{dx} = \frac{AQ}{r^2} \frac{m_i V_A}{V_g \tau} \exp\left(-\frac{r}{V_g \tau}\right) - \frac{2}{5} \frac{1}{\cos \alpha} \frac{T_p}{m_p u_\infty^2} \cdot \frac{\omega_{ci}}{V_A} \frac{W^2}{B_o^2} \quad (1)$$

where Q is the gas production rate, τ and V_g are the characteristic time of photoionization and the velocity of cometary gas expansion, respectively, $A \cong 10$ is a numerical factor, m_j is the mass of particles of species j, $V_A = B_o / \sqrt{4\pi \rho_\infty}$ is the Alfvén speed in the unperturbed solar wind with mass density ρ_∞. B_o is the magnetic field strength, α is the angle between the solar wind flow and the magnetic field, and u_∞ and T_p are velocity and proton temperature of the unperturbed solar wind.

The first term on the r.h.s. of this equation describes the growth of Alfvén waves calculated in the quasilinear approximation. It is assumed that in spite of a fast isotropization of the velocity distribution of cometary ions picked up by the solar wind, a small anisotropy of this distribution is maintained due to continuous creation of new ions by photoionization. The second term on the r.h.s. of Equation 1 describes the saturation of wave growth due to the induced scattering of waves by solar wind protons that is the main nonlinear effect in this problem. The induced scattering of waves results in a wave energy flux in k-space from the region of resonant wave-particle interaction towards larger scales (small k). The wave growth saturates at a high level with magnetic field fluctuations of the order of the unperturbed magnetic field strength. The solution of Equation 1 is shown in Figure 1 by a dotted line (for details see Galeev et al. (1986)). In our theoretical estimates we have used the solar wind and cometary gas parameters measured aboard the "Vega-1" spacecraft: $n = 12\ cm^{-3}$, $u = 5.1 \cdot 10^7$ cm/s, $T_p = 1.2 \cdot 10^5$ °K, $Q = 1.3 \cdot 10^{30}$ mol s^{-1}, $V_g \tau \cong 2 \cdot 10^{11}$ cm (Gringauz et al., 1986) and $B_o \cong 11$ nT (Riedler et al., 1986).

As has been stated by Sagdeev et al. (1986), one of the most important consequences of Alfvén wave generation is the fast isotropization of the velocity distribution of cometary ions. In this case, when describing kinetically the solar wind loading we should take into account that the

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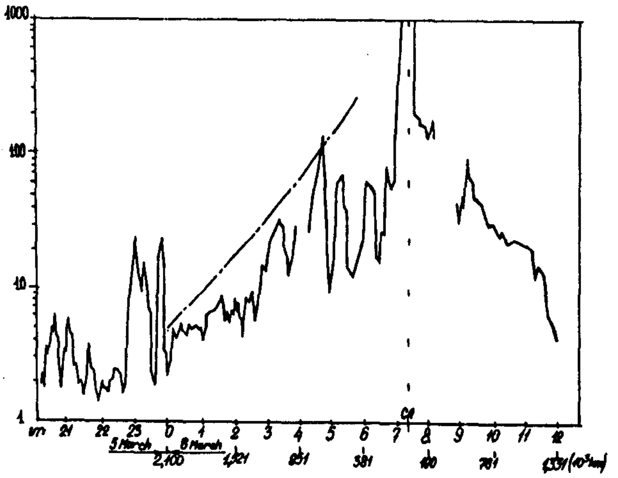

Fig. 1. The energy of magnetic field fluctuations $\int [|B_{xf}|^2 + |B_{yf}|^2 + |B_{zf}|^2]\, df$ in the frequency range 10^{-3} Hz < f < 10^{-2} Hz for various distances from the comet.

energy, but not the magnetic moment of the picked-up particles is conserved and thus modify the one-dimensional system of equations given by Wallis and Ong (1975) that describes the loading:

$$\frac{d}{dx}\,[f(u, v)u] = \frac{1}{4\pi v^2}\,\delta(v-u)\,\frac{d}{dx}\,(\rho u) \qquad (2)$$

$$\frac{d}{dx}\,(\rho u) = \frac{Qm_i}{4\pi\, r2\, V_g \tau}\, e^{-r/V_g\tau} \qquad (3)$$

$$\frac{d}{dx}\,(\rho u^2 + p) = 0 \;, \qquad (4)$$

$$p = \frac{4\pi m_i}{3}\int_0^\infty v^4 f(u, v)\, dv \qquad (5)$$

where f(u, v) is the velocity distribution function of cometary ions, ρ , u , p are mass density, hydrodynamic velocity and pressure of the loaded solar wind, respectively. Solving the system of equations (2) - (5) we obtain implicit dependencies of solar wind velocity and pressure on the degree of loading

$$\rho u = \frac{\rho_\infty u_\infty^2}{2u}\,(3 - \sqrt{u_\infty/u}\,) \qquad (6)$$

$$p = \frac{\rho_\infty u_\infty^2}{2}\,\left(\sqrt{\frac{u_\infty}{u}} - 1\right) \quad . \qquad (7)$$

By computing the sound speed $c_s = \sqrt{dp/dp}$ with help of these equations we obtain the local acoustic Mach number in the solar wind flow:

$$M^2 = 12\,(\sqrt{u/u_\infty} - 5/12) \qquad (8)$$

It follows form the obtained solution (6) for ρu and Equation 3 that continuously decelerating flow is possible only for $u/u_\infty > 1/4$, i.e. for a local Mach number $M \geq 1$. This means that, as in ordinary gasdynamics, a smooth transition from supersonic to subsonic flow is impossible and a shock has to form. Following the results of the gasdynamic calculations we assume here that the shock is formed at the point where the local Mach number reaches the value $M = 2$. From Equations 8 and 6 we find the degree of solar wind loading in front of a shock ($\rho u/\pi_\infty u_\infty = 40/27$), and finally with the help of Equation 3 we obtain the position of the $M = 2$ surface:

$$1 = \frac{27}{13}\int_{-\infty}^{\xi s} \frac{\exp(-\lambda\sqrt{\xi^2 + \eta_s^2})}{\xi^2 + \eta_s^2}\, d\xi \qquad (9)$$

where

$$\lambda = \frac{r_o}{V_g\tau}\,,\quad \xi_s = x_s/r_o,\ \eta_s = y_s/r_o,\quad r_o = \frac{Qm_i}{4\pi\rho_\infty u_\infty V_g \tau}$$

The subsolar stand-off distance of the cometary shock was calculated with the help of Equation 2 for the above listed solar wind and cometary gas parameters. Assuming also that $m_i/m_p \cong 23$ for a water dominated cometary gas, we obtain $x_s(y_s = 0) = 2.7 \cdot 10^5$ km . The $M = 2$ surface is plotted in Figure 2 by a dotted line.

The theoretical shape of the bow shock obtained by a two dimensional particle in cell simulation of the solar wind interacation with comets (Galeev and Lipatov, 1984) is also shown in Fig. 2 as well as the trajectory of the Vega spacecraft. We see that at the flanks the bow shock position deviates significantly from the $M = 2$ surface.

An identification of the bow shock crossings during the Vega encounters has been carried out by various detectors performing plasma (Gringauz et al., 1986), energetic particles (Somogy et al., 1986), and plasma wave (Klimov et al., 1986) measurements. The results are shown in Figures 3 and 4.

The most accurate determination of the shock position was given by the low frequency plasma wave analyzer APV-N (Klimov et al., 1986). It registered a sharp rise of wave intensity at frequencies below the lower-hybrid resonance at 3:46 UT, which corresponds to a distance of $(10.1 \pm 0.1) \cdot 10^5$ km from the nucleus for the inbound crossing of "Vega-1" (see Fig. 3). The magnetic field data at this moment ($B_x = -6$ nT , $B_y = 5$ nT, $B_z = 8$ nT) permit to calculate the angle

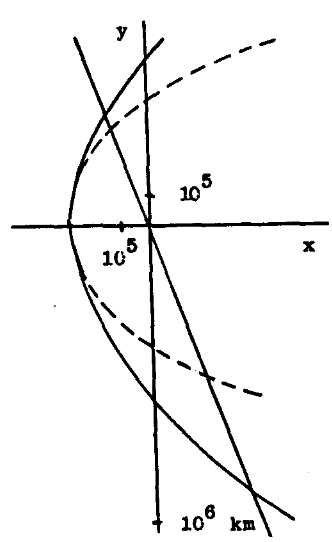

Fig. 2. The calculated positions of the bow shock front and the M = 2 surface as well as the "Vega-1" flyby trajectory.

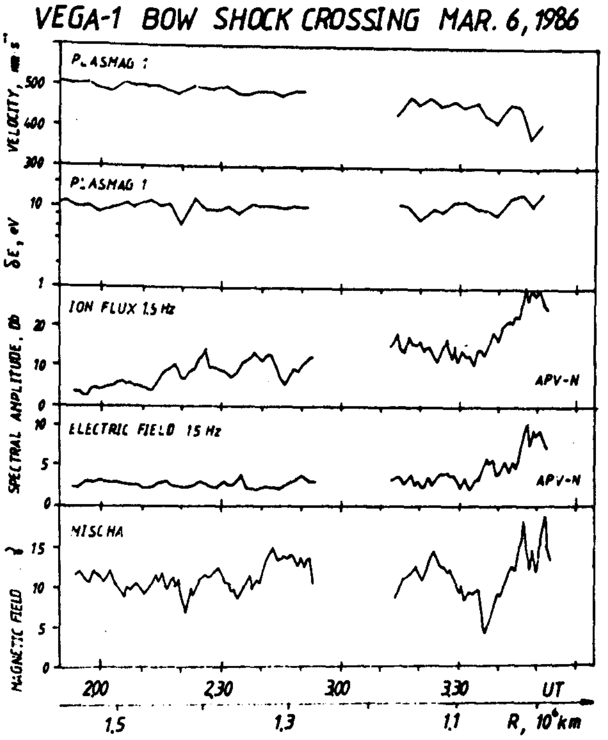

Fig. 3. The behavior of solar wind parameters during the inbound bow shock crossing by the "Vega-1" spacecraft on March 6, 1986. From top to bottom: solar wind velocity and effective temperature measured in solar direction; spectral amplitude of ion flux fluctuations and electric field oscillations with the frequency f = 1.5 Hz; magnetic field strength.

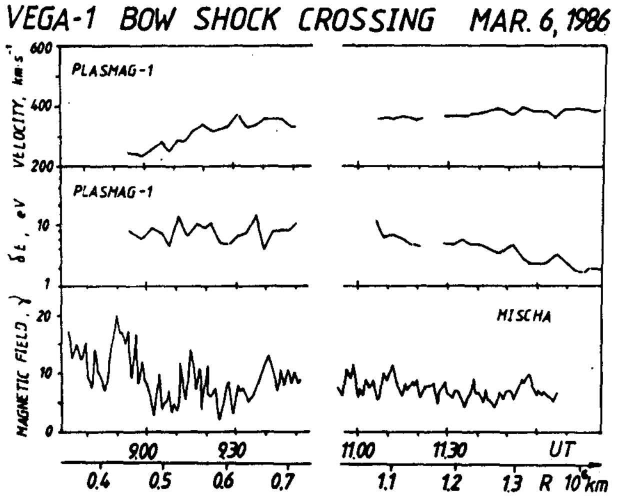

Fig. 4. Same as in Fig. 3 for the outbound bow shock crossing by the "Vega-1" spacecraft. The plasma wave data are absent.

between shock normal and magnetic field ($\theta_{Bn} \cong 90^{\circ}$) and lead to the conclusion that "Vega-1" crossed a quasiperpendicular shock. Similar sharp rises of the lower-hybrid wave intensity were observed in front of the quasi-perpendicular Earth bow shock and have been explained as having been generated by solar wind protons reflected from the shock front (Vaisberg et al., 1983). By analogy it seems reasonable to assume that in our case the detected waves are excited by the picked-up cometary ions that are reflected by the shock and then accelerated along its front by the self-consistent electric field $\vec{E} = -\underline{u} \times \underline{B}/c$. The accelerated ions form a beam moving almost perpendicular to the magnetic field and exciting high frequency magnetosonic waves with frequencies up to the lower-hybrid resonance. The wave spectra for electric and magnetic field oscillations in the vicinity of the lower hybrid resonance are shown in Figure 5. The ratio between electric and magnetic field amplitudes agrees well with the theoretical estimate for magnetosonic waves $E/B \cong (V_A(c)\sqrt{m_p/m_e} \cong 1/50$ (Fig. 5). All measurements mutually agree quite well and fit the theoretical calculations (Fig. 2). The burst of MHD turbulence serves as precursor of the shock. This is because the effect of convection of newly born cometary ions becomes very strong near the shock front where the gradients of plasma parameters are large. Thus the anisotropy of the velocity distribution of cometary ions is maintained at such a high level that the growth rate of plasma instability as well as the strength of MHD turbulence are also high. Due to the presence of this turbulence the cometary bow shock differs strongly from the well-studied planetary bow shocks and makes the identification of shock crossings somewhat difficult. In particular, the heating of solar wind protons due to stochastic Fermi acceleration by MHD turbulence (Amata and Formisano, 1985) is so large in the foreshock region that the peak of α particles becomes indistinguishable. This happened at the outbound crossing of the cometary bow shock by "Vega-1" Fig. 4). Here the level of MHD turbulence was larger than at the inbound shock crossing and considerable solar wind heating took place in the upstream region at distances of the order of 10^6 km from comet (Fig.

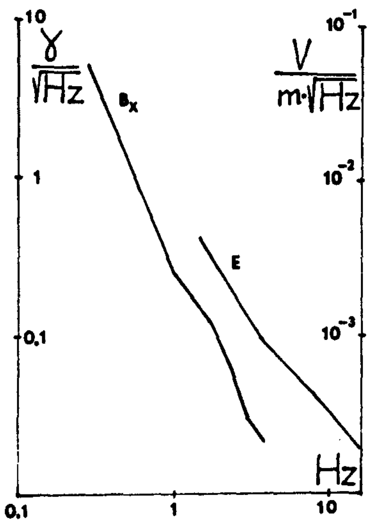

Fig. 5. The spectra of magnetic and electric field oscillations in plasma waves within the bow shock front measured on "Vega-1" by the spectrum analyzers of magnetometer "Misha" and low frequency plasma wave analyzer APV-N, respectively.

4). The position of the shock front on the outbound crossing can be identified by the decrease of solar wind velocity (Fig. 4) and by the enhancement of the level of MHD turbulence in the vicinity of the shock front (Fig. 1). It stands at the distance of $(6 \pm 1)\ 10^5$ km from the nucleus. This also agrees reasonably well with the theoretical estimates of the bow shock position shown in Fig. 2. The bow shock crossing by "Vega-2" was registered only for the inbound part of the trajectory approximately at the same distance from the comet as for "Vega-1", since neither solar wind nor cometary parameters were changed significantly. But the structure of this shock was much more diffuse. That is due to the fact that the bow shock in the second crossing was quasiparallel with an angle $\theta_{Bn} \cong 45^0$.

The study of the structure of cometary bow shocks is of a great importance for the problem of collisionless shocks in a plasma, the first theory of which has been proposed more than 25 years ago (Sagdeev, 1959). As for the Earth's bow shocks, there are two different types of the cometary shocks - quasiparallel and quasiperpendicular. The computer simulation of the quasiperpendicular shock formed in an electron-proton plasma loaded by heavy ions (Galeev et al., 1985) shows that because of their large gyroradii heavy ions picked up by the solar wind leak easily out into the upstream region from behind the shock front. Thus they decelerate the incoming plasma flow and form a foot on the magnetic field profile in the shock with characteristic spatial scale of the order of the heavy ion's Larmour radius. That is approximately 10^4 km for solar wind conditions quoted above.

The quasiparallel bow shock registered by "Vega-2" is of quite different nature. There exists a close analogy between this type of cometary shock and cosmic ray diffusive shocks (Sagdeev et al., 1986). In both cases the high energy particles (cosmic ray protons or heavy ions picked up by the solar wind) moving along the magnetic field excite an intensive Alfvénic turbulence. The escape of particles from the shock front into the upstream region has the character of diffusion due to strong particle scattering by the excited Alfvén waves. Thus particles diffuse forward to the distance $L_{DIF} \cong D/u$ where $D \cong (v_i/\omega_{ci})\ B_o^2/\Sigma|B_k|^2$ is the diffusion coefficient. This spatial scale defines the characteristic width of a quasiparallel cometary bow shick that, for our onditions, is equal to

$$L_{DIF} \cong r_{Li}\ B_o{}^2/\sum_k |B_k|^2 \cong (5 - 10) \cdot 10^4 \text{ km} \qquad (10)$$

B_k being the Fourier component of the magnetic fluctuations. We derived an estimate of $|B_k{}^2|$ from the temporal fluctuations of the magnetic field measured by "Vega-2". The estimated width of the shock front is several times larger than that of a quasiperpendicular shock. Thus the bow shock crossing by "Vega-2" was characaterized by gradual changes of plasma velocity and temperature, magnetic field strength and plasma wave intensity.

References

Amata, E., and V. Formisano, Energetization of positive ions in the cometary foreshock region, Planet. Space Sci., 11, 1243-1250, 1985.

Axford, W.I., Acceleration of cosmic rays by shock waves, in Proc. of 17th International Cosmic Ray Conference, Paris, 1981, Vol. 12, 155-203, Service de Docum. du CEN, Saclay, 1982.

Galeev, A.A., and A.S. Lipatov, Plasma processes in the cometary atmospheres, Adv. Space Res., 4, 229-237, 1984.

Galeev, A.A., A.S. Lipatov, and R.Z. Sagdeev, Numerical simulation of near-comet shock waves: some features of the structure and mechanisms of energy dissipation, JETP, 89, 1495-1504, 1985.

Galeev, A.A., R.Z. Sagdeev, V.D. Shapiro, V.I. Shevchenko, K. Szego, Solar wind loading and MHD turbulence near comets, Plasma Astrophysics, Course and Workshop Organized by International School of Plasma Physics, 18-27 May, 1986, Sukhumi, USSR, ESA SP-251, in press.

Gringauz, K.I., T.I. Gombosi, A.P. Remisov et al., First in situ plasma and neutral gas measurements at comet Halley, Nature, 321, 282-284, 1986.

Klimov, S., S. Savin, Ya. Aleksevitch et al., Extremely low frequency plasma waves in the environment of comet Halley, Nature, 321, 292-293, 1986.

Riedler, W., K. Schwingenschuh, Ye.G. Yeroshenko, V.A. Styashkin, C.T. Russell, Magnetic field in comet Halley's coma, Nature, 321, 288-289, 1986.

Sagdeev, R.Z., Shocks in rarefied plasma, Report on IV International Conference on Ionizational Phenomena, Uppsala, Sweden, 1959.

Sagdeev, R.Z., V.D. Shapiro, V.I. Shevchenko, and K. Szego, MHD turbulence in the soalr wind-comet interaction region, Geophys. Res. Lett., 13, 85-88, 1986.

Schmidt, H.U., and R. Wegmann, Plasma flow and magnetic fields in the comets, edited by L.L. Wilkening, 538-560, Univ. of Arizona Press, Tucson, 1982.

Somogyi, A.S., K.I. Gringauz, K. Szego et al., First observations of energetic particles near comet Halley, Nature, 321, 285-287, 1986.

Tsurutani, B.T., and E.J. Smith, Strong hydromagnetic turbulence associated with comet Giacobini-Zinner, Geophys. Res. Lett., 13, 259-262, 1986.

Vaisberg, O.L., A.A. Galeev, and G.N. Zastenker et al., Acceleration of electrons at the front of strong collisionless shocks, JETP, 85, 1232-1241, 1983.

Wallis, M.K. and R.S.B. Ong, Strongly cooled-ionizing plasma flows with appplications to beams, Planet. and Space Sci., 23, 713-720, 1975.

Winske, D., C.S. Wu, Y.Y. Li, Z.Z. Mon and S.Y. Guo, Coupling of newborn ions to the solar wind by electromagnetic instabilities and their interaction with the bow shock, J. Geophys. Res., 90, 2713-2726, 1985.

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