ISOMAGNETIC DISCONTINUITY IN A COLLISIONLESS SHOCK WAVE IN A PLASMA

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As is well known, in shock-wave physics one encounters critical Mach numbers (M_{c1}, M_{c2}, ...) at which a qualitative change takes place in the structure of the front. One example, in ordinary gas dynamics, is the isothermal density discontinuity produced in a shock-wave front in a gas having a high thermal conductivity [1]. In magnetogasdynamics a shock wave can experience also an isomagnetic density discontinuity [2]. Analogous phenomena occur also in the collisionless shock waves in plasma. Thus, if the dissipation is due to anomalous (turbulent) resistance, then ($M \to M_{c1}$) the close of the density front increases continuously ($dn/dx \to \infty$) as the Mach number approaches a certain critical value [3]. In gas dynamics, a similar growth of the front slope is limited ultimately by the viscosity. In a collisionless plasma this mechanism does not exist, and it was therefore initially assumed that the transition through the critical value M_{c1} is accompanied by formation of mutually-interpenetrating plasma streams. As will be shown below, however, as $M \to M_{c1}$ under conditions of an increasing slope of the density profile, a major role is assumed by charge-separation effects, which prevent the collapse of the resistive front. This results in a narrow transition region of width $\delta \sim r_D$, in which the density changes appreciably while the magnetic field remains practically constant. In fact, we have here a nonlinear electrostatic wave "superimposed" on the resistive shock front.

The present paper is devoted to a study of the electrostatic discontinuity in a collisionless shock front in a plasma. Such a discontinuity was first observed in [4] with a microwave interferometer. It was established that the density discontinuity appears at $M \gtrsim 3$ (the Mach number is $M = u/V_A$, where u is the wave velocity and V_A the Alfven velocity in the initial plasma). However, the interferometry method does not have high resolution, and has therefore not permitted a detailed investigation of the phenomenon. We used a simpler method, namely probe measurements of the potential $\phi(x)$, the distribution of which is qualitatively similar to the density distribution. This has made it possible to reduce the temporal resolution to (1.5 - 2) × 10^{-9} sec (the corresponding spatial scale is of the order of 2 × 10^{-2} cm). Figure 1 shows the

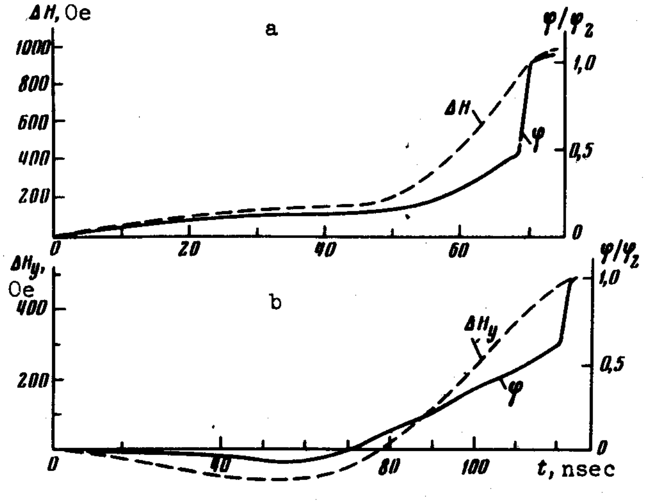

Fig. 1. Isomagnetic discontinuity of the potential in a transverse shock wave (a) and in an oblique one (b); a - $M = 4$, $H_0 = 300$ Oe, $n_0 = 3.4 \times 10^{14}$ cm^{-3}; b - $M = 2.5$, $H_0 = 310$ Oe, $n_0 = 7.5 \times 10^{13}$ cm^{-3}, $\theta = 20°$.

distributions of the magnetic field H and of the potential ϕ in a transition layer of a transverse shock wave (a) and an oblique one (b). The profile of ϕ revealed a fundamental singularity, namely, the potential experiences a discontinuity on the end of the front at an almost constant magnetic field. We have investigated in greatest detail a transverse wave, so that the exposition that follows pertains mainly just to this case. It has been established that the discontinuity on the potential profile is formed in a wide range of initial parameters, in plasmas of different gases (H_2, He, Ar), for all Mach numbers lying in the interval between the first critical value $M_{c1} = 2.8 - 3$ and the second $M_{c2} = 4.5 - 5.5$. Within the interval from M_{c1} to M_{c2}, the discontinuity amplitude $\Delta\phi$, normalized to the value of the potential ϕ_2 behind the wave front, depends on M. An experimental plot of this dependence is shown in Fig. 2.

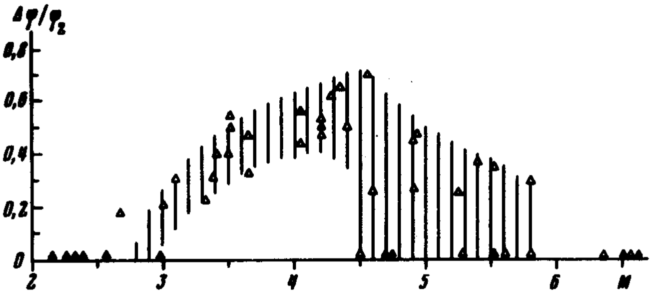

Fig. 2. Relative amplitude of the isomagnetic discontinuity vs. the Mach number (hydrogen).

Measurements of the time width of the discontinuity yielded a value of τ lying on the limit of the pass band of the circuit ($f_0 \simeq 0.8 - 1$ GHz), so that this value should be regarded only as the upper limit of the width of the discontinuity. In special regimes, however, (low concentration, heavy gas - argon), is was possible to ascertain that the measured value 2×10^{-2} cm is of the same order as the Debye radius.

At small Mach numbers ($M < M_{c1}$), the profiles of the magnetic field and of the potential are similar and are in good agreement with the MHD model of the resistive front. In the region $M > M_{c2}$, the distributions of H and ϕ have a monotonic form without singularities, with a width $\Delta \sim c/\Omega_p$ (Ω_p - ionic plasma frequency).

An interesting regularity is observed in the dependence of the potential ϕ_2 behind the wave front on the Mach number. At $M < M_{c1}$ the value of ϕ_2 is close to $\tilde{\phi} = (m_i u^2/2e)(1 - 1/h^2)$ ($h = H_2/H_0$ is the relative amplitude of the wave). In the interval between M_{c1} and M_{c2} the ratio $\phi_2/\tilde{\phi}$ decreases gradually to 0.5 - 0.6, and then remains practically constant.

The foregoing experimental data agree with the assumption that the isomagnetic jump is produced at $M = M_{c1}$ by the charge-separation effects, i.e., it has an electrostatic character. This picture agrees with the results of measurements of the width of the discontinuity and the qualitative form of the dependence of $\Delta\phi/\tilde{\phi}$ on M. In addition, it becomes possible to explain the vanishing of the isomagnetic discontinuity at $M = M_{c2}$.

It is known that the cause of the collapse of an electrostatic wave of large amplitude is the reflection of a certain fraction of the ions from the potential front; this collapse is due to the thermal velocity scatter of the ions. The critical Mach number at which the electrostatic wave collapses, $M_s^* = u_s/c_s$ ($c_s = \sqrt{T_e/m_i}$), depends strongly on the ratio T_i/T_e [5]. To estimate M_{c2} it is necessary to connect the Mach number M_s of the electrostatic wave with M. Within the framework of the magnetohydrodynamics this can be done by using the laws of conservation of the energy and momentum fluxes on the isomagnetic discontinuity. It is necessary here to take into account the heat flux produced as a result of the good thermal conductivity of the electrons and directed away from the isomagnetic discontinuity (as well as from the isothermal one for electrons) to the resistive section of the front. It is easy to show that the thermal flux is

$$q_e = n_0 u T_e \ln(u_s/v_2),$$

where u, u_s, and v_2 denote, in the coordinate frame of the wave, the velocity of the plasma ahead of the wave, ahead of the discontinuity, and behind the wave front. It is known that $M_s^* = 1.6$ for $T_i = 0$. This yields $M_{c2} = 6.2$. Allowance for the finite ionic temperature leads to a sharp decrease of M_{c2}. For example, if we have directly ahead of the discontinuity $T_i/T_e = 0.1$, then M_s^* decreases to 1.3, and we obtain $M_{c2} = 4.3$. Such a strong dependence of M_{c2} on T_i is apparently the cause of the appreciable scatter of the points on Fig. 2 in the region $M \sim M_{c2}$.

The ions reflected from the wave front (when $M < M_{c2}$) are the reason for the appearance of the characteristic pedestal on the profile of the magnetic field. It is interesting that in a transverse wave the pedestal appears at Mach numbers close to M_{c1}. In an oblique wave, however, the value of M at which the oscillatory structure disappears and the pedestal appears exceeds M_{c1}. The reflection of the ions is equivalent to a certain thermalization of them, and the appearance of an effective ion temperature and hence of an ion pressure p_i decreases the potential ϕ_2 behind the wave front compared with $\tilde{\phi}$, as is indeed observed in the experiment.

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