Nature of the isomagnetic discontinuity in a collisionless shock wave

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It is concluded on the basis of the experimental data that the dissipative mechanism that produces the isomagnetic discontinuity on the front of a collisionless shock wave at Mach numbers $M_{c1} < M < M_{c2}$ is turbulent ion viscosity. The cause of the viscosity is taken to be two-stream ion instability.

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Earlier experiments[1] have shown that when the first critical Alfven Mach number $M_{c1}=u/V_A\approx 3.0$ is approached (u_s is the shock-wave velocity and $V_A=H_0/(4\pi m_i n_0)^{1/2}$ is the Alfven velocity, a narrow region in which an abrupt change of the potential (isomagnetic jump)[2,3] takes place at a practically constant field is produced in the front of a collisionless shock wave moving transversely to the magnetic field. The minimal width of the jump can reach several Debye lengths, which is considerably less than the resistive width $\Delta_p\approx 10c/\omega_0$, of the shock front, where c is the speed of light and $\omega_0=(4\pi n_0 e^2/m_e)^{1/2}$ is the plasma frequency (Fig. 1a). With further increase of the Mach number, the relative amplitude of the potential discontinuity $\Delta\varphi$ increases and the discontinuity vanishes at $M=M_{c2}\approx 4.5-5.5$ (Fig. 2a).

The formation of a steady-state front structure with an isomagentic discontinuity is due to the appearance of two opposing effects: unlimited increase in the slope of the density profile because of the instability of the resistive front at $M=M_{c1}$, and the presence, alongside the resistive dissipation, of a certain mechanism that effectively counteracts this increase in slope over a scale $\delta\ll\Delta_r$.

Possible mechanisms that hinder the increase of the slope of the density front are dispersion and turbulent ion viscosity. The role of dispersion of ion-sound waves in the formation of the isomagnetic jump was considered in[1], where model constructed on the basis of the analysis reduces to the following: the isomagnetic discontinuity is an electrostatic laminary wave that is produced on the crest of the shock front as a result of the counteraction of the nonlinear increase of slope and the dispersion-induced spreading of the ion-sound waves. The vanishing of the discontinuity at $M=M_{c2}$ is interpreted as a breakdown of the electrostatic wave as it reaches the

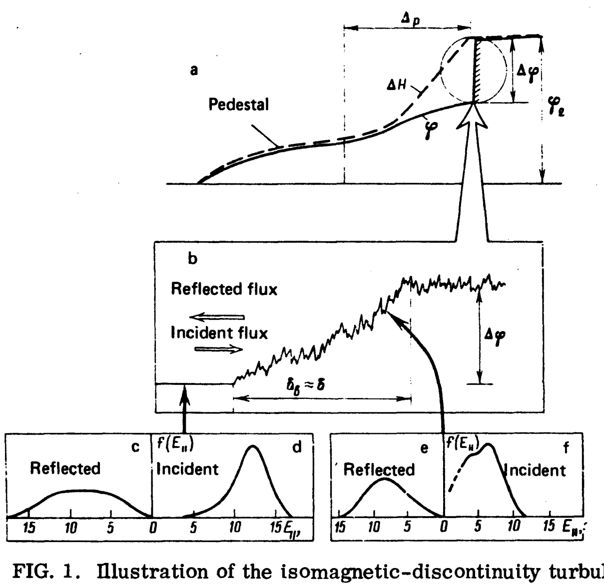

FIG. 1. Illustration of the isomagnetic-discontinuity turbulence due to the development of two-stream ion instability: a—distributions of the magnetic field (dashed) and of the potential (solid) in the shock-wave front at K, the isomagnetic discontinuity is shown in the circle; b—structure of the turbulent isomagnetic discontinuity of the potential; c, e—energy spectra of the reflected ions ahead of the shock front and in the region of the isomagnetic discontinuity; d, f—energy spectra of the ion flux entering the front ahead and past the isomagnetic discontinuity ($E_\parallel$ is in arbitrary units).

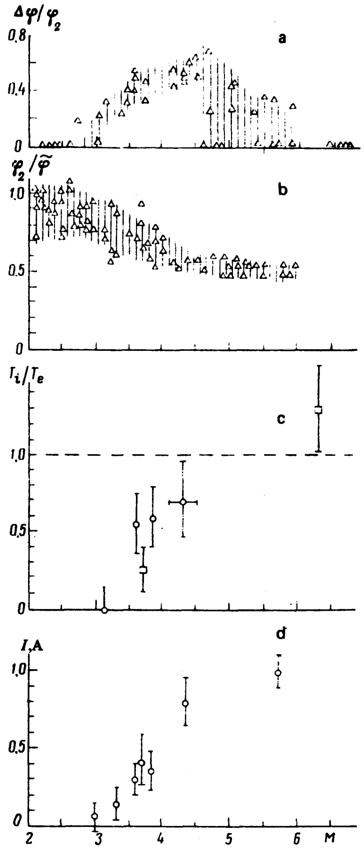

FIG. 2. Dependence of the following shock-wave parameters on the Mach number: a—of the relative amplitude of the isomagnetic potential discontinuity; b—of the ratio of the amplitude of the potential barrier to the decrease of the ion kinetic energy in the shock wave; c—of the ratio of the ion and electron temperatures behind the front; d—of the ion current (in amperes), which is proportional to the number of ions reflected from the potential barrier.

critical Mach number $M_{sc}=u_s/(T_e/m_i)^{1/2}\approx 1.8$ (for an ion temperature $T_i\approx 0$).[4] Here u_s is the velocity of the electrostatic wave and T_e is the electron temperature prior to the discontinuity.

In the present paper we consider, on the basis of an analysis of the experimental data, the role of turbulent ion viscosity in the formation of the isomagnetic discontinuity.

Experiments with nonlinear ion-sound waves have shown that laminar electrostatic fronts of even sufficiently small amplitude, $M_s\approx 1.1$ to 1.2, become turbulent in the course of their propagation even at distances on the order of hundreds of Debye radii, if the ratio of the ion and electron temperatures in the unperturbed plasma is not too small ($T_i/T_e\gtrsim 0.05$).[5] The cause of this process is that the finite ion temperature gives rise to ions that are reflected from the front and move relative to the unperturbed plasma with an average velocity $\approx 2u_s$. The cause the buildup of ion-sound and ion Langmuir oscillations, as a result of which turbulence sets in and the laminar-wave front broadens.[5] On the other hand, a study of the transverse shock waves in the Mach number range $M_{c1}<M<M_{c2}$, at which the front structure with the isomagnetic discontinuity is observed, has shown that the appearance of the discontinuity, first, correlates with a decrease of the ratio

$$\frac{\varphi_2}{\varphi}=\varphi_2\Big/\frac{m_iu^2}{2}\left(1-\frac{1}{h^2}\right),$$

where 2 is the potential barrier in the shock wave, $h=(\Delta H+H_0)/H_0$ is the relative amplitude of the wave, H_0 is the unperturbed magnetic field (Fig. 2b); this is equivalent to in increase, due turbulent viscosity, of the ion pressure in the wave front[2]; second, it correlates with the increase of the ratio T_i/T_e behind the front (Fig. 2c) the values of T_e and n were measured by a laser scattering method, and T_i was calculated from the known T_e and n by using the relation for a planar shock wave on the discontinuity[6,7]; third, it correlates with an appreciable increase of the number of ions that are reflected from the front and move with velocity $2u$, a number that increases with increasing M (Fig. 2d)[8]; fourth, it correlates with the formation of a "pedestal" ahead of the front on the magnetic-field profile.

It follows directly from these data that the low-amplitude laminar electrostatic wave that forms the isomagnetic discontinuity during the earlier state of its development should become turbulent very rapidly as the Alfven Mach number (and accordingly M_s) increases. As seen from Fig. 2c, the ratio T_i/T_e reaches a value ~0.2 already at $M\approx 3.2$ and a noticeable number of reflected electrons capable of causing the buildup of two-stream instability is registered (Fig. 2d). The question is, to what size can the front of the laminar wave broaden, and are the ions effectively heated in this case? In other words, what is the characteristic scale of the turbulent ion viscosity. To answer this question, studies were made of the instabilities of two opposing streams of different density in a non-isothermal plasma. The principal results of these studies reduce to the following:

(a) The development of the instability can lead to formation of a quasistationary electrostatic turbulent shock front (the case $M_s\approx 2$ to 3 was investigated).[9]

(b) The shock-front width determined by the characteristic scale δ_v of the turbulent ion viscosity amounts to ~$20r_d$, where $r_d=(T_e/4\pi ne^2)^{1/2}$, it is comparable with the width δ of the isomagnetic discontinuity (Fig. 1c).

(c) The ions of the denser incident stream are effectively heated over the scale δ_v (Figs. 1d,f).[11]

(d) The less dense opposing ion stream emerges from the turbulent region smeared out, but the decrease of its directional velocity does not exceed 10–20%. Outside the turbulent region it practically does not interact with the incident stream (Figs. 1c, e).[11]

The foregoing results lead to the following qualitative pattern of formation of the isomagnetic discontinuity. During the earlier stage of formation, at $M\gtrsim 3$ and at sufficiently low values of $T_i/T_e<0.1$ the discontinuity is a laminar electrostatic wave. With increasing M the amplitude of the electrostatic wave increases and with it the number of ions that are reflected from its front and move relative to the unperturbed plasma with an average velocity close to $2u$. Owing to the development of the two-stream instability, the laminar wave becomes turbulent with a width ~$(10–100)r_d$. The ion heating occurs mainly in this region, while in the remaining larger part of the front resistive dissipation prevails, i.e., it is the electrons that are "heated" for the most part.

The formation of a "pedestal" on the profile of the magnetic field at $M\approx 3$ is apparently connected with the appearance of reflected ions which, interacting with the plasma in the region of the jump, move ahead of the front almost without collisions with a velocity u_{ref}, where $u<u_{ref}<2u$, with u_{ref} close to $2u$.[8] Within the framework of the described model, the vanishing of the discontinuity with increasing Mach number as $M\to M_{c2}$ can be represented as follows: since the ratio T_i/T_e increases with increasing M, there should be violated, when a certain value $M\approx M_{c2}$ is reached, the condition

$$\frac{T_i}{T_e}<\alpha^{2/3} \qquad (1)$$

($\alpha<1$ is the relative density of the reflected ions) for the buildup, by the ion beam, of oscillations with a characteristic wavelength

$$\lambda_m\sim r_d\ll\rho_e\simeq\frac{(2T_em_e)^{1/2}c}{e(H_0+\Delta H)}$$

and accordingly the formation of a turbulent discontinuity with $\delta_v\sim(10–100)r_d$ becomes impossible. At $M>M_{c2}$, when there is no isomagnetic discontinuity, reflected ions are registered none the less (Fig. 2d) and collisionless heating of the ionic component of the plasma is observed. A possible cause of the latter, taking into account the available experimental data,[10] can be assumed to be the buildup, by the reflected ions, of electrostatic oscillations with $\lambda_m\sim c/\omega_0$ and characteristic frequencies $\omega \approx e(2H_0+\Delta H)/2c(m_e m_i)^{1/2}$, the development of which does not necessarily call for satisfaction of the non-isothermy condition (1). Since in this case[10] the viscosity-dissipation scale

$$\delta_v \sim \frac{c}{\omega_0}\left(\frac{m_i V_A^2}{e\Phi}\right)^2 \qquad (2)$$

(Φ is the characteristic amplitude of the turbulent oscillations of the potential) is comparable with the resistive front width $\Delta_r \approx 10c/\omega_0$, ion heating can occur in a greater part of the transition layer and the profiles of H and φ can accordingly remain similar.

It is interesting to note that at $M > M_{c2}$ the value of the potential barrier φ_2, which is determined only by processes that occur in the front, amounts to approximately to half the losses of the ion kinetic energy, $\tilde{\varphi} = \frac{1}{2}m_i (u^2 - u_2^2)$, where u_2 is the ion velocity behind the front in the coordinate system connected with the wave (Fig. 2b). This result, according to an analysis made by Galeev *et al.*[13] for a shock wave near the earth, also favors the indicated mechanism of energy dissipation of the ion stream. Using as an example the experimentally obtained shock front with an isomagnetic discontinuity[1] (see Fig. 2a on p. 2082 of[1] [p. 1122 of the translation]), which shows the time profiles of the magnetic field ΔH and of the potential φ in the wave front), we shall make comparative estimates of the scales of the Coulomb electron-ion (λ_{ei}) and ion-ion (λ_{ii}) collisions, of the anomalous resistive dissipation, and of the turbulent ion viscosity under the following initial experimental conditions: $n_0 \approx 2\cdot 10^{14}$ cm^{-3}, $H_0 \approx 330$ Oe, $M=4$, $h=2.9$, $u \approx 10^7$ cm/sec. To estimate the plasma parameters behind the front we shall use the data of Fig. 2c and the relations on a plane shock discontinuity in the hydrodynamic approximation.[1,14]

Knowing the quantity

$$\beta = \frac{n_0 h(T_i+T_e)}{H_0^2/8\pi} = \frac{(h-1)^3}{4-h} \approx 3.25$$

and recognizing that for $M=4$ we have $T_i/T_e \approx 0.5$ (Fig. 2c), we find that behind the wave front $T_e \approx 30$ eV and $T_i \approx 16$ eV. This yields estimates of the corresponding characteristic scales behind the front, $\lambda_{ei} \approx 17$ cm, $\lambda_{ii} \approx 5$ cm, $r_d \approx 10^{-4}$ cm, $\rho_e \approx 3\cdot 10^{-2}$ cm, giving in turn $\delta_v \approx (10-100) r_d \approx (10^{-3}-10^{-2})$ cm, $\Delta_r \approx 10c/\omega_0 \approx 0.4$ cm. We obtain the experimental values of Δ and δ, knowing the time scales of the magnetic-field gradient in the wave, $\Delta t \approx 70$ nsec and the isomagnetic discontinuity of the potential 1 nsec (see Fig. 2a on p. 2082 of[1], p. 1122 of the translation), $\Delta \approx \Delta t u \approx 0.7$ cm, $\delta \approx \tau u \approx 10^{-2}$ cm. Thus, the measured scales of Δ and δ are much less than λ_{ei} and λ_{ii} and agree in order of magnitude with the values of Δ_r and δ_v. Moreover $\delta \lesssim \rho_e$, an important factor, as noted above, in the formation of the isomagnetic discontinuity.

We have thus shown on the basis of an analysis of the known and of the newly obtained experimental data that the mechanism of formation of the isomagnetic discontinuity in the front of a collisionless shock wave at Mach numbers $M_{c1} < M < M_{c2}$ is apparently due to the turbulent ion viscosity. At a sufficiently low amplitude of the discontinuity ($M \gtrsim M_{c1}$), the decisive role in its formation can be played by dispersion of the ion-sound waves.

We note in conclusion that the experimental material used in the analysis is not sufficient to draw final conclusions, and the proposed picture of the nature of the isomagnetic discontinuity requires further experimental and theoretical verification.

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