Turbulent shock wave in a low-density unmagnetized plasma

O. L. Volkov, V. G. Eselevich, G. N. Kichigin, and V. L. Papernyĭ

Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation, Siberian Section, USSR Academy of Sciences

(Submitted April 4, 1974)
Zh. Eksp. Teor. Fiz. 67, 1689–1692 (November 1974)

It is found that a turbulent shock wave forms when a supersonic stream of low-density plasma strikes a magnetic barrier. The formation of the shock front is attributed to the development of ionic beam instability induced by the part of the stream that is reflected by the magnetic barrier.

1. Sagdeev[1] was the first to give a detailed discussion of the existence of shock waves in a low-density plasma. Such waves have been observed experimentally in a plasma in a magnetic field (see, e.g.,[2]). The formation of shock waves in an unmagnetized plasma has been attributed to the development of turbulence on account of instabilities of the anisotropic[1] and beam[3] types. The results of the experiments reported here confirm the possibility of a shock wave being produced as a result of the development of ionic beam instability.

2. The experiments were performed with the "SOMB" device (Fig. 1). The plasma stream was produced in a cylindrical vacuum chamber 2 m long and 0.6 m in diameter, which was pumped down to $\sim 5 \times 10^{-6}$ mm Hg. The supersonic plasma stream was produced by a method similar to that described in[4]. The plasma flow, which was quasistationary over the time interval $\Delta t = 200–300\ \mu$sec, had the following characteristics: density, $n_0 = 10^6–10^7$ cm^{-3}; electron temperature, $T_e \approx 5$ eV; ion temperature[1)] (Ar^+), $T_i \approx 0.1–0.5$ eV; flow velocity, $u \approx (0.5–1.0) \times 10^6$ cm/sec; Mach number, $M = u(T_e/m_i)^{-1/2} \approx 2–3$; mean free path for electrons and ions between collisions with neutrals, $\lambda \sim (10^2–10^3)$ cm. A magnetic field localized in space (the "magnetic barrier") was produced at a distance of 100 cm from the plasma source by a solenoid of rectangular cross section having the following dimensions: $\Delta x = 1.5$ cm, $\Delta y = 15$ cm, $\Delta z = 40$ cm. The solenoid was wound at a 1 cm pitch with wire whose diameter (including the insulation) is 0.1 cm. The maximum field gradient $\Delta H/\Delta x$ was $\sim 10^3$ Oe/cm.

The ion density in the plasma in front of the magnetic barrier was investigated with cylindrical Langmuir probes 20 cm long and 0.15 cm in diameter, which could be moved about in the xy plane (Fig. 1). The 0.15 cm diameter of the probes was much smaller than the Debye radius $r_D = \sqrt{T_e/4\pi n_0 e^2}$. The energy spectrum of the ions in the plasma stream was investigated with a cylindrical electrostatic analyzer, the ion energy spectrum being measured within the time interval $\Delta t \approx 10\ \mu$sec.

3. The spatial distribution of the ion density averaged over the random fluctuations (Fig. 2) indicates that there is a perturbed region in front of the "magnetic barrier" in which the density n and the amplitude $\tilde{n}$ of the fluctuations are considerably larger than the corresponding unperturbed quantities n_0 and $\tilde{n}_0$ ($\max(n/n_0) \approx 2$, $\tilde{n}_0/n_0 \sim 0.05$, and $\tilde{n}/n \sim 0.2$). This region is bounded by a transition layer that separates it from the unperturbed plasma. In the xy plane, the boundary of the perturbed region, which is at rest in the laboratory system, has the shape of an arc that envelops the barrier at a distance L_x of 15 cm (Fig. 1).

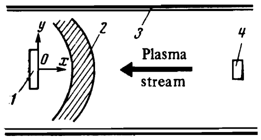

FIG. 1. Experimental setup: 1—solenoid, 2—shock front, 3—vacuum chamber, 4—plasma source.

The principal features of the transition layer are characteristic of a collisionless shock front:

a) The density n and the normal flow velocity component u change suddenly within the layer (Fig. 2), the product nu remaining approximately constant across the break.

b) The layer is quasistationary since its structure (averaged over the fluctuations) does not change during the time $\Delta t \approx 100\ \mu$sec, while an ion passes through the transition region in the much shorter time $\tau \sim \Delta/u \approx 6\ \mu$sec (Fig. 2).

c) The energy of the stream is dissipated within the boundary of the disturbed region, as is evinced by the broadening of the ion energy distribution (averaged over the fluctuations) beyond the front in the low-energy direction (Figs. 3, a and b).

d) The thickness $\Delta \approx 6$ cm of the layer is much smaller than the mean free path $\lambda \gtrsim 100$ cm of the particles between binary collisions.

A search for possible reasons for the formation of a shock front of thickness Δ much smaller than the mean free path λ revealed:

a) The existence of a plasma stream reflected from the magnetic barrier, whose ion density n_{ref} and flow velocity u_{ref} satisfy the conditions $m_{ref} \ll n_0$ and $u_{ref} \approx -u$ (Fig. 3,c).

b) A progressive broadening in the low-energy direction of the energy spectrum of the reflected beam on receding from the barrier, with a simultaneous decrease in its flow energy (Figs. 3, c, d, and e).

These facts, together with the high fluctuation level in the disturbed region ($\tilde{n}/n \lesssim 0.2$), indicate the buildup of an instability. In the present case we have ion and electron streams in relative motion while the conditions

$$\sqrt{T_e/m_e} > 2u > \sqrt{T_e/m_i}, \tag{1}$$

and

$$\sqrt{T_i/m_i} < \sqrt{T_e/m_i}\,\alpha^{1/3}, \quad \alpha = n_{ref}/n_0, \tag{2}$$

are satisfied; hence the following instabilities can develop: electron-ion instability with the logarithmic increment $\gamma_{ei} \sim (m_e/m_i)^{1/2}\omega_{0i}$ where $\omega_{0i} = \sqrt{4\pi n_0 e^2/m_i}$; and 2) hydrodynamic ion-ion instability with the logarithmic increment $\gamma_{ii} \sim \alpha^{1/3}\omega_{0i}$[5]. Since $\gamma_{ii} \gg \gamma_{ei}$, it is the ion-ion instability that will develop[2)]. The frequen-

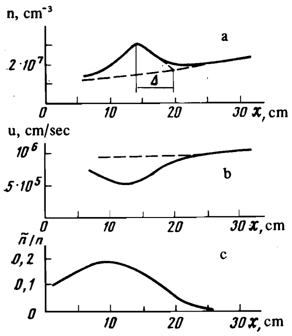

FIG. 2

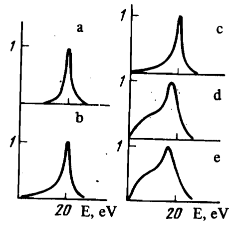

FIG. 3

FIG. 2. Spatial distribution of the ion density (a), flow velocity (b), and fluctuation amplitude (c) in the shock wave for $H_{max} \approx 500$ Oe and $n_0 \approx 10^7$ cm^{-3} (the dashed sections are for H = 0).

FIG. 3. Longitudinal-energy spectra (normalized to unit height at the maximum) of the ions in the incident stream (a—ahead of the shock front, x = 30 cm; b—behind the shock front, x = 14 cm) and in the reflected stream (c—behind the front, x = 10 cm; d—in the front, x = 16 cm; e—ahead of the front, x = 25 cm).

cies of the oscillations that were observed in the experiment and are characteristic of this instability are of the order of ω_{0i}.

A qualitative picture of the formation of the shock front can be drawn as follows. When the supersonic plasma stream strikes the magnetic barrier, part of it is reflected and moves with the flow velocity $u_{ref} \approx -u$. The reflected ion beam excites oblique waves in the plasma (since $u > c_s$), which, increasing in amplitude, move up stream together with the reflected beam (the growth in the amplitude of the fluctuations at $x \lesssim 10$ cm seen in Fig. 2,c). Experimental observation of a similar effect of "carrying away" of oscillations by an ion beam is reported in[6]. The reduction in the amplitude of the oscillations at x > 10 cm is apparently due to the spreading of the beam, which causes both the logarithmic increment of the instability and the group velocity of the oscillations to decrease. As a result, ahead of the barrier (x < 20 cm) there arises a zone of strong turbulence in which the effective collision frequency is much greater than the electron-ion Coulomb collision frequency. On entering the "collision" zone, the supersonic plasma stream is "compressed" and "decelerated," and soon becomes a subsonic stream. A shock front is formed. Behind the shock front (x < 15 cm) the "heated" and "moderated" plasma stream expands as it flows toward the magnetic barrier, and almost all of it passes through the barrier (the density n_{ref} of the reflected beam is $\sim 0.1 n_0$). This is shown by the fact that behind the front (x < 15 cm) the density falls to the value $n \approx n_0$ (Fig. 2,a). In this picture, in fact, all the magnetic barrier does is to produce a weak reflected plasma stream.

The authors are grateful to R. Z. Sagdeev for the idea of performing the experiment and to A. M. Fridman for fruitful discussions.

1) The temperature of the ions in the stream was found from the formula [4] $T_i \approx T_0^2/4E$, in which T_0 is the temperature determined from the measurements (Fig. 3) and E is the flow energy of the ions in the stream; this formula is valid for $T_0 \ll E$.

2) The instability passes from the hydrodynamic stage to the kinetic stage at the distance $l_x \sim u/\gamma_{ii}$ from the barrier, because of the "spreading" of the beam.

1 R. Z. Sagdeev, Voprosy teorii plazmy [Problems of Plasma Theory] 4, Atomizdat, 1964.

2 S. G. Alikhanov, A. I. Alinovskiĭ, G. G. Dolgov-Savel'ev, V. G. Eselevich, R. Kh. Kurtmullaev, V. K. Malinovskiĭ, Yu. E. Nesterikhin, V. I. Pil'skiĭ, R. Z. Sagdeev, and V. N. Semenov, III Mezhdunarodnaya konferentsiya po fizike plazmy, Novosibirsk, doklad 24/AI, 1968 (Third International Conference on Plasma Physics, Novosibirsk, Report 24/AI), 1968.

3 E. N. Parker, Phys. Rev. 112, 1429 (1958).

4 S. G. Alikhanov, V. G. Belan, G. N. Kichigin, and P. Z. Chebotaev, Zh. Eksp. Teor. Fiz. 60, 982 (1971) [Sov. Phys.-JETP 33, 532 (1971)].

5 A. B. Mikhaĭlovskiĭ, Teoriya plazmennykh neustoĭchivosteĭ [Theory of Plasma Instabilities], I, Atomizdat, 1970, Chapter 3.

6 A. Y. Wong and R. W. Means, Phys. Rev. Lett. 27, 973 (1971).

Translated by E. Brunner
183