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GENERATION OF COLLISIONLESS SHOCK WAVES PROPAGATING ALONG A MAGNETIC FIELD

Yu. E. Nesterikhin, A. G. Ponomarenko, and B. A. Yablochnikov
Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences
Submitted 22 August 1966
ZhETF Pis'ma 4, No. 10, 403-409, 15 November 1966

An experimental investigation of the conditions for the excitation of shock waves propagating in a rarefied plasma along the magnetic field is of fundamental significance at the present time.

As is proposed in [1,2], the possible generation of shock waves in an interplanetary plasma as streams of charged particles ("solar wind") move toward the earth is the basic factor underlying such physical phenomena as the sudden occurrence of geomagnetic storms, the singularities of the magnetic field measured by the "Pioneer," "Mariner-2," and "IMP-1" at 12 - 14 earth radii, single pulses and the existence of electrons with energy 1 - 100 keV, radiation belts, auroras, etc. [3,4]. In nuclear fusion, the possibility of generating such waves is directly connected with the problem of transforming the translational energy of plasma streams into random motion, i.e., heat, upon injection of plasmoids along the magnetic field [5].

We present here the results of preliminary experiments devoted to this problem. A column of preliminary plasma was produced in a quasistationary magnetic field $H_0 = 0 - 3$ kOe by discharging capacitor C_1 into coil 2 in a glass vacuum chamber (length ~400 cm and diameter $2R \approx 20$ cm) filled with hydrogen ($p \simeq 10^{-3} - 5 \times 10^{-4}$ mm Hg). The longitudinal electron-density distribution is shown in Fig. 1. Some 50 - 70 μsec later, capacitor C_2 was discharged into conical coil 3 to produce a fast plasmoid with density $n_1 \simeq (5 - 7) \times 10^{13}$ cm^{-3} and velocity $u_{\parallel} > v_a = H_0/\sqrt{4\pi n_0 M}$. We note that in this case we deal with a plasma having a clearly pronounced pressure anisotropy

$$p_{\parallel} > p_{\perp} = H_0^2/4\pi \qquad (1)$$

In a weak magnetic field, it should be unstable against excitation of perturbations of the "Alfven type" (the so-called hose instability [2,5]). The kinetic energy of the plasmoid should become transformed into the energy of the alternating magnetic field $\tilde{H}_{\perp}$ and the transverse particle motion in the plasma within a time on the order of $\tau \gtrsim 1/\omega_{ci} = cM/eH$. At present there is still no theory allowing a detailed description of the sequence and significance of the physical processes occurring during supersonic motion of plasmoids under conditions where there are no collisions. We therefore proceed to report the experimental results, confining ourselves during the course of the exposition to a comparison with the existing theoretical estimates and experimental data [2,6-8].

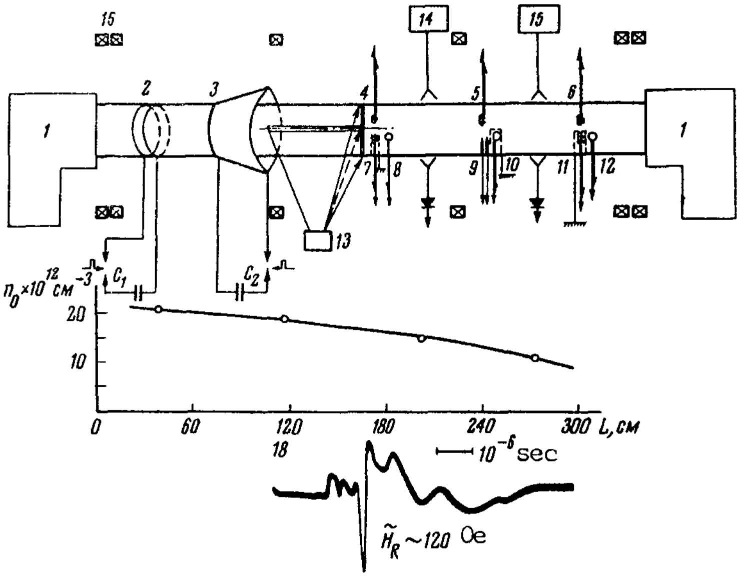

Fig. 1. Block diagram of setup. 1 - Vacuum pump, 2 - shock coil producing the preliminary plasma, $C_1 = 1.2$ μF, $U_1 = 25$ kV, $T_1 = 6$ μsec; 3 - shock coil producing a plasma stream along the magnetic field, $C_2 = 1.2$ μF, $U_2 = 25 - 50$ kV, $T_2 = 3.2$ μsec; 4,5,6,7 - magnetic probes to measure the components H_R and H_θ, distance between probes ≈ 70 cm; 8,10,12 - magnetic probes measuring the component H_Z; 9 - double Langmuir probe; 13 - electron-optical converter (photography through horizontal and vertical slits); 14,15 - microwave sounding, $\lambda = 0.4$, 0.8, and 3 cm; 16 - coils for stationary magnetic field; 17 - longitudinal distribution of electron density in the preliminary plasma; 18 - typical oscillogram of signal from magnetic probe (4), RC = 15 μsec, NS = 5.

The main diagnostics methods and a block diagram of the setup are shown in Fig. 1. In the first experiments we noted that, owing to the nonstationary nature of the process, both the structure of the frontal part of the supersonic stream and the oscillations of the rear section of the moving plasma pinch depend strongly on $u_{\|}/v_a$, H_0, n_0, and on their distributions along the chamber. Figure 2 shows the aggregate of experimental data obtained with the electron-optical converter, the magnetic probes measuring the components $\tilde{H}_R$, $\tilde{H}_\theta$, and $\tilde{H}_Z$, and the double Langmuir probe. The main results can be summarized as follows: when (1) is satisfied, a magnetic disturbance is actually seen to be produced after a time on the order of $\tau \gtrsim 1/\omega_{ci}$ on the front of the moving plasmoid (the components $\tilde{H}_R$ and $\tilde{H}_\theta$ increase, for in the case of Alfven disturbances the $\tilde{H}_Z$ component should remain unchanged (see Fig. 2). The values of $\tilde{H}_R$ and $\tilde{H}_\theta$ increased in the experiments to 100 - 200 Oe, which is approximately half the stationary field H_0. As the plasmoid moves forward in the preliminary plasma, the slope of the leading front of the magnetic signals increases, reaching the characteristic dimension $\Delta \lesssim u_{\|}/\omega_{ci} \lesssim 15$ cm.

At velocities $u_{\|} \gtrsim v_a$ we could trace in greater detail the fine structure of the magnetic fields $\tilde{H}_R$ excited by the plasmoid. In this case the leading front of the disturbance did not assume its final shape by the instant of its arrival at the measuring magnetic probe,

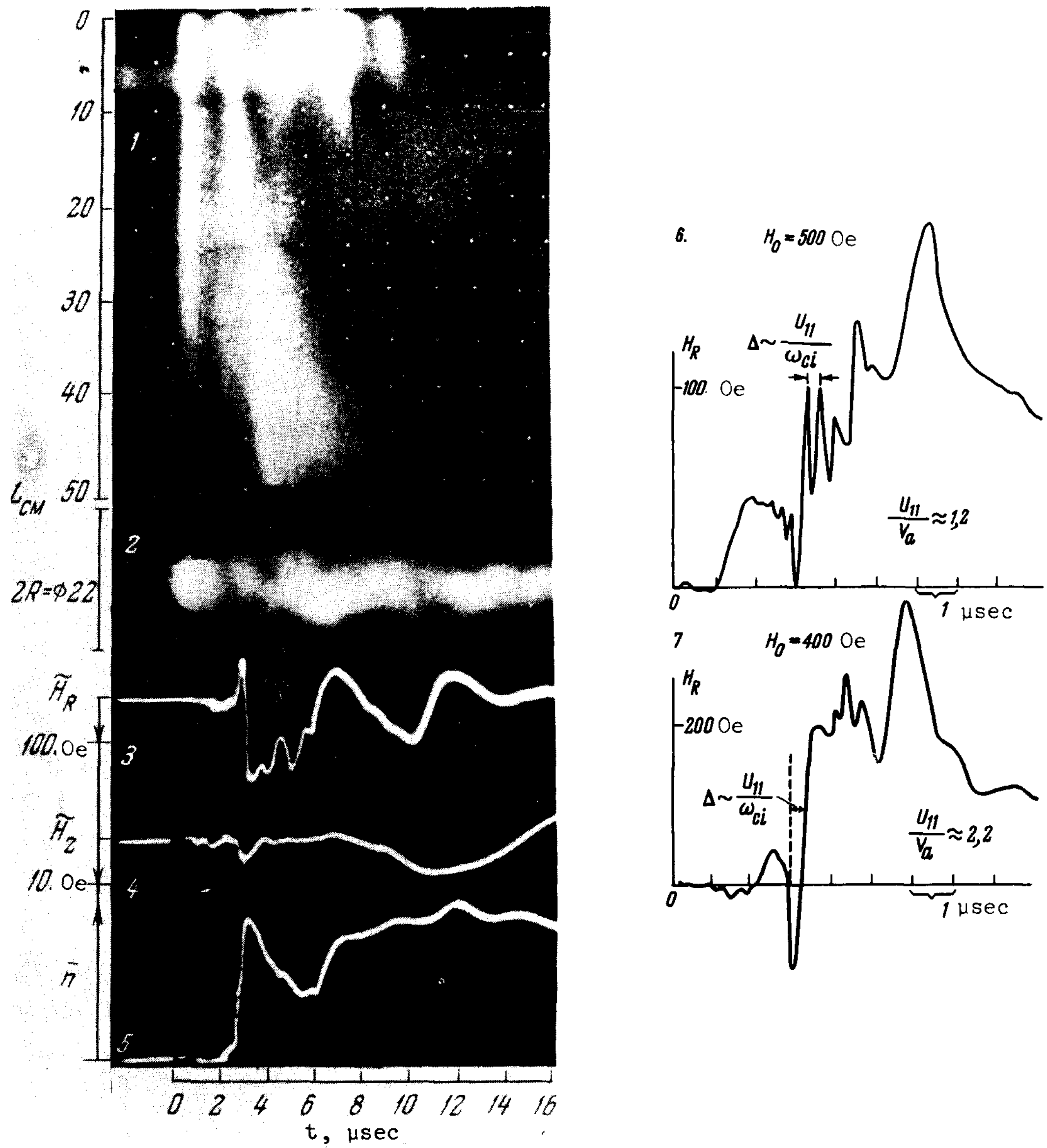

Fig. 2. Experimental results describing the formation of the front of the magnetic disturbance in supersonic flow of a plasma along a magnetic field. 1 - Streak photograph of the horizontal slit (L = 50 cm), obtained with the electron-optical converter; 2 - vertical slit, L = 22 cm; 3 - signal from magnetic probe (4), RC = 20 μsec; 4 - signal from magnetic probe (8), RC = 25 μsec, H_0 = 400 Oe; 5 - signal from double Langmuir probe; 6 and 7 - signals from magnetic probe (4), illustrating the appearance of oscillations on the leading front of the disturbance, $p = 7 \times 10^{-4}$ mm Hg.

but we see here, too, a periodic profile with characteristic dimension Δ. The conversion of the translational energy $Mn_1u_{\parallel}^2/2$ into the energy of the magnetic field $\tilde{H}$ causes part of the ions to lose velocity, and the plasmoid is noticeably decelerated (see the streak of the horizontal slit with L = 50 cm, obtained with the electron-optical converter, Fig. 2).

Behind the front of the magnetic disturbance, we have observed large-scale Alfven-type oscillations ($\omega \lesssim \omega_{ci}$) propagating with velocity $\omega \approx v_a$ (the Alfven velocity in the plasmoid). The growing transverse energy of the plasma particles produces additional ionization and an increase of the diamagnetic signal ($\tilde{H}_Z$). The leading density front, measured by the diamagnetic and Langmuir probes, coincides with the front of the magnetic signal $\tilde{H}_R$. It must be noted that we observed in the experiments an escape of the fast component from the plasmoid produced by the injector, and the only particles participating in the formation of its frontal part were those with velocity satisfying the relation $u_{\parallel} \lesssim R\omega_{ci}$. The profile of the magnetic field $\tilde{H}_{\perp}$ was altered as the field moved along the chamber and as the value of $Mnu_{\parallel}^2$ decreased, namely, the field amplitude decreased, the oscillations behind the front wave attenuated, and the leading fron of the magnetic signal assumed more and more the form of a single pulse with characteristic dimension $\sim\Delta$ (Fig. 3). The profile of the particle density in the plasmoid behaved similarly.

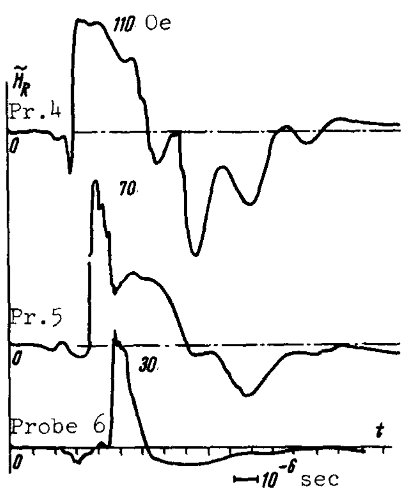

Fig. 3. Transformation of the front of a magnetic disturbance as the plasmoid moves along the magnetic field H_0. RC = 25 μsec, NS = 12, p = 8 x 10^{-4} mm Hg.

There is no doubt that the observed effect is influenced not only by attenuation, but also by dispersion effects and by disturbances that move relative to the quasistationary field H_0. It was further established that in the absence of a preliminary plasma no instability sets in, and the magnetic probes register trapped magnetic fields $\lesssim 5$ Oe, with a characteristic time on the order of the period of the injector current (3 μsec). The increase in the quasistationary field leads to a decrease in the ratio $u_{\parallel}/v_a$, and although the characteristic frequencies of the oscillations $\sim\omega_{ci}$ increase, nonetheless, starting with $H_0 \gtrsim 1$ kOe, we observed in our experiments stabilization of the initial disturbance and a dissolution of the leading front of the plasmoid.

We are unable to state at present to what degree the described phenomenon can be identified with the formation of a collisionless shock wave.

We note, however, that our results are qualitatively close to the field pattern observed in investigations of the structure of the magnetic field in the magnetosphere by the "Pioneer" satellites.

The experimentally measured width of the leading front of the disturbance, which has the character of a shock wave, is in qualitative agreement with the theoretical estimates given in [2,6]

$$\Delta \sim \frac{Mc}{eH_0} u_{\parallel} \sim 10 \text{ cm}, \quad \frac{u_{\parallel}}{v_a} \gtrsim 1.$$

The authors thank R. Z. Sagdeev for stimulating discussions and help.

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GAS-LIQUID COEXISTENCE CURVE FOR SULFUR HEXAFLUORIDE NEAR ITS CRITICAL POINT

L. A. Makarevich and E. S. Sokolova
State Institute for Nitrogen Industry
Submitted 29 August 1966
ZhETF Pis'ma 4, No. 10, 409-413, 15 November 1966

Several recent papers [1-5] discuss the form of the coexistence curve near the critical point. The authors of these papers attempt to derive an equation for the coexistence curve near the critical point, with allowance for the higher terms in the series expansion of $(\partial p/\partial v)_T$. Thus, for example, Giterman [6] derived an equation for the coexistence curve near the critical point by using the singularity observed by Voronel' [7,8] in the behavior of C_v near the critical point.

The authors obtained exact data on the gas-liquid equilibrium of sulfur hexafluoride in the temperature interval $T_{cr} - T \cong 0.001 - 0.800$°C. The investigations were made with previously-described apparatus [9], which was improved to increase the experimental accuracy.

The sulfur hexafluoride used in the work was purified with a specially constructed high-pressure rectification column and its purity was not lower than 99.995%.

The absolute temperature was measured with a platinum precision resistance thermometer accurate to ±0.005°C. The change in temperature was measured with a Beckman thermometer calibrated against a platinum thermometer, with accuracy ±0.001 - 0.002°C. The Beckman thermometer was enclosed in a thermostatically controlled jacket to eliminate errors connected with the projecting mercury column. The thermometer error due to variation of atmospheric pressure did not exceed ±0.001°C. The temperature at which one of the phases vanished was determined visually with accuracy ±0.001 - 0.002°C. The accuracy of the volumetric measurements was ±0.05%. The critical molar volume was determined accurate to ±0.2% visually. The