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PHYSICS OF INTERPLANETARY PLASMA AND LABORATORY EXPERIMENTS

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I. POSSIBILITY OF SIMULATING COSMIC PHENOMENA

ACCORDING to modern concepts, the global picture of the interaction between the solar wind and the earth's magnetic field is as follows. During the course of the radial expansion of the hot plasma of the solar corona ($T \sim 100$ eV), which recalls expansion from a nozzle, the translational velocity becomes so large that the flow becomes supersonic. Incidence of the plasma on the earth's magnetic field produces a cavity, the magnetosphere, where the conditions are such that the charged particles are captured in the radiation belts, which are traps with magnetic mirrors. Near the limit of the magnetosphere, a shock wave is produced (the solar wind represents, as it were, a gas-dynamic medium and not a Knudsen gas).

On the night side, the force lines stretch out and form the geomagnetic tail. In the solar wind itself, even far from the magnetosphere, there are noticeable microfluctuations (the wind plasma is, as it were, a turbulent medium).

In this picture, which is at first glance simple, all the processes, with the exception of the production of the cavity are the consequences of the so-called anomalous properties of the plasma, which are due to the collective interactions (microinstabilities). This is precisely why no satisfactory model could be constructed for these phenomena without involving additional hypotheses.

The interplanetary medium is a giant reservoir filled with plasma, in which various phenomena connected with collective interactions take place. Many of these phenomena recall processes investigated in a laboratory low-density plasma. It is therefore natural for physicists to demonstrate concrete cosmic phenomena in the laboratory, for example the interaction between the solar wind and the earth's magnetic field.

The overwhelming majority of data on the solar wind and its interaction with the earth's magnetic field have been obtained with the aid of artificial satellites and rockets. The contribution of model experiments to the understanding of the phenomena occurring in outer space is incomparably smaller than the possibilities offered by such experiments. The main obstacle to the organization of laboratory experiments has been for a long time the absence of any data on the parameters of the interplanetary plasma. Therefore the first attempts to simulate phenomena in the earth's magnetic field consisted of immersing a magnetic dipole in a gas-discharge plasma. The organization of model experiments became justified only after the development of the idea of E. Parker[1-4] concerning the existence of a continuous solar wind and after the first data were obtained on the parameters of the interplanetary plasma[5-6].

According to the available data, the mean values of the solar-wind parameters are as follows: 1) The solar wind is essentially a fully ionized hydrogen plasma of density 5–6 cm^{-3}. 2) The translational velocity of the plasma is $(3-5) \times 10^7$ cm/sec. 3) The temperature of the electrons in the quiescent solar wind is several electron volts and exceeds by several times the temperature of the ions. 4) The magnetic-field force lines emerging from the surface of the sun are dragged by the plasma stream, becoming twisted into an Archimedean spiral as the result of its rotation. In the region of the earth's orbit, the force line makes an angle of approximately 45° with the sun-earth axis. The field intensity at the earth's orbit is $\sim 10\gamma$ (10^{-4} Oe)[7-9].

The idea that the solar wind is a continuously flowing medium with definite values of the concentration, temperature, and magnetic-field vector is only the first approximation to reality, since numerous discontinuity surfaces have been observed in the solar wind, and all these quantities (or some of them) change jumpwise on passing through these surfaces. The figures presented here give only an idea of the stationary picture, on which fluctuations that lead particularly to drift of the boundary of the magnetosphere are superimposed under real conditions.

Knowledge of the average characteristics of the plasma stream together with known value of the magnetic moment of the planet suffices to reconstruct the configuration of the magnetic field and to obtain in the laboratory the most interesting phenomena that accompany the interaction of the solar wind with some particular planet. During the initial stage of the simulation, particular importance attaches just to experiments with constant values of the plasma parameters, since such measurements make it possible to obtain more complete information on the physics of the processes than investigations under outer-space conditions. Results of measurements performed with satellites of the IMP type during the motion of the satellite along one side of an elliptical orbit (in the direction towards the earth or away from the earth) have shown that the instruments sometimes have time to register several times the passage of a shock wave through the satellite[10,11]. In the intervals between such passages, the instruments register either the unperturbed solar wind, or else the plasma behind the front of the shock wave. In other words, the front of the shock wave drifts in space relative to a certain mean distance to the earth, with a velocity larger than the satellite velocity. Knowledge of this velocity is essential for the determination of the width of the shock-wave front and for the study of the reproducibility of its form. All the data on the dimensions of the shock front were obtained in a rough approximation on the basis of an estimate of the average drift velocity of the front of the shock wave, starting from the number of intersections of the front by the satellite and with the radial component of its velocity. Besides the errors in the determination of the velocity of the "slow" drift of the shock-wave front, even greater errors may be introduced by more rapid low-amplitude oscillations, the existence of which cannot be excluded beforehand. The presence of such rapid oscillations of the front position should be registered by the satellite as a seeming broadening of the wave front in the region of the turbulent plasma behind the shock-wave front. Thus, measurements performed on a single space ship are patently insufficient to explain the structure of the shock wave. It is necessary to have a series of satellites, moving along closely-lying orbits separated by distances smaller than the width of the shock wave. Then, by performing synchronous measurements and using a correlation technique, it is possible to obtain reliable data on the spatial distribution of the main characteristics of the plasma inside the shock wave.

In a laboratory experiment, all these difficulties disappear if the plasma source has good reproducibility. In addition, the use of several probes and a study of the correlation of their readings is not such a difficult problem as simultaneous measurements on a series of satellites.

The main obstacle in the recent development of model experiments has been the impossibility of duplicating under laboratory conditions the exact model of the interaction between the solar wind and the magnetic field of the earth or other planets. These difficulties can be understood also from general similarity considerations. Considering, for example, the similarity ratio for a gas discharge[12-13], it is easy to verify that exact reproduction of the phenomena in the near-earth space calls for the production of plasma-stream temperatures and for magnetic-field intensities such that their attainment would automatically solve one of the main problems of technical physics—the problem of controlled nuclear fusion. The difficulties of exact simulation have led to a number of experiments, in which the only similarity condition was the equality of the magnetic and gas-kinetic pressures on the plasma-field boundary. Since the value of the results of such investigations to the understanding of the physics of the phenomena is slight, no attempt was made in these investigations to use modern methods of plasma diagnostics, and the main conclusions were frequently formulated only on the basis of the form of the glow of the neutral gas near the terrella. Actually, the impossibility of exact simulation does not mean at all that the characteristics of phenomena in space cannot be reproduced in the laboratory. A typical example is the history of the discovery of one of the most interesting phenomena in the magnetosphere—belts of trapped radiation. Observation of rapid charged particles captured by the earth's magnetic field[14,15] was accidental, and the main features of this phenomenon were not understood immediately, although the possibility of prolonged containment of charged particles in adiabatic traps was by that time considered in detail by A. M. Budker[16] and independently by R. Post[17], and was first confirmed experimentally in the well known experiments of S. N. Rodionov[18], and later by many others. In Rodionov's experiments, an axially-symmetrical trap with a field intensified on the ends was filled with electrons obtained in β decay of tritium, and the lifetime of the electrons prior to escape from the trap was measured. In later experiments[19], it was possible to show that the lifetime of a charged particle prior to its escape from the trap may amount to several dozen seconds. During that time, the particle can experience approximately 10^9 reflections from the place of condensation of the force lines, and to execute more than 10^{10} Larmor revolutions. Thus, the first experiments on adiabatic containment of charged particles in a magnetic field were essentially model experiments relative to the radiation belts. This case spurred the space researchers to investigate thoroughly all the accomplishments of laboratory-plasma physics. Further study of the radiation belts and of adiabatic traps has demonstrated the presence of a closer analogy. Even the first investigations of the radiation belts have shown that retention of a plasma in the earth's magnetic field cannot be regarded as stable. From time to time, an unexpected ejection of particles along the force lines is observed; its cause remained unexplained until recently. A similar leakage of plasma was frequently observed also in the laboratory in different adiabatic traps. As experimental facts have accumulated, an opinion has gradually been established that the cause of such sharp leaks is the development of cyclotron instability, occurring in the presence of anisotropy in velocity space[20]. Since the condition for the retention of a particle in an adiabatic trap is of the form $\sin\alpha > \sqrt{H_0/H_{max}}$ (α—angle between the velocity vector and the direction of the force line, H_0—magnetic field at the center of the trap, and H_{max}—maximal magnetic field in the mirror), the anisotropy in velocity space is an inseparable property of such systems. As a result of the development of the instability, the angle α can decrease and the particle can emerge from the trap along the force line[21,22]. Simultaneously with the loss through the magnetic mirrors, a drift of plasma across the force lines is also observed, and correlation measurements with a pair of wall probes located on a single force line have shown that the plasma leaks cannot be attributed to macroscopic flute instability.

In[22], extensive experimental material was obtained indicating that the leakage of the hot electrons from an adiabatic trap under conditions $T_e \gg T_i$ can be attributed to none other than electron cyclotron instability. Among the most reliable data confirming this conclusion is primarily the burst of microwave radiation accompanying the leakage of the particles. The main contribution to the spectrum of the radiated oscillations is made by the fundamental harmonic (~10 W), and the intensity of the succeeding harmonics attenuates very rapidly. It is interesting to note that the dumping of the particles can be either spontaneous or artificially induced, by applying to the trap cavity a weak pulse at a frequency close to the Larmor electron frequency.

The next step in simulating the radiation belts should be made in a direction towards explaining the mechanism of their filling by the plasma. This question is also of fundamental significance in the problem of realization of thermonuclear fusion and is presently under detailed study. However, the experimental data are still patently insufficient to consider in detail the mechanism of the capture of the charged particles in the magnetic field of the earth. Summarizing all the foregoing, it is natural to draw the following three conclusions:

1) Simulation of cosmic phenomena in the laboratory permits investigations to be carried out under conditions when measurements on satellites and rockets are impossible or difficult.

2) Exact simulation of the interaction between the solar wind and the planets is impossible.

3) Individual cosmic phenomena can be successfully reproduced and investigated in the laboratory.

Starting from the foregoing conclusions, we can state the problem of limited simulation in general form[23,24]. To reproduce some particular cosmic phenomenon in the laboratory, there is no need to follow the similarity laws accurately. It suffices to satisfy the conditions under which the investigated phenomenon takes place. Mathematically this means that there is no need to retain accurately all the dimensionless parameters that enter in the equations describing the interaction between the solar wind and the planet's magnetic field. It is only necessary that the dimensionless parameters characterizing the course of the given concrete phenomenon, which are of the order of magnitude of unity, be as identical as possible in outer space and in the laboratory. On the other hand, if a given dimensionless parameter in outer space is many orders of magnitude smaller or larger than unity, then this parameter should be accordingly small or large compared with unity in the model experiment, but there is no need to retain the same order of its magnitude, at any rate when the phenomenon is investigated in first approximation. Let us consider in succession the most interesting phenomena connected with the interaction of the solar wind with the earth's magnetic field, and the possibility of simulating them in the laboratory.

1. When the solar wind flows around the earth's magnetic field, a closed magnetosphere free of solar wind is produced on the daytime side. The field of the earth's dipole is concentrated in this region. It is separated from the unperturbed plasma stream by a transition layer. A magnetic cavity free of plasma is formed under conditions of sufficiently high electron temperature, when the plasma stream cannot penetrate deeply into the magnetic field. The condition for separate existence of the plasma and of the magnetic field, in the magnetohydrodynamic approximation, is equivalent to the requirement $\mathrm{Re}_m \gg 1$. Here Re_m is the magnetic Reynolds number:

$$\mathrm{Re}_m = \frac{4\pi\sigma L\bar{v}}{c^2}, \tag{1}$$

where σ is the plasma conductivity, $\bar{v}$ is the directional velocity, and L is the dimension of the magnetosphere. When the solar wind interacts with the geomagnetic field, $\mathrm{Re}_m \sim 10^{12}$ if the conductivity is calculated on the basis of Coulomb collisions of the particles. Choosing in the laboratory experiment $L \sim 50$ cm, $T_e \sim 15$ eV, and $\bar{v} = 3 \times 10^7$ cm/sec, we obtain $\mathrm{Re}_m > 10^3$, i.e., the conditions for the formation of the magnetic cavity are fulfilled. It should be noted immediately that when the problem is formulated in this manner we do not take into account the transition-layer broadening due to the anomalous resistance. Its value is connected with the character of the collisionless dissociation and should be obtained directly from experiment.

2. Measurements performed with artificial satellites have shown that at distances 10–13 earth's radii there exists a stationary shock wave, which goes over into the Mach cone with increasing distance from the sun-earth axis. It was noted earlier that the position of the shock-wave front drifts continuously, but for convenience in the measurements we assume the plasma-stream parameters to be constant during the entire experiment. To form the shock wave, the plasma-stream velocity should exceed the velocity of propagation of the perturbation. In a magnetoactive plasma, the perturbation propagates with a velocity

$$v_{ac} = \sqrt{v_A^2 + \left(\gamma \frac{p}{\rho}\right)^2} \tag{2}$$

and consequently, the Mach number $M = \bar{v}/v_{ac}$ should be larger than unity; here $v_A = H/\sqrt{4\pi\rho}$. Under the conditions of the solar wind, $M \sim 8$–10. This Mach number at a chosen stream velocity 3×10^7 cm/sec can be obtained in a model experiment if a magnetic field of approximately 30 Oe is frozen in a plasma with concentration 10^{13} cm^{-3}.

Besides hydromagnetic waves, ion-acoustic oscillations can be excited in the solar-wind plasma, since the high electronic thermal conductivity causes the electron temperature to exceed the ion temperature, i.e., the main condition for the excitation of such oscillations is satisfied. The growth of the slope of the front when ion sound propagates in a plasma with $T_e \gg T_i$ was recently demonstrated experimentally[25], and there is therefore every reason for examining the role of ion sound in the formation of the shock wave, in addition to hydromagnetic waves. The pressure of the magnetic field of the solar wind in low enough ($nkT \gtrsim H^2/8\pi$) to prevent excitation of ion-acoustic waves. In this case the second term under the square root in (2) is the square of the velocity propagation of the ion sound $v_s = \sqrt{T_e/M}$, where M is the ion mass.

3. One of the most interesting features of the shock wave produced near the boundary of the magnetosphere is the impossibility of attributing the dissipation to ordinary Coulomb collisions between the particles. It suffices to say that the region of energy dissipation is much smaller than the magnetosphere, and the ratio of the classical particle mean free path in the solar wind to the dimension of the magnetosphere is $\lambda/L \sim 10^3$. Such a ratio is practically unattainable in laboratory experiments, but by using plasma parameters chosen from conditions (1) and (2), and by setting the dimension of the magnetosphere in the experiment at L = 50 cm, we obtain $\lambda/L \sim 10$, which ensures absence of collisional dissipation.

4. Magnetic measurements performed on the nighttime side of the earth have shown unexpectedly the existence of a geomagnetic tail elongated along the direction of the solar-wind velocity vector[26]. The tail is divided by a layer in which the magnetic field intensity is close to zero (neutral layer). Above and below the neutral layer, the force lines are parallel and have mutually opposite directions. The magnetic pressure of the geomagnetic tail is balanced by the gas-kinetic pressure inside the neutral layer. The last measurements[27] have confirmed the assumption that the geomagnetic layer extends beyond the moon's orbit.

The origin of the neutral layer is debatable, and it is therefore difficult to write for its simulation a dimensionless parameter that determines the conditions for its existence. The most likely mechanism of formation of the geomagnetic tail is the penetration of the solar-wind plasma to the nighttime side, and the subsequent elongation of the force lines by the stream. Favoring such a mechanism are the results of experiments in which a trap with a sharp-end configuration was filled with plasma[28].

A plasma stream having parameters close to those chosen from the condition (1) and (2) was directed in the trap along its axis. Elongation of the force lines was observed as a result of the penetration of the plasma into the magnetic field and subsequent dragging of the lines by the stream. The penetration of the plasma in the magnetic field is apparently the consequence of anomalous resistance. Thus, considering the available experimental data, one can assume that the possibility of penetration of a plasma in a model experiment on the nighttime side with subsequent formation of a neutral layer is not excluded.

5. It is necessary to consider also one dimensionless parameter, which determines the application of the hydrodynamic approximation to this problem. This is the ratio of the characteristic dimensions of the experiment to the Larmor radii of the ions ρ_i and of the electrons ρ_e in the boundary layer. Both these parameters greatly exceed unity in the case of outer space. At the chosen experimental parameters, only the ratio L/ρ_e is much larger than unity, but the small Debye radius of the plasma does not allow the ions to break away from the electrons. Thus, in this case the conditions become comparable. As to the characteristic plasma length c/ω_0, the relation $L(c/\omega_0) \gg 1$ is satisfied.

6. Besides investigations of the macroscopic picture of the interaction of the solar wind with the earth's magnetic field, the most important problem of model experiments is the study of the spectral characteristics of microscopic fluctuations of the electric and magnetic fields. In final analysis, it is precisely the microfluctuations that lead to establishment of macroscopic characteristics, including the effective Reynolds number expressed in terms of the anomalous resistance. This region has been least investigated, both in the laboratory and in outer space. This is just the region containing the key to the understanding of the entire set of phenomena in outer-space plasma, such as the origin and diffusion of cosmic rays (the motion of a trial particle in a specified fluctuating field), the structure of the front of a collisionless wave (energy dissipation and formation of the front), etc.

Table I.

Parameter	Outer space	Model
Directional velocity	$(3-5)\cdot 10^7$ cm/sec	$3\cdot 10^7$ cm/sec
Concentration	5 cm^{-3}	10^{13} cm^{-3}
Electron temperature	20—100 eV	20 eV
Frozen-in magnetic field	10^{-4} Oe	30—40 Oe
Dimension of magnetosphere	10^{10} cm	50 cm
Ion temperature	10 eV	3–5 eV

Summarizing the requirements imposed on the laboratory experiment, let us list the plasma-stream parameters satisfying the requirements of limited simulation of the interaction between the solar wind and the earth's magnetic field (Table I).

An analysis of Boltzmann's equations, recently performed by K. Schindler[29] and V. B. Baranov[30], also leads to analogous requirements.

It follows from the here-considered principles of limited simulation that the formulation of the problem of reproducing, under laboratory conditions, of phenomena occurring in the near-earth space reduces to creation of an artificial solar wind with the parameters listed in Table I. The production of fast streams of hot plasma has for many years already been one of the main trends in work on high-temperature plasma. The method most successfully developed was the electrodynamic method of acceleration, based on the stretching of the current loop under the influence of its own magnetic field. If the loop has a moving element in the form of a small plasma cloud, then the plasma will be accelerated as a unit by a force $F = (1/2c^2)I^2 dL/dx$ in the x direction; here I is the current in the loop and L is its inductance.

Electrodynamic plasma accelerators have already been under development for approximately ten years (see, e.g.,[31-36]) and differ from one another in their operating conditions and in slight structural features. The most widespread are plasma accelerators with two coaxially arranged cylindrical electrodes, connected through a discharge gap to a low-inductance capacitor bank. A batch of hydrogen is introduced into the space between the electrodes by a high-speed valve; after ionization, this hydrogen serves as the moving element of the closed circuit. The instants of time when the capacitor bank is turned on and the gas is admitted are set by a programming device. Under most conditions, the rapid plasmoid from the coaxial injector contained a frozen-in magnetic field which was captured during the acceleration process[37]. Numerous investigations have shown that the initial notions concerning the acceleration of a plasmoid as a moving element provide only an approximate picture of the acceleration, without describing a number of important details. It is apparently impossible to exclude the contribution made to the acceleration by such an effect as the thermal expansion of the plasma, analogous to the expansion of the solar corona. In other words, there exists apparently a definite analogy between the formation of solar wind and acceleration of a plasma in a plasma accelerator.

The characteristics of the plasma stream are exceedingly sensitive to such accelerator-operation conditions as the parameters of the capacitor bank, the amount of introduced gas, and the time interval between the instant of injection of the neutral gas and the instant of turning on the capacitor bank. By varying the initial conditions, it is possible to obtain a regime in which the electrodynamic accelerator produces a fully ionized hydrogen plasma with parameters necessary for the performance of model experiments. The dependences of the main parameters of the plasma stream on the initial conditions, which make it possible to choose the necessary acceleration regime, are given in[38].

II. EXPERIMENTAL SETUP

The principal experimental setup for simulating the interaction between the solar wind and the earth's magnetic field is simple. A plasma accelerator, ensuring the necessary characteristics of artificial solar wind, together with a magnetic dipole, whose moment is chosen such that a given distance R from its surface the pressure of the magnetic field $H^2/8\pi$ balances the pressure of the plasma stream $\rho\overline{v}^2$, are placed in a vacuum chamber. The situation is more complicated when it comes to the correct choice of measurement methods that yield the necessary information on the changes of the plasma parameters and of the magnetic field in the region adjacent to the magnetic cavity. The measurement methods should be such as to distort the measurement process as little as possible. The most important parameters are the magnetic-field intensity, the plasma density, and its electron temperature.

So far there are no reliable contactless methods of measuring the magnetic-field intensity vector. In all research on the simulation of cosmic phenomena, without exception, the magnetic fields are measured by magnetic probes—coils that register the change of a definite component of the magnetic field. Magnetic probes are made as small as possible, and attempts are made to monitor their disturbing action. Sometimes, by introducing additional distortion on purpose, several magnetic probes are used to record simultaneously the magnetic field vector in different points of space. The use of several probes makes it possible to perform correlation measurements for the purpose of clarifying the character of the dissipative processes on the shock-wave front.

The most reliable method of measuring the plasma concentration is an interferometric method at a wavelength smaller than the characteristic dimension of the concentration jump. The minimal expected dimension c/ω_0 for the chosen plasma parameters is approximately 1 mm. It would be most convenient to use an interferometer with a broad field of view, operating in the visible region of the spectrum. Then one experiment yields the simultaneous density distribution in a large region of space, and some influence of the insufficiently good reproducibility of the initial conditions is eliminated. Unfortunately, modern interference-measurement techniques do not make it possible to register photographically a change of concentration $\sim 10^{13}$ cm^{-3} at a characteristic plasma dimension of several dozen centimeters. This explains, in particular, the use in model experiments of plasma streams with relatively high densities ($\sim 10^{14}$ cm^{-3}). (By the same token, rigorous satisfaction of the collision-free conditions is sacrificed.) One can, however, follow a different path, using an interferometer with photoelectric registration and by measuring the course of the concentration at one point. Repeated measurements for other points makes it possible to obtain the spatial distribution in the necessary region. Such measurements, for various reasons[39], are best carried out not in the visible but in the infrared region, at the 3.39 μ line radiated by a helium-neon laser.

All the measurement methods based on passing a beam through the plasma have one essential shortcoming: they make it possible to measure only the average value of the concentration along the beam ($\int n\, dl$). In interactions with a plasma of a terrella of spherical form, the plasma parameters change strongly along the beam and the construction of the original function from integral measurements is a hopeless task.

The foregoing difficulties disappear when a two-dimensional dipole, made up of two parallel conductors with currents flowing in mutually opposite directions, is used. The magnetic field intensity of such a two-dimensional dipole is a function of the coordinates r and φ only, and does not depend on the coordinate z; consequently, sounding with electromagnetic radiation or with particle beams directed along the current-carrying rods makes it possible to obtain the spatial distribution of the concentration and of the temperature. The values of the parameters along the beams can change only as a result of an initial spatial inhomogeneity of the plasma stream. By using a well-collimated probing beam and choosing a sufficiently large distance from the plasma injector, it is possible to reduce to a minimum the influence of such inhomogeneities. Thus, in the initial stage of the investigations, when the main phenomena in the near-earth space are simulated, the two-dimensional dipole has considerable advantages over three-dimensional ones.

The most perfect method of measuring the electron temperature of a fully ionized plasma is to analyze the width of the line of light scattered by the electrons (see, e.g.,[40]). An analysis of the line width of the scattered radiation has become possible as a result of the development of powerful lasers, and yields a temporal resolution of $\sim 10^{-8}$ sec. Unfortunately, this method is suitable only for the measurement of a relatively dense plasma. So far, the world record is at the level $\sim 10^{14}$ cm^{-3}. At lower densities it is impossible to obtain the necessary ratio of the useful signal to the background of parasitic scattering by the elements of the apparatus. The plasma temperature can be assessed indirectly from the intensities of the spectral lines; thus, for example, the burning out of the hydrogen lines is evidence of the presence of an electron temperature exceeding several electron volts. In some cases, particularly in measurement of the temperature of an unperturbed stream or in the investigation of the plasma in a neutral tail, Langmuir probes can be used, particularly double electric probes, with the same stipulations as for magnetic probes. For measurements on the shock-wave front, under conditions of appreciable magnetic-field gradients, the reliability of the measurements of the electron temperature with Langmuir probes is low.

III. SIMULATION OF THE MAGNETOSPHERE

In the first work of the simulation of the interaction between the solar wind and the earth's magnetic field, the main method of obtaining information was photography of the glow of the plasma around the terrella. In all experiments without exception, the photography was only in the visible part of the spectrum. In many cases, a rather distinct glow boundary was observed on the photograph, located at a certain distance away from the terrella, and the contours of the dark region near the terrella recalled the shape of the magnetosphere on the daytime side. On individual photographs the obtained glow boundary was so sharp, that the corresponding photographs were more similar to images of the cut along the dipole axis than to photographs of flow around a three-dimensional dipole. By varying the initial conditions, the authors of these investigations have obtained images recalling in form the earth's radiation belts or hook-like glowing formations. The latter, as a rule, were identified with the process of penetration of the plasma into the magnetosphere through the neutral points. It is important to note that the glowing "radiation belts" were observed under poor vacuum conditions, when one cannot speak of some noticeable effect of containment of the plasma in the magnetic field.

As to the distribution of the glow of the neutral gas in the plasma at low temperatures characteristic of earlier experiments, we note the following. At not too high concentrations and at an electron temperature not exceeding several electron volts, the plasma-radiation spectrum consists mainly of lines of neutral atoms. The intensity of such lines is determined by the number of excitation acts and is expressed as follows:

$$J = n_e n_0 \langle \sigma v \rangle, \qquad (3)$$

where n_e is the electron concentration, n_0 is the concentration of the neutral atoms, and $\langle \sigma v \rangle$ is the excitation probability and is a function of the temperature. Any change in the glow intensity is determined by the change of one or several of the indicated quantities. These quantities themselves are not independent. Thus, for example, an increase in the electron temperature, leads to the burning out of the atoms, and an increase of the concentration of the neutral atoms leads to a decrease in the electron temperature owing to the loss of energy to the excitation of the levels and to the ionization. Consequently, an analysis of the shape of the glow integrated over the spectrum can give only an indication of the possible existence of a phenomenon, but has no force of proof.

It would be, of course, incorrect to deny completely the significance of the first investigations on the simulation with the aid of photography. This pertains particularly to the first investigations of the group of W. Bostick[41]. Photographs of the glow of the plasma flow around the terrella have shown that there is an external analogy between the phenomena in outer space and the phenomena in the laboratory, even in the case when the experiment is produced without an analysis of the similarity laws. At the present time, photographic investigations are mainly of historical value, since they have stimulated laboratory investigations of phenomena under conditions comparable with those in outer space. It is hardly meaningful to stop and discuss here all the features of model experiments by the photography method.

The first experiments clearly demonstrating the crowding out of the magnetic field of the dipole from the region of the plasma flux and formation of the magnetosphere near the dipole were performed approximately simultaneously by five groups of physicists: Bostick (1963)[41,42], J. Cladis, T. Miller, and J. Baskett (1964)[43]; M. Bachynski, B. Gibbs, F. Osborne, J. Gore (1963–1964)[44-50]; N. Kawashima, N. Fukushima, S. Mori (1964–1965)[51-54]; and L. Danielsson, L. Lindberg, and G. Kasai (1964–1965)[55-57]. All the foregoing investigations were performed at small Reynolds numbers ($Re_m \lesssim 1$) under conditions when the mean free path was smaller than or commensurate with the characteristic dimension of the experiment. In addition, the conditions for most experiments differed from the conditions in outer space in the absence of the magnetic field frozen into the plasma stream. In some experiments this field was incomparably large compared with the gas-kinetic pressure. The main characteristics of the plasma in the experiments on simulating the interaction of solar wind with the earth's magnetic field is contained in Table II. Table III, for convenience in comparing the conditions for the formation of an artificial magnetosphere, lists the corresponding dimensionless parameters.

All the measurements were made with the aid of magnetic probes, and the data from the various laboratories do not contradict one another.

At large distances from the dipole, where the magnetic pressure of the dipole field is smaller than the kinetic pressure of the stream, the plasma crowds out the magnetic field completely (within the limits of the measurement accuracy). Near the terrella, there was always observed an increase in the intensity of the magnetic field compared with the field of the unperturbed dipole. Such an increase in the intensity is the consequence of the compression of the magnetic flux by the plasma. It is shown in[48] that formation of the compressed-field region, which can be interpreted as the magnetosphere, begins with a certain plasma-source power. The authors note that when the total energy delivered to the source is less than 720 J, a "typical injection interaction" is observed. On the other hand, measurements performed at energy inputs 1620 and 2490 J have shown a distinct forcing out and a rather sharp boundary of the magnetosphere.

At first glance it is quite tempting to connect the penetration of the plasma at low source power with plasma injection into the magnetosphere and with subsequent formation of radiation belts. There is no doubt, however, that a simpler and more natural assumption is that when the energy input to the source is decreased,

Table II. Plasma parameters in model experiments

Authors	v, cm/sec	n, cm^{-3}	T_e, eV	$\frac{T_e}{T_i}$	H, Oe	Literature
Alikhanov et al.	$1.2\cdot 10^7$	$2\cdot 10^{14}$	1,5	1	300	58, 59
Managadze, Podgornyi, et al.	$3\cdot 10^7$	10^{13}	15	5	40	23, 24, 60–62
Roberts and Turner	$3\cdot 10^4$ 10^6	10^8 10^{12}	—	—	—	63
Cladis, Miller, Baskett	$6\cdot 10^6$	$5\cdot 10^{12}$	3	0,6	0	43
Osborne, Bachynski, Gore, Gibbs	$2\cdot 10^6$	$2\cdot 10^{13}$	3	—	0	44–50
Kawashima, Fukushima, Mori	$4\cdot 10^6$	$5\cdot 10^{14}$	3	—	0;700	51–54
Pugh, Patrick	$2\cdot 10^7$	$8\cdot 10^{12}$	50	—	150	64
Danielsson, Lindberg, Kasai	$5\cdot 10^6$	10^{14}	2	—	700	55–57
Swedish project	$2\ 5\cdot 10^7$	$2\cdot 10^{13}$	5	—	200	65–66

Table III. Dimensionless parameters in experiments on simulation of the magnetosphere

Authors	Re_m	$M_A=\frac{\bar{v}}{v_A}$	$M_s=\frac{\bar{v}}{v_s}$	$\lambda\ L$	$\beta=\frac{nkT}{H^2/8\pi}$
Managadze, Podgornyi, et al.	10^3	10	8	10	4
Roberts and Turner	10^{-3} 3	— —	10^{-2} 1	1 1	
Cladis, Miller, Baskett	40	—	10	1	
Osborne, Bachynski, Gore, Gibbs	12	—	1	10^{-1}	
Kawashima, Fukushima, Mori	3	1 *)	4,5	$5\cdot 10^{-2}$	10^{-1} *)
Danielsson, Lindberg, Kasai	6	0,3 *)	3,5	10^{-1}	10^{-2} *)
Parameters that follow from the principle of limited simulation	10^2	7–10	3–5	10	$\geqslant 1$

*It is not clear whether the external applied field, perpendicular to the velocity, is frozen in the plasma.

the stream velocity and the plasma temperature are decreased, and consequently the thickness of the skin layer increases. As a result, the boundary of the magnetic field becomes spread out and becomes commensurate with the dimensions of the magnetosphere. Osborne et al.[50] give no data on the changes of the plasma parameters with changing operating conditions of the source, but if account is taken of the fact that the data given there correspond to $Re_m = 12$ and apparently correspond to the best operating conditions of the injector, then, using the published characteristics of the coaxial injector, it is possible to state that lowering the energy input by a factor of 3 can decrease the magnetic Reynolds number to unity. In other words, at an energy $\sim$700 J, the magnetosphere dimension obtained in[50] should become comparable with the thickness of the skin layer. Such a conclusion agrees with the statment made by the authors of the article, that when the source power is decreased the boundary between the field and the plasma first spreads out and then disappears completely.

It should also be noted that the value $Re_m \sim 12$, obtained from the conductivity by means of the formula $\sigma = 1.9 \times 10^2 T_e^{3/2}$ (eV)/ln Λ is an overestimate. The point is that an analysis of the balance of the stream and magnetic-field pressures shows that the average ion mass exceeds the hydrogen-atom mass by one order of magnitude. In addition, it is noted in the article that in most experiments the plasma was essentially a barium plasma. This means that the conductivity of the plasma should be lower, owing to the presence of doubly-charged ions (the second ionization potential is 10.1 eV, and the electron temperature of the plasma is 3 eV), and furthermore the effective electron interaction cross sections are determined not only by the Coulomb scattering but also by excitation and ionization processes, which also decreases the conductivity.

The formation of the magnetosphere was investigated in greater detail in[43]. A hydrogen plasma was used with a lower density and a larger directional velocity (see Tables I and II), although the collision-free conditions $\lambda/L \gg 1$ for the formation of the magnetosphere can likewise not be assumed satisfied here, the plasma parameters being closer to those that follow from the principle of limited simulation.

The main result obtained in that investigation is a study of the shape of the magnetosphere boundary on the daytime side. The experimental points agree satisfactorily with the theoretical curve obtained earlier[67] for supersonic flow around a dipole. Such an agreement still does not prove that the model of supersonic flow can be accepted without stipulation for this experiment. The point is that if we assume an ion temperature of 4 eV, as do the authors of[43], then the mechanism responsible for the formation of the shock wave cannot be understood. The absence of a magnetic field frozen into the plasma does not permit shock wave formation as the result of propagation of magnetohydrodynamic waves. Dissipation due to ion-acoustic oscillations are likewise apparently excluded, since excitation of ion sound requires $T_e > T_i$. The only dissipation mechanism may be Coulomb collisions, but in order for their effectiveness to be sufficiently high it is necessary that the plasma concentration be somewhat higher or the temperature somewhat lower than the values indicated in the article. The absence of direct proof of the existence of a shock wave is emphasized by the authors of the article themselves. Notice should be taken also of the presence of plasma flow through regions of the proposed position of the neutral points. Unfortunately, the entire information concerning this phenomenon is contained in a single phrase, and neither the experimental conditions nor the magnitude of the penetrating plasma flux is indicated.

A series of experiments on the simulation of the magnetosphere was performed in Japan by Kawashima, Fukushima, and Mori. These experiments are characterized by an even larger contribution of Coulomb collisions than the preceding experiments. The investigation methods were the same; in addition, double electric probes were used to determine the density. The measurements were performed with helium and argon. The width of the transition region turned out to equal the dimension of the magnetosphere (~10 mm). Effective penetration of the plasma into the magnetosphere was observed: at a distance ~5 mm from the surface of the dipole, the density was 0.5 of the density in the flux. The low magnetic Reynolds number ($Re_m = 3$) and the small mean free path ($\lambda = 0.5$ mm) did not make it possible to obtain conditions comparable with those in outer space.

In individual experiments of the Japanese group, they used an additional homogeneous magnetic field applied parallel to the dipole axis. Whenever the direction of this field coincided with the direction of the field in the magnetosphere on the daytime side, the boundary of the magnetosphere moved away. Reversal of the mutual field directions contributed to an increase of the plasma flow to the terrella. It is not clear whether these experiments can be considered in connection with investigations of the influence of the field frozen into the plasma on the effective interaction between the solar wind and the earth's magnetic field, since there are no direct indications in the papers of Kawashima and coworkers that the field is frozen into the plasma.

The work performed in Sweden[56-57] agrees so well with the Japanese work with respect to the investigation method, both with respect to the parameters and with respect to the results, that there is no need to consider it separately. A common shortcoming of these investigations is the low value of the ratio of the particle mean free path in the stream to the dimension of the magnetosphere. Such experimental conditions do not make it possible to compare directly the results of the experiments with the phenomena in outer space, where collisionless dissipation is predominant. Another important factor is the correct choice of the magnetic field frozen into the plasma. Complete absence of a magnetic field means impossibility of energy dissipation through the instability of the Alfven waves. On the other hand, too strong a magnetic field prevents the buildup of ion-acoustic oscillations, even if $T_e \gg T_i$. Another general shortcoming of the foregoing investigations is the absence of data on the density profile, in other words, the absence of direct proof of the existence of a boundary between the plasma of the artificial solar wind and the magnetic field of the magnetosphere. None of the foregoing shortcomings are encountered in the work performed at the Institute of Outer Space Research of the USSR Academy of Sciences[23,62] where all the experimental parameters, including the magnetic field intensity in the plasma, were chosen in accordance with the principle of limited simulation. For comparison with the conditions of other experiments, these data are also listed in Table III. To exclude the disturbing action of the probes, the measurements of the density were made by a contactless method and a two-dimensional dipole was used in the experiments. The advantage of such a system was discussed in Ch. II.

Experiments performed with a collisionless plasma[62] have shown that, starting with a certain distance from the dipole, determined by the equality of the magnetic-field pressure and the plasma-stream pressure, the magnetic field of the dipole is completely forced out by the plasma. If the intensity of the field initially frozen into the plasma is zero, then the intensity in the region where the field is forced out is also equal to zero, within the limits of the accuracy of the present experiment (~1 Oe). Near the dipole, the magnetic field increases when the plasma flows around the dipole, as was observed in earlier experiments. Figure 1 shows a typical result of an experiment on the interaction between a collisionless plasma containing no frozen-in field and a dipole. The ordinates represent the magnetic field intensity, and the abscissas the distance from the center of the dipole to the plasma source (the analog of the sun-earth axis). The figure shows clearly the forcing out of the field at large distances from the dipole and the increased intensity near the dipole. The dashed curve shows the field of the unperturbed dipole. The solid curve represents the distribution of the magnetic field when a stream of collisionless plasma flows around the dipole. The point of intersection of the curve corresponds to equality of the stream and magnetic-field pressures.

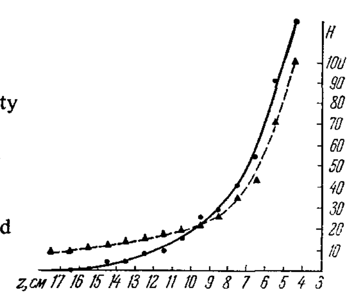

FIG. 1. Magnetic field intensity in a laboratory experiment (daytime side) in the case of flow of a plasma containing no frozen-in magnetic field. The dashed curve shows the field of the unperturbed dipole.

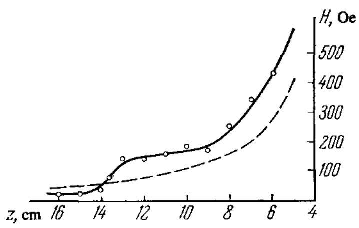

FIG. 2. Vertical component of the magnetic field intensity in the case of flow around a dipole by a plasma stream with parameters chosen on the basis of the principle of limited simulation.

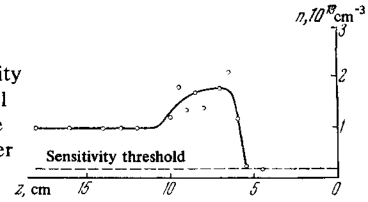

FIG. 3. Distribution of density on the daytime side in the model experiment. The values given are averaged along the interferometer beam.

Figure 2 shows the distribution of the magnetic field of a dipole around which a plasma flows with a frozen-in magnetic field of 40 Oe[62] (the value 40 Oe follows from the choice of the same Alfven Mach number as in the plasma of the solar wind). Here, as in outer space, the instruments register at large distances from the dipole the magnetic field frozen in the plasma. Near the earth (or the terrella) the dipole field is distorted relatively little. A rather sharp jump of the intensity is observed in the transition region. The numerous peaks of magnetic field in the transition region on the curve obtained in outer space are possibly the consequence of the drift of the position of the shock wave with velocity exceeding by several times the velocity of the satellite. We shall return to a discussion of the magnitude of the jump and to the question of the width of the transition layer in the experiment when we discuss simulation of a collisionless shock wave.

The available experimental data concerning the shape of the magnetosphere, obtained in the hydrodynamic approximation[78,79], and the results of measurements in outer space have shown that the force lines are deformed in such a way that the dipole axis experiences a kink, as it were, and both semiaxes—the northern and the southern ones—are inclined forward. When a collisionless plasma flows around a two-dimensional dipole, the inclination of the semiaxes is clearly seen. Further refinement of the course of the force lines was not carried out in this experiment, since the plans of this cycle of investigations did not include a detailed comparison of the magnetic-field maps on the daytime side for the geomagnetic field and outer space. To carry out such experiments, just as for simulation of magnetic storms, it is necessary to employ apparatus of much larger scale.

The reported magnetic measurements point unambiguously to the existence of a magnetosphere in the model experiments, including the case when the experimental conditions are known to be collisionless. An independent verification was obtained by experiments on the distribution of the density along the velocity vector of the unperturbed stream. Data obtained with the aid of a laser interferometer, operating on the 3.39 μ infrared line, are shown in Fig. 3. In that region where the magnetic probe registers only the field frozen into the plasma, the concentration does not change when the magnetic field is turned off, i.e., the perturbing action of the dipole does not come into play. Near the dipole, in the region where the magnetic field intensity increases under the influence of the plasma flux, the density was not more than 20% ($\sim 2 \times 10^{12}$ cm^{-3}) of the density in the unperturbed flux. For comparison with data on artificial satellites, Fig. 4 shows one of the curves obtained with the apparatus "IMP-2". This curve, how-

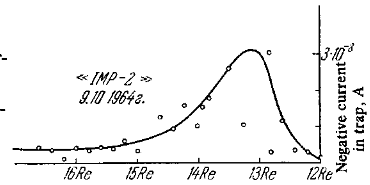

FIG. 4. Probe saturation current ($\sim n_e\sqrt{T_e}$), measured on a satellite, as a function of the distance to the earth.

ever, unlike the one obtained in the laboratory, represents not the density directly, but the probe saturation current, i.e., the product of the density by the square root of the temperature. Since the plasma becomes heated on the front of the shock wave, actually the density jump near the boundary of the magnetosphere turns out to be not as strong as represented by the curve of Fig. 4.

Summarizing the work on the simulation of the magnetosphere, we can state that laboratory experiments make it possible to simulate the magnetosphere under conditions comparable with those in outer space. The data of cosmic and laboratory measurements are in agreement. Further work on laboratory investigations of the magnetosphere should follow the path of searches for the possible ways of plasma penetration into the magnetosphere, particularly through neutral points.

Experiments on the simulation of the magnetosphere become more and more popular; unfortunately, most of them are performed without a detailed analysis of the initial conditions. Thus, for example, in a recent paper by A. Rubin[68], the presence of a boundary between the plasma in the field is distinctly shown. Unfortunately, only the stream velocity ($v = 3 \times 10^6$ cm/sec) and the density ($n = 9 \times 10^{13}$ cm^{-3}) are given. A smooth change in density is observed on the boundary of the magnetic field. Rubin apparently investigated subsonic flow with a small particle free path, so that a detailed comparison of his results with data obtained by measurements in outer space and data on the investigation of flow of a collisionless plasma around a magnetic dipole would not be correct.

IV. SIMULATION OF A SHOCK WAVE AT THE BOUNDARY OF THE MAGNETOSPHERE

An investigation of collisionless shock waves is one of the most urgent problems of modern plasma physics. Besides being of purely scientific interest, a study of such waves in the laboratory is stimulated additionally by searches for ways of heating plasma to thermonuclear temperatures. The main premises of the theory of collisionless shock waves in a plasma were formulated long before the start of their detailed investigation in the laboratory. A dimensional analysis shows that the structure of a collisionless shock wave is determined by five basic dimensionless parameters:

1. The Mach number M.
2. The ratio of the density of the thermal energy to the energy density of the magnetic field $\beta = nkT/(H^2/8\pi)$.
3. The ratio of the energy density of the magnetic field to the density of the relativistic energy contained in the plasma electrons, $\alpha = (H^2/8\pi)/nmc^2$. Another physical meaning of the parameter α is that it is equal to the square of the ratio of the cyclotron frequency of the electrons to the Langmuir frequency.
4. The angle between the direction of the force lines and the front of the shock wave, θ.
5. The ratio of the electron temperature to the ion temperature, $\gamma = T_e/T_i$.

Both the width of the shock wave front and the character of its structure vary with the values of these parameters. The most characteristic conditions for the formation of a shock wave were investigated theoretically, and the basic results of the calculation of the front width Δ can be represented as follows:

1. $H \approx 0$, $\gamma \gg 1$, $\Delta \approx 10\lambda_D$, where $\lambda_D = \sqrt{kT/8\pi ne^2}$ is the Debye radius. The structure of the shock wave can in this case be determined by the intense ion-acoustic oscillations. The theory of this phenomenon has been well investigated for Mach numbers smaller than the so-called critical value (for the given case, $M_{cr} \approx 1.6$). At such Mach numbers, the shock front is a backward-traveling regular oscillator structure with wavelength $\lambda \sim \lambda_D$. When $M > M_{cr}$, the only rigorous conclusion that can be drawn from modern theory is the breaking of the front and the appearance of a multi-stream motion of the ions. This raises the trivial temptation to attribute the dissipation to the development of multi-stream ion instability with width $(10-100)\lambda_D$.

2. $1 < M_A < M_{cr} \sim 3$, $\theta = 0$, $\alpha \ll 1$, $\beta < 1$. $\Delta \approx c/\omega_0$, where $\omega_0 = \sqrt{4\pi e^2 n/m}$ is the Langmuir frequency.

At not too small values of α, the front is damped backward-moving oscillating structure with characteristic length c/ω_0.

3. $M_A > 1$, $\sqrt{m/M} < \theta < \pi/2$, $\beta < 1$. Forward outgoing damped oscillations with characteristic length $c/\Omega_0\theta$, where $\Omega_0 = \sqrt{4\pi e^2 n/M}$ is the ion Langmuir frequency.

4. $M_A > M_{cr} \approx 3$, $\theta = 0$, $\alpha \ll 1$, $\beta < 1$. $\Delta \sim c/\Omega_0$—breaking of the front takes place.

5. $\beta > 1$. In this case there is a possible class of shock-wave structures, in which the dissipation is determined by oscillations with wavelength ρ_i[67]. Depending on the Mach number, there can be either an oscillatory structure or a turbulent structure (e.g., one determined by the Alfven or magnetosonic turbulence with whistlers).

We shall not stop to discuss here the numerous experimental investigations of straight and oblique shock waves, which confirm the main premises of the theory. The shock waves were excited in these investigations by using a short magnetic-field pulse as the piston. The conditions under which the experiments were performed are listed in Table IV.

It can be assumed at present that the existing concepts can serve as a zeroth approximation for comparison with experiment.

It follows from the foregoing data that the character of the front depends sufficiently strongly on the initial conditions. Therefore in the analysis of work on simulation of a shock wave near the earth's magnetosphere it is necessary to clarify first the extent to which the experimental conditions agree with the conditions of the interaction between the solar wind and the earth's magnetic field.

Table IV

Authors	α	β	M_A	θ	Reference
Paul et al.	$2\cdot10^{-5}$	$2\cdot10^{-1}$—2	1—20	0—$\pi/2$	69
Alikhanov et al.	10^{-5}—10^{-1}	10^{-4}—10^{-1}	1—6		58
Smolkin, Sholin, et al.	10^{-6}—$5\cdot10^{-4}$	10^{-4}—$2\cdot10^{-2}$	1—8	0	70
Martone	10^{-4}	$5\cdot10^{-2}$	2—6	0	71
Hintz	$2\cdot10^{-5}$	$2\cdot10^{-2}$—1	1,5—9	0	72
Robson, Sheffield	$2\cdot10^{-5}$	$1,5\cdot10^{-1}$	2,5—6	0	73
Chodura et al.	$1,5\cdot10^{-5}$	$1,5\cdot10^{-1}$	10^{-2}—5	0—30°	74

If it is assumed that in the solar wind $\beta \gtrsim 1$, then the most probable types of structures are 1 and 5. Actually, apparently, in a strong shock wave there occurs a superposition of several processes, i.e., all the fundamental oscillations in the plasma are excited.

The values of the dimensionless parameters characterizing the singularities in a collisionless shock wave produced by the interaction between the solar wind and the earth's magnetic field, and the values of the same parameters under laboratory experiments, are presented in Table V.

The numbers marked with an asterisk were obtained at an electron temperature $T_e = 50$ eV, estimated from the energy balance. Since the method of determining the temperature is not reliable, and the value of T_e is too large for apparatus of this type, the corresponding value of T_e is apparently an overestimate, possibly by as much as one order of magnitude. The value of β is also overestimated. The fact that the electron temperature of the plasma in this experiment is not high is also indicated by the strong glow of the hydrogen plasma, as follows from the figures shown in . The results of three investigations listed in Table V were first reported at the Conference on Shock Waves in Novosibirsk.

In the experiments of E. Pugh and R. Patrick[64], the plasma was transported from the source to the interaction region in a longitudinal leading magnetic field. Besides the longitudinal magnetic field, there existed in the plasma stream an azimuthal component, H_φ, passing through zero on the axis of the apparatus. The presence of H_φ apparently means that current flows through the plasma along the symmetry axis of the apparatus. The plasma stream interacted with the magnetic field of an annular coil of approximately 20 cm diameter, located in such a way that its axis coincided with the axis of the apparatus, and consequently also with the plasma-velocity vector in the unperturbed stream. The direction of the coil field was opposite to that of the leading field. The obtained configuration of the force lines in the interaction region was similar to the configuration in traps with opposing fields, but was further complicated by the presence of a non-zero component H_φ. Photographs of the plasma also recalled the corresponding frames of filling of opposing-trap fields with plasma[75]. All the measurements, including the determination of the momentum of the plasma stream, were made with magnetic probes.

Pugh and Patrick[64] have demonstrated clearly the existence of a magnetic-field region free of plasma. Although the shape of the plasma-free region differed, in accordance with the specific features of the experiment, from that of the earth's magnetosphere, these experiments can be regarded as model experiments with respect to the shock waves.

On the plasma-field boundary, the probes registered jumps of all three components of the magnetic field. A typical field distribution on the boundary is shown in Fig. 5. The azimuthal component increases in the boundary layer by a factor 2—2.5. The radial component is

Table V.

	$\frac{\lambda}{c/\Omega_0}$	M_A	M_s	α	β	γ
Kosmos	10^7	6—8	5	10^{-4}	1	~5
Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences [58]	$3\cdot10^{-2}$	2,4	10	$2\cdot10^{-5}$	10^{-1}	1
Avco, USA [64]	$2\cdot10^2$	1.6—1.9	4 *	10^{-4}	1 *	?
Institute of Space Research, USSR Academy of Sciences [23	20	8—10	8	10^{-5}	3	~5

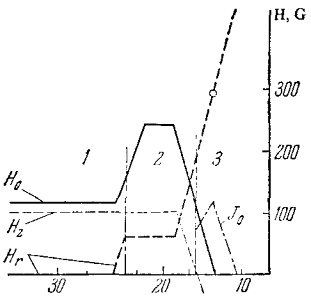

FIG. 5. Distribution of components of the magnetic field in the experiments in USA. H_z in the plasma is antiparallel to the dipole axis. The measurements were made at a distance of 5 cm from the apparatus axis.

completely forced out of the region of the unperturbed stream, and finally, the axial component passes through zero, since the field of the coil is connected to oppose the leading field. The presented field distribution in the boundary region corresponds to the form that should be observed when a shock wave is produced, and is interpreted by the authors of the paper as the front of an oblique collisionless shock wave. Such a wave, at Mach numbers smaller than critical, should not break and should not have a forward-moving oscillator structure. The absence of direct data on the plasma temperature, unfortunately, does not make it possible to discard completely the influence of the Coulomb collisions on the wave structure.

The experiments made at the Institute of Nuclear Physics of the Siberian Division of the USSR Academy of Sciences were performed with a two-dimensional dipole[58]. Just as in the preceding paper, a strong leading magnetic field was used, and therefore the magnetic-field vector in the unperturbed dipole was parallel to the plasma-velocity vector. The experiments were performed at subcritical Alfven Mach numbers. There could be no energy dissipation on the ion-acoustic oscillations, since the characteristic conditions for a space plasma, $\beta \gtrsim 1$ and $T_e > T_i$, were not satisfied. A distinguishing feature of[58] is the use of a rich arsenal of diagnostic means, including a laser interferometer with a wide field of view. The choice of the density in the flux was limited by the registration threshold of the interferometer. The initial density was 2×10^{14} cm^{-3}, corresponding at a temperature of 1.5 eV to a mean free path shorter than the width of the front. In spite of the fact that the collision-free conditions were poorly satisfied, an oscillator structure of an oblique wave was observed, with forward-moving oscillations of the magnetic-field components. The obtained oscillograms (Fig. 6) hardly differ from the hand-drawn pictures of the proposed wave structure contained in the review[76]. It is noted in[58] that the oscillations are observed only in a sufficiently well magnetized plasma, i.e., when $\omega_H \tau_e \gtrsim 1$. When the magnetization condition is not satisfied, the front has no oscillatory character and becomes aperiodic. The jump of the concentration on the front is approximately equal to 3. A system of filters was used to investigate the oscillations obtained in the region of the density jump. Their characteristic frequency is $\sim 1.5 \times 10^6$ Hz, with $\Omega_H = 3 \times 10^6$ Hz and $\omega_g = \sqrt{\Omega_H \omega_H} = 1.2 \times 10^8$ Hz. We shall henceforth use the following notation: $\omega_H = eH/mc$ and $\Omega_H = eH/Mc$.

The closest to the conditions in space are the parameters of the work done at the Institute of Space Research, USSR Academy of Sciences, contained in the last row of Table V. The most essential feature of the present investigations is the large number of the Alfven Mach number compared with the critical value, and the possibility of energy dissipation by ion-acoustic oscillations, owing to satisfaction of the conditions $T_e > T_i$ and $\beta \gtrsim 1$. There can be no noticeable contribution of the Coulomb collisions to the energy dissipation, since the mean free path in the plasma exceeds the width of the transition region between the plasma and the field by two orders of magnitude.

Magnetic measurements made on the daytime side have shown that in the boundary region between the unperturbed plasma stream and the magnetosphere there occurs a reorientation of the magnetic-field vector (if the field frozen into the plasma and the field of the magnetosphere on the daytime side are antiparallel) and sharp peaks are observed. Principal attention was paid in the experiment to investigations of the shock wave near the frontal point. Therefore an appreciable number of the measurements is devoted to the study of the variation of the field along the z axis, which is parallel to the plasma velocity vector and crosses the symmetry axis of the two-dimensional dipole. By virtue of the symmetry of the problem, the intensity of the unperturbed field along the z axis has only a vertical component, i.e., $H(z, 0) = H_y(z)$. A typical dependence of the intensity of the magnetic field on the distance to the dipole axis is shown in Fig. 2. It is seen from the figure that on the boundary of the unperturbed stream there is a rather sharp increase of the magnetic field, which then goes

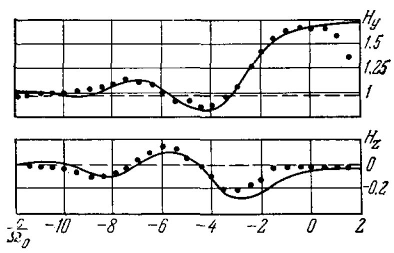

FIG. 6. Oscillator structure of oblique shock wave.

over into a slight plateau, after which the magnetic field increases again, forming the magnetosphere. By starting from the theory of shock waves produced in supersonic flow around an obstacle, such a magnetic-field profile can be naturally attributed to the formation of a shock wave that moves away from the magnetosphere. According to purely external attributes, and in analogy with the field profile obtained in cosmic investigations, the first increase of the intensity can be identified with the shock-wave front. The section of weak variation of the magnetic-field intensity is analogous to the plasma stream behind the front of the shock wave or to the so-called region of turbulent plasma, if one uses the terminology taken from work performed with artificial satellites. The curve shown in Fig. 2 was obtained by averaging over a large number of measurements. Therefore no field fluctuations are seen here. Finally, the second increase of the intensity corresponds to the magnetopause in the geomagnetic field or to the magnetic piston exciting the outgoing shock wave. The increase of the vertical component of the magnetic-field intensity in Fig. 5 is by an approximate factor of 5. On the other hand, from the Hugoniot relation it follows that the magnetic field intensity on the shock-wave front in a gas with three degrees of freedom can increase by not more than four times. The apparent discrepancy is due to the slight increase of the magnetic-field component parallel to the rods with current (H_x). Under the conditions of this experiment, such a component increases by no more than a factor of 2. As a result, the component of H in the plane of the shock-wave front increases by approximately four times and simultaneously, the flow around the dipole changes the slope of the magnetic-field intensity vector.

The fluctuations of the magnetic field in the boundary region between the unperturbed plasma and the magnetic field can be clearly observed during the stage of formation of the magnetosphere in model experiments. The obtained field peaks are particularly large in those cases when the frontal part of the plasmoid carries an appreciable frozen-in field. Then in the transition region, during the time of formation of the magnetosphere, one observes a sharp magnetic-field peak, several times larger than the mean value of the field frozen in the unperturbed plasma. The position of this peak and its magnitude do not reproduce well from experiment to experiment. The results of the magnetic measurements during the stage of formation of the magnetosphere are shown in Fig. 7. The position of the peak and its absolute magnitude are represented on the plot by a single point. The abscissa of this point corresponds to the average position of the peak, and the ordinate to its average magnitude. The amplitude of the peak changes from experiment to experiment by a factor 2—3, and the position of its maximum drifts in the region of ±1 cm from its mean position. The strength fluctuations and the poor reproducibility do not make it possible to construct the contours of the peak accurately. The figure therefore shows only the mean value.

The appearance of a magnetic-field peak at the initial stage of the interaction between the plasmoid and the magnetic field can be naturally attributed to compression of the magnetic flux frozen in the frontal part of the plasmoid. If the magnetic-field distribution in the frontal part of the plasmoid is steeper than the density distribution, then the ratio H/n of the magnetic field intensity to the plasma density is much higher in this region than in the remaining plasma. The increase of the density on the shock-wave front leads to an increase of the field frozen in the plasmoid. As a result of the compression by a plasma stream of relatively low density, the plasma in the frontal part becomes more strongly compressed, and if the field contour is sufficiently steep, such an increase can lead to a cumulative burst of field larger by several times than the average increase on the shock front.

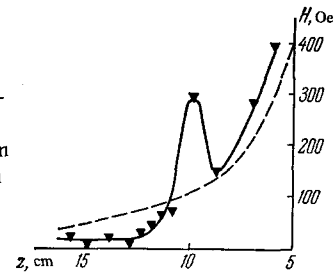

FIG. 7. Distribution of the magnetic field on the daytime side in a model experiment with non-uniform distribution of the magnetic field in the plasmoid.

Control experiments have shown unambiguously that the nature of the observed fluctuations is connected with the inhomogeneity of the field frozen in the plasmoid. On the other hand, it is known that in solar wind there are discontinuities, on both sides of which the total pressure is the same:

$$\frac{H^2}{8\pi} + nk(T_e + T_i) = \text{const}.$$

For certain types of discontinuities, for example for those in which the sum $T_e + T_i$ experiences a jump, the ratio H/n also changes jumpwise. This means that conditions analogous to those considered in the present experiment are realized in the solar-wind plasma, i.e., the fluctuations of the magnetic field in the solar wind should increase following passage of the plasma stream through the shock wave. The interaction of the solar wind with the magnetic field of the earth, apparently, is accompanied by an intensification of such fluctuations, which are observed also behind the front of the shock wave in the so-called zone of turbulent plasma.

An independent confirmation of the formation of a shock wave in experiments on supersonic flow of a magnetic dipole is afforded also by the results of a direct measurement of the plasma density along the z axis[62] (see Fig. 3). The region in which the plasma density is approximately twice as large as the density in the unperturbed stream has a dimension of 4—5 cm, which agrees with the dimensions of the transition region as determined from the magnetic measurements. The density profile shown in Fig. 3 characterizes the width of the transition region and proves the existence of a magnetosphere, namely a plasma without flow, but the magnitude of the density jump (~2) is apparently undervalued, owing to edge effects. The point is that the interferometer measures the average concentration along the path of the beam. Since the lengths of the dipole rods is 25 cm, and the region of increased density is located at a distance 8—10 cm from the dipole axis, the mean density may be noticeably lower than in the region where the role of the edge effects is negligibly small. On the basis of estimates, we can assume that the actual magnitude of the jump is by an approximate factor of 3.5.

The formation of a shock wave at a density $\sim 10^{13}$ cm^{-3} and a temperature ~ 15 eV cannot be attributed to dissipation due to Coulomb collisions, since the mean free path greatly exceeds the characteristic dimension of the region of interaction with the magnetic field. The formation of a shock wave in the experiment under consideration may be due only to collisionless processes, foremost among which are the buildup of ion sound and the instability of the Alfven waves. At present it is difficult to choose uniquely between the possible dissipation mechanisms. However, the presence of such a mechanism is indicated also by the appreciable width of the transition region between the plasma and the magnetic field, compared with c/ω_0 ($\omega_0 = \sqrt{4\pi e^2 n/m}$—electron Langmuir frequency).

The experimentally obtained width of the transition layer, $\Delta = 4-5$ cm, agrees sufficiently well with the width of the shock front in the case of flow around an obstacle by a collisionless plasma with velocity exceeding the critical Alfven velocity, and with the width of the front that should be expected also in the development of magnetohydrodynamic instabilities[76,77]. The obtained value of $\Delta \approx c/\Omega_0$ agrees sufficiently well with the front width measured on space vehicles.

V. NEUTRAL LAYER

In the experiments aimed at simulating the shape of the geomagnetic field on the nighttime side, it was assumed that the plasma stream penetrates through the boundary of the magnetosphere. The expression was expressed many times in the literature that the penetration occurs most probably through neutral points, which in the two-dimensional case degenerate into neutral lines. Another mechanism whereby the plasma enters the geomagnetic tail may be anomalous diffusion and the instability of the boundary between the plasma and the magnetic field.

After penetrating into the magnetic cavity, the plasma stream should drag with it the force lines on the nighttime side, and by the same token lead to the formation of a neutral layer, which was recently observed with the aid of artificial satellites. The field intensity in the neutral layer is zero. The force lines near the central plane are parallel to the neutral layer and have opposite directions in the northern and southern half-spaces. Actually, the magnetic field in the central plane apparently does not vanish exactly, but its thickness is small enough to be able to use such an approximation. The now accepted term "neutral layer" should be also understood in this sense. From the assumption that the geomagnetic tail is stretched out by the plasma stream it follows that the force lines are closed through the neutral layer over its entire extent, but the vertical component of the intensity in the neutral layer should be much smaller than the average magnetic-field vector in the tail $H_y \sim H_0 a/L$.

Figure 8 shows the force lines in a plane passing through the magnetic axis and the earth-sun line, as ob-

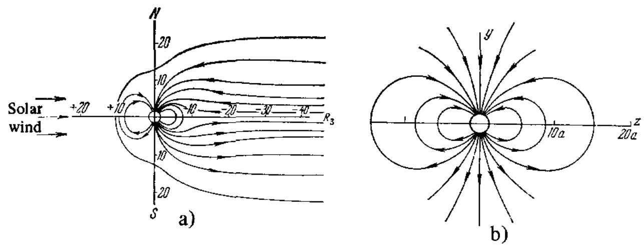

FIG. 8. a) Shape of the earth's force lines in accordance with artificial-satellite data; b) Configuration of unperturbed dipole.

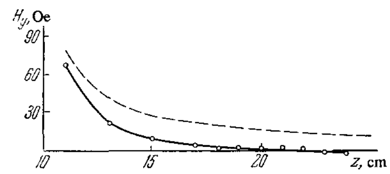

FIG. 9. Vertical component of magnetic field on the nighttime side in the model experiment. The dashed line shows the field of the unperturbed dipole.

tained with satellites. Figure 8b shows for comparison the configuration of the unperturbed field of the magnetic dipole. From a comparison of the configurations we see that when the neutral layer is produced, the vertical component of the magnetic field H_y should "vanish" at a certain distance from the center of the dipole. The term "zero value of H_y" is arbitrary to the same degree as the term "neutral layer."

Let us see now how the shape of the magnetic field changes on the nighttime side in the case of flow around a magnetic dipole in experiment[23,62]. The measurement was performed with a magnetic probe having two coils of 6 mm diameter, so placed that the probe could measure simultaneously two components of the magnetic field intensity, H_y and H_z. Figure 9 shows the experimental distribution of the vertical component H_y for 1) the field of the unperturbed dipole (dashed curve) and 2) the field in the case of flow of a plasma around the two-dimensional dipole (solid curve).

We see from a comparison of the curves that the interaction between the plasma and the magnetic field of the dipole leads to a vanishing (within the limits of measurement accuracy) of the vertical component of the field intensity, starting with a distance ~ 15 cm from the center of the dipole. However, the good qualitative agreement between this experimental curve and that obtainable when the neutral layer is produced, still does not serve as unambiguous proof of its formation. The point is that the vanishing of the component H_y along the z axis does not mean an increase in the horizontal components H_z directed to opposite sides above and below the proposed neutral layer.

A similar curve was obtained experimentally earlier in[43], prior to the report of the existence of a neutral layer in the geomagnetic field, but the lack of more detailed data on the dipole field configuration in the plasma stream did not make it possible to observe there the neutral layer under laboratory conditions before it was discovered with the aid of artificial satellites. In addition, the inaccuracy in the adjustment of the magnetic probe in the central plane of the dipole and the possible existence of slight asymmetry in the plasma stream do not make it possible to establish whether the component H_y is actually equal to zero in this plane.

Much more information was provided by an experiment in which both magnetic field intensity components were measured simultaneously near the central plane. Such measurements were undertaken at several fixed values of the coordinate z. In each series of measurements, the magnetic probe was moved in a vertical direction, crossing the equatorial plane, and at each point the components H_y and H_z were measured simultaneously. The measurement results make it possible not only to determine the direction and magnitude of the field intensity vector, but also to trace the gradual transition from the configuration of the weakly-disturbed field near the center of the dipole to the configuration of the neutral layer at large distances. Plots of the distribution of the magnetic field for two fixed values of the coordinate, z = 13 and 18 cm, are shown in Figs. 10 and 11.

At a distance 13 cm from the center of the dipole, the neutral layer does not yet appear, but a tendency of the component H_y to decrease and of H_z to increase can already be seen. The curves obtained at distances 18 and 23 cm from the center indicate the vanishing of the magnetic field on the z axis; the component perpendicular to the axis has a near-zero value in a certain interval above and below the axis, measured to be 2—3 cm. As to the H_z component, it also vanishes on the z axis and its absolute magnitude increases smoothly on both sides of the axis. In other words, the distribution observed corresponds precisely to the configuration of the neutral layer in the earth's magnetic field.

Another interesting feature of the experimental results is the change of the direction of the H_y component at a distance larger than 20 cm from the center of the dipole in the region adjacent to the neutral layer. At a distance 25—30 cm, the vertical component in the equatorial plane again becomes different from zero and has a direction opposite to that of the unperturbed field of the dipole. It should be noticed, in particular, that these experimental results cannot be regarded as highly important, since the vertical component of opposite sign had a magnitude smaller than the field frozen in the free plasma stream; in addition it is impossible to exclude the influence of the chamber wall on the field configuration far from the terrella. It is possible that the behavior of the intensity vector during the course of formation of the neutral layer is connected with the development of the layer instability considered in[80,81].

The complete picture of the directions of the intensity vector in the model experiment is shown in Fig. 12. It shows a rather extended section in which the force lines near the equatorial plane are parallel to the stream velocity on one side of the plane, and antiparallel on the other, i.e., the configuration observed is precisely the one corresponding to the neutral layer observed with the aid of artificial satellites. At large distances from the dipole, the force lines diverge. It is difficult to state at present whether such a divergence is the consequence of development of instability or whether it is connected with the experimental conditions. Estimates show that the time of development of the instability[81] exceeds the time of the experiment, and at the same time the loss of plasma to the side walls of the vacuum chamber should lead to a decrease in the external plasma pressure on the magnetic tail with increasing distance from the dipole.

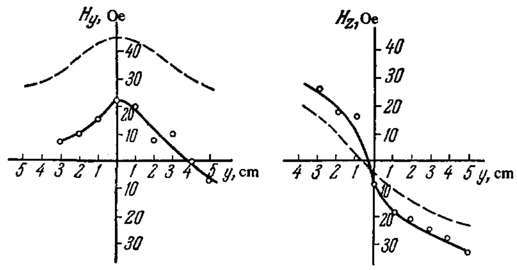

FIG. 10. Change of magnetic-field components H_y and H_z on the nighttime side following the crossing of the central plane of the dipole at a distance 13 cm from the dipole axis.

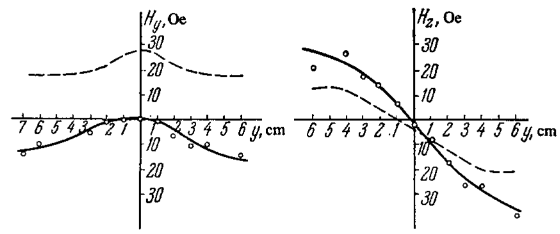

FIG. 11. The same as Fig. 10, but at 18 cm from the dipole axis.

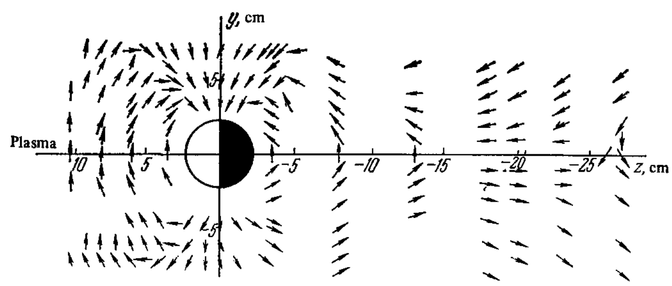

FIG. 12. Distribution of the directions of the magnetic-field vectors.

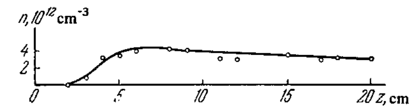

FIG. 13. Distribution of the density in an artificial geomagnetic tail.

To confirm the hypothesis that the tail becomes elongated as the result of dragging of the force lines, it is necessary to have direct experimental data on the presence of plasma in the region of the neutral layer. Figure 13 shows the distribution of the concentration in the central plane on the night side, showing that the plasma concentration is commensurate here with the concentration in the unperturbed stream.

The elongation of the force lines along the plasma stream and the presence of plasma inside the artificial geomagnetic tail indicate uniquely the existence of a mechanism of strong interaction between the plasma and the magnetic field, connected with the penetration of the plasma into the field. The widely held opinion, that a special role is played by neutral points in the effect of the influx of plasma, is not sufficiently well founded, for in order to fall in the tail after penetrating into the region of the neutral points, the plasma should move across the force lines of the magnetic field, shifting their position in the direction of motion. Actually, when the plasma flows around the dipole, the force lines in the region of the dipole axis are shifted compared with the unperturbed field not backwards but forward. On the other hand, the influx of the plasma as a result of complicated drift trajectories cannot explain the short time of tail formation. In the experiment, this time is comparable with the transit times of the plasma flux.

A much more likely hypothesis is that the plasma flowing around the dipole diffuses continuously. If the diffusion rate is sufficient to ensure an influx of the plasma, and the backward diffusion is hindered, then the force lines of the magnetic field become elongated along the velocity vector of the unperturbed stream. Such a situation takes place in the case of classical (collisional) diffusion, when the plasma becomes heated as a result of its penetration into the field, and consequently the diffusion coefficient decreases. However, the time of the classical diffusion in this experiment is patently insufficient to ensure the influx of the plasma into the tail of the magnetosphere.

Estimates show that the Bohm diffusion time[83] enables the plasma to enter the neutral tail. Assuming the length of the boundary between the plasma and the field to be 20 cm and substituting into the formula

$$\delta \sim \frac{c}{\omega_0} \sqrt{\omega_H t} \tag{4}$$

for the plasma parameters, we obtain a diffusion depth equal to 5 cm. The backward diffusion should also be hindered here, but for other reasons than in the case of classical diffusion. The point is that the smearing of the initially sharp boundary of the density and of the field can serve as the cause of a decrease in the coefficient of anomalous diffusion (a similar statement is valid also for anomalous diffusion as a result of ion-acoustic instability).

Another mechanism whereby the tail of the magnetosphere becomes elongated may be the occurrence of tangential tension as a result of the instability of the tangential discontinuity (velocity jump) on the boundary between the solar-wind plasma and the magnetosphere plasma. This mechanism can play an important role in the formation of the geomagnetic tail in outer space, where the velocity of the Bohm diffusion is smaller by approximately one order of magnitude than that needed for the plasma to penetrate into the neutral layer.

VI. TURBULENT PHENOMENA IN SOLAR WIND AND THEIR SIMULATION

Recently, data were reported on direct satellite and rocket measurements, of the spectrum of the fluctuations of the electric and magnetic fields[83]. Information of this type is highly important, since the microfluctuations of the interplanetary plasma play the key role in a number of fundamental phenomena, such as the transport processes (diffusion, viscosity, electric conductivity)—through establishment of the effective mean free path, generation and propagation of cosmic rays (which reduces essentially to the problem of the behavior of a trial particle in a specified field with a specified oscillation spectrum).

For a reproduction of turbulent phenomena in the laboratory, let us consider the conditions for their excitation and the possibility of their simulation. The most probable hypotheses concerning the origin of turbulent pulsations in interplanetary plasma are as follows:

1. Langmuir (plasma) turbulence. Langmuir plasma near the plasma frequency $\omega_0 = \sqrt{4\pi e^2 n/m}$ are frequently excited spontaneously in a laboratory plasma. For the interplanetary plasma we have $\omega_0 \sim 10^5$ Hz. As a rule, the source of such oscillations is two-stream instability. Although phenomena of this kind indeed accompany activity in the solar corona, it is not very probable that they play an important role in the interplanetary plasma.

2. Ion-acoustic (phonon) turbulence. Such an instability develops as a rule when $T_e > T_i$ and the density of the electric field exceeds a certain critical value. This critical value is obtained from the condition that the average directional velocity of the electrons relative to the ions exceed by several times the velocity of ion sound $\sim\sqrt{T_e/M}$. The upper limit of the spectrum in ion-acoustic turbulence is close to the ion Langmuir frequency $\Omega_0 = \sqrt{4\pi e^2 n/M}$. In the interplanetary plasma $\Omega_0 \sim 300$ Hz. It can be expected that this turbulence is generated in the shock wave front also near the magnetosphere, i.e., where large electric currents flow (or where interpenetrating ion beams are produced).

It is easy to produce in a laboratory experiment the conditions necessary for the development of ion-acoustic instability, although its detection is very difficult. The characteristic scale of such a turbulence is on the order of several Debye lengths. When the plasma density in a model experiment is sufficient for the occurrence of ion sound, this scale turns out to be much smaller than the possible dimensions of the receiving antennas.

Under such conditions, fluctuations of a field with different wavelengths will be received differently by a probe, since the signal at the probe is attenuated by a factor $2\pi l a/\lambda^2$; here l and a are the length and radius of the probe, respectively. The use of two electric probes of 0.5 mm diameter and 3 mm length has made it possible to observe on the front of a shock wave oscillations with frequencies ~ 100 MHz, which turned out to be not coherent at distances up to 0.5 mm at $\lambda_D = 10^{-3}$ cm. This result can apparently be treated as observation of ion-acoustic instability on the shock-wave front. Excitation of ion-acoustic instability can be observed also by the Raman-scattering method.

3. Alfven turbulence. In a high-pressure plasma ($\beta > 1$) such a turbulence can be easily excited in the presence, say, of pressure anisotropy. Thus, in the simplest case, when $p_{\parallel} > p_{\perp} + (H^2/4\pi)$, a hose instability is produced—transverse oscillations accompanied by a shift of the force lines with characteristic wavelength of several Larmor radii. In the opposite case, when $p_{\perp}/p_{\parallel}$ is larger than a certain critical value, magnetosonic turbulences are excited. It should be noted that both types of pressure anisotropy can be realized in the solar-wind plasma in collisionless expansion of the solar corona or compression of the plasma on the shock-wave front.

The simulation conditions presuppose that the characteristic dimension of the probe is much smaller than the Larmor radius of the ions ρ_i. The upper limit of the fluctuation spectrum is of the order of the ion Larmor frequency. In connection with the exceeding complexity of the physical picture of turbulence of this type, attempts were made to simulate them in a computer experiment. Instead of complete formulation of the problem of flow of the solar wind around the magnetosphere, it is possible to insert in the computer a model of a magnetized plasma, in which there is a certain pressure anisotropy from the very beginning.

One-dimensional Alfven instability results from hose instability ($p_{\parallel} > p_{\perp} + (H^2/8\pi)$) and is the most convenient object for a computer experiment[86], since such an instability is amenable to a hydrodynamic description (the so-called hydrodynamics of Chew, Goldberger, and Low). In this case computer simulation reduces to a numerical solution of the Chew, Goldberger, and Low equations for a specified initial anisotropy of the pressures and with small initial fluctuations introduced.

Figure 14 shows the time variation of the energy of the fluctuating magnetic field. The initial exponential section of the curve corresponds to the linear regime of development of a hose instability; it is then seen how the action of nonlinear effects causes the fluctuation of the magnetic field to go over into some steady state. It is seen from the figure that the growth of the amplitude stops after a time on the order of several Larmor periods, and the quasistationary state is reached after a time equal to several dozen $1/\Omega_H$. The mean square turbulent magnetic field as a function of the initial ratio $p_{\parallel}/p_{\perp}$ is shown in Fig. 15. The magnitude of this quasistationary magnetic pressure p_m at small plasma anisotropy ($p_{\parallel}^0/p_{\perp}^0 = 1.25-1.8$) increases approximately linearly with increasing ratio $p_{\parallel}^0/p_{\perp}^0$; when $p_{\parallel}^0/p_{\perp}^0 \sim 8$, the magnetic pressure of the fluctuations reaches a value $2H_0^2/8\pi$, and then the growth of the turbulent magnetic pressure is sharply decreased, going over practically to a plateau, and at $p_{\parallel}^0/p_{\perp}^0 = 50$ we get $p_m \approx 4H_0^2/8\pi$.

An attempt to observe Alfven instability was undertaken in experiments of the Institute of Space Research of the USSR Academy of Sciences on supersonic flow of plasma around a two-dimensional dipole at a gas-kinetic to magnetic pressure ratio $\beta \sim 4$. The anisotropy of the plasma can be ensured here by compression of the plasma on the shock-wave front.

The experiments were performed with the aid of two magnetic probes with loops of 2 mm diameter. The intensity of the magnetic field behind the shock-wave front was approximately 200 Oe at a concentration of 3×10^{13} cm^{-3}. The ion energy under these conditions was ~200 eV, corresponding to a Larmor radius ~10 cm. By placing the probes at different distances from each other, it was possible to determine the distance over which the probe readings stop to correlate with each other.

Amplitude fluctuations of the order of $\sim H_0$ were observed on the front of the shock wave and behind its front up to the boundary of the magnetosphere. The registered level of oscillations with frequency of approximately 1 MHz increased by more than one order of magnitude when the probe moved from the region of the unperturbed plasma stream into the region of the shock front (Figs. 16 and 17). The oscillations registered by

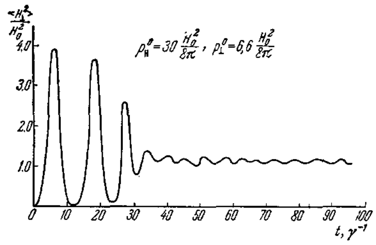

FIG. 14

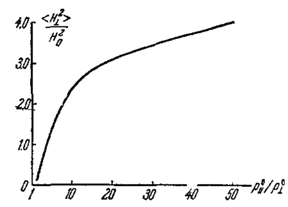

FIG. 15

FIG. 14. Time variation of the energy of magnetic-field fluctuations in computer simulation.

FIG. 15. Mean square of the intensity of magnetic-field fluctuations in a computer experiment as a function of $p_{\parallel}^0/p_{\perp}^0$.

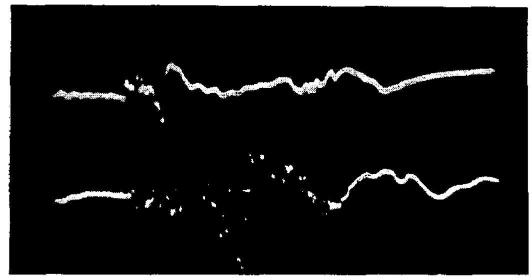

FIG. 16. Magnetic-field fluctuations. The upper trace plots the fluctuations in the unperturbed stream, and the lower one inside the front of the shock wave.

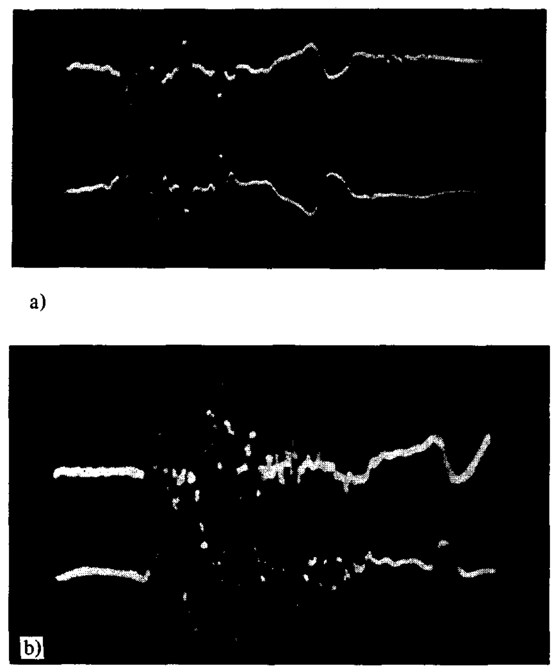

FIG. 17. Fluctuations registered within the front of a shock wave at distances between probes 1 cm (a) and 2 cm (b).

two probes were well correlated with each other up to distances 2–3 cm. At larger distances, the character of the fluctuations changed, this being apparently connected with the existence of a strong wave-damping mechanism in the plasma. The characteristic frequency of the oscillations and the appreciable wavelength (compared with the wavelengths at all other characteristic dimensions, with the exception of ρ_i), makes it possible to state that the observed fluctuations are apparently the result of Alfven instability.

Magnetic-field fluctuations with frequencies close to Ω_H were observed also in experiments performed at the Institute of Nuclear Physics, Siberian Branch, USSR Academy of Sciences and by Avco in the USA.

VII. CONCLUSION

Recently performed laboratory experiments have demonstrated the possibility of simulating a number of macroscopic phenomena occurring in outer space. Foremost among them are the formation of the magnetosphere and of a collisionless shock wave on the daytime side of the earth, and the formation of a neutral layer on the nighttime side. The scales of the phenomena in outer space and of the corresponding laboratory models were determined by the same characteristic plasma dimensions.

Experiments aimed at simulating microfluctuations in the solar-wind plasma have only just started, but their data already make it possible to assess the mechanisms of energy dissipation in a collisionless shock wave located at the earth's magnetosphere. Besides studying collisionless dissipation due to collective processes in a plasma, an investigation of the fluctuations of electromagnetic fields in a plasma is important for the understanding of the origin of cosmic rays. This problem is far from being solved, although the formation of fast particles in a plasma was observed not only in outer space but also in the laboratory[83-85].

Among the urgent problems faced by the laboratory experimenters is also the riddle of polar lights. So far, there is no representation that makes it possible to set up correctly an experiment in which this phenomenon can be simulated.

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