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SUMMARY

The possibility is investigated of simulating the interaction between the solar wind and the Earth's magnetic field An accurate simualtion of all the processes occurring in the magnetosphere proves to be actually unrealizable. However, there is a possibility of selecting the experimental parameters so as to reproduce under laboratory conditions the most interesting outer space phenomena. The results of experiments on the formation of the neutral sheet are presented as an example of the accuracy of a limited simulation.

* * *

It was reported earlier[1,2] that in the simulation of the interaction between the solar wind and the Earth's magnetic field phenomena were detected which accompany the collisionless shock wave in the vicinity of the magnetosphere. The experiments were carried out with a two-dimensional magnetic dipole in a plasma flow characterized by the following parameters: concentration $n \sim 10^{13}$ cm^{-3}, electron temperature $T_e \sim 15$ ev, flow velocity $\bar{v} \sim$ $\sim 3 \cdot 10^7$ cm/sec. The magnetic dipole was a rectangular shaped flat copper coil 4 cm wide and 30 cm long (the distance between the conductor centers was 2 cm). The coil was located in the horizontal plane in such a manner that the directed plasma velocity vector was to be perpendicular to its larger side and parallel to its smaller side. The magnetic field intensity at magnetosphere boundary was 300-500 oe. The aforementioned values do not correspond to the simulation of outer space conditions investigated by Alfven [3] but the selected parameters prove nonetheless to be suitable for a laboratory simulation of solar wind flow around the geomagnetic field.

The current article presents a substantiation of the model experiment and contains some additional experimental date on the formation of the neutral sheet on the night side.

The Basic Principles of Simulation. A precise simulation of the interaction between the solar wind and the geomagnetic field encounters virtually insurmountable difficulties. Thus, for instance, in order to preserve the magnetic Reynolds number, plasma temperature in a simulation experiment should have the same order of magnitude as in a thermonuclear reactor. However, in order to determine a number of peculiarities in the interaction of a plasma with a magnetic dipole, and, in particular, to investigate the shape of a steady shock wave on the "diurnal" side and the formation of a neutral sheet on the "night" side, it is not necessary to follow exactly the laws of similarity. It is sufficient that the conditions for the course of the investigated phenomenon be fulfilled. This means that the dimensionless parameters characterizing the interaction equal by order of magnitude to the unity, should be as far as possible identical in the outer space and in the laboratory. But when in outer space a given dimensionless parameter is by many orders lower or higher than the unity, this parameter should also be correspondingly low or high by comparison with the unity in the model experiment. However, in any case when investigating the phenomenon in a first approximation, it is not necessary to preserve the same order of its magnitude. Let us investigate systematically the basic dimensionless parameters characterizing the interaction between the plasma flow and a magnetic dipole.

1. The magnetic cavity free of plasma is formed under conditions of sufficiently high electron temperature, when the plasma flux cannot penetrate deeply into the magnetic field. The condition for a separate existence of a plasma and of a magnetic field is equivalent to the requirement $Re_m \gg 1$. Here Re_m is the magnetic Reynolds number

$$Re_m = \frac{4\pi\sigma L\bar{v}}{c^2}$$

where σ is the plasma conductivity, $\bar{v}$ is the directed velocity, and L is the magnetosphere dimensions.

At solar wind interaction with the geomagnetic field $Re_m \sim \sim 10^{12}$. In the present experiment the plasma temperature was ~ 15 ev which responds to $Re_m > 10^3$, i.e. the conditions for magnetic cavity formation were fulfilled.

2. To form a shock wave in the vicinity of the plasma-field interface, plasma flow must be supersonic. In the solar wind the directed velocity exceeds that of ion sound by a factor of 5-10

[4,5]. At a flow velocity in the model experiment of $3 \cdot 10^7$ cm/sec and a temperature $\sim$ 15 ev, this value amounts to 7-8, i.e. the selected velocity and temperature fulfill the conditions for shock wave formation. Similar considerations with respect to a disturbance propagating at a velocity of the magnetic sound result in the necessity of having in the plasma a frozen-in field of $\sim$ 30 oersted.

3. To form a collisionless shock wave the length of the free path must exceed the characteristic dimensions of the system. In the solar wind the ratio between the length of the free path and the magnetosphere dimensions is 10^3. In the present work, at a concentration of 10^{13} cm^{-3}, this ratio is $\sim$ 10. Therefore here, as in outer space, the onset of the shock wave cannot occur at the expense of Coulomb collisions.

4. In the boundary layer "plasma-field" the ion and electron curvature radius is much smaller than the dimensions of the layer. In the present experiment this condition is valid only for electrons. However, the small Debye radius of plasma does not permit ions to detach themselves from electrons. Consequently, the conditions can bear comparison in this respect too.

It is interesting to note that in the experiments currently planned at the Royal Institute of Technology (Stockholm) [6], plasma parameters virtually coincide with the parameters of our own experiments, whose results were discussed for the first time at the International Conference on shock waves in a plasma (Novosibirsk, August 1967). At that Conference Shindler has noted in his report that the indicated parameters are close to optimal.

The Neutral Sheet. When organizing experiments on simulation of the geomagnetic field shape on the night side, it was assumed that plasma flow penetrates through the boundary of the magnetosphere. The penetration takes place most probably either through the neutral points, which in a two-dimensional case degenerate into neutral lines, or is due to the instability of the plasma-magnetic field interface.

Having penetrated into the magnetic cavity, the plasma flow must carry along the lines of force to the night side and thereby bring about the formation of a neutral sheet, which has been recently detected by means of artificial Earth satellites [7]. The entrainment of the lines of force by the plasma flow having penetrated into the magnetic field was previously detected under laboratory conditions during plasma injection along the axis of a short coil [8]. The field intensity in the neutral sheet is zero. The lines of force in the vicinity of the median plane are parallel to the neutral sheet and have opposite directions in the northern and southern hemisphere. Fig. 1a shows that the shape of the Earth's magnetic field lines of force in the plane passing through the magnetic axis and the Earth-Sun line according to the data of the artificial satellites. For the sake of comparison, Fig.1b shows the configuration of an unperturbed

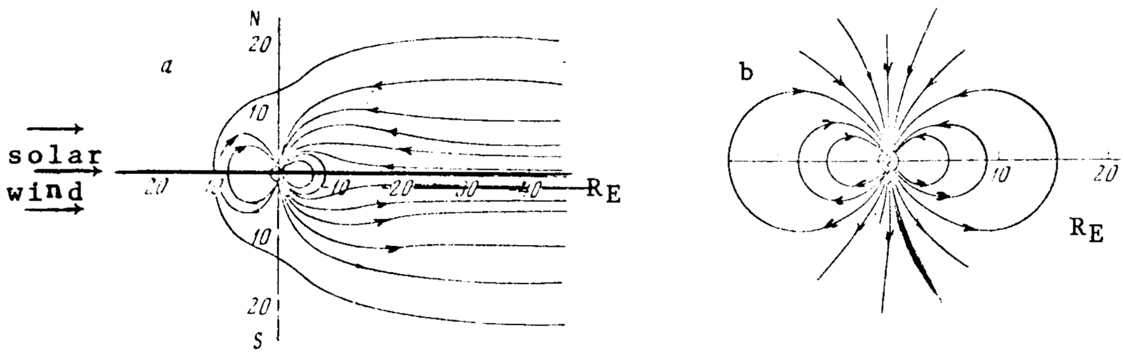

Fig.1

field of a magnetic dipole. Comparison of the configurations shows that during the formation of the neutral sheet the magnetic field's vertical component H_y must vanish at a certain distance from the dipole center.

Now let us investigate the changes in the magnetic field configuration on the night side during the blowing of the magnetic dipole in the course of the present experiment. The measurements were carried out with a magnetic probe using two coils of 6 mm in diameter which were placed in such a manner that the probe could simultaneously measure two magnetic field intensity components H_y and H_z. Fig.2 shows the experimental distribution curves of the vertical component for two cases: a) unperturbed dipole field (dashed curve); b) field during the blowing of a two-dimensional dipole by a plasma flow (solid curve).

Comparison of the curves shows that the interaction of the plasma with the magnetic dipole results in the vanishing of the vertical component of field intensity, starting from a distance of ∿ 15 cm from the dipole center. However, the good coincidence of this experimental curve with the curve taking place at the creation of the neutral sheet is not yet an unambiguous proof of its formation. In fact, the vanishing of component H_y along the axis Z does not yet mean that the horizontal components H_z, oriented in various directions above and below the presumed neutral sheet, are increasing.

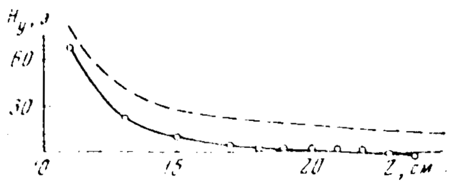

Fig.2

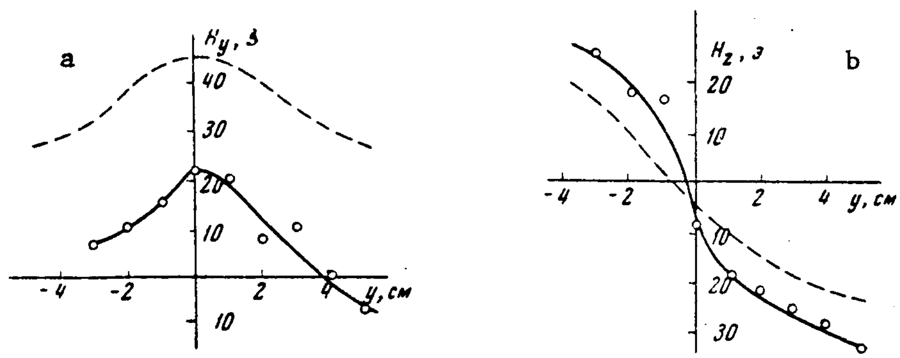

Fig.3

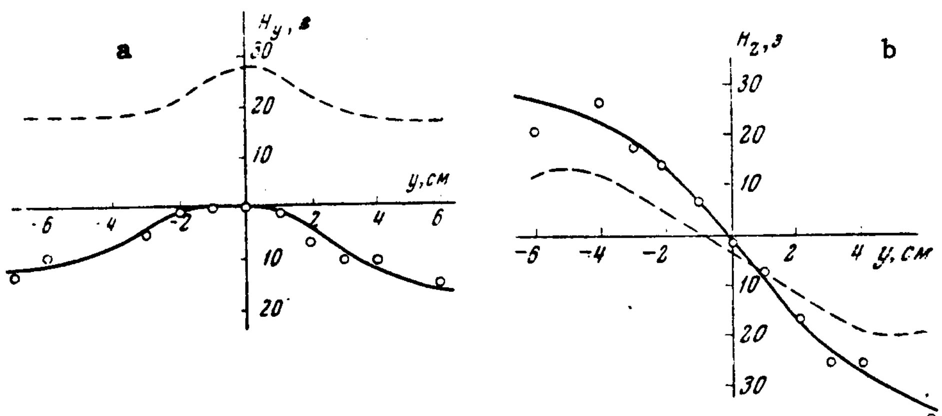

Fig.4

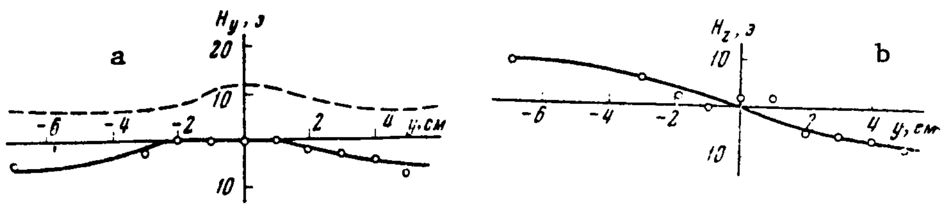

Fig.5

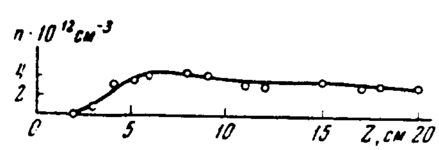

Fig.6

Previously, a similar curve was experimentally obtained in [9] before the data on the existence of the neutral sheet in the geomagnetic field were available. However, the lack in this work of detailed data on dipole field configuration in the plasma flow had not made it possible to detect the neutral sheet under laboratory conditions before it was detected by means of artificial Earth satellites. Besides, inaccuracies in the alignment of magnetic probes in the median plane of the dipole and the possibility of a slight asymmetry of plasma flow do not make it possible to eastablish whether the component H_y in this plane is actually exactly zero.

A considerably more extensive information is provided by the experiment in which both components of magnetic field intensity are measured simultaneously near the median plane. Such measurements were carried out for several fixed values of the coordinate Z. In each series of measurements the magnetic probe was moved in the vertical direction intersecting the equatorial plane, and at each point components H_y and H_z were measured simultaneously. The results of measurements provide the possibility of determining not only the direction and value of field intensity vector, but also to trace the gradual transition from feebly-disturbed field configuration in the vicinity of the dipole center to the neutral sheet configuration at long distances. Figs. 3,4 and 5 show the distribution of the magnetic field respectively for three fixed values of the coordinate Z, i.e.13, 18 and 23 cm.

At a distance of 13 cm from the dipole center the neutral sheet is not yet formed but the tendency is already perceptible to the decrease of the component H_y and increase of the component H_z.

The curves taken down at distances of 18 and 23 cm from the center are evidence of the vanishing of the magnetic field intensity on the axis Z, whereupon the component perpendicular to the axis is zero within a certain interval above and below the axis, measured at 2 - 3 cm. As regards the component H_z, it is also zero on the axis Z, and its absolute value smoothly increases on both sides of the axis. In other words, the observed configuration is precisely that which responds to the configuration of the neutral sheet.

Another interesting peculiarity of the experimental results is the variation in the direction of the H_y component at a distance of $\sim$ 20 cm from the dipole center in the region adjacent to the neutral sheet. At a distance of 25 - 30 cm the vertical component in the equatorial plane is again nonzero and has a direction opposite to that of the unperturbed dipole field. Such a behavior of the intensity vector during the .ormation of the neutral sheet may be linked with the development of its instability [10,11]. In this connection, the possibility of an effect of chamber walls is not excluded.

Discussion of the Results. The magnetic field configuration on the "night side" observed in the present work is in complete agreement with the concept of neutral sheet formation on account of the entrainment of the magnetic field lines by the plasma flow penetrating through the magnetosphere boundary. Equilibrium between the gas kinetic pressure of the plasma flow and the magnetic field pressure is the condition of existence of the neutral sheet. A final corroboration of the validity of our assumption can be made only through an experimental verification of the presence of plasma in the region of zero values of the magnetic field.

The detection and the measurement of plasma concentration in this region was carried out by means of a double Langmuir probe, as the sensitivity of the laser interferometer [1] previously used for determining the concentration at the shock wave front was insufficient for such measurements. Measurements carried out with a double Langmuir probe have shown that plasma concentration on the night side is $\sim 5 \cdot 10^{12} cm^{-3}$ up to the region in which the tail of the magnetic field may have been distorted by chamber wall effect. The distribution of concentration in the neutral sheet, obtained by the double probe, is plotted in Fig.6.

Thus, the combination of the obtained experimental data makes it possible to conclude that the model experiments have detected the neutral sheet, whose formation is linked with the penetration of plasma in the magnetosphere. The current density through the plasma in the region of the neutral sheet is ~ 5 a/cm^2.

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