EFFECT OF THE FROZEN-IN MAGNETIC FIELD ON THE FORMATION OF VENUS' PLASMA SHELL BOUNDARY: EXPERIMENTAL CONFIRMATION

Ju. V. Andrijanov and I. M. Podgorny
Space Research Institute, Academy of Sciences
Moscow, USSR

ABSTRACT

The results are given of laboratory simulation of solar-wind interaction with plasma shells of nonmagnetic planets. It is shown that the momentum transfer from the plasma flow to the shell occurs due to the presence of a frozen-in magnetic field. Without a magnetic field frozen-in, the ionosphere has no sharp boundary and a shock wave does not form in the flow.

INTRODUCTION

Laboratory experiments with an artificial magnetosphere allowed a number of regularities to be found in the behavior of the near-Earth plasma. It was shown, for example, that particles penetrated into the magnetosphere through annular polar clefts [1]. The application of a system of partitions yielded the conclusion that the source of the radiation belt is located on the nightside [2]. In earlier laboratory experiments, a shock wave was studied for large Mach numbers [3, 4]. Studies of the plasma flow around a non-conducting body demonstrated that it was possible to simulate the Moon's wake [5]. The authors tried to reproduce in the laboratory and to study the nature of the process of flow around nonmagnetic celestial bodies with a plasma shell. First to be mentioned among these bodies are Venus and comets.

Venus

The interaction of the solar wind with Venus was investigated aboard Venera and Mariner spacecraft (see, for example, [6 through 9]) and the presence of a shock wave was reliably identified. However, the character of the interplanetary plasma interaction with the planet is still to be determined. Possible types of interaction can be subdivided into two main classes: plasma flow scattered from particles in the atmosphere and the momentum transfer from the interplanetary-to-planetary plasma via the magnetic field. A tangential discontinuity is a particular case of the second type of interaction. However, a tangential discontinuity can hardly remain stable under actual conditions. If the formation of an obstacle is associated with a magnetic field frozen-in the solar wind, then the necessary condition for a shock wave to exist is the following inequality:

$$\mathrm{Re}_m = 4\pi\delta_i\bar{v}h/c^2 > 1 \qquad (1)$$

where δ_i is the conductivity and h is the thickness of the ionospheric layer. If, in a model experiment, an ionosphere with $T_e \sim 5$ eV is produced, then a plasma shell of about 1 cm thick at the surface of the obstacle will be sufficient for the inequality 1 to be valid.

Comets

Other objects with a gaseous shell are comets. The first laboratory experiments on cometary simulation [10, 11, 12] were based on the well-known Alfvén hypothesis on the existence of an effective mechanism of neutral gas ionization by a plasma flow with velocities exceeding the critical value $v_{cr} = (2W_i/M)^{1/2}$. Here, W_i is the ionization potential. These experiments differ in the way the cloud of gas is produced (whether it is gas injection or dry ice evaporation), but they all indicate the effect of plasma cloud dragging by the plasma flow with a frozen-in magnetic field. This effect results in an elongated plasma configuration similar to a cometary tail of Type I. The photographs taken made the authors of [12] assume that a shock wave had formed at the plasma cloud in a supersonic flow.

In that paper [12], the main interests were the studies of phenomena near the boundary between the plasma cloud and the artificial solar wind; that is, effects near the comet nucleus were studied.

EXPERIMENT

The choice of parameters of the plasma flow used in the experiments is based on the principle of limited simulation [13, 14]. Those dimensionless parameters, which to an order of magnitude are unity, are assumed as close as possible to their values in space. Those parameters that differ greatly from unity in space are taken as being appropriately larger or smaller than unity, but the order of magnitude is not always maintained.

A qualitative change in the nature of a process with changing dimensionless parameters usually occurs when the latter is close to unity. Hence, this principle allows a correct laboratory simulation of various cosmic phenomena, and has been proven by the experiments with a terrella and a lunella.

Table 1 shows that all of the parameters but ρ_i/L meet this principle fairly well. As for ρ_i/L, apparently its value is not decisive since the inequality $\rho_e/L \ll 1$ is valid both in space and in the laboratory and a small Debye radius, $\lambda_D = (KT/4\pi ne^2)^{1/2}$, implies that separation of ions and electrons cannot occur at distances larger than ρ_e.

A hydrogen plasma with dimensionless parameters listed in table 1 was generated by a coaxial electrodynamic accelerator. The plasma velocity was $\bar{v} = 1.5 \times 10^7$ cm/s, its density $n = 9 \times 10^{12}$ cm^{-3}, electron temperature $T_e \sim 15$ eV, and the intensity of the magnetic field frozen-in the plasma flow was B = 25 G. To produce a frozen-in field the plasma accelerator was put into a solenoid. This technique facilitated performing control experiments with zero field, in which case a current did not flow through the solenoid. The most important data were obtained when the angle formed between $\bar{v}$ and B was equal to 45°. Experiments were carried out in a cylindrical vacuum chamber 70 cm in diameter and 270 cm long.

Table 1
Comparison of Basic Dimensionless Numbers

Dimensionless Parameters	Space*	Experiment
Mach number (M_s)	$5 \div 10$	4
Alfvén Mach number (M_A)	5	7
Ratio of plasma to magnetic pressure [$\beta = nkT/(B^2/8\pi)$]	1	8
Squared ratio of Larmor to Langmuir frequencies [$(\omega_{ce}/\omega_0)^2$]	10^{-5}	10^{-4}
Ratio of electron Larmor radius to model dimensions (ρ_e/L)	$5 \cdot 10^{-4}$	$5 \cdot 10^{-2}$
Ratio of ion Larmor radius to model dimensions (ρ_i/L)	10^{-2}	2
Ratio of Debye radius to model dimensions (λ_D/L)	$5 \cdot 10^{-6}$	10^{-3}
Ratio of mean free path to model dimensions (λ/L)	10^5	5

*Data correspond to Explorer-35 experimental conditions.

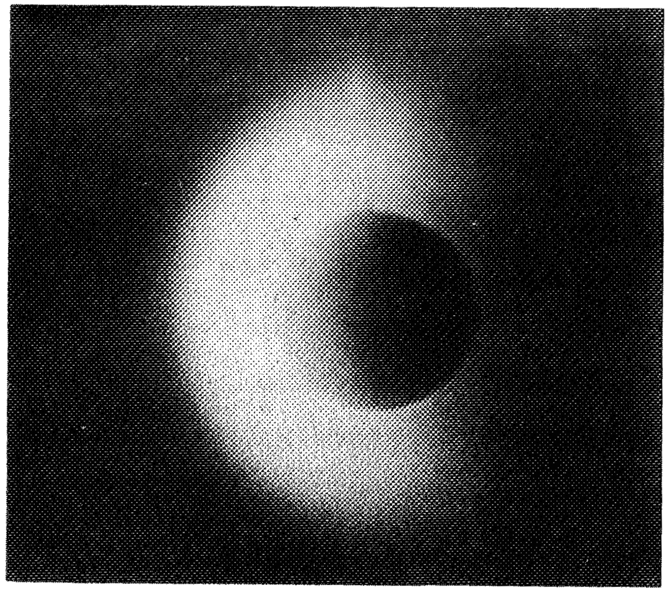
Sensors to record parameters were mounted 100 cm from the accelerator and the obstacle moved, in an artificial solar-wind flow, along the symmetry axis of the camera (Z-axis).

A wax sphere 10 cm in diameter was used as a model of Venus. It was chosen because of its low evaporation temperature and low thermal conductivity. The plasma flow in contact with the surface of the sphere vaporized the wax and ionized the vaporization products. The phenomena that accompany the interaction between the solar wind with an artificial ionosphere thus formed were studied.

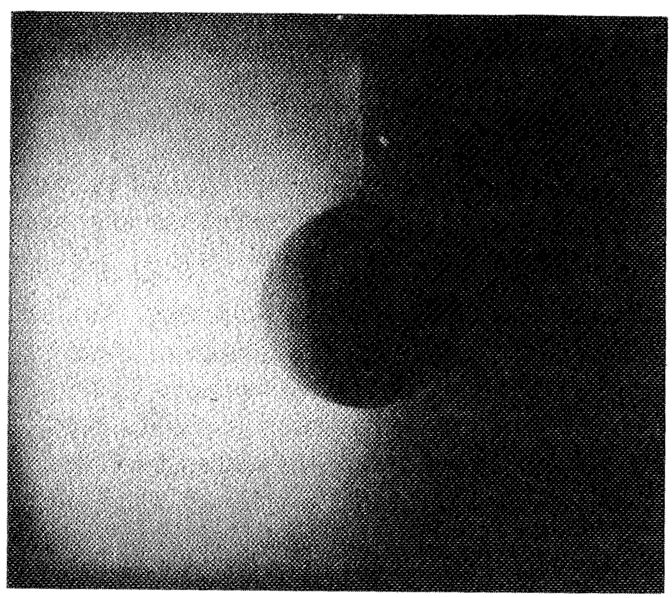
The magnetic field was measured by a set of magnetic probes. Two types of probes were employed: open probes of ~1 cm in diameter and miniature probes ~5 mm in glass tubes. The plasma density and electron temperature were measured by double probes. Directed double Langmuir probes turned out to be extremely useful for shock wave investigations [15]. One side of a flat ion-collecting electrode was insulated and its uninsulated collecting surface was appropriately oriented. The area of the probe, S, was 3 mm^2.

EXPERIMENTAL RESULTS

The decisive role of the magnetic field frozen-in the solar wind, while interacting with the plasma shell, is clearly demonstrated by comparing figure 1(a) and figure 1(b). Figure 1(a) is a photograph of the flow around a model of Venus, with the frozen-in magnetic field equal to 25 G. A specific feature of figure 1(a) is the rather bright glow of the wax vaporization products with a sharp boundary on the dayside. The glow of the artificial solar wind is absent on the photograph since the emission of fully-ionized hydrogen plasma is extremely



(a)



(b)

Figure 1. Photographs of the glow near the wax sphere in a plasma flow with (a) and without (b) a frozen-in magnetic field.

weak in the visible spectral region. The plasma flow pressure is obviously balanced by the pressure of the ionosphere thus formed. It should be emphasized that a sharp boundary appears only if a magnetic field is frozen-in the artificial solar wind.

Another photograph is given in figure 1(b) for comparison. It was obtained in similar conditions, the only difference being the absence of the frozen-in field in the plasma flow. In this case, the glowing area has no distinct boundary, and its brightness gradually weakens with distance from the model. The diffuse glowing area around the obstacle in the plasma flow, without the frozen-in magnetic field, implies that the interaction between the artificial solar wind and artificial ionosphere in this case is far too weak and conditions are unfavorable for a shock wave to form. If a frozen-in magnetic field does exist, there is every reason to expect a shock wave to appear, and here the ionosphere can act as an obstacle. Such a shock wave was recorded by magnetic and electric probes. A directed probe, oriented perpendicular to the flow, with its collecting surface facing the plasma accelerator, records almost a constant saturation current, $J_{\parallel}$, when it moves along the Z-axis (figure 2(a)). This means that flux is conserved (nv = constant) and can control the validity of the technique used.

The probe whose surface is oriented parallel to $\bar{v}$ measures current due to the motion of ions perpendicular to the Z-axis (figure 2(b)). In this case, the saturation current, $J_{\perp}$, is determined by Bohm's formula and is proportional to $n\sqrt{T_e}$. Beginning with 6 cm, $J_{\perp}$ increases with the probe approaching the model. At about 3 cm from the surface of the model, a second increase of the probe saturation current is clearly seen. This increase coincides with the boundary of plasma glow (figure 1(a)). The probe current, before the second increase where the curve almost reaches saturation, is about three times as high as that in the unperturbed flow. Since the probe usually showed only a slight T_e increase (by a factor of 1.5), the $J_{\perp}$ increase is evidence of an increase in density. The plasma density grows approximately by a factor of 3, within experimental accuracy, and corresponds to the Hugoniot adiabat for a Mach number of 3. Note that this Mach number is obtained from the $J_{\parallel}/J_{\perp}$-ratio. $J_{\perp}$ drops immediately at the surface of the obstacle, and that is obviously related to the weak ionization of vaporized material in a layer ~5 mm thick.

The existence of a shock wave is also confirmed by the spatial distribution of the magnetic field component perpendicular to the plasma flow (figure 2(c)). A second increase of the magnetic field is also observed near the glow boundary; it implies that the latter is also a boundary of the obstacle responsible for the shock-wave formation. Of interest is the change in the magnetic-field orientation near the plasma shell boundary. The curves of figure 2(c) and (d) show that the longitudinal and transverse components in the unperturbed plasma flow are almost equal, that is, the field orientation is ~45°. Near the boundary of the obstacle, the transverse component increases by about five times while the longitudinal component decreases by a factor of 3 to 4. Otherwise, the field line coincides with the plasma shell boundary, to an accuracy of 3° to 4°. The error in the probe plane orientation is also approximately 3° to 4°.

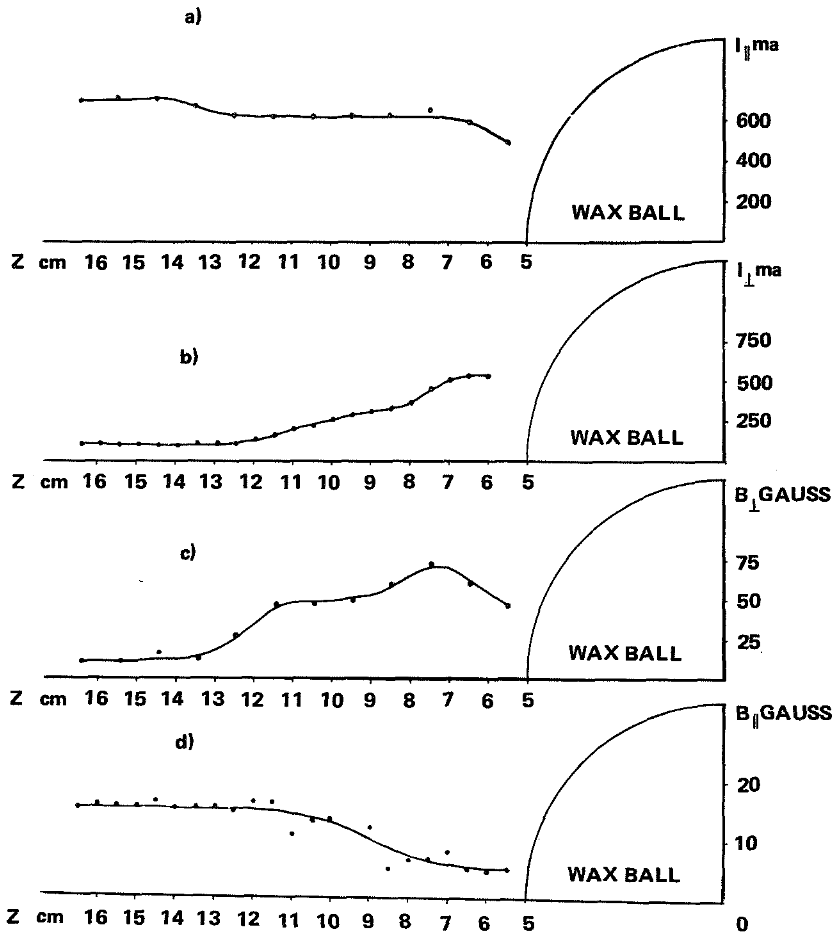


Figure 2. Dayside distribution of plasma parameters along the Z-axis, with the plasma flow around the wax sphere. (a) Plasma flux ($n\bar{v}$) measured by the probe with the collecting surface facing the accelerator; (b) Recording made by the probe with the collecting surface facing the Z-axis (the probe current is proportional to $n\sqrt{T_e}$; (c) Distribution of the vertical magnetic component; (d) Distribution of the longitudinal magnetic component.

The formations of an obstacle and a shock wave are also observed in figure 3. This illustrates the spatial saturation-current distribution of the probe with its surface opposite to the flow direction. The probe measures radomization of the flow. The solid line shows the visible boundary of the ionosphere. It should be emphasized that a flow pattern of this kind can be observed only with a magnetic field frozen-in the plasma flow. If it is not the case, no phenomena similar to a shock wave have been observed and the probe current gradually grows when it approaches the surface of the model (figure 4) thus demonstrating the glow distribution of figure 1(b).

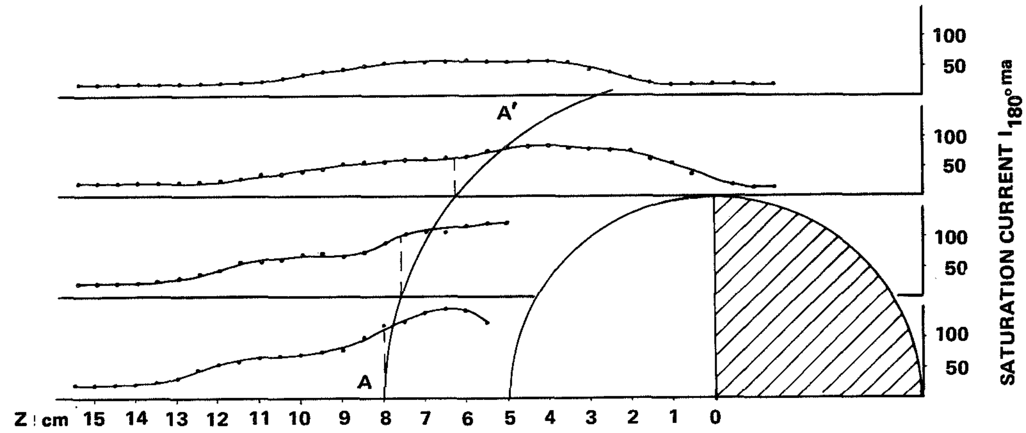


Figure 3. Spatial probe current distribution with the probe looking in the direction opposite to the plasma flow. The first probe current increase is attributed to a shock wave. Beyond the plasma glow boundary (A, A′ line), another increase of the probe saturation current is observed.

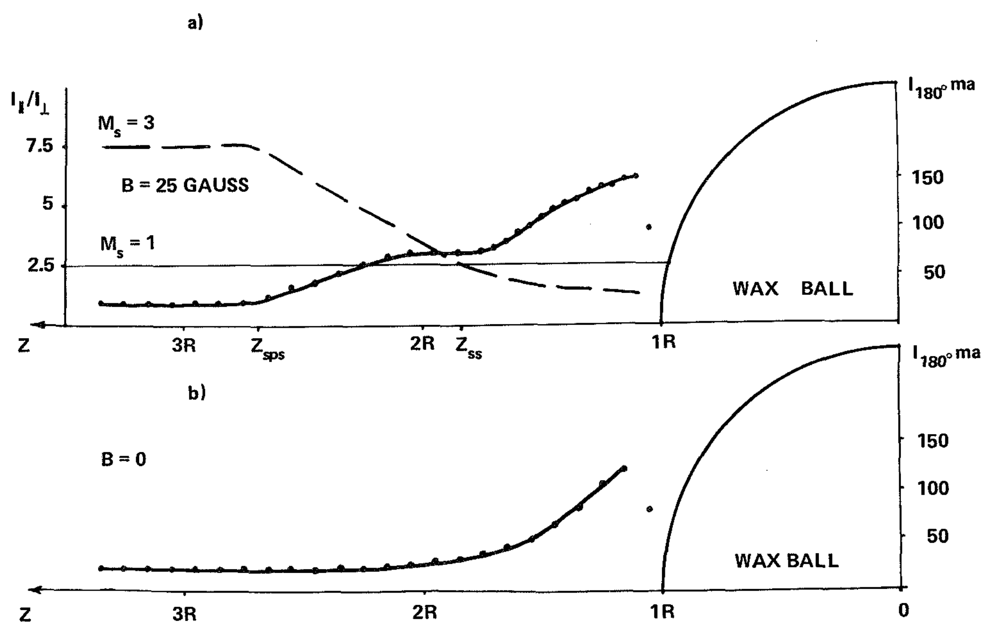


Figure 4. Distribution of plasma perturbations on the dayside of the wax sphere. They are recorded by the probe facing the model with (a) and without (b) magnetic field frozen-in the plasma flow. The dashed line shows the Mach number distribution. Transition from a supersonic to subsonic stream occurs between Z_{sps} and Z_{ss} points.

DISCUSSION

The results given above unambiguously show how essential the frozen-in magnetic field is in the process of momentum transfer from the plasma flow to the planet's ionosphere. This experimental fact in itself is not unexpected. The lines of the magnetic field frozen-in the plasma that flows around a conducting obstacle align along the boundary, and if another plasma acts as an obstacle, then ions from one plasma flow to another can penetrate them to a depth equal to their Larmor radius. However, the plasma shell is at least an order of magnitude thinner than ρ_i, hence the presence of the frozen-in magnetic field results in a strong interaction of the plasma flow with the ionosphere and the momentum is transferred over a distance much less than ρ_i.

The sharp glow boundary observed can be treated as a cold plasma boundary, its width being equal to the Larmor radius of cold ions, and the plasma shell can be regarded as transparent for ions of the artificial solar wind. The Larmor radius of ions in the flow and their mean free path, before collisions with charged particles, are large as compared with the thickness of the shell, and the space charge should be compensated by electrons from the ionosphere. However, this does not explain the formation of a shock wave, and it is necessary to assume the presence of effective deceleration of the ion flow in the plasma with magnetized electrons. The instability of the flow with magnetized electrons was observed by the authors [4]. A rough estimate based on spectral data show that fast ion scattering on neutral atoms can be neglected.

A similar effect was observed in laboratory experiments conducted in Sweden [16]. There, flow deceleration in a plasma in the presence of a transverse field was studied by various experimental methods and the effect of collision-free deceleration was ascertained. There is no theory of this phenomenon and explanations offered cannot be treated as unambiguous.

The results of the studies of the spatial distribution of the density and magnetic field fit well with the concepts about the formation of a collisionless, stationary shock wave which, as is known, was detected near Venus. The width of the shock front determined from the measurements of the magnetic field and density amounts to tenths of the ion Larmor radius calculated from the thermal velocity. A more exact value of the bow shock width was obtained from the curve of Mach numbers when the plasma flow crossed the bow shock. Mach numbers were determined from the probe measurements at different distances from the model. The plot in figure 4(a) yields the width of the shock front as equal to 0.2 to 0.3 ρ_i. These data agree well with laboratory simulation of the solar-wind interaction with the Earth's magnetic field and do not contradict space measurements.

The laboratory experiment on the supersonic interaction and super-Alfvénic plasma flow with ionized products of wax vaporization can also be regarded as a model for comets. Similar processes occur not only on the boundary between the two plasmas but are a general character of the interaction, too, if the most common model of a comet with a vaporizing, hard nucleus is assumed.

A strong interaction between plasma flow with a frozen-in magnetic field and the plasma shell was discovered in this work and allows an assumption to be made that a similar, though not so well-developed, effect can occur near the surface of the Moon. Plasma with a density of $\sim 10^4$ cm^{-3} and a scale height of ~ 100 m was observed on the dayside of the Moon [17, 18]. The thickness of the Moon's plasma shell is less than the Larmor radii of ions and electrons, and an obstacle that can give rise to a shock wave similar to that near Venus cannot form. However, the possibility still exists of a semitransparent obstacle formation that produces certain perturbations of the interplanetary medium. In particular, irregular increases of the magnetic field along the Mach cone on the nightside that have been observed [19] may be caused by this perturbation.

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QUESTIONS

Podgorny/Cloutier: What is the collisional mean free path for the gas in your experiment?

Podgorny: In the plasma shell, the mean free path for the energetic directed ions is about 200 cm and for the thermal electrons 10 cm. The neutral particle density in the shell is not larger than the charged particle density.

Podgorny/Dessler: Because the ion cyclotron radius is so large (approximately 60 cm) compared with the scale of the phenomena being observed (approximately 1 cm), wouldn't it be best to present your observations as basic plasma physics that would be helpful in understanding interplanetary phenomena? Treating your experiments as a direct analogy of the solar-wind interaction problem seems to me to be a difficult step.

Podgorny: The ratio of the thermal cyclotron radius of the ions to the dimension of the body is about one, but in most cases a more representative value is the hybrid cyclotron radius, for which the ratio is much less than one. As for comparison of the shell thickness and the cyclotron radius for total ion energy, they greatly differ, thus confirming the existence of a strong collisionless interaction.