"HEATED LAYER" EFFECT IN INTERACTION OF AN INTERPLANETARY SHOCK WAVE WITH A GEOMAGNETIC TAIL

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Using the numerical solution as the base the conditions of propagating a parallel MGD shock wave in the presence of a heated layer are analyzed, a new "raking regime" of interaction not observed with no magnetic field is revealed. A flow steadiness criterion is obtained, and conditions for the onset of a similarity precursor are estimated.

As early as the 50s it was found that ahead of the front of a shock wave (SW) propagating along a layer (channel) with an elevated sonic velocity a wedge-shaped precursor may appear. Hess and Taganov studied this phenomenon and, independently of one another, obtained the condition whether SW interaction with a layer would be steady or not [1, 2]. Later on it was shown that if the main flow had similarity, then a growing precursor also possessed similarity and was time-dependent in the same manner [3-5]. For example, in the problem on a flat piston pushed into a gas with a constant speed, it is directly proportional to time. After some short period of establishing the initial state the rate of growth of a precursor becomes layer-thickness-independent. Hence, in an ideal gas an infinitely thin disturbance of the initial state may result in a global flow change.

This phenomenon also exists in magnetic gasdynamics. If is not very large, then the flow pattern is strongly affected by the field direction. The most simple case is when the force lines of a magnetic field are also parallel to the incident wave front and the "heated layer," since there is no pressure anisotropy in the flow plane [6]. The present article is concerned with a rapid parallel flat piston-induced MHD shock wave interacting with a thin reduced-density layer parallel to a magnetic field. This configuration has been chosen because the formation of such a layer may be easily conceived, and the pressure anisotropy in this case is substantial and will cause new effects. There is an important and interesting field of use of these results in the physics of the magnetosphere - interaction of interplanetary shock waves with a geomagnetic tail. This application is discussed at the end of this article.

Since parallel MHD shock waves have a limited evolution range [7], we have assumed that $\beta_0 \geq 2/\gamma$, where $\beta = P/(H^2/8\pi)$; P is the gasdynamic pressure; H is the magnetic field intensity. In this case, SW always undergoes evolution. The subscript "0" will denote parameters before a SW front; "1," immediately behind it (these are related by the front conservation equations).

By analogy with [1, 2], the steady flow criterion is obtained. Since in the chosen geometry a current pipe coincides with a magnetic power one (provided steady flow), the Bernoulli equation in the ordinary gasdynamic form is valid. Upon supplementing this equation with the magnetic pipe flow conservation condition and the isoentropy condition, we have a system describing the current pipe evolution behind the SW front:

$$\left(\frac{\gamma}{\gamma+1}\right)\frac{P}{\rho}+\frac{V^2}{2}=c_1,$$
$$\rho = P^{1/\gamma}/c_2,\ H=\frac{P^{1/\gamma}V}{(2c_3)^{1/2}}, \tag{1}$$
$$c_1=\left(\frac{\gamma}{\gamma+1}\right)\frac{P_1}{\rho_1}+\frac{V_1^2}{2},$$

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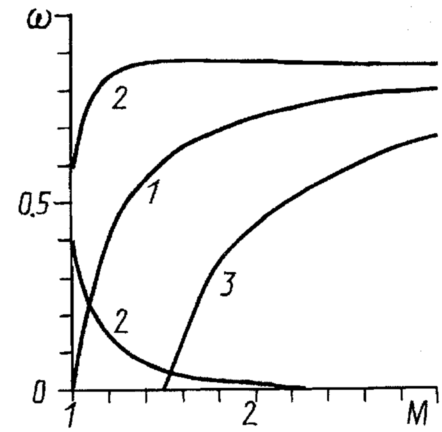


Fig. 1. Steady flow criterion at no magnetic field (1) and for $\beta_0 = 6/5$ (2); 3) approximate boundary of similarity flow existence.

$$c_2 = \frac{P_1^{1/\gamma}}{\rho_1}, \quad c_3 = \frac{P_1^{2/\gamma} V_1^2}{H_0^2},$$

P_1, V_1, and ρ_1 are determined by the relations for a shock wave $H_1 = H_0$.

It is convenient to describe a "heated layer" by the initial layer-to-ambient plasma density ratio $\omega = \rho_0'/\rho$ ($'$ will stand for reduced-density layer parameters). Steady flow is possible if varying its velocity the "heated layer" plasma can acquire a total (magnetic plus gasdynamic) pressure equal to the total pressure behind the principal SW front; otherwise, the channel will be choked and the "heated-layer" substance cannot escape from the front region as in the case of steady flow:

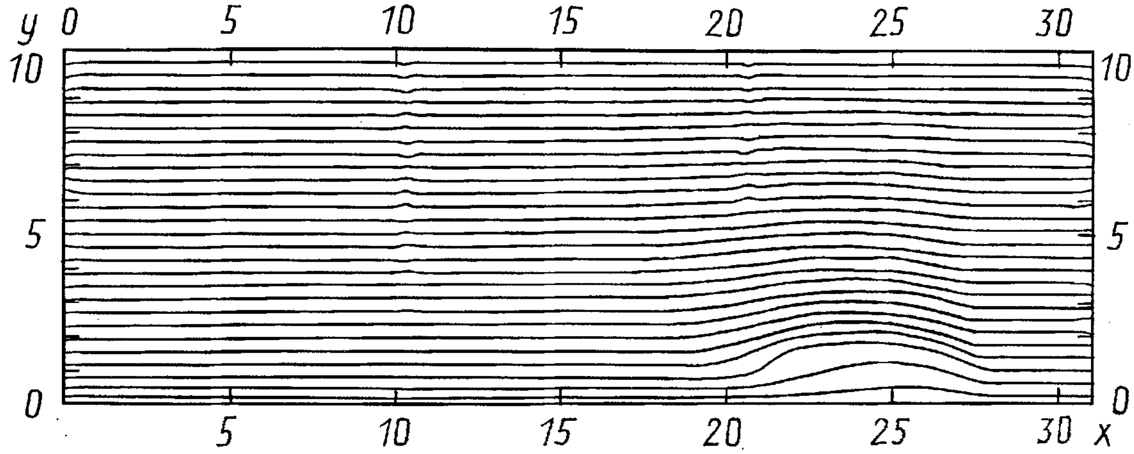
$$\max_{V'} \left(P' + \frac{H'^2}{8\pi} \right) > \left(P_1 + \frac{H_0^2}{8\pi} \right). \tag{2}$$

Designating in (1) ρ', P', and H' through V' and finding a maximum (2) it is possible to draw a line separating the regions of possible and impossible steady flow (with no regard to instabilities) on a plane (M, ω). Figure 1 shows this boundary at no magnetic field (curve 1) and for $\beta_0 = \beta_0' = 2/\gamma$, $\gamma = 5/3$ (curve 2). The first line is Taganov-Hess' criterion [1, 2]. The regions above the curves correspond to steady flow. Note that curve 2 has two branches; there appears a new stability region beneath the upper branch, where, in order that formula (2) be satisfied, the current pipe must shrink, the pipe plasma must be accelerated, and the magnetic pressure must be predominant. In the upper region the plasma decelerates, the pipe expands, and the thermal motion prevails.

To find the unsteady flow structure we have made a set of calculations. McCormack's second-order smoothing circuit [8] has been used.

Modeling has shown that in ideal MHD the unsteady interaction is not obligatorily accompanied by flow separation, contrary to gasdynamics. Over some range of the Mach numbers and layer densities SW simply "rakes up" the "heated-layer" substance with no formation of a large-scale similarity vortex structure. Such a regime (in an ordinary gas) was proposed by Hess [1] for the first time but it proved to be unstable. A magnetic field can prevent separation. This is shown in Figs. 2 and 3, displaying the magnetic force lines and the density isolines for flow with M = 2, $\omega = 0.75$, $\beta_0 = 6/5$ for a time moment when SW has passed 60 thicknesses of the "heated layer" along it. The coordinate x is reckoned from the position of the piston generating SW.

Similarity flow is exemplified in Figs. 4 and 5 for M = 4, $\omega = 0.4$, $\beta_0 = 6/5$. The flow pattern is similar to the one observed in gasdynamics [3] but the magnetic forces (approximately twice) decrease the rate of growth of the precursor and increase the time of establishing the similarity regime. This increases the necessary computational time, if we want to study the similarity phase, and requires a careful choice of the network. A transition from the initial time of establishing a similarity regime to a similarity phase is not accompanied by a sharp flow pattern change; therefore, it may be followed only through the rate of growth of the precursor: it becomes constant.



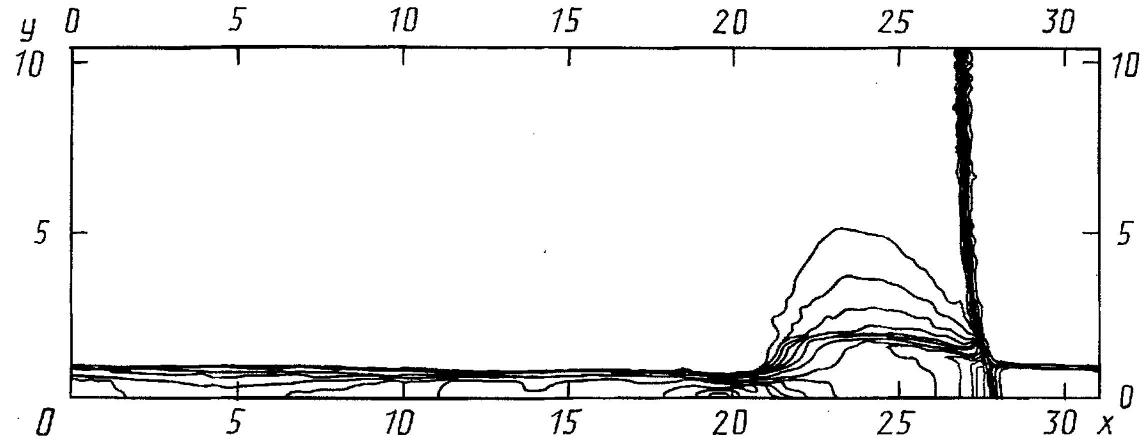


Fig. 2. Magnetic force lines for flow with M = 2, $\omega = 0.75$, $\beta_0 = 6/5$.

Fig. 3. Density isolines for flow with M = 2, $\omega = 0.75$, $\beta_0 = 6/5$.

Since of most interest is the similarity interaction, it is significant to estimate the interaction boundary. Physically, a reasonable estimate can be obtained if account is taken of the fact that a magnetic field in the considered geometry hinders the formation of a vortex structure characteristic of the similarity precursor. The condition of the existence of the similarity precursor is

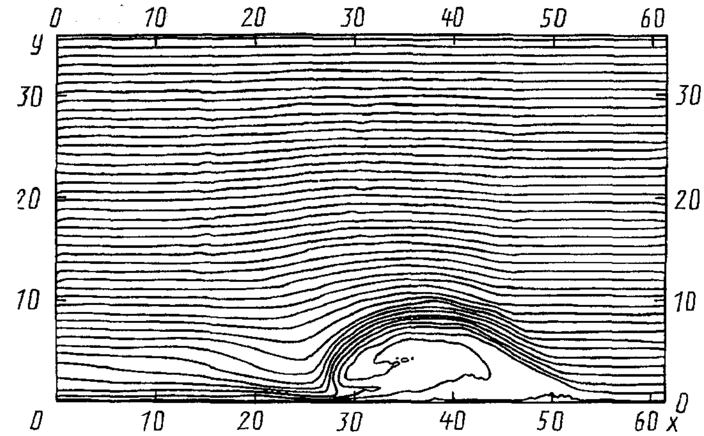
$$P'_{st} < \left(P_1 - \xi \frac{H_0}{4\pi} \right), \tag{3}$$

where P'_{st} is the "heated-layer" plasma deceleration pressure in a system connected with the SW front; ξ the matching parameter, equal to unity to a first approximation. We have taken the tension of the magnetic force lines at the initial moment as the characteristic force scale from the field side. This estimate for $\beta_0 = \beta'_0 = 2/\gamma$ and $\gamma = 5/3$ is plotted in Fig. 1 (curve 3); condition (3) is valid for the points beneath the curve. Calculations of the variants with M and ω close to this boundary suggest that the parameters ξ must be somewhat smaller than unity; however, a more exact determination of ξ is made difficult by the fact that in the vicinity of critical conditions the time of establishing a similarity phase is somewhat delayed, so that SW can pass through the entire design domain. At $H_0 \to 0$ estimate (3) smoothly changes to Taganov-Hess' criterion.

In nature there exists a class of objects having the "heated-layer" properties as understood in the present article. A geomagnetic tail and structures similar to it near other heavenly bodies represent very elongated channels with very low-density plasma. For a cross section of $\simeq 40R_E$ in the Northern-Southern and of $\simeq 60R_E$ in the morning-evening directions the geomagnetic tail is up to $1000R_E$ in length [9].

Shock waves in the solar wind generated by solar activity pass near the Earth several dozen times a year and can have a Mach number (more than 10) calculated in terms of a fast sonic velocity [10-12].

The structure of the remote geomagnetic tail is complex and is not clear to the end. But in modern concepts



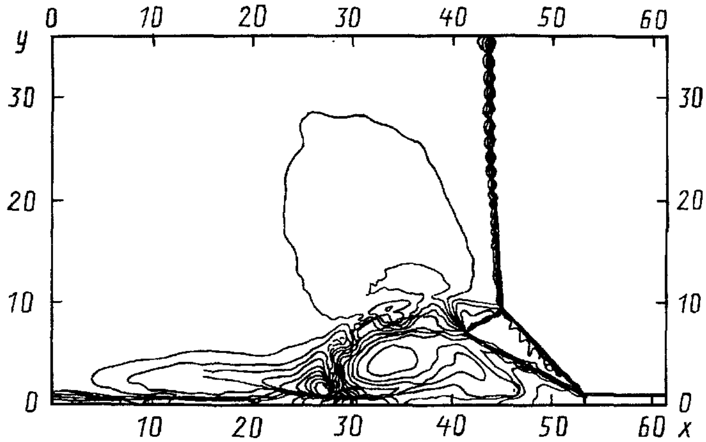


Fig.4. Magnetic force lines for flow with M = 4, $\omega = 0.4$, $\beta_0 = 6/5$.

Fig.5. Density isolines for flow with M = 4, $\omega = 0.4$, $\beta_0 = 6/5$.

three main regions inside a tail can be distinguished: portions of the tail, plasma layer, and a mantle. According to satellite measurements [3], the magnetic field intensity on the tail portions is about 9γ, and the density is ~0.1 cm^{-3}, which is two orders less than the characteristic density values in the solar wind around the magnetosphere. In a plasma layer about $10R_E$ thick, the densities are somewhat higher: 0.2-0.3 cm^{-3}, for plasma $\beta > 1$. The problem on the shape and parameters of the mantle: the layer surrounding the tail portions and serving as a transition region between them and the ambient plasma of the solar wind is most intricate. Following [4], the external boundary is a tangential disruption except for two "windows," one on each portion, where the boundary represents a rotational disruption followed by a sheaf of slow rarefaction waves smoothly bringing the parameters of the solar wind plasma passed through the rotational disruption up to the values characteristic of the tail portions. Thus, the mantle thickness constantly increases as the mantle moves to great distances from the Earth unless it overlaps the entire tail cross section. This complicates the form of the tail cross section. These effects cannot be ignored even for strong interplanetary shock waves, since the solar plasma outflowing through the "windows" changes the tail density distribution, thereby cardially influencing SW propagation.

Despite the complex structure of the geomagnetic tail, many results are qualitatively applicable for it. In particular, if the Mach number (calculated in terms of a high sonic velocity) for interplanetary SWs is greater than ~3, it may be expected that a large-scale vortex structure can develop near the front. For smaller Mach numbers there may appear unsteady interaction similar to the "raking one" considered above. The tail plasma will build up in some cavity bounded by the magnetic force lines in the SW front region and will be squeezed out of the tail like toothpaste from a tube. Superficially, this resembles the formation and motion of a plasmoid during the exposive phase of a substorm but with different physical mechanisms. Possibly, these processes can impose on one another for weak SWs.

Elevated dissipation of a magnetic field in the plasma layer must also introduce some corrections for this picture; however, since the characteristic times of recombination processes are dozens of minutes and SW covers a distance equal to the tail diameter with a velocity of 1000 km/sec approximately for 5 min, at least, for strong SWs the dissipation may be neglected to study processes near the front.

Changes in the geomagnetic tail when passing the interplanetary shock waves are a very interesting problem, and we shall apparently continue these studies.

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REFERENCES

1. R. G. Shreffer and R. H. Christian, J. Appl. Phys., **25**, No. 2, 324-331 (1954).
2. K. E. Gubkin, Mechanics in the USSR for 50 years [in Russian], Vol. 2, Moscow (1970), pp. 289-311.
3. V. I. Artemiev, I. V. Nemchinov, et al., Mathematical Modeling [in Russian], **1**, No. 8, 1-11 (1989).
4. V. I. Artemiev, I. E. Markovich, I. V. Nemchinov, and V. A. Sulyaev, Dokl. AN SSSR, **32**, No. 4, 245-246 (1987).
5. H. Mirels, Proc. 16th Intern. Symp. on Shock Tubes and Waves, VCH, Weinheim, N.Y. (1988), pp. 177-183.
6. P. E. Aleksandrov and I. V. Nemchinov, Inzh.-Fiz. Zh., **62**, No. 3, 380-385 (1992).
7. L. D. Landau and E. M. Lifshits, Continuum Electrodynamics [in Russian], Moscow (1975).
8. V. P. Golovizhin, A. I. Zhmakin, and A. A. Fursenko, Zh. Vychslit. Mat. Mat. Fiz., **22**, No. 2, 484-488 (1982).
9. S. Chapman and S.-I. Akasofu, Solar-Earth Physics [Russian translation], Vol. 2, Moscow (1975).
10. E. J. Smith et al., "Shocks and storm sudden commencements," in: Solar Wind-Magnetosphere Coupling, ed. by Y. Kamide and J. A. Slavin, Tokyo, TERRAPUB (1986), pp. 345-365.
11. M. Drayer, J. R. Smith, S. T. Wu, et al., "MHD simulation of the "geoeffectiveness" of interplanetary disturbances," in: Solar Wind-Magnetosphere Coupling, ed. by Y. Kamide and J. A. Slavin, Tokyo TERRAPUB (1986), pp. 191-207.
12. Y. C. Whang and L. F. Buriaga, J. Geophys. Res., **90**, A A11, 10765-10778 (1985).
13. J. A. Slavin, E. J. Smith, D. G. Sibeck, et al., J. Geophys. Res., **90**, No. A11, 10875-10895 (1985).
14. D. G. Sibeck, S. J. Bame, J. A. Slavin, et al., J. Geophys. Res., **90**, No. A10, 9561 (1985).