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Formation of surge prominences in the solar atmosphere. II. Two-dimensional hydromagnetic numeric experiments

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1. Introduction

We proposed in a previous paper (Dermendjiev et al., 1985) a one-dimensional non-stationary hydromagnetic model of surge prominences. The investigation of this model has shown that it reproduces satisfactorily the main dynamic characteristics of the surge (time and space scales and velocity) only in the case when we set as a boundary condition a quick and at the same time short-lived increase of the magnetic field in the lower chromosphere. This requirement is quite indicative and in our opinion the essence of the physical mechanism of the surge formation lies in it.

The present paper is a continuation of the above-mentioned article and it concerns the problem of the growth of magnetic energy in the solar photosphere and chromosphere in relation to the problem of surge formation. We discuss in Section 2 some observational and theoretical aspects, throwing new light upon the physical mechanism of surge formation. The hydromagnetic model is presented and discussed in Section 3. The result from the numerical simulations are given in Section 4. They show that the nonlinear process of interaction between the compressible conductive media, as is the solar photospheric plasma, and the magnetic field penetrating in it, is accompanied by the formation of a self-maintained relatively denser and hotter layer, which arises as a consequence of the predominantly Joule heating. On the basis of these results we conclude in Section 5 that a unifying element exists in the magnetic and thermal mechanisms of surge formation proposed by different authors.

2. Observational and theoretical considerations

A detailed description of the morphological and dynamical characteristics of the surge prominences, as well as of the surge formation mechanisms was presented in our previous paper (Dermendjiev et al., 1985). Here we shall refer only to some observational and theoretical results, which directly or indirectly concern the problem of surge formation.

The observations show that almost the entire magnetic flux passing through the solar photosphere is located in discrete elements with magnetic field intensity ranging from 0,3 T in sunspots to no less than 0,1 T in facular and network elements. These discrete elements possess very similar properties, independent of their being in active or quiet regions. A detailed survey of the small-scale solar magnetic fields is done by Stenflo (1976) and Zwaan (1978).

The amplification of the magnetic field takes place mainly beneath the solar surface and the lifetime of the smallest flux elements is very short. A great part of the magnetic flux in the quiet regions comes directly from the subphotospheric layers and it is not a result of the turbulent diffusion of the magnetic fields in the active regions. The corresponding magnetic elements occupy only a small part of the solar surface and their dimensions in the quiet regions are usually less than $2,10^5$ m. The photometric features connected with the magnetic elements, the so called bright points, have the same or larger dimensions. The large concentration of bright points (BP) in the active regions forms the picture of the so called filigree structure registered for the first time by Dunn and Zirker (1973) on H-alpha filtergrams.

The lifetime of the concentrated magnetic flux and BP depends on their dimensions. According to Mehltretter (1974) the lifetime of the facular BP with size of $1,5.10^5$ m is from 5 to 15 min, while for structures which are an aggregate of BP and "micropores" it is from 10 to 30 min. On the basis of an extensive observational material Muller (1981) found that the lifetime of the photospheric BP varies from 12 to 35 min with a mean value of 25 min.

Quite recently Mein et al. (1984) found out that the BP of the filigree structures inside the active regions, observed in the wings of the H-alpha line, are associated with plasma jets in the chromosphere above the BP. The dynamical structure of these jets resembles the structure of larger features, such as surges. This result is not a surprise with respect to the connection of BP and chromospheric plasma jets. As early as a decade ago Roy (1973) drew attention to the fact, that the surges resemble clusters of very fine jets of chromosphere plasma, the lower end of each being connected with a chromosphere BP, i. e. the Ellerman bomb.

These observational results lead to the idea that the energy of the small-scale magnetic fields is transformed in some way into a thermal energy in the photospere and lower chromosphere and, as a result, a BP is generated and consequently a plasma jet above it which is moved by the thermal plasma pressure gradient. If one proceeds from such point of view, the dispute for the nature of the moving force of the surge—magnetic or thermal one, becomes pointless

The elementary magnetic fields seem to be constantly involved in a number of solar phenomena. However, here we will not examine the question of the formation of small-scale magnetic fields. We shall only note that they generate in these places of the photosphere network in the quiet regions and floccules of the active regions where descending streams of matter appear. For a discussion on this problem we refer to Stenflo's (1976) review paper.

Irrespective of how the small-scale magnetic fied is formed, its appearance in the photosphere is always accompanied by the formation of BP, or a cluster of BP, i. e. filigree structures. The lifetime of the magnetic elements, as well as of the photometric phenomena, depends on their dimensions, but on the average it is ~15 min. Evidently a process proceeds for a comparatively short time which by its physical nature is similar to the skin effect and the dissipative instability in the magnetic hydrodynamics.

The physical picture of the emergence of a small-scale magnetic field in the photosphere and the lower chromosphere is similar to the physical treatment examined by Tichonov et al. (1967), but differing in that here a magnetic flux penetrates in a plasma medium. Consequently, we could study such a process by means of a one-dimensional hydromagnetic model. The process of interaction between the penetrating magnetic field and the plasma medium is, however, highly non-linear. Besides, as the advancement of computational physics has shown, the vector and topological properties of the magnetic field are essential for the process proceeding. We have, therefore, developed a two-dimensional hydromagnetic model.

In previous papers (Dermendjiev, 1983; Dermendjiev, Zahariev, 1985) we studied by means of two-dimensional hydromagnetic computer simulations the process of the magnetic energy increase in a homogenous hydrogen plasma medium. The results obtained unambigiously show that a relatively denser and hotter layer forms directly above the lower boundary where the magnetic puls is applied. Those results do not, however, give complete idea of the process of formation of this layer, because of the short duration of these simulations, and they do not allow us to draw the conclusion to what extent the point of view for the mechanism of surge fomation here maintained might be accepted or rejected. We shall try to answer these questions in the next Section.

3. Two-dimensional hydromagnetic model

The model in cartesian coordinates describes a magnetic arch system, supposed to exist in the solar photosphere, linearly growing with time. Its magnetic flux perturbations simulates the emergence of a magnetic flux through the photosphere. Due to the symmetry, only the right-hand part of the magnetic arch is considered, which is expressed by equation (1):

$$\begin{aligned} B_x &= B_0 \cos\left(\frac{\pi}{2}\frac{x}{L_0}\right)\left(1+\frac{1}{B_0}\frac{dB}{dt}t\right), \\ B_z &= -B_0 \sin\left(\frac{\pi}{2}\frac{x}{L_0}\right)\left(1+\frac{1}{B_0}\frac{dB}{dt}t\right), \\ t &= 0,\ 1,\ 2,\ \ldots,\ \tau, \end{aligned} \tag{1}$$

where L_0 is the size of the region of interest, B_0 is the initial value of magnetic induction, $\frac{dB}{dt}$ is the growth of the magnetic field and τ is the duration of the magnetic pulse.

We describe the behaviour of the plasma medium of the photosphere and the lower chromosphere during the pertubation of the magnetic flux by the equations of two-dimensional magneto-hydrodynamics of compressible media (2-8), obtained by making the following assumptions: 1) The investigated medium is a completely ionized hydrogen plasma; 2) Joule heating is limited to the electrons only; 3) Viscosity, and radiation are neglected; 4) The transport coefficients are isotropic, and 5) The thermodynamic properties of the medium are described by the equation of the ideal gas.

Taking into account these assumptions time dependent equations written in modified SI are as follows:

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x}(\rho U) - \frac{\partial}{\partial z}(\rho V), \tag{2}$$

$$\frac{\partial}{\partial t}(\rho U) = -\frac{\partial}{\partial x}(\rho U^2) - \frac{\partial P}{\partial x} - \frac{\partial}{\partial z}(\rho UV) - \frac{B_z}{\mu_0}\left(\frac{\partial B_z}{\partial x} - \frac{\partial B_x}{\partial z}\right), \tag{3}$$

$$\frac{\partial}{\partial t}(\rho V) = -\frac{\partial}{\partial z}(\rho V^2) - \frac{\partial P}{\partial z} - \frac{\partial}{\partial x}(\rho UV) - \frac{B_x}{\mu_0}\left(\frac{\partial B_x}{\partial_z} - \frac{\partial B_z}{\partial_x}\right) - \rho g_\odot, \tag{4}$$

$$\frac{\partial B_x}{\partial t} = \frac{\partial}{\partial z}\left[\tilde{\eta}\left(\frac{\partial Bx}{\partial z} - \frac{\partial Bz}{\partial x}\right)\right] - \frac{\partial}{\partial z}(B_x V - B_z U), \tag{5}$$

$$\frac{\partial B_z}{\partial t} = \frac{\partial}{\partial x}\left[\tilde{\eta}\left(\frac{\partial B_z}{\partial x} - \frac{\partial B_x}{\partial z}\right)\right] - \frac{\partial}{\partial x}(B_z U - B_x V), \tag{6}$$

$$\frac{\partial}{\partial t}(\rho T) = -(\gamma - 1)\rho T\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial z}\right) - \frac{\partial}{\partial x}(\rho TU) - \frac{\partial}{\partial z}(\rho TV)$$
$$+ \frac{\gamma - 1}{R}\left[\varkappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\tilde{\eta}}{\mu_0}\left(\frac{\partial B_x}{\partial z} - \frac{\partial B_z}{\partial x}\right)^2\right], \tag{7}$$

$$P = \rho RT, \tag{8}$$

where $\gamma = 5/3$ is the ratio of specific heats, $\tilde{\eta}$ is the magnetic eddy diffusivity, $\varkappa$ is the electron thermal conductivity, R is the gas constant and $g_\odot$ is the gravity on the surface of the Sun. The independent variables x and z coordinates are directed tangent and radially upward to the solar limb respectively. The dependent variables are the density ρ, gas pressure P, horizontal U and vertical V velocity, horizontal B_x and vertical B_z components of the magnetic field induction, and temperature T.

For the finite-difference approximation of the model (1-8) on an Euler network we used a two-step modification of the Lax-Wendroff finite difference scheme and a two-dimensional representation of the Dufort-Frankel finite difference scheme (Dermendjiev, Zahariev, 1985).

4. Results and discussion

We use the following scenario for the computer simulations. We arrange a two-dimensional 80×80 network, with a step $\Delta x = \Delta z = 10^4$m, in the solar atmosphere in such a way that the beginning of the network is situated at the bottom of the photosphere. The initial atmosphere is assumed to be motionless with temperature and density satisfying the empirical H. S. R. A. atmosphere (Gingerich et al., 1971). On its lower boundary we set magnetic field perturbations (1) which simulate the magnetic flux emergence.

The model allows the current component in y direction, therefore from the physical point of view it can be expected for skin layers to be formed in the plasma medium during the increase of magnetic field.

In order to have an idea of the process of magnetic flux emergence through the initial atmosphere, let us compute the values of some characteristic times and dimensionless parameters. According to the above described scenario, the initial atmosphere has a length scale $L_0 = 8.10^5$ m. Then for the density disturbances time scale $\tau_s = L_0/(\gamma P_0/\rho_0)^{1/2}$ we obtain $97 \lesssim \tau_s \lesssim 108$ s, and for the Alfvén wave disturbances time scale $\tau_A = L_0/(B_0^2/\mu_0\rho_0)^{1/2} = 106$ s in the case when a magnetic field $B_0 = 0{,}15$ T is applied. If we assume that the magnetic flux penetrates with a velocity $V_0 = 2.10^3$ m/s which is close to the turbulent velocity of the photospheric plasma, then we obtain for turnover time scale $\tau_t = L_0/V_0 = 400$ sec. Magnetic eddy diffusivity is $\tilde{\eta} = V_0 L_0 = 1{,}6.10^9$ and magnetic diffusion timescale $\tau_d = L_0^2/\tilde{\eta} = 400$ sec. From the physical point of view $\tau_t = \tau_d$ means that the process of penetration of the field is accompanied by a rapid dissipation.

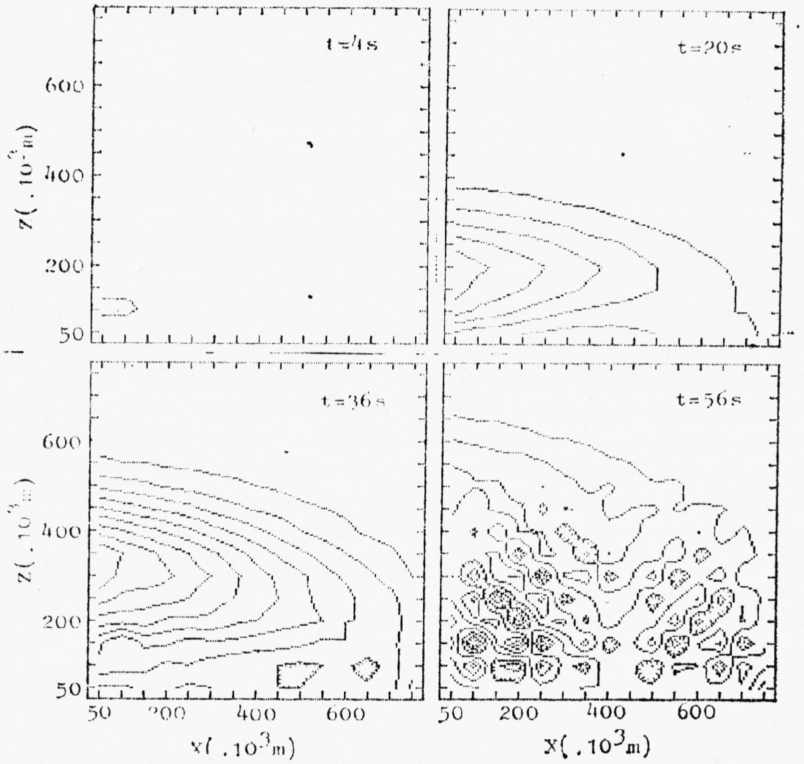

Fig. 1. Density profiles for four consecutive times: $t=4$ s (level of $\rho/\rho_0 = 1{,}025$ is presented), $t=20$ s (levels 1,05; 1,10; 1,15; 1,20; 1,25), $t=36$ s (levels 1,05; 1,10; 1,15; 1,20; 1,25; 1,30; 1,35; 1,40 1,45), $t=56$ s (levels 0,80; 1,00; 1,20; 1,40; 1,60; 1,80)

The plasma beta is $\beta = 2\mu_0 P_0/B_0^2 = 10^{-2}$, therefore the magnetic pressure at the lower boundary dominates the plasma pressure. For a collision-dominated model of hydrogen plasma at a temperature $T \sim 6000$ K we obtain coefficient of thermal conductivity $\varkappa = 1{,}8 . 10^{-10} T^{5/2}/\ln \Lambda = 5{,}02 . 10^{-2} [Wm^{-1} K^{-1}]$. This value is rather smaller than the value of magnetic eddy diffusivity. Even the magnetic diffusivity of the collision-dominated hydrogen plasma $\eta = 5{,}2 . 10^7 \ln \Lambda T^{-3/2} = 10^3 [\mathrm{m}^2\ \mathrm{s}^{-1}]$ has a bigger value than the value of the thermal conductivity. Therefore the magnetic field dominates and we cannot consider the thermal conductivity as a function of the temperature and the coordinates.

At the boundaries the independent variables, except for the magnetic field on the lower boundary, are engaged in calculations in such a way that the first-order extrapolation is satisfied, as recommended by Chu and Sereny (1974) for the one-dimensional numeric simulations. In our opinion such a setting of the boundary conditions in a two-dimensional hydromagnetic simulation is rather acceptable.

The process of magnetic field penetration depends on three parameters: B_0, $\frac{dB}{dt}$ and τ. Due to the short characteristic time of this process, in our case the parameter B_0 is crucial. For it the magnetographic observations (Stenflo, 1976) give values ranging from 0.1 to 0.2 tesla. We set a value of $B_0=0,15$ T. For the growth of the magnetic field we give $\frac{dB}{dt}=10^{-3}$ T/s which means that in ~100 sec the magnetic pulse would be doubled. As we shall see below, however, during the skinning time the boundary magnetic pulse does not increase substantially. The perturbations are continuously maintained throughout the computer simulation.

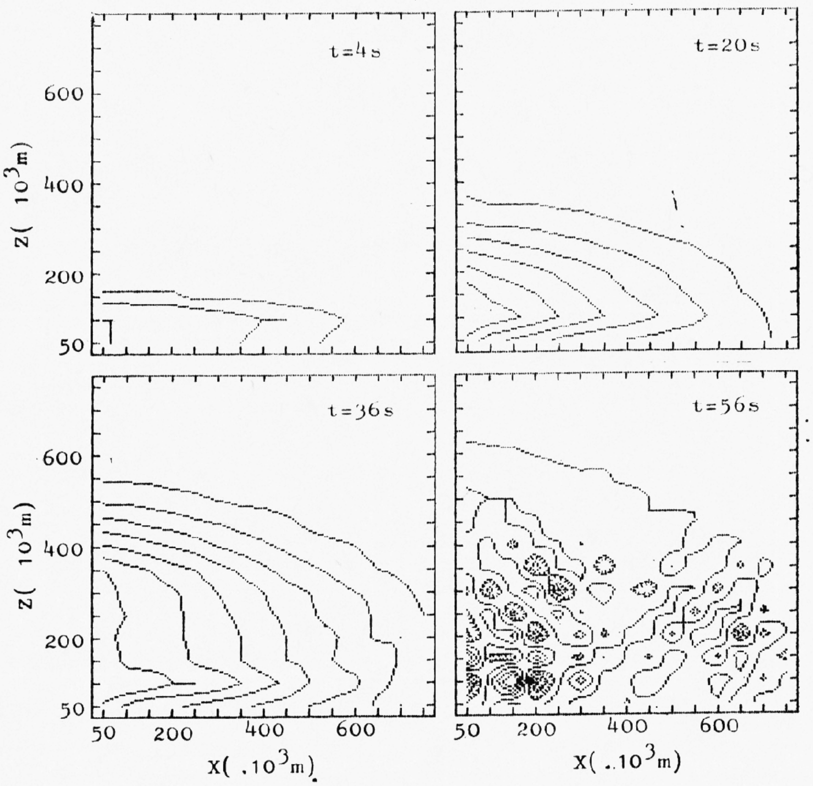

Fig. 2. Temperature profiles for four consecutive times: $t=4$ s (levels of $T/T_0=1{,}025$; 1,05; 1,10 are presented), $t=20$ s (levels 1,05; 1,10; 1,15; 1,20; 1,25; 1,30), $t=36$ s (levels 1,05; 1,10; 1,15; 1,20; 1,25; 1,30; 1,35), $t=56$ s (levels 0,80; 1,00; 1,20; 1,40; 1,60; 1,80; 2,00)

The problem of displaying the output values is very difficult. The complete set of physical parameter profiles for each time step is an excessively large body of data. Therefore we have selected four consecutive sets for the temperature and density profiles (Fig. 1 and Fig. 2) and three consecutive sets of vectors of magnetic field and velocity field profiles (Fig. 3 and Fig. 4) to indicate the thermodynamic response of the solar photosphere and chromosphere and velocity and magnetic fields established by the emergence of the magnetic flux.

Due to the continuous presence of magnetic field gradient Joule dissipation increases and within 35 sec a relatively hotter ($T/T_0 \sim 1.2$) and denser ($\rho/\rho_0 \sim 1.25$) zone in the lower chromosphere is created (Fig. 1 and Fig. 2). It can be considered as an analogy of the so called T-layer (Tichonov et al., 1967). This hotter and denser zone gives a reasonable simulation of a chromospheric BP, the phenomenon notified as Ellerman bomb or moustache, because of the characteristic H-alpha emission profiles. Recently Kitai (1983) obtained from observational data that in the chromospheric layers of the moustache bright points a hotter ($\Delta T = 1500$) and denser ($\rho/\rho_0 = 3$) zone is formed in which the matter shows a movement, usually upward, with a velocity of a 6.10^3 m/sec. Our results are in accordance with Kitai's results if we consider the chromospheric layer at height $\sim 4.10^5$ m above the zero level and $t = 55$ sec (Figs 1, 2).

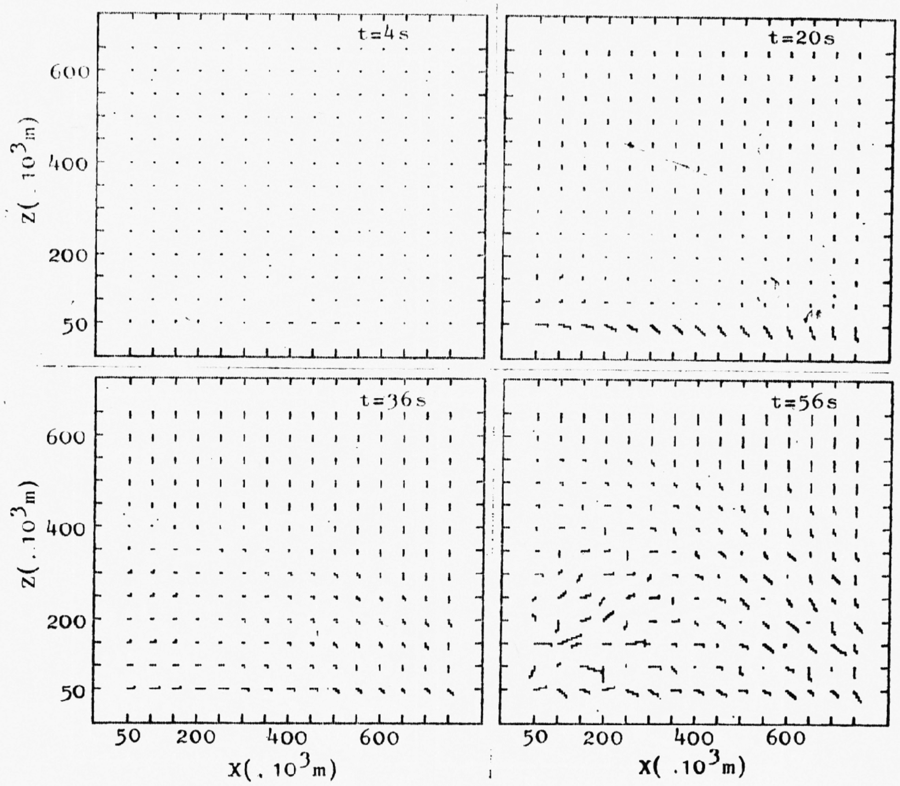

Fig. 3. Velocity field profiles for four consecutive times $t = 4$ s, 20s, 36 s, 56 s

As one can trace on Fig. 3, the plasma medium shows movement similar to the movement of the matter in a magnetic arch system with a velocity reaching to 2.10^4 m/sec. From the temperature and density profiles, however, one can see that the hotter and denser zone as a whole expands with a velocity of 7.10^3 m/sec , in good agreement with the observational data.

The magnetic field (Fig. 4) deforms strongly during the skining process. The gradients increase and this coincides in time and place with the formation of the hotter and denser zone. After 45 s an overheating instability developes with a characteristic time 4 s and as a result a shock wave is formed. The steep gradients of the temperature and density on the respective profiles give us a reason to make such a conclusion. Unfortunately the numerical method used by us does not give a possibility to trace the development of this instability. It is not difficult, however, to realise its consequences, i. e. the dynamical response of the upper chromosphere and the corona.

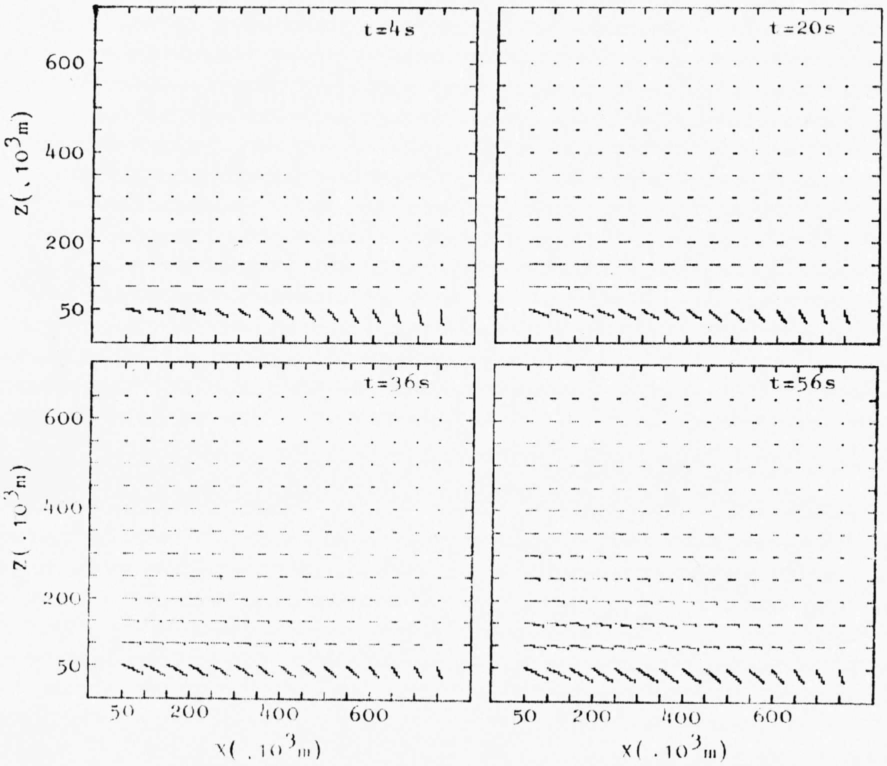

Fig. 4. Magnetic field profiles for four consecutive times t=4 s, 20s, 36 s, 56 s

Nakagawa et al. (1975) have shown by means of hydrodynamic simulation that the surge-like phenomenon in the solar corona forms when a short-lasting temperature pulse ($\Delta T=1,25T_0$; $\tau=5$ min) is applied. Later, Steinolfson et al. (1979) have shown that surge-like plasma jets from the upper chromosphere form when a thermal pressure pulse (P/P_0) ranges from 5 to 20. The authors suppose that such a pulse can arise during a small flare event.

In our simulations for the bright point zone in the lower chromosphere we obtain $T=1,6\ T_0$ and $P/P_0\sim 4$. Therefore, it is possible for the created temperature gradient to be a moving force of chromospheric jet which in its movement along the lines of force of a preexisting large-scale magnetic field resembles a jet of a surge prominence or of a surging arch.

5. Conclusions

The results obtained throw a new light on the problem of surge formation. A new interpretation of the mechanism of surge formation is possible, taking into account the equal importance of the magnetic and hydrodynamic processes and their consecution. The results do not contradict the commonly accepted opinion that the fast changes in the magnetic structures provide the energy needed for chromospheric plasma jets. They also present an opportunity to make some important conclusions concerning the question how this energy is supplied.

We idealize the picture of the fast changes in the magnetic field and guided from some recent observational results we reduce it to the picture of short time-scale emergence of small-scale magnetic flux through the photosphere.

The process of penetration of the magnetic flux in the photosphere and lower chromosphere we examine by means of relatively simple two-dimensional hydromagnetic model in which the radiation and viscosity are neglected.

The result obtained shows that following Sokolov et al. (1978) it is possible to divide this process into two physical processes with different characteristic time: relatively slow formation of the skin layer in chromosphere plasma and fast development of overheating instability.

During the time of the skinning phase, the magnetic energy is efficiently transformed into Joule heat in the zones with large magnetic field gradients. At the time of overheating instability the jet-like surge is created which can be treated simply as a hydrodynamic phenomenon, because the plasma moves along the force line of a preexisting large-scale magnetic field.

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Образование возвратных выбросов в солнечной атмосфере. II. Двухмерные гидромагнитные численные эксперименты

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(Резюме)

Построена нестационарная двумерная гидромагнитная модель всплывания маломасштабного магнитного поля в солнечной фотосфере и нижней хромосфере. В рассматриваемой модели учитываются эффекты теплопроводности, силы тяжести и Джоулевой диссипации, а вязкость и излучение пренебрегаются. Численные эксперименты, проводимые на ЭВМ, показывают, что процесс всплывания протекает в двух фазах: 1) относительно медленное формирование горячего и плотного скин-слоя и 2) последующее быстрое развитие тепловой неустойчивости. Обсуждается возможность о новой физической интерпретации процесса формирования возвратных выбросов.

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