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Formation of Surge Prominences in the Solar Atmosphere*

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I. One-Dimensional Hydro-Magnetic Numeric Experiments

I. Introduction

The surge prominences are short-living solar fenomena during which large quantities of plasma from the lower layers of the solar atmosphere are ejected into the corona with a velocity which may reach values of several hundred kilometers per second (Newton, 1942; Ellison, 1949; Giovanelli and McCabe, 1958; Gopasyuk, 1963). A ballistic maintenance by dynamic effects is characteristic for them (Zirin, 1978). After reaching the maximum height, they fall back into the chromosphere, usually along the same trajectory by which they rose. Unlike the spray, the surge my be roughly defined as a well-collimated ejection along the magnetic field force lines of the active regions from the place where a prominence is not originally present (Zirin, 1978).

The surge prominences are associated genetically with the solar flares. It is usually assumed that the fast changes of the magnetic structures provide the energy necessary for the ejection of plasma. As a result of such changes part of the local magnetic field assumes an open configuration which facilitates the ejection.

In this paper we have studied with the aid of numeric simulations one possible mechanism for surge formation, which is similar to the plasma "raking-up" mechanism. With the aid of this mechanism the energy of a magnetic field with dipole configuration is transformed within a very short time directly into the kinetic energy of the surge. In Section II we outline the observational and theoretical aspects of surge formation. Section III contains the hydromagnetic model, while the results and their discussion are provided in Section IV.

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* In this article is used the unit of measurement $1 Å = 10^{-10}$ m.

II. Observational and Theoretical Considerations

It is considered at present that surge formation is closely related to the structure and dynamics of the local solar magnetic fields. This conclusion follows mainly from the observation data where, as a rule, the surges are observed in the active regions (see: Tandberg-Hanssen, 1974) and their movements are along the magnetic force lines (Smith, 1964; Rompolt, 1965).

Many efforts have been made to clarify the physical aspects of this phenomenon, associated with its dynamics and location. Koval (1965) comes to the conclusion that surges are formed in close vicinity to sunspots as a result of changes (mainly increase) of the magnetic field during the phase of sunspot groups growing; if the surge is formed outside a sunspot group then small spots, pores or flocculs occur in the place where the surge has been ejected, i. e in a sense the surge precedes the development of regions with strong magnetic field.

The comparison of high-resolution on- and off-band H_α filtergrams of disk solar surges and magnetic data (Roy, 1973 a) shows that the surges constitute clusters of very fine jets. They are formed in regions of evolving magnetic features with dimensions of about 10^4 km and significant changes of the magnetic flux over a period of less than one day. Probably the surge-formation mechanism is closely associated with the mechanism of raising magnetic flux with one polarity in a region with already existing magnetic flux with opposite polarity. Besides, the surge trajectories outline the magnetic force lines of the dominant local magnetic field, calculated with a current-free approximation.

Platov (1973) divided the evolution of surge prominences into two stages: direct formation and acceleration, and material movement along the force lines, as a mechanism responsible for the surge formation regulating the plasma motion only during the first stage. During this stage a considerable line-broadening in the surge spectrum is observed, which is determined by non-thermal motions — probably plasma compression in the sight line direction (transverse to the surge axis). Such process of longitudinal acceleration and simultaneously transverse compression is possible, since the local magnetic field of the surge plasma increases.

According to Roy (1973 b), the surge behaviour, studied from the curves velocity-height, is described quite well by the mechanism of diamagnetic ejection. However, the deceleration of the outward-moving plasma, which takes place after the maximum velocity has been reached, is stronger than when gravity alone is acting. Besides, during the return stage, the acceleration toward the solar surface is less than free-fall. Roy comes to the conclusion that non-force-free effects in the surge supporting magnetic field could explain the braking.

The problem of surge location and origin has been studied a lot during the last twenty years and the physical description has been continuously improved. According to Gopasyuk et. al. (1968) and Gopasyuk and Ogir (1963), surges are ejected from the penumbra or even the umbra of spots. Later, Rust (1968) showed that the so-called satellit spots, which lie on the boundary between the penumbra of the spots and the undisterbed photosphere and have polarity opposite to that of the surrounding dominant magnetic field, are the places from which surges are ejected. On the basis of high-resolution observations, Roy (1973) further detailed the picture and brought attention to the thin structure of the surge prominences. It came out that the surge is actually a cluster of fine dark (sometimes bright) jets, each connected at its lower end to an Ellerman bomb brightening; if the magnitographic observations indicate the existence of a satellite spot, then these brightenings overlie it.

A theoretical model of the surges must provide a mechanism which could accelerate a plasma volume with macroscopic dimensions and high electric conductivity to considerable velocities in a short time. Historically, the first was the diamagnetic ejection, proposed by Schluter (1957). Later, Sweet (1958) studied the possibility of plasma acceleration by rapid reconnection (i. e. diffusion) of a magnetic field, while Altschuler et. al (1968 a; 1968 b) investigated it during relaxation of the magnetic field generated by two antiparallel coaxial current loops. Platov et al. (1973) studied surge formation as a result of plasma raking-up, associated with the growth of a dipolar local magnetic field. Recently, Carlqvist (1979) proposed a mechanism of surge-formation based on current disruption in the filamentary current.

The basic assumption in all of the above-mentioned mechanisms is that the surge kinetic energy is supplied by releasing the energy of suitably selected magnetic field. However, there is another possibility.

The close association between surges and flares during which large quantities of termal energy is released indicates that the reason for surge formation could be gas-dynamic. During the last few years a number of studies have been published investigating that possibility. McClymont (1978) proposed a simple projectile model in which the ejection is assumed to have been caused by the adiabatic expansion of impulsively heated layer of the chromosphere. Recently, Steinlfson et al. (1979) and Dermendjiev (1981) numerically simulated the surge formation during a sudden gas-dynamic impulse.

Among the above-mentioned mechanisms there is not a single one to be generally accepted. There are a number of arguments against the possibility of each one of them. The diamagnetic ejection, for example, does not provide any explanation for the observed subsequent practically free fall of plasma along the same trajectory — it could only "ooze" down slowly, due to gravity. The reconnection of magnetic force lines, on the other hand, has a tendency to demolish the initial magnetic field configuration, while observations indicate that surges are often repeated in the same place. Besides, since surges are a relatively common phenomenon, it is not likely that the presurge magnetic configurations are very complicated or require unusual initial conditions. The main deficiency of the Altschuler et. al.'s mechanism is the assumed downward motion of a large quantity of coronal plasma, which is significantly greater than the surge plasma (Kiepenheuer, 1968; Platov et al., 1973). In the Platov et al. 's mechanism, the phase of surge falling is not studied, while the main deficiency of the simple projectile model is that the obtained surge temperature is greater than the observed when the chromospheric layers are heathed enough, in order to move the surge to realistic heights.

The numerical experiments, which are an important link between theory and observations, allow to simulate surge dynamics, in particular their thermodynamic properties, the time scales, the physical dimensions and surge mass and energy. The results of such simulations are in general in good agreement with that from observations, but such simulations do not take into account the effect of the magnetic field.

Briefly, the general surge characteristics are as follows (Tandberg-Hanssen, 1974): the maximum height attained by surges ranges from 2×10^4 to 10^5 km, where for most of them it is less than 5×10^4 km. They last from 2 min. to 2.5 hours, with a mean lifetime of approximately 25 min. Surge velocities vary from 100 to 200 km $\sec^{-1}$.

III. A Hydromagnetic Model

The physical considerations on which the model is based have been discussed in detail in an earlier paper by one of the authors (Dermendjiev, 1982). Briefly, the idea is as follows:

We assume magnetic flux variations as a result of emerging time-variable magnetic dipoles. In the one-dimensional case, where we are interested in the magnetic field behaviour only at the top of the dipole loop, the magnetic field perturbations are the following:

$$(1)\qquad \begin{aligned} B_x &= B_0\left(1+\frac{\mathrm{d}B}{\mathrm{d}t}\,t\right), \\ B_y &= 0, \end{aligned}$$

where B_0 is the initial value of the magnetic field at the base; $\frac{\mathrm{d}B}{\mathrm{d}t}$ is the increase ot the magnetic field; B_x and B_y are the horizontal and vertical components of the magnetic field, respectively. The movement of chromospheric plasma in the field of such developing dipole will simulate a surge jet.

As a first approximation, this motion could be described with the equations of the one-dimensional magnetohydrodynamics of compressible fluid, where the dissipation process and radiation have been neglected

$$(2)\qquad \begin{aligned} &\frac{\partial\rho}{\partial t} = -\frac{\partial(\rho V)}{\partial y}, \\ &\frac{\partial}{\partial t}(\rho V) = -\frac{\partial}{\partial y}\left(\rho V^2+P+\frac{B^2}{8\pi}\right)-\frac{\rho G M_\odot}{y^2}, \\ &\frac{\partial B}{\partial t} = -\frac{\partial}{\partial y}(VB), \\ &\frac{\partial P}{\partial t} = -V\frac{\partial P}{\partial y}-\gamma P\frac{\partial V}{\partial y}\,. \end{aligned}$$

Here the independent variables are the y coordinate, directed vertically upward from the solar limb and the time t. The dependent variables are the density ρ, gas pressure P, velocity V and the horizontal component of the magnetic field, which in (2) is indicated by B. G and $M_\odot$ are the gravity constant and the solar mass, respectively. We assume also that the thermodynamic properties of the media are described by the equation for an ideal one atom ($\gamma=5/3$) gas.

The similarity of (2) with the hydrodynamic equations for compressible media allows us to use a direct two-step finite difference conservative scheme method (Lax and Wendroff, 1960). We simulate a hydrostatical initial atmosphere, without a magnetic field, with a density and a pressure which satisfy the empirical model of the solar atmosphere (Allen, 1973).

In hydrodynamics and magnetohydrodynamics the improper definition of the boundary conditions of numerical experiments often leads to difficulties and errors. For this reason in our numerical experiments we observe the Chu and Sereny (1974) recommendations by using first order extrapolation for the variables which are not specified on the boundaries.

The system (2) is approximated on a network with nodes $1\leq j\leq 150$ space step $\Delta=350$ km and time step Δt, satisfying the Courant-Friedrichs-Lewy condition $\Delta t\leq\Delta/|V|+\left(\frac{\gamma P}{\rho}+\frac{B^2}{4\pi\rho}\right)^{1/2}$ for stable approximation at every node of the network. The network beginning is placed in the lower chromosphere where we simulate an impulsive increase of the magnetic field in a time interval τ.

IV. Results and Discussion

The emerging magnetic flux depends on three parameters: B_0, $\frac{dB}{dt}$, and τ. By specifying suitable values for these variables, it is possible to simulate respectively fast/slow emergence of strong/week magnetic flux. In our numerical experiments we specify combinations of the three parameters varying respectively B_0 from 0.2 to 10 gs, $\frac{dB}{dt}$ from $1 Gs/\text{min}$ to $10\ Gs/\text{min}$ and τ from 0.5 min to 5 min. The magnetic impulse is interrupted after τ haselapsed and the plasma behaviour is studied numerically within the region specified 20 more minutes.

The phenomenon simulated displays great variety — from phenomena similar to spiculs up to fast ejections. A phenomenon similar to a surge jet, in its physical characteristics as well as in its dynamics, is simulated with values

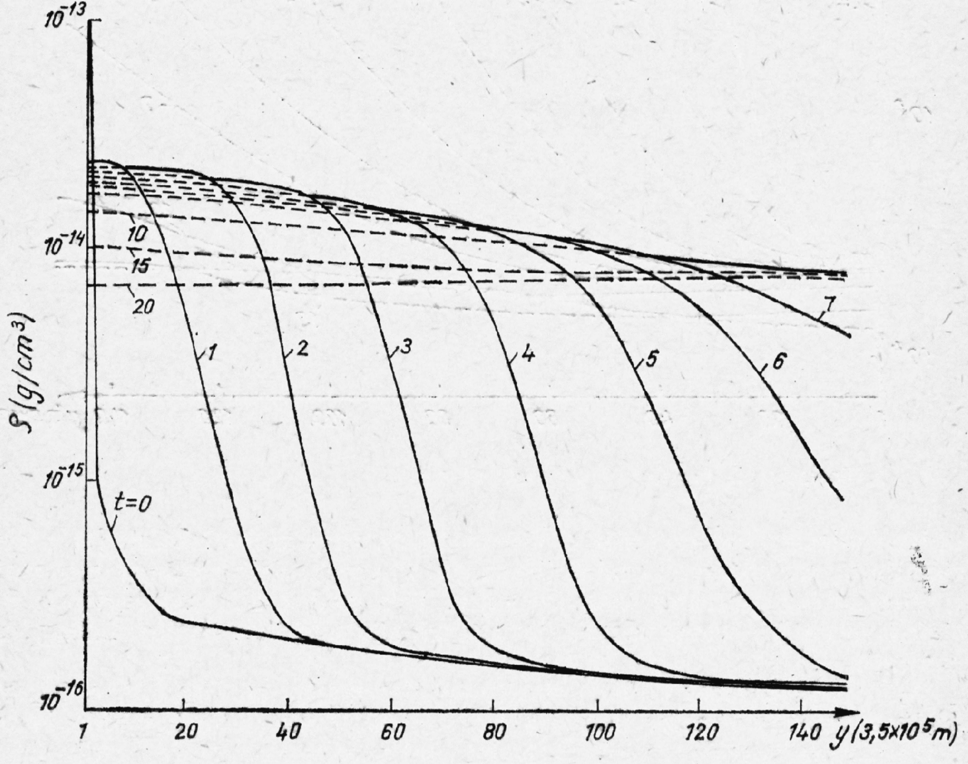

Fig. 1. Density profiles of a simulated surge

close to $B_0 = 4$ gs; $\frac{dB}{dt} = 1$ gs/min, and $\tau = 1$ min. The profiles of density, temperature, velocity and magnetic field, obtained during this simulation are shown on Figs 1, 2, 3 and 4 as functions of the height above the network base for ten values of t — from $t=0$ to $t=20$ min, at an interval of 1 min.

It is possible to trace how with the introduction of the pulse a radial flow of "dense" and "cold" plasma develops on Figs 1 and 2, where the density and temperature profiles are shown. The curves for $t=0$ illustrate the initial density profiles and the initial temperature. The steep gradient of these profiles indicates the presence of a weak shock wave at the leading jet edge. The main effects are observed behind the shock, where density is almost constant and the temperature increases insignificantly. This cold and dense region is the simulated surge jet, which moves upward initially and then begins falling back—downward.

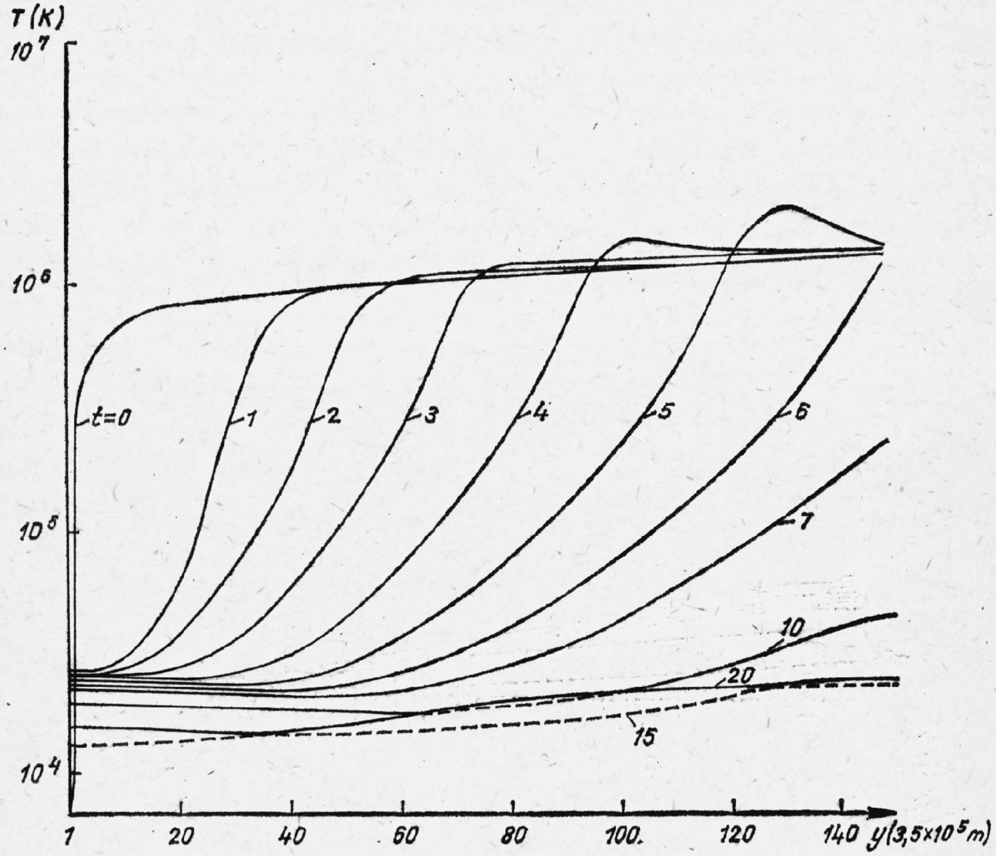

Fig. 2. Temperature profiles of a simulated surge

As it could be seen on the velocity profiles shown on Fig. 3, the jet reaches quickly a velocity greater than 100 km/sec. After the pulse has been interrupted, the plasma in the top part of the jet continues to accelerate, while the plasma in the lower part decelerates. After the tenth minute, the plasma in the lower part of the jet begins to fall, while after the 12th minute the velocity profiles become negative, i. e. the jet plasma is moving exclusively downward. Such movements correspond to the description provided by Newton (1942) and Roy (1973) of the surge motion.

The dynamic effects during the jet plasma fall in the denser layers of the chromosphere are not taken into account, since the lower and upper boundaries are assumed as free, i. e. we simulate an infinitely wide container which is open from both ends. The plasma can flow out freely through the lower and the upper ends.

The magnetic field profiles (Fig. 4) are similar to those of the densities for the corresponding times which is in agreement with the raking-up process.

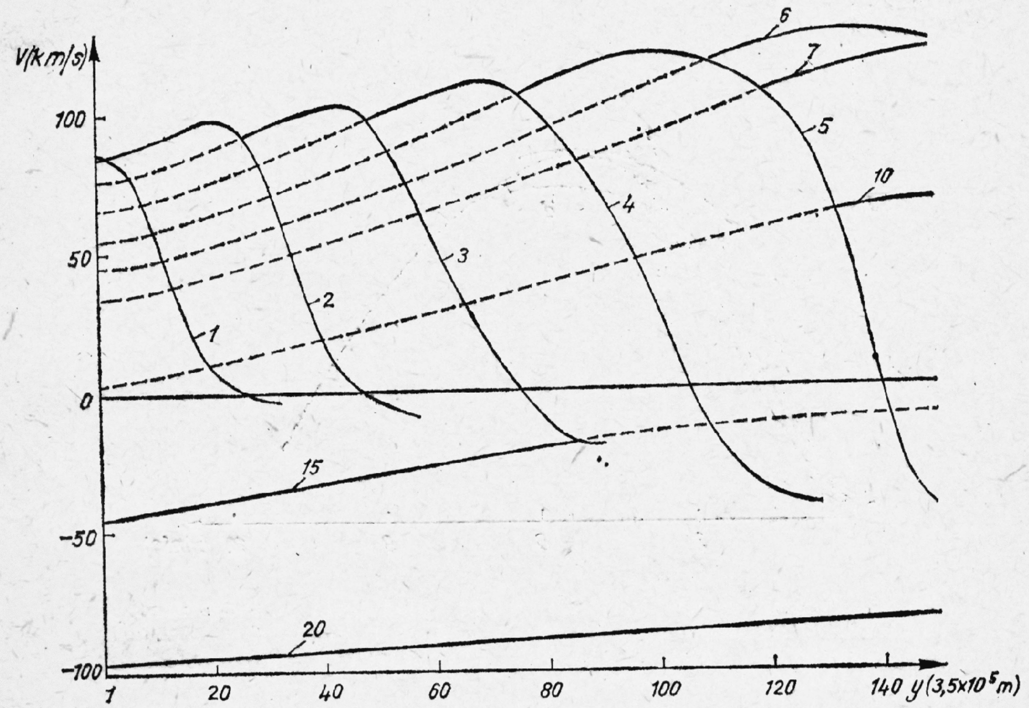

Fig. 3. Velocity profiles of a simulated surge

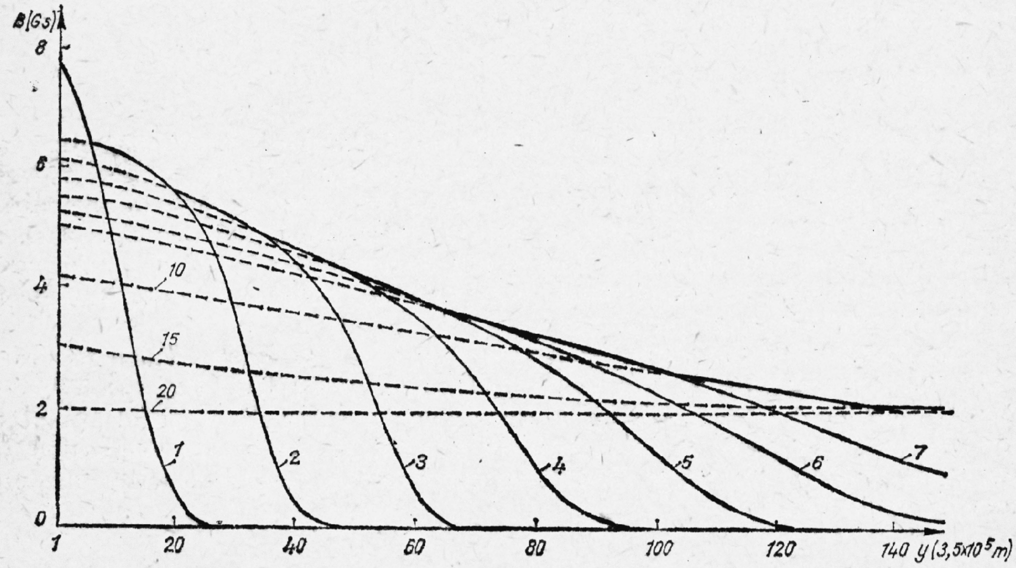

Fig. 4. Magnetic field profiles of a simulated surge

On Fig. 5, with dashed lines is shown the trajectory of 9 % density level defined with respect to the density of the chromospheric plasma when $j=1$. This trajectory shows the path of the leading upper edge of the jet as a function of time. On the same figure for comparison are shown the curves for the heights of the surge tops as a function of time, obtained by Roy (1973) by observations with a H_α filter sequence, respectively —2, —7/8, —5/8 and —1/4 Å.* As it could be seen, there is a very good agreement between our results and the observation data.

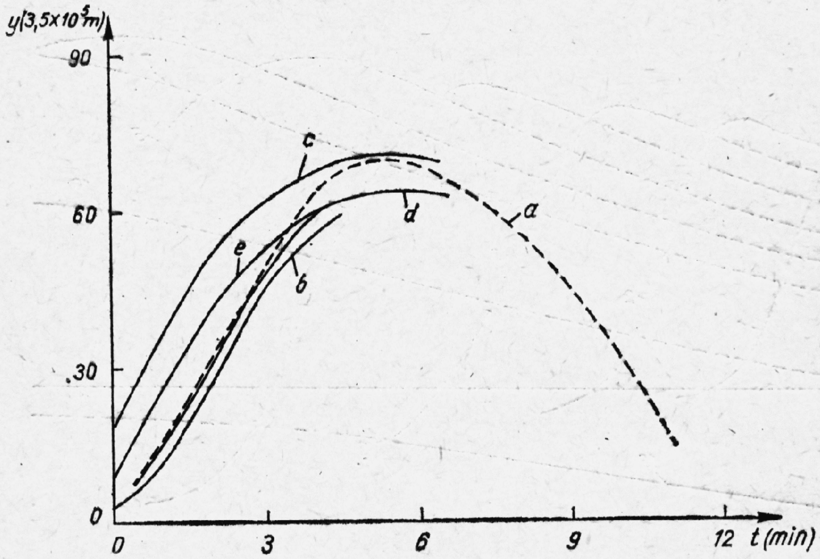

Fig. 5. Height versus time for (a) the fluid level at width density equal 9 % of the initial base density (b, c, d, e) of surge tops obtained from observations (Roy, 1973 b) with filter sequence —2 Å, —7/8 Å, —5/8 Å and —1/4 Å, respectively
$b \rightarrow -2$Å ; $c \rightarrow -7/8$ Å ; $d \rightarrow -5/8$ Å ; $e \rightarrow -1/4$Å

V. Conclusions

We have shown that the relatively simple one-dimensional hydromagnetic model could reproduce the main observed characteristics of the surge. A very good agreement with the observations is achieved, even though in the numeric simulation the dissipation process has not been taken into account, such as thermal condition and radiation. This study demonstrates also the ability of numeric experiments to supplement observations, aiming at determining the physics of separate solar phenomena.

The question of the surge energy source, i. e. the force which moves it within the solar corona, is still under discussion. Basically, the problem is whether this force is magnetic or thermodynamic. From theoretical point of view the magnetic force is an acceptable possibility. As it was emphasized in Section II, most of the surge formation mechanisms assume exactly the presence of such force.

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*1Å $=10^{-10}$ m.

Assuming magnetic pressure from an increasing with the time magnetic field as a possible motion force, we simulated numerically the dynamics of a chromospheric plasma jet in solar atmosphere. After the magnetic pressure pulse is interrupted, the plasma is left to fall free in the presence of the emerged magnetic field, which is slowly relaxed.

Our simulations show that the plasma raking-up process is fast, with relatively quick changes of the magnetic field which is in agreement with Platov et al. (1973) results. Besides, a necessary condition is that the action of the magnetic force is with short duration, i. e. $\tau \approx 1$ min. Only under these two conditions the simulated jet has surge dynamic characteristics.

When the magnetic field pulse is interrupted, we specify a new boundary condition, which "functions" as on open bottom of the container and the plasma falls freely, without the effect of the denser media in the chromosphere. As a result, such dynamic effects are not reflected in the density and temperature profiles as secondary shock wave in proximity of the impulse localization. Actually, it is not clear whether or not there could be such effects, because the magnetic field which remains together with the plasma in the region under study will not allow fast fall. This subject, as well as a two-dimensional model of surge prominences are subject of our future studies.

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Образование возвратных выбросов в солнечной атмосфере

I. Одномерные гидромагнитные численные эксперименты

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(Резюме)

Построена нестационарная одномерная гидромагнитная модель возвратных выбросов. При помощи численных экспериментов исследована возможность образования таких выбросов в результате „сгребания" с последующим движением хромосферной плазмы при импульсном возрастании магнитного давления. Модель воспроизводит главные динамические характеристики возвратных выбросов — временные и пространственные масштабы и скорости — и показывает, что выбросы можно интерпретировать как отклик солнечной атмосферы на импульсное возрастание магнитного давления в нижней хромосфере. Модель зависит от трех граничных параметров — начального магнитного поля, возрастания поля и продолжительности действия импульса. Полученные результаты показывают, что динамика выбросов воспроизводится при быстром и кратковременном возрастании магнитного поля. Сравнение этих результатов с наблюдательными данными показывает их хорошую согласованность.

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