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Magnetohydrodynamic model of the X-ray elementary solar flare bursts

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1. Introduction

Earth-based observations offer the possibility to investigate the Sun only in the optical and radio range of the electromagnetic emission, the Earth atmosphere being non-transparent for a shorter wavelength emission. The introduction of special devices operating beyond the dense Earth atmosphere, at first on baloons and rockets and later on circumterrestrial orbital stations, marked the beginning of studies of the Sun in the far ultraviolet and X-ray spectral ranges. In the course of the last two decades a number of global discoveries have been made during experiments carried out at orbital solar observatories (OSO) SKYLAB, Solar Maximum Mission (SMM), HINOTORI, etc., the most important of which were those of the coronal bright points and the elementary solar bursts.

A huge quantity of observational material obtained by automatic X-ray telescopes has indicated that a number of active formations of the Sun are sources of hard and soft X-ray emissions. The time and spatial resolution of the detectors made it possible to determine both the dimensions and the duration of the emitting regions, as well as the rather complicated correlation between the elementary X-ray bursts, the small-scale magnetic fields and the microwave radioemission.

The investigation of the structure and development of X-ray emitters is important for the comprehension of the mechanism of the solar flare energy release, as well as its transfer. Usually the process of initial release of energy is supposed to raise high-energy electrons and sometimes relativistic electrons and ions too. Hard X-ray and microwave emissions which are direct indicators of high-energy electrons are originated by synchrotron and gyrosynchrotron emissions, respectively. The acceleration of these electrons is presumably caused by the electric currents in the magnetic arch systems.

What is the nature of the initial release of energy ? This is obviously a small-scale, short-lasting magnetohydrodynamic process, and consequently, its manifestations should be searched for in the shortest time-scale active structural elements observable in the hard X-ray and microwave emissions. These are actually the sub-bursts, having a duration only fractions of the second, occurring within the framework of elementary solar bursts with a lifetime of several seconds.

In this paper a magnetohydrodynamic (MHD) model of an elementary solar burst is proposed. Section 2 presents contemporary observational results related to flare bursts. Section 3 submits a description of the proposed MHD model together with its general outlines, and Section 4 contains some conclusions concerning the model.

2. Observational results

As far as the nature of solar flares is concerned, Giovanelli (1947, 1948) pointed out that they are essentially electromagnetic phenomena. Later on Dungey (1958) indicated that the magnetic neutral points provide suitable conditions for particle acceleration, and Sweet (1958) pointed out that energy can be released in the entire current sheet formed in the magnetic structure and not only in a separate magnetic neutral point.

All attempts made in the development of a solar flare theory have shown a strong tendency to focus the attention on the fact that energy is released during the impulsive phase referred to as a flash phase or an expansion phase by earlier studies, initially based on H_α-line observations. It was implicitly assumed that the physics of the impulsive phase explains the complete flare process.

After the processing of the observational data from the solar experiment carried out on SKYLAB (Sturrock, 1980) it became clear that most of the flares release their energy during an onset phase which precedes the impulsive phase. Most clearly this process can be detected in the soft X-ray emission, and particularly in the initial phase of emission.

The early analyses of the hard X-ray emission (Frost, 1969; Van Beek et al., 1974; De Jager et al., 1976) have shown that the impulsive phase of a solar flare typically comprises a large number of events of a relatively short duration. The resemblance in shape of the individual spikes in the X-ray flux led to the introduction of the term "elementary flare burst" by Van Beek et al. (1974), in order to mark off the process responsible for these phenomena. The time scale of such a burst is in the range of 5-20 s, and their energy varies between 10^{27}-10^{29} ergs.

There is evidence (Kaufman et al., 1980) of quasiquantization of energy release in a solar flare. The rapid variations in the millimeter-wave radio flux are interpreted as an effect of the successive superposition of individual "sub-bursts" having time scales of the order of 50 ms. The fluctuations of the hard X-ray flux measured during the experiments on SMM exibit a comparable time scale (Kiplinger et al., 1983). A good correlation is observed also on subsecond time scales between the microwave emissions of different frequencies, as well as between microwaves and hard X-rays (Takakura et al., 1983). Kaufman et al. (1984) reported a spikelike burst observed in microwaves and hard X-rays with a duration of about 5 s, consisting of "slow" components with a duration of 1 s. At its peak intensity the burst displayed a recurrent microwave subsecond structure with a time scale of about 30 to 60 ms.

Recently Sturrock et al. (1984) distinguished in the energy release in solar flares four phases of different duration for which the action of different processes is proposed. The release of free energy of an elementary magnetic tube may produce an "elementary burst" lasting several seconds. The formation of magnetic "islands" during this process may be considered to be the reason for the generation of sub-bursts lasting parts of the second. The impulsive phase lasting few minutes may be viewed merely as a composite effect of many elementary bursts. The gradual phase lasting tens-of-minutes or longer includes the onset phase and the later phase of energy release. It is analogous to the "gradual phase" introduced by Kane (1974) to denote the soft X-ray emission phase which follows the impulsive phase of solar bursts. As for the physical processes, Sturrock et al. (1984) suppose that the gradual phase involves a steady process of reconnection of magnetic field lines, while the impulsive phase involves a very fast stochastic process of reconnection.

3. Magnetohydrodynamic and hydrodynamic consideration

As it was pointed out under Section 2, the hard X-ray emission exibits a fine structure of time scales of about 3 ms, while elementary hard X-ray bursts last 5 to 20 s (Van Beek et al., 1974). According to Sturrock et al. (1984) the fine structure may be explained in terms of this reconnection of discrete small-scale magnetic field structures. In this process fluctuations during the reconnections can be expected to play an important role. The same authors note the general importance of studying the possibility of formation of a cell-like structure of the magnetic field in active regions which could lead to the generation of pulse-like phenomena during the process of energy release.

Obviously to evolve a physical model of an elementary burst it will be necessary to study the possibility of generation of pulse-like plasma turbulent structures. This problem is relatively new in solar physics. Besides, it is too complicated as a theoretical problem, so that in order to work out at least some semi-quantitative physical model, it has to be solidly based upon the results of the respective lab plasma and hydrodynamics experiments.

Laboratory experiments show that in different plasma configurations are formed comparatively stable plasma structures, coaxilly surrounded by plasma named dynamical stable current filaments (DSCF) (Komelkov et al., 1960; Vasiljev et al., 1960; Komelkov et al., 1962). In the general case they are formed when sharp non-uniformity in the distribution of currents and magnetic pressure arises. In particular they are observed when the plasma cluster is extracted through an axial gap. More stable DSCF are formed by applying an external longitudinal magnetic field (Coltage et al., 1958; Bezbatchenko et al., 1958).

In the most general case a plasma current filament and a coaxial plasma are formed in a thoroidal eddy structure. In such plasmoids proper longitudinal and azimuthal magnetic fields can be observed usually of the same value of the order of 10^2-10^4 G. In both polarities the longitudinal magnetic field can be detected 2-3 ms after the discharge formation in the chamber. It is supposed that the source of this field is the dynamically stable current filament with an internal helix along its axis known to be the source of hard X-ray emission up to 200-250 KeV as well.

Such current filaments remain stable over long time intervals (5-200 ms) at large pressure range (10^2-10^5 dina/cm^2) and different plasma density (10^{-10}-10^{-3} g/cm^2). On these grounds one may suppose that similar dynamic structures could be expected to appear in nature wherever a sudden strong nonhomogeneity in the distribution of currents and magnetic pressure arises.

On the other hand, hydrodynamics provides some interesting results associated with the buoyant vortex structures.

Vortex rings and Hill's spherical vortexes in an ideal fluid are known to be structures where the impulse depends only on the full vorticity and on the radius (Lamb, 1932; Turner, 1957), although the energy depends essentially on the vorticity distribution in the moving region. The late is ring-shaped when the ratio $R/A>86$ (where R is the radius of the region in which the vorticity arises, and A is the radius of the circular cross-section of the region of vorticity distribution) and it has a depression in the centre for $14<R/A<86$. For small values of R/A the shape is like an oblate spheroid and the vorticity is concentrated in the core of the vorticity structure. When such a buoyant vortex ring is rising through a stratified fluid, a part of the heavy fluid is drawn behind the ring and does not actually enter the moving region. Afterwards it falls back and below the ring and a "column" of retrieved fluid is formed. The regularities mentioned above are not explicitly dependent on the physical properties of the medium. They are equally valid for gas and fluid media, but depend essentially both on the way in which the ring has been produced and on the resulting vorticity distribution.

Nowadays it is generally accepted that a magnetic convection leads to the concentration of the magnetic flux on the periphery of the convective cells in the form of magnetic flux tubes (c. f. Weiss, 1966). Theoretical studies of the three-dimensional turbulent convection (Knobloch, 1981) have shown that contrary to the prediction of the theory of the emergence of large-scale magnetic fields and their subsequent fragmentation, small-scale magnetic flux tubes would be the first to form in an incipient active region. In such a cluster of small-scale magnetic tubes it is more probably for a stochastic process of local magnetic line reconnection to occur.

Such a process runs quickly accompanied by a pulse-like release of energy and as a result plasma structures similar to hydrodynamic starting vortex rings or spherical Hill vortexes may form (Fig. 1*a*). When the ratio R/A is sufficiently small, vorticity will be concentrated in the core of the structure. One possible development of such a vortex is presented in Fig. 1 *b*, *c*, *d*.

Vorticity concentration creates conditions for curving the current lines and as a result an internal helix could form along the axis of the plasma structure. This is of great importance to the further evolution of the vortex. The centrifugal force is not in the direction of the magnetic field and, therefore it changes the velocity of the plasma particles $\vec{V}_\perp$, thus causing a drift motion with instantaneous velocity $\vec{U}=\bar{f}\times\vec{H}/m\omega H$, where $\omega=V_\perp/r=eH/mc$ is the

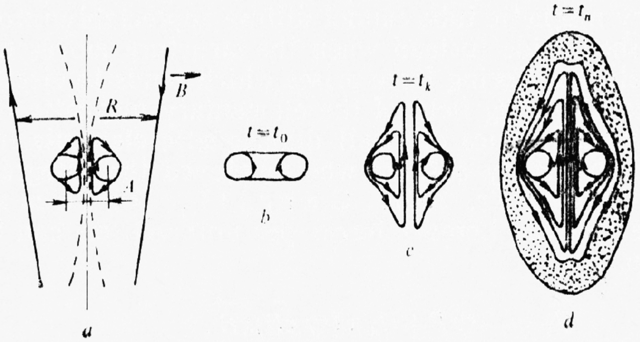

Fig. 1 *a*, *b*, *c*, *d*

angular frequency of the circular movement. ω has a different sign for electrons and ions so that the electrons will drift in an opposite direction to that of the ions, i. e. an electric current will flow.

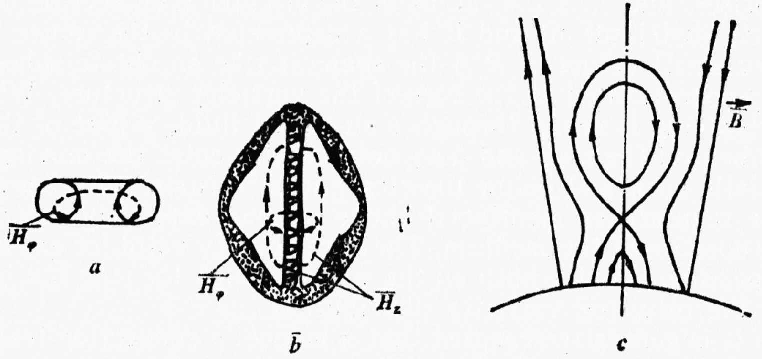

Fig. 2 *a, b, c*

As a result inside the plasma spheroid a current cord is formed in which it is possible for the electrons to be accelerated to high energies. The synchrotron and gyrosynchrotron emission of the accelerated electrons may provide a burst-like event.

However, it is interesting to note another cosequence of the current cord formation. Initially, as a result of the vorticity movement in the ring, a thoroidal electric current arises, inducing an azimuthal magnetic field H_φ (Fig. 2*a*). Later on, as a result of the axial helix formation, a longitudinal magnetic field H_z appears. Thus a relatively stable plasma structure forms "tightened" between these two magnetic fields (Fig. 2*b*) and embedded in the elementary magnetic flux tube (Fig. 2*c*).

Due to the high electric conductivity of the solar atmosphere, the field lines of the elementary magnetic tube cannot diffuse appreciably into the structure, but will be pushed aside instead when the structure moves upward. In the magnetic tube field a restoring force arises which tends to eject the structure outwardly in the diverging field of the elementary magnetic tube.

The dynamics and energetics of small diamagnetic elements in solar atmosphere was studied by many authors who employed the integral forms of the MHD equations (Parker, 1957; Gargill, Pneuman, 1984).

The gas pressure and the Lorentz forces per unit volume can be written in a differential form as

$$\vec{F}_V = -\nabla P + {}^1/_4\pi(\nabla x\vec{B})x\vec{B},$$

where P is the gas pressure and $\vec{B}$ is the magnetic field vector. If that expression is integrated over the entire volume of the structure, the resulting force acting on the mass centre can be expressed in the form of a surface integral, i. e.

$$\vec{F} = \int\int_s [1/4\pi(\vec{B}_e . \vec{ds})\vec{B}_e - (P_e + B_e^2/8\pi)\vec{ds}]. \tag{1}$$

The corresponding equation of motion for the mass centre then will be given by

$$(2) \qquad M\frac{d^2r}{dt^2} = -GM_\odot\frac{M}{r^2} + \iint_s [1/4\,\pi(\vec{B}_e \,.\, \vec{ds})\vec{B}_e + (P_e + B_e^2/8\,\pi)\vec{ds}],$$

where M is the total mass of the structure, r is the radial distance to the mass centre, $M_\odot$ and G are the solar mass and gravitational constant respectively, and P_e and B_e are the gas pressure and magnetic field intensity of the elementary magnetic flux outside the structure.

Since the structure is embedded and completely detached from the magnetic flux tube, $\vec{B}_e\vec{ds}$ is identically zero everywhere and the tension forces give no net contribution to the motion of the centre of masses and equation (2) can be written as

$$(3) \qquad M\frac{d^2r}{dt^2} = -GM_\odot\frac{M}{r^2} + \iint_s (P_e + B_e^2/8\,\pi)\vec{ds}\,.$$

There are only few theoretical and observational considerations which indirectly support the hypothesis of formation of such small-scale plasma structures. According to Orszag and Tang (1979), small-scale eddies can be produced through a MHD flow as an enhanced cascade process on top of a large convective eddy by local reconnections of lines of forces of adjacent, tight magnetic ropes. In the solar atmosphere it is known that local reconnections could occur when a new magnetic flux emerges next to a preliminarily existing magnetic arch system. The observation of chromospheric bright points and initial phase of solar flares show that small-scale kernel-like features are preceded by the small-scale magnetic flux emergence.

Would such a short-living structure be destroyed by resistive diffusion of the magnetic field of the flux tube before the formation of current helix in it? Some regularities and estimates based on the analysis of laboratory plasma experiment data (Komelkov et al., 1960, 1962) may be obtained.

Thus, for example, the life time of DSCF is approximately equal to the time that the current needs to travel the distance $S = 2\pi\frac{l}{\delta}r$, where l is the length of the helix, δ is the helix loop spacing and r is the loop radius. This means that the DSCF life time is equal to the time necessary for their formation. The helix velocity and the distance between the loops depend on the pressure as follows:

$$(4) \qquad V = 1{,}5V_0(\lg P_0 - \lg P)\,, \quad \delta = 1{,}5\,\delta_0\,G_f(\lg P_0 - \lg P)\,,$$

where V_0, P_0 and δ_0 are the velocity, pressure and loop distance respectively obtained in a laboratory experiment, and G_f is the geometric factor.

Assuming that the fortex has a characteristic dimension $L = 10^3$ km, the radius of the helix structure then will be $r = 1/4\ L = 2{,}5.10^2$ km, and the corresponding geometric factor $G_f = L/R = 10^7$ ($R = 10$ cm is the radius of the laboratory chamber). With experimental values $P_0 = 10^2$ dyna/cm^2, $V_0 = 59$ km.s^{-1}, and $\delta_0 = 1$ cm (Komelkov et al., 1960), and the pressure $P = 10^{-3}$ dyna/cm^2 which is characteristic for the upper part of the chromosphere-corona transient region, we obtain according to (4) $V = 458$ km.s^{-1} and $\delta = 750$ km respectively. Then for the time of DSCF formation $t = S/V$ we obtain the value 4,3s.

It would be interesting to compare this time to the characteristic time of the resistive diffusion $\tau = 4\,\pi\sigma L^2$, i. e. the time for which the Joule dissipation would destroy this structure. Electric conductivity for turbulent plasma is expressed by the formula $\sigma=5{,}0.10^{-8}\, n^{1/2}$ (Priest, 1982), where n is the electron concentration. For the base of the corona and the adopted dimensions of the plasma vortex structure we get $\tau=6.10^3$ s. Consequently, a vortex of a characteristic dimension $L=10^3$ km might form a dynamically stable current filament.

4. Discussion and conclusions

In this work we make an attempt to treat the most essential issues of the generation and development of the small-scale dynamic plasma structure. We propose a physical picture of the elementary flare burst formation based upon results obtained by other authors at laboratory plasma experiments for stable pinch creation and also in hydrodynamics.

In elementary magnetic tubes in the solar atmosphere similar conditions may arise. It is possible for the local reconnection of their force lines to run as a stochastic process. Instantaneous energy release during this process could lead to the generation of vortex structures similar to those studied by hydrodynamics both theoretically and experimentally in various gas and fluid media. In the cases when the vorticity concentrates in the core of the structure a longitudinal magnetic field (except the azimuthal) arises and the whole structure can be considered as a small-scale diamagnetic element in the diverging field of the elementary magnetic tube.

One of the most essential conditions necessary for the generation of electric currents is the formation of the so-called current cord along the longitudinal axis of the structure. A number of hydrodynamic and plasma laboratory experiments show the presence of helix-like traces. By means of probe, photographic and spectral measurements some results concerning helix loop dimensions, loop spacing, plasma velocity, magnetic fields and X-ray energy have been obtained (Komelkov et al., 1960).

Our investigation of the stability of such structures in the solar atmosphere by comparing the time necessary for the DSTF formation and the resistive diffusion characteristic time of the external field, gives optimistic results. Helix-like structures form comparatively quickly and their duration ($t=4{,}3$ s) is significantly shorter than the characteristic time ($\tau=6.10^3$ s) needed for Joule dissipation to destroy the structure.

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Магнитогидродинамическая модель элементарных вспышечных всплесков, наблюдаемых в рентгеновском излучении

В. Н. Дерменджиев

(Резюме)

Предложена МГД модель элементарных вспышечных всплесков, наблюдаемых во время импульсивной фазы солнечных вспышек в микроволновом и рентгеновском излучении. Основное предположение в модели, а именно—образование токового шнура в тороидальном вихре, сделано на основе обобщения результатов, полученных в лабораторных плазменных и гидродинамических экспериментах.

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