VIII. SOLAR FLARES

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PLASMA PROCESSES IN SOLAR FLARES

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ABSTRACT. A rationale is presented for a conception that appearance of flares in active regions is due to the interaction of large-scale convective elements. Such an interaction gives rise to shear motions in the vicinity of the inverse polarity line of the photospheric magnetic field which generate vortical motions leading to non-equilibrium state of the magnetic configuration. Modern concepts of manifestations of turbulent plasma processes are described in terms of theoretical models for solar flares. Plasma effects arising at propagation of electron beams and thermal fluxes in the solar atmosphere are considered. Their role in the interpretation of hard X-ray and type III radio bursts is pointed out. The role of the turbulent Stark effect for diagnostics of collective plasma processes in solar flares is emphasized.

An important role in modern flare theory is played by plasma processes and, in particular, by physical effects connected with a turbulent state of plasma. In some phenomena taking place in the plasma of the solar atmosphere, collective plasma characteristics are especially clearly manifested - the interaction of plasma particles with external and self-consistent electric and magnetic fields. Not only can these fields control the plasma motion but also can, in turn, be changed and be induced themselves in the case of different plasma motions (Kaplan et al., 1977; Altyntsev et al., 1981).

One of the aspects of collective plasma features is the turbulence, a state of plasma connected with the presence of oscillations or noise whose interaction with plasma particles influences essentially its macroscopic characteristics. Such noise and oscillations arise because of some plasma instabilities (Kadomtsev, 1976). In the solar plasma such instabilities may be caused by electric

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currents flowing in the active region (AR), shock waves propagating out of the flare region, beams of energetic particles, by thermal fluxes, etc. All presently available flare models based on magnetic field dissipation mechanisms in AR take advantage of the concepts of turbulent processes in plasma.

Observational data accumulated over the past decades revealed a close relationship between flares and AR magnetic fields. It is known that most frequently flares arise in complicated multipolar sunspot groups during their fast evolution (see a review by Altyntsev et al., 1981). In the upper chromosphere and lower corona of the Sun where flares are produced, observational data do not show the existence of some other energy source capable to provide the flare energetics, except for the magnetic field energy. Therefore, at present the most well-grounded idea is that the flare energy source is provided by the magnetic field. In this connection the question of the energy storage mechanism in AR magnetic configuration is of great interest. We report here a conception proposed by Golovko et al. (1986, 1988) which, from our point of view, answers the relevant question of magnetic energy storage.

It is well known that the dynamics of the magnetic field and matter in photospheric layers of the solar atmosphere are determined by a complicated interaction between structural features of various scales. There exist a three-stage hierarchy of convection, namely granulation, supergranulation and large-scale structures consisting of elements with a characteristic scale of sizes, lifetimes and mass velocities in them (Kaplan et al., 1977). Besides the whole of this complex picture of motions is affected by the differential rotation of the Sun. For example, see a paper by Monin (1987) on the interconnection of differential rotation with the large-scale velocity field pattern at the solar surface. It is evident that, as the observed photospheric velocity field is formed, these structures must determine the evolution of the magnetic configurations - complexes of activity, AR and separate sunspots - and ultimately they must influence flare activity.

Indeed, Stepanyan (1983) has shown that although the places of AR formation do not show an obvious dependence of large-scale structures (giant cells),the activity level, however, is significantly higher near the borders of the above-mentioned structures. This conclusion may be extended to structures of smaller scales typical of supergranulation. It has been soundly confirmed by an analysis of flare development in the May 1981 complex of activity carried out by Banin (1984) on the basis of H-alpha filtergrams. Moreover, in many papers the correlation of flare location with horizontal shear motions near an inverse polarity line (IPL) was found (Zirin and Tanaka, 1973; Harvey and Harvey, 1976). There are broad lines of observational evidence now for shear motions of plasma elements with frozen-in magnetic field along the IPL. Of course, such mass motions must lead to the appearance of a shear structure of magnetic configuration. The large value of magnetic field shear serves as one of indications of flare production (Gaizauskas and Harvey, 1986; Machado et al., 1986; Moore et al., 1988). The orientation of dark filaments, emergence of new magnetic flux, and local deformation of the IPL are often also recognized as flare activity predictors. There are observational indications on vortical motions of matter close to IPL connected with flares also (Martres et al., 1973; 1983; Mein et al., 1984).

Analysis of the observational facts presented above leads to the following physical picture which permits us to establish causal relationships responsible for producing a pre-flare situation (build-up) and, ultimately, for the flare process. The interaction of structural features of different scales (supergranular and larger cells, for example) must lead to the generation of shear motions along the IPL in complexes of activity and separate AR with the production of vortices. Vortical motions of matter give rise to local enhancements of the magnetic field near the IPL and, as a consequence, to accumulation of an excess (non-potential) energy in a magnetic configuration, to current sheet formation and therefore to flare generation. Within the frames of this scheme, the excess energy in magnetic field configurations is derived from the energy of hydrodynamical motions of structural features, the scale of which may be well above the flare region size while the flare itself as a relaxation process of excess energy release in the magnetic field configuration. In other words, by changing and complicating the magnetic field the shear motions of the matter, together with a system of the vortices generated, ultimately brings the magnetic configuration to a non-equilibrium state. Once its stability threshold is attained, the accumulated energy starts to be rapidly released, thus indicating the flare onset. This scheme is illustrated in Fig. 1.

The first detailed description of this scheme was given in papers by Golovko et al. (1986, 1988) which also presented computation results on the velocity field in AR McM 11976 that produced a series of large flares in August 1972. They confirm the proposed mechanism.

In connection with the above-said, the problem of the evolution and stability of equilibrium magnetic configurations (loop structures of the magnetic field on the Sun) which are influenced by slow motions of field line footpoints at the photosphere may be of great interest for astrophysical applications. It is possible that, when a displacement of footpoints of a loop deformed by photospheric mass motions reaches some critical value, the equi-

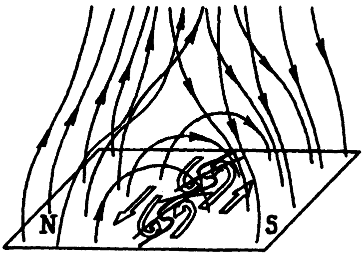

Fig. 1. Magnetic field configuration above the photospheric plane and the horizontal velocity field in the vicinity of the inversion polarity line (IPL).

Legend:
- inversion polarity line;
- magnetic field lines of force;
- direction of mass motions in the photospheric plane.

librium state of the configuration may, then, be upset and become unstable and a forced transition into a new equilibrium state will take place. If the magnetic energy of the new equilibrium state is less than that of the unstable state, then a free magnetic energy release will occur during the transition process. Besides, magnetic configuration topology in the new equilibrium state may be of quite a different kind, which means a topological reconstruction of the configuration will be taking place. Particularly, the closed loop structure may become partially open. Such problems are of interest with regard to understanding the solar flare nature (for example, Priest (1982)).

Recently Matyukhin and Tomozov (1986, 1989a,b) examined the problem of the quasi-static evolution of loop magnetic structures on the Sun (one magnetic loop and a loop arcade) with given boundary conditions. Slow shear (and vortical) motions of magnetic loop footpoints were considered to be boundary conditions, i.e., the kind of velocity field was analogous to that computed in papers by Golovko et al. (1986, 1988). It was shown that for a loop arcade a shear motion such as a viscous boundary layer leads to its topological reconstruction, with the energy released comparable with that released in large solar flares, i.e., 10^{32} ergs (for one magnetic loop, the value of free energy is 10^{28} - 10^{29} ergs). The topology of the original arcade configuration, when a critical value of magnetic shear is reached, becomes an open one. Note that such a scenario of the magnetic arcade evolution on the Sun explains quite well the main energy characteristics of large solar flares and predicts the origination of open magnetic structures in ARs of the Sun after flares.

We now examine the role of collective processes in different stages of a flare event. We shall restrict our attention only to some aspects which, we believe, are of particular interest. First of all, it is related to magnetic field dissipation in a solar flare energy release region in the explosive phase. This is characterized by energy release in the form of thermal fluxes and energetic particles. According to the electromagnetic nature of flares, for rapid dissipation of current energy in an electric circuit formed in AR plasma it is required that the plasma resistance should be sufficiently large. As is known, classical resistance of solar plasma is too small. Therefore, it is necessary to include collective effects which sharply enhance the plasma resistance. Collective effects connected with the generation of plasma waves and their interaction with particles are natural to arise within thin current sheets with typically high current densities. In some flare models the kinetic instabilities are able to cause a plasma sheet to change to a turbulent state. This change is possible when the current sheet rises into a lower corona where the energy balance of plasma in the sheet is upset due to thermal instability (Heyvaerts et al., 1977). As the result, the current density increases sharply in the sheet, a chain of kinetic instabilities develop, giving rise to anomalous resistance of sheet's plasma and, accordingly, the energy release rate increases rapidly (Tomozov, 1971, 1972).

Electric fields, MHD and plasma turbulence, and shock waves have customarily been treated as the main mechanisms of particle acceleration in flares. Strong electric fields are produced and plasma turbulence is generated in the flare energy release region itself where the magnetic field reconnection process (in the current sheet, for example) occurs. Theoretical investigations showed that the Langmuir and ion-sound turbulence modes may be important ones in interpreting the heating and electron acceleration in a current sheet (Tomozov, 1972; Kaplan et al., 1977; Smith, 1977a,b;1980; Brown and Smith, 1980). Laboratory simulation of current sheets confirmed the existence of these turbulence modes (Altyntsev et al., 1982; 1987). The ion-sound turbulence leads to intensive heating of the bulk of electrons. At the same time, the Langmuir turbulence effectively accelerates only fast electrons. The high efficiency of heating and electron acceleration processes in the current sheet is confirmed by laboratory experiments (Altyntsev et al., 1977). Recently in course of laboratory experiments it was succeeded in finding that instability of merging of magnetic islands plays a very important role in maintaining the high rate of magnetic field reconnection in the current sheet (Altyntsev et al., 1987). Very effective mechanisms of ion acceleration in flares are provided by shock waves and MHD turbulence (Smith and Brecht, 1988; Melrose, 1983) propagating from the region of primary energy release. A potential-jump induced acceleration mechanism along the front of a magnetosonic shock wave of large amplitude has recently been extensively discussed for purposes of interpreting a prompt acceleration of particles (protons and electrons) in the impulsive phase of flares (Ohsawa and Sakai, 1988). The existence of such an acceleration mechanism in the current sheet was recently confirmed through laboratory experiments (Altyntsev et al., 1988). The present status of the problem of particle acceleration in flares is reviewed by Vlahos et al. (1985).

As argued by a large number of authors (for example, Švestka, 1976), particle acceleration in flares consists of two stages, each of which differs by its specific mechanisms, energy characteristics of fast particles, and by time scales. As a result of the first-phase production an acceleration of electrons of up to an energy of 100 keV and of protons of up to an energy ~ 20 MeV takes place directly in the energy release region and the electrons are accelerated more effectively as compared to protons. During the second phase of acceleration (the typical time of a few minutes) the most probable mechanism of which is an acceleration at shock fronts, relativistic electrons and ions with an energy over 200 MeV appear. However, Chupp's measurements (1983) revealed that there was virtually no time delay between bursts of hard X- and gamma-ray emissions, which led Chupp to the conclusion that electron and proton acceleration to maximum energies takes place directly in the energy release region by a single mechanism without involving the second phase. Of course, the above conception of two-stage acceleration of particles in flares (Švestka, 1976) disagrees with presently available observational data on hard X- and gamma-ray emissions of flares. As suggested by Bai (1986), it is possible to avoid this discrepancy, by revising the classification of flares. A very attractive model in which these results can be explained, is a topologically non-equilibrium MHD system arising during the course of merging of two magnetic loops with compensated longitudinal currents (Bardakov, 1987). In this model the magnetic field energy is transformed into fast hydrodynamical motions with formation of shocks. It may be noticed that in the frames of Golovko et al's (1986) scheme such an MHD system may well be the case.

Thus, it may be argued that the role of collective plasma processes is important during the stage of initial flare energy release. But these processes should be taken into account also when studying secondary flare processes in the solar atmosphere; we, now, shall discuss them.

Heat and energetic particle fluxes propagating from the region of initial energy release where magnetic field "annihilation" takes place, give rise to a disturbance of a large volume of the solar atmosphere, thereby causing the flare event proper. While penetrating into dense chromospheric layers, electron fluxes generate X-ray radiation in both the soft and hard spectral regions. Whereas the soft (0.5-10) keV X-ray radiation involves thermal emission of a hot plasma "evaporating" from the chromosphere and its interpretation is easily done, the origin of hard X-ray bursts (the energy of quanta is more than 15 keV) is not clear yet. The power-law character of the hard X-ray spectrum led to the construction of non-thermal models in which X-ray quanta are the bremsstrahlung radiation of fast electron beams decelerating in a dense chromospheric plasma. Naturally, this radiation must be polarized. In the beam's interpretation of the hard X-ray radiation it was necessary to understand how a directed electron beam penetrates into the chromosphere without scattering by plasma waves generated by the beam's particles. It was found that the mechanism for nonlinear stabilization similar to that suggested to interpret type III radio bursts, is able to diminish considerably the role of turbulent scattering for the electrons with an energy in excess of 10 keV (Livshitz and Tomozov, 1974). Allowance for strong Langmuir turbulence effects made it possible to extend the conclusion about the possibility of nonlinear stabilization to dense electron beams with $n_b/n_e = 10^{-2}$ as well (Vlahos and Papadopoulos, 1979). Thus, nonlinear stabilization of the beams is a striking example of collective interactions of plasma waves with particles in solar flares.

Later on, some difficulties of nonthermal models of X-ray bursts were encountered, namely uncertainties in the interpretation of power-law spectra; the need for an exceptionally large number of energetic electrons; etc. Some of the just-mentioned weaknesses of the nonthermal model of hard X-ray radiation have been overcome in a thermal model in which the existence of high-temperature plasma ($T_e \gg 10^8$ K) is supposed. In this model, the number of energetic electrons is decreased and the requirements to source energetics are reduced.

Different types of sporadic solar radio emission are related to a wide range of secondary phenomena associated with propagation of hot plasma and energetic particles into upper coronal layers and out into the interplanetary medium. Most types of solar radio bursts, intimately connected with flares, are explained by plasma mechanisms, including turbulent processes (Kaplan et al., 1977). Apparently, type II and III radio bursts are the most striking manifestations of collective plasma effects in the flare radio emission. Type II bursts are generated due to a shock wave front moving in the corona and radio emission of type III arises as a result of plasma wave generation by accelerated electron fluxes. The interpretation of type III radio emission is based upon the plasma hypothesis, according to which an electron flux excites high-frequency Langmuir waves due to a beam instability and plasma waves are, then, converted to electromagnetic ones. The generation of radio emission is by no means the only manifestation of plasma effects in type III radio bursts. It is known from observational data that the source velocity of these bursts (0.3-0.4 of the speed of light) was in fact constant from lower levels of the solar corona to a distance of 1 AU where only deceleration and expansion of the beams are observed. The mysteriosness of this result is that the well-known mechanism of quasi-linear relaxation must lead to destruction of the beam even in coronal regions of the solar atmosphere. In order to overcome this difficulty, it is necessary to identify the mechanism for beam's stabilization which is also connected with collective plasma processes (Kaplan and Tsytovich, 1972). This mechanism implies that, due to processes of nonlinear scattering off ions, Langmuir plasmons, which are excited by a beam, change their direction and phase velocity in such a way that they become off resonance with beam's particles and, therefore, beam's relaxation is proceeding much more slowly. Note that solar type III radio bursts represent a sort of a natural laboratory for studying the interaction of energetic beams with plasma. Of course, a complete theory of type III bursts consistent with observations has not yet been developed, and investigations in this area are being underway on a large scale (see, for example, Smith, 1974; Smith and Sime, 1979).

To sum up, we will remark that the turbulent Stark effect can be used, on the basis of spectral observations in the optical range, as a direct diagnostic tool for gaining insights into collective processes in solar flares. Revealing this effect is a challenging problem due to difficulties encountered when obtaining pertinent observational data and taking into account instrumental errors while processing such data as well as by virtue of incomplete theory. But it is highly important to resolve this problem because this promises to provide new insights into the nature of solar flares.

Of course, the range of problems under consideration does not include all the diversity of manifestations of collective plasma effects in solar flares. Many unsolved problems regarding our understanding of the origin of solar activity are left (in particular, with regard to solar flares). Nevertheless, a comprehensive study of these problems carried on by plasma physicists and astrophysicists promises to help towards answer to some of them in the near future.

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