PLASMA TURBULENCE IN THE CURRENT LAYER OF A SOLAR FLARE

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Abstract: A common picture of physical processes connected with and energy dissipation of a magnetic field in a current layer of the solar flare model proposed by Syrovatskii is considered. The problems of the time development of a plasma turbulence and of the quasi-stationary oscillation spectra establishment are discussed. High-frequency Langmuir plasmons with an energy density about 10-times less then one being in ion-sound branch which accelerate resonance electrons up to relativistic energies are generated by the development of ion-sound turbulence in a layer at the expense of the beam instability on "runaway" electrons. Ion-sound plasmons realize the function of a ion injection mechanism in an acceleration regime on Langmuir waves.

Energy spectrum of accelerating electrons and ions abandoning the current layer bounds must have a universal form: $f_e \sim \varepsilon^2 \exp - \varepsilon/\varepsilon_0$ (ε_0 value for electron and ion components is different). It is noted an important role of a magnetic field value forming current layer and determining a threshold energy of the particles abandoning an acceleration region.

Abandoning a current layer energetic electrons get into a closed magnetic configuration formed by the active region fields and generate the X-ray emission penetrating into dense layers of the chromosphere. It is discussed the mechanism of non-linear stabilization of anisotropic electron beams using for explanation of the X-ray emission polarization of the solar flares observed on a number of "Intercosmos" satellites.

In recent years the intense development of plasma astrophysics stimulated, on the one hand, by extensive theoretical investigations in the field of physics of the turbulent plasma, and on the other, by the accumulation of a deal of experimental data, led astrophysicists to interpret a large number of observational data, related to physical processes, occurring in active regions of the Sun, Seyfert nuclei galaxies, quasars and in the neighbourhood of pulsars.

From this point of view, the most powerful manifestations of solar activity, flares, are of the greatest interest. Actually, we believe, there is no reason to doubt that the main energetic reservoir of the solar flare mechanism lies in the magnetic field of the active region and, as a direct cause of the flare, is responsible for a rapid reorganization of the magnetic configuration as a result of the development of a large scale plasma instability.

We may consider that the established decisive role in the development of the flare process is played by the reorganization of the magnetic fields in the active region of the Sun, which leads to the appearance of neutral lines. The observational fact of the generation of flare knots in the initial flare phase, mainly generated along the neutral lines of the field, was established by Severny and his collaborators (Severny, 1958; Gopasyuk et al., 1963; Severny and Steshenko, 1969) from a series of magnetic field observations which have been conducted over a period of several years by means of a magnetograph.

Using these data, Syrovatskii (1966) built a theoretical model of the flare process which described the main observational phenomena well. The idea of a current layer forming in the region of the oppositely directed magnetic field annihilation, forms the basis of his investigations; hereby, the acceleration of cosmic rays becomes associated with a disturbance of the regular structure of the current layer and the appearance of a strong magnetic field. This process was called "dynamic dissipation".

It should be noted that the current layer plasma is transformed by the instability into a turbulent state when the electric field appears in the latter (Kadomtsev, 1964; Tsytovich, 1966); the plasma is strongly heated, and a group of particles, resonant with the plasma waves, may be accelerated to high energies. On the other hand, the dynamic dissipation process requires the presence of large gradients of the magnetic field, which are difficult to establish in conditions typical of solar flares (Kaplan and Tsytovich, 1972; Tomozov, 1972a). At the same time, plasma waves can accelerate particles very effectively, so that the development of the flare process may be presented as follows: magnetic field annihilation-appearance of an electric field-plasma wave generation-plasma heating-acceleration of cosmic rays, etc. (Tomozov, 1971).

Let us first investigate the idea of the plasma turbulent state by analogy with fluid turbulence. We know that the turbulent motion in an incompressible fluid is associated with the appearance of vortex motions of its elements, reaching velocities, the critical value of which is characterized by the Reynolds number (Landau and Lifshits, 1954). Normally, the characteristic size of the emerging vortex is within the range of the size of the region where the liquid flows. In time, the large scale fluid vortex formed splits up generating smaller scale vortices and a process of turbulent energy flow to the smallest scale where it, finally, transforms into heat thanks to viscosity. From simple assumptions of local isotropy and constancy of the energy flowing from the larger to the smaller scales, Kolmogorov (1941) determined the spectrum of turbulence, i. e. the vortex energy distribution at characteristic wave numbers $k: \infty k^{-5/3}$. The situation in the plasma is much more complicated than in the fluid, first of all, because the number of degrees of freedom existing in the plasma is much larger on account of the presence of electromagnetic interaction of the particles. Therefore, if a wave motion is excited in the plasma and its energy dissipation is sufficiently small, the energy would be redistributed in all the possible wave mode types due to different non-linear interactions between the oscillations, and the plasma passes into a turbulent state. Usually, plasma turbulence is preceded by a certain instability which leads to the cascade process of excitement generation-plasmons. The largest difference with respect to the fluid turbulence is due to the fact that because of the non-linear process of plasma wave interactions, the flow of turbulent energy in the collisionless plasma is directed to larger characteristic scales (the usual size of the plasma oscillations equals the Debye radius).

The plasma turbulence has its own specific energy dissipation mechanisms (Tsytovich, 1971). The first possibility is related to turbulent heating when plasma oscillations are pumped rapidly into the absorption region. This mechanism is especially important for low frequency ion-sound oscillations; this is of interest for plasma physics due to the problem of obtaining hot plasma, and in astrophysical research to explain physical processes in flares, active nuclei of galaxies, etc. The turbulence of high frequency Lengmour plasmons can also heat plasma at the time of spectral pumping when the characteristics of the plasma are such that the electromagnetic quanta, which appeared as a result of the Lengmour conversion, are strongly absorbed by the plasma.

The second possibility of turbulent energy dissipation arises from the transformation of turbulent pulsations in electromagnetic radiation which freely leaves the plasma. The mechanism of emission losses of energy is especially important for establishing quasi-stationary spectra of the Lengmour pulsations.

And, finally, another possibility is associated with the acceleration of resonant particles; the Lengmour oscillations accelerate particles in the most effective way. The second and the third channels of the loss of turbulent energy are very closely interconnected and depend on the evolution of the Lengmour plasmon spectrum under conditions of the analysed physical situation.

Over the past ten years, the problem of the energetic process in current layers of cosmical and laboratory plasmas has acquired special importance. The current layer formation in a plasma under laboratory conditions, as a rule, is connected with the application of an external electric field, whereas in astrophysical objects this process takes place either as a result of the interaction of oppositely directed magnetic fields, or of the appearance of a sharp gradient of the magnetic field in the shock wave front. Syrovatskii's accurate calculations (1966, 1971a) in the hydrodynamic approach allowed one to determine in general, under what conditions in the Sun's active region the current layer, the "heart" of the flare, is formed, where the magnetic energy is intensively pumped into the plasma.

Recently, several authors have declined to divide the flare into 3 phases — initial, flash, lading (Sweet, 1969; Svestka, 1970; Syrovatskii, 1972). According to Syrovatskii (1972) all three phases may be explained by a change of the physical mechanisms which are active during the flare. The initial, comparatively quiet stage of the flare is accompanied by individual local bright spots in the spectral H-alpha line by the enhancement of the plasma filament motions and by the increase of the radio emission level in the microwave band and of the soft X-ray emission. During this flare stage the magnetic configuration in the active region recombines, the current layer is being formed, in which the process of turbulent plasma heating is responsible for the observed manifestation of flare commencement (Syrovatskii, 1972). The flash phase is usually related to the fast increasing of the brightness and area of the flare, merging of local bright knots into one, appearance of a dividing ribbon structure, bursts of hard X-ray emission, which are superimposed on an increasing thermal X-ray background and microwave radio bursts in the centimetre band. The acceleration of the energetic particles is the main physical mechanism in this stage, owing to dynamic dissipation (Syrovatskii, 1972), or to the statistical acceleration by plasma waves (Tomozov, 1972a). Finally, the third stage is the process of cooling of the flare region, the role of the acceleration mechanisms and the energy generation is weak, however, some increasing of the emission flux in the H-alpha spectral line and the soft X-ray range may be observed. This phase is the longest, i. e. the cooling of the hot area on the Sun takes place over several hours.

Let us consider the analysis of the common physical pattern and the temporary development of the plasma instabilities in the current layer in Syrovatskii's model (Fig. 1) (Tomozov, 1971; 1972a). During the formation of the current layer and the appearance of the magnetic field gradient, the electric field appears and the Bunemann instability develops in the initial isothermic plasma with $T_e = T_i$ (T_e, T_i are the electron and ion temperatures, respectively) (Bunemann, 1959). This heats the electrons rapidly, the increment of the generation of the Bunemann instability decreases simultaneously and it passes into the ion-sound stage. The break of the electron and ion temperatures is preserved in the subsequent development of this process. The current layer plasma resistivity, which at first depends on the collision of particles, decreases sharply, because the interaction frequency of the electrons with the ion-sound plasmons is much higher than the frequency of the collisions with ions in the turbulent current regime (Tsytovich, 1967). The theoretical analysis of the plasma processes in the current layer showed (Tomozov, 1972a; Kaplan, Tsytovich, 1972). That the most probable generation mechanism of the high-frequency Lengmour plasmons is the bunch instability in the "escaping" electrons.

The low-frequency ion-sound plasmons, which determine the plasma resistivity of the layer, change the transversal dimension of the magnetic field annihilation region, increasing it in comparison with the classical resistivity sharply (it is assumed that the plasma stream approaches the layer at a constant velocity). In turn, the increase of the thickness of the current layer decreases the magnetic field gradient and may bring about the breakdown of the ion-sound instability from which the possibility of the existence of the machanism of the reversed relation follows (Tomozov, 1972a). The low efficiency of the cooling mechanisms in the plasma layer allow one to draw the conclusion of a vibrational regime of energy dissipation with a characteristic period of 10^{-5} s, however, the layer thickness may be stationary, as well as the regime of

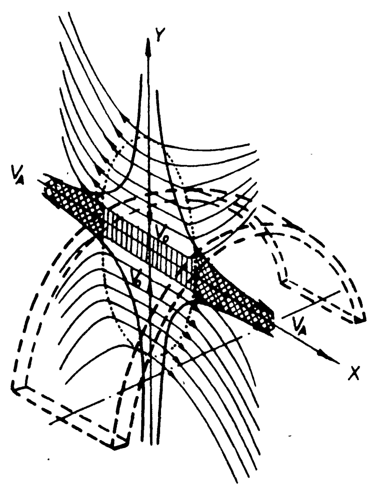

Fig. 1. The geometry of Syrovatskki's model. A plaine arc, outlined by thick dashed lines, represents the current layer; its cross-section is denoted by vertical hatching; the lines of force of the magnetic field are shown by curved thin lines. The hyperbolic trajectories show the directions of plasma motion, the double hatching represents the region of compressible gas, leaving the current layer.

turbulization after averaging over long time intervals. The ion-sound pulsations, interacting effectively with the basic mass of electrons, heat them; a small fraction of the electrons $(10^{-2}-10^{-3})$, whose force of deceleration by waves is smaller than the accelerating force of the induced electric field, directed along the current layer, enters the "escape" regime and generates the high-frequency Lengmour plasmons by means of Cherenkov's effect. The estimations, made in the author's paper (Tomozov, 1971), showed that the Lengmour and ion-sound plasmon energy densities may be compared in order of magnitude. Friedman and Hamberger (1969) were the first to show the possible role of plasma turbulence in a current layer.

The problems of electron and ion acceleration by plasma waves in a plane quasi-stationary spectrum approximation of Lengmour's turbulence, which appears to be correct under the conditions in a current layer, were examined in Tomozov's papers (1972a, b). The characteristic energies of the accelerated electrons leaving the current layer boundaries when their radii of rotation in the magnetic field are comparable with its thickness in the turbulent current regime, were estimated and found to be within the interval from 5 Mev to 1 Bev (the magnetic field intensity being $H = 100$ Oe). In the current layer the electrons are accelerated without injection (high-energy "tail" of the distribution function); a mechanism of preliminary acceleration to satisfy the resonance conditions of Lengmour's oscillations is necessary for ions. The function of the injection mechanism can be carried out by the ion-sound pulsations, the phase velocities of which are within an interval where the most effective interaction with the fundamental particle mass in the plasma takes place, as shown by Tsytovich (1971) in general and by Tomozov (1972b) for the current layer of a flare. As shown earlier, because Lengmour and ion-sound oscillations co-exist in a current layer, the turbulence of the ion-sound waves is a natural injector of heavy ions into the acceleration regime of the high-frequency plasmons. The condition, under which the accelerated ions leave the region of acceleration, is analogous to that proposed for the electrons, and their characteristic energies range from 10^{-6} to 10^{-1} $m_i c^2$ (Tomozov, 1972b). It should be noted that a magnetic field, forming a current layer, plays a double role, determining, on the one hand, the energy losses in the plasma layer and, on the other hand, the threshold energy of the particles, leaving the layer (for ions the exit energy $\propto H^3$). The distribution function of the accelerated particles becomes universal: $f_\varepsilon \propto \varepsilon^2 \exp(-\varepsilon/\varepsilon_0)$ (the quantity ε_0 differs for the electron and ion components).

In this way, a statistical mechanism of particle acceleration by turbulent oscillations becomes highly effective under solar flare conditions.

Undoubtedly, this investigation does not solve the problems of the solar-flare current-layer theory, related to plasma astrophysics. In particular, an accurate solution is required to the problem of finding an equilibrium function of the electron distribution in the turbulent plasma of the current layer, on the behaviour of which the estimates of the number of electrons taking part in high-frequency plasmon generation, depend. The problems of a turbulent plasma emission in a current layer, the conditions of its escape from the flare region and also the calculation of the large-scale instabilities of a plasma layer, which can bring about the disruption of its structure and the turbulization regime, requires a separate investigation.

To conclude, let us turn to the question of possible physical phenomena, generated as a result of energetic electron propagating from the acceleration region — the current layer — in the plasma surrounding a flare. The problems of flare plasma heating by energetic electrons and of the change of the spectrum of energetic electrons when they penetrate into a dense plasma, were examined by Syrovatskii and Shmeleva (1972). The accelerated electrons moving in a dense plasma, generate plasma oscillations as a result of Cherenkov's effect and at some distance from the current layer the plasma must certainly be turbulent. That is why the calculation of Stark's effect due to plasma oscillations (Tomozov, 1973) on the behaviour of hydrogen lines is of interest for interpreting the spectral observations of flares.

Electric fields of ion-sound pulsations display an effect on lines, which have no central Stark component—H-beta, H-delta, etc., thus, the decrease in the intensity in the centre of the line, owing to satellite divergence, must be observed; the Lengmour plasmons define the behaviour of lines with the central Stark component—H-alpha, H-gamma. For Stark's turbulent effect to take place, the average intensity of the electric field of the turbulent oscillations must exceed the intensity of Holtsmark's field. Accurate observations of the behaviour of the hydrogen line contours during the explosive phase of a flare may, in principle, apparently allow one to obtain information on the nature and intensity of the plasma turbulence. The zone of quasi-stationary turbulence in the neighbourhood of the current layer where Stark's effect on the plasma oscillations may be displayed, must be long enough ($10^8 - 10^9$ cm) to be observable by spectrographic methods.

The observations of polarized solar-flare X-ray emissions by a number of satellites of the "Intercosmos" series, bearing direct evidence of the propagation of anisotropic electron beams in the lower solar corona and allowing for some conclusions to be drawn about the flare structure, are of great interest (Tindo et al., 1971; Lifshits et al., 1972). The energetic electrons, leaving the acceleration region, and controlled by the magnetic fields of the active region, are decelerated in a dense plasma, emitting X-ray quanta. The interpretation of polarization observations of solar-flare X-ray emissions requires the calculation of non-linear mechanisms of electron beam stabilization (Lifshits, Tomozov, 1973) under the conditions of the lower corona. It was shown that an electron beam stabilized by non-linear processes with an average energy of 15 keV can cover a distance in the solar corona comparable with the free path of an individual electron. The forming of anisotropic electron flows is connected with the magnetic field topology in the neighbourhood of the acceleration region, the current layer of the flare.

Thus, a calculation of the plasma instabilities in the current layer and the surrounding plasma, their influence on the processes of heating, acceleration, propagation and emission of particles permits the whole complicated complex of interacting physical mechanisms, which cause a solar flare, to be investigated from a single point of view and progress to be made in understanding this most powerful phenomenon of solar activity.

References

BUNEMANN, O. (1959): Phys. Rev., *115*, 503.

FRIEDMAN, M. and HAMBERGER, S. M. (1969): Solar Phys., *8*, 104.

GOPASJUK, S. I., OGIR, M. E., SEVERNY, A. B., and SHAPOSHNIKOVA, E. F. (1963): Izv. KrAO, *29*, 15.

KADOMTSEV, B. B. (1964): Problemy teorii plasmy, *4*, 188.

KOLMOGOROV, A. N. (1941): Dokl. AN USSR, *30*, 299.

KAPLAN, S. A. and TSYTOVICH, V. N. (1972): Plasmennaya astrofisika. Moscow, Nauka.

LANDAU, L. D. and LIFSHITS, E. M. (1954): Mekhanika sploshnykh sred.

LIFSHITS, M. A., BANIN, V. G., VALNICHEK, B. et al. (1972): Preprint IZMIRAN, No. 24.

LIFSHITS, M. A. and TOMOZOV, V. M. (1973): Astron. Zh., *51*,

SEVERNY, A. B. (1958): Izv. KrAO, *20*, 22.

SEVERNY, A. B. and STESHENKO, N. V. (1969): Materialy mezhdunarodnogo seminara po solnechno-zemnoi fizike. Vol. 1. KrAO.

SVESTKA, Z. (1970): Solar Phys., *13*, 471.

SWEET, P. A. (1969): Ann. Rev. Astron. Atrophys., *7*, 149.

SYROVATSKII, S. I. (1966): Astron. Zh., *43*, 340.

SYROVATSKII, S. I. (1971a): JETP, *60*, 1727.

SYROVATSKII, S. I. (1971b): Trudy mezhdunarodnogo seminara po probleme "Generaziya kosmicheskikh luchei na Solntse".

SYROVATSKII, S. I. (1972): Preprint No. 1, P. N. Lebedev Phys. Inst., Moscow.

SYROVATSKII, S. I. and SHMELEVA, O. P. (1972): Astron. Zh., *49*, 334.

TINDO, I. P., IVANOV, V. D., MANDELSHTAM, S. L., and SHURYGIN, A. I. (1971): Preprint, P. N. Lebedev Phys. Inst.; Solar Phys., *24*, 429 (1972).

TOMOZOV, V. M. (1971): Astron. Zh., *48*, 556.

TOMOZOV, V. M. (1972a): Astron. Zh., *49*, 802.

TOMOZOV, V. M. (1972b): Astron. Zh., *49*, 1069.

TOMOZOV, V. M. (1973): Astron. Tsyrk., No. 749, 1.

TSYTOVICH, V. N. (1966): UFN, *89*, 89.

TSYTOVICH, V. N. (1967): Nelineinye effekty v plasme. Nauka.

TSYTOVICH, V. N. (1971): Teoriya turbulentnoi plasmy. Atomizdat.