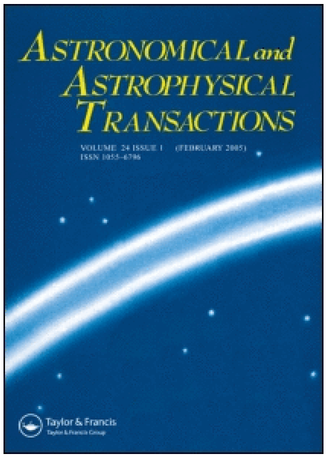

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UNSTEADY STATE OF TURBULENT CURRENT SHEETS OF FLARES

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The stability of the turbulent current sheet of a flare is analysed. It is argued that the equilibrium state of the current sheet is extremely unstable relative to some group of processes: dissipative instabilities of tearing type, MHD-instabilities of line pinches, overheating of the turbulent plasma and threshold dependence of conductivity on the current value. The final state of the flare current sheet has to be an extremely inhomogenious layer, consisting of numerous clusters of bad turbulent low conductive domains and good normal ones. Current propagation in this medium is a percolation process with its fundamental properties: a threshold regime of current dissipation which explains the threshold character of the flare phenomenon itself, a universal power spectrum of statistical dependence on the flare parameters, and a universal power energetic spectrum for accelerated high-energy particles.

KEY WORDS Solar flares, turbulent current sheets, the stability

1 INTRODUCTION

This investigation has its source in the numerous discussions with my teachers Prof. S. B. Pikel'ner and Prof. S. A. Kaplan on the problem of a flare's current sheet steady state. In spite of our attempts, we, like other investigators, did not answer this question – all versions of solutions meet with numerous instabilities of the current sheet itself. My teachers supposed that this instability is not a random uncomfortable defect, caused by an incorrect choice of boundary conditions or something similar. They expected that it is on the basis of the flare processes and as a result of this contradiction we can understand new and unusual physics with radical progress in our understanding of the flare process as whole. Unfortunately we had no time to finish it together. In this report I would like to suggest a possible solution of this problem in the way of current percolation through a randomly inhomogeneous current sheet, arising as a result instabilities.

At the present time the nature of solar flares (and similar phenomena in flare stars, cataclysmic variables, accreting relativistic binaries and active galactic nuclei) is not a mystery. Numerous physical observations and numerical experiments, and theoretical models lead to the same conclusion – the source of energy is a magnetic field $W_f = \Delta\left(\frac{H^2}{8\pi}\right)$ and the flare itself is due to extremely fast conversion of the magnetic energy into acceleration of particles and anomalous heating. The magnetic energy conversion may be described as the well-known process of Joule dissipation with power $Q = \frac{j^2}{\sigma}$ where $j = \left(\frac{c}{4\pi}\right) \cdot \mathrm{rot}\, \mathbf{H} \propto \frac{\Delta H}{a}$ is the current density, a is the thickness of the current region, and σ is the electrical conductivity of the plasma in the dissipation region. This description leads inevitably to the natural conclusion – for an explanation of a great observed power Q of the flare process we are forced to suggest that two conditions are realized in the flare region:

(1) extremely small thickness of the magnetic gradient region ($a \ll L$), where L is the scale of the magnetic structure in the object. This means that the current structure has to be similar to a thick sheet (flat, cylindrical, torroidal, ...);

(2) extremely low conductivity σ_{flare} (high resistance) in the dissipation region $\sigma_{\mathrm{flare}} = \sigma_* \ll \sigma_0$

(σ_* is the anomalous conductivity, σ_0 the "normal" Coulomb conductivity). This condition in the high temperature plasma of a corona (solar, stellar, accreted) may be satisfied in only one way (Kaplan *et al.*, 1977) – development of plasma turbulence, with strong interaction between current electrons and plasma waves. The second condition is not independent of the first one – a high current velocity of electrons leads to plasma turbulence if it is higher than a threshold value. In other words, only one state is able to provide the flare's energy release – *a thick turbulent current sheet.*

But the next group of questions (about the mechanisms of energy release and acceleration of particles) is in a more dubious and debateable state.

The first group of models based on the MHD-flow approach to flare processes (Sweet, 1969; Petchek, 1964; Parker, 1966) was made for the limiting case of two-dimensional geometry with reconnection in a very compact region of the singular X-point of the magnetic field. It was shown that a stationary solution of MHD-flow is possible with a reconnection in the singular point and shock waves in the neighbourhood, which convert the energy of the external disturbance into energy of plasma motion and heating.

Another magnetostatic approach was proposed by Syrovatsky (1981) and his group. He showed that in the two-dimensional geometry with a singular point any external disturbances will reconstruct the magnetic field in the neighbourhood of the singular point with multiple duplication of itself. A new configuration will form with a neutral line containing a strong current in this singular layer. The resulting state isn't a stationary state, but it is a dynamic redistribution of the fields and currents with Alfven times. The authors suggested that abnormal dissipation in the layer, caused by plasma turbulence generation, will lead to any steady state pattern and to flows similar to the Petcheck–Sweet consideration.

The next step, taking into account the longitudinal magnetic field in three-dimensional geometry, changed this pattern to an equilibrium state of an almost force-free magnetic field with a magnetic shear

$$\Theta = \frac{\partial\,(H_\xi/H_\psi)}{\partial z} \neq 0.$$

This configuration was considered by Spicer (1977) as a steady state which includes some elements of the Syrovatsky approach (singular line and separatrices) and the Petcheck–Sweet approach (MHD flow with reconnection). This scheme suggests a very small thickness of current sheet (shear region) necessary for plasma turbulence generation. For the standard ion-sound wave generation it leads to a lower threshold of electron velocity in the current $u = j/ne > u_{\rm cr} = c_{S_i}$; we have an upper limit of the current sheet size:

$$a < a_{\rm cr} = \frac{c}{4\pi}\frac{\Delta H}{ne\,u_{\rm cr}} = 2\times 10^5\ {\rm cm}\ \Delta H_{2.5}\, n_8^{-1}\, T_8^{-1/2}$$

(here we use the standard designation $Y_N = Y/10^N$). It is evident that for higher density in the chromosphere and for higher threshold on the current velocity (Buneman mode, for example) we have a stronger limit on the size of the current sheet $a < 10^2$–10^3 cm.

There is a problem of the catastrophic transition of dispersed currents to the concentrated state in this approach. In principle, possible ways for this transition were proposed by Priest (1982); nevertheless up to now in the problem of flare origin these difficult questions are still open.

2 PROBLEM OF THE STABILITY OF THE TURBULENT CURRENT SHEET

After such successful progress in the understanding of the equilibrium state of the flare current sheet it is natural to ask the next question: is the equilibrium state stable, and what happens with the flare current sheet if it isn't? In this way we will come to the grievous conclusion: the well-known equilibrium state of a turbulent current sheet is not stable and the previous pattern of the flare cannot be considered as final. The instability of the turbulent current sheet forces us to reconsider radically our approach to flare energy release and to obtain a new equilibrium and stable state by taking into account the dynamical instability property. First of all let us consider the main instabilities of a turbulent current sheet of a flare:

2.1 Tearing Mode Instability

These instabilities (Furth *et al.*, 1963) lead to a redistribution of a flat current in the plasma with finite conductivity into a set of parallel current strings (see Figure 1). The most unstable mode (tearing) has a time of development $\tau_t \approx \tau_A\,{\rm Re}_H^{1/2}$, where $\tau_A = a/V_A \approx 10^{(-5)-(-3)}$ sec – the Alfven time, $\tau_d = a^2/(c^2/4\pi\sigma)$ is the diffusion time, ${\rm Re}_H = \tau_d/\tau_A$ is the magnetic Reynolds number.

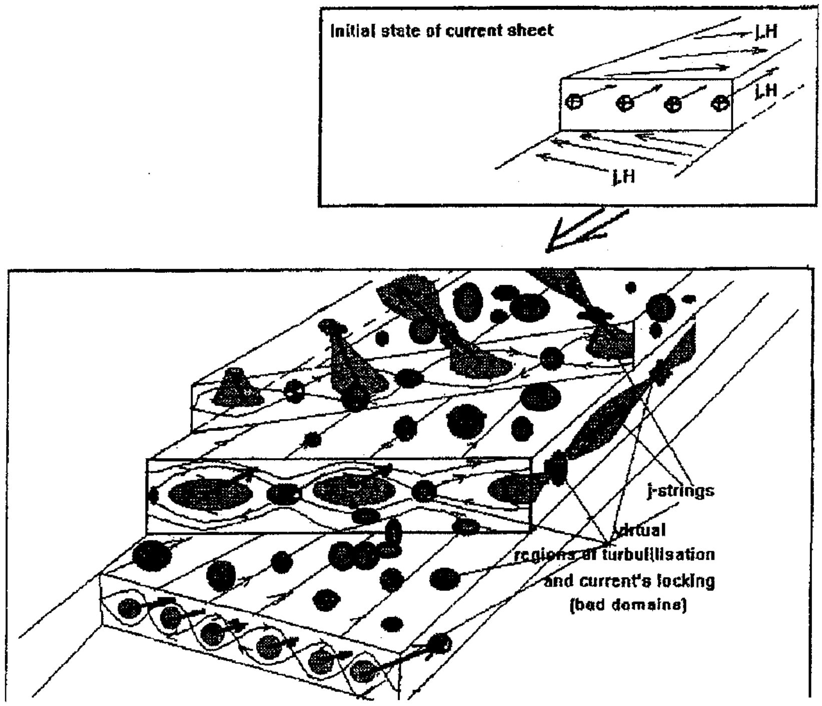

Figure 1 Instabilities of the turbulent current sheet and structure of "domains" of sheet plasma.

For standard parameters of the current sheet $H_{2.5}$, n_8, T_6 this corresponds to a time of flat current sheet splitting into a string system in about 10–100 s for column conductivity and 1–10 ms for turbulent conductivity. The tearing mode is very important for our consideration since it has no threshold in flare conditions and may not be suppressed (stabilization by fast plasma evacuation from the sheet proposed by Bulanov and Sasorov (1978) doesn't act for a thick current sheet of flares). In the non-linear state of the tearing-mode the opposite process of coalescence instability takes place. This leads to sticking together of numerous thick elementary current strings into a number of strong ones with additional energy release on the same tearing time scale. The final structure is determined by competition between the coalescence of magnetic islands (current strings) and plasma ejection from the current sheet by magnetic tension with Alfven time (10–1000 ms).

2.2 Pinch Type Instabilities (Sausage, Kink, ...)

Current strings are in the Z-pinch state with external pressure of azimuthal fields H_φ balanced by inner pressure of the plasma $n_* kT_*$ and longitudinal field $H_{\|}$. This state is unstable with respect to a set of MHD fast instabilities (Priest, 1982) (sausage, kink and other more complicated ones) which result in the local current string collapsing and breaking at numerous points along the string with electrostatic double layer generation (in sausage mode) and/or a kink of the current string with straightening of its braided field lines (in a kink mode). There is some stabilization of the pinch mode by the influence of the longitudinal magnetic field (the criteria of Kruskal-Shafranov (Shafranov, 1957; Kruskal *et al.*, 1954) on the length of pinch $H_{\|}/H_{\perp} > \Lambda_{\rm cr} = \alpha \cdot (l/a)$). However this stabilization is not effective for thick long current strings ($l/a > 10^{2-3}$) produced by the tearing mode in a turbulent current sheet of a solar flare.

The next two processes 2.3, 2.4 disrupt the steady state of the current sheet under the action of the specific property of plasma turbulence: a very narrow threshold of plasma turbulence generation – the value of the directed velocity in the current has to exceed the phase velocity of the excited waves $u/V_{\rm ph} > 1$. For an opposite sign of the ratio (even for ($u/V_{\rm ph} - 1 \ll 1$) we have a very fast dissipation of plasma waves in the same plasma. It may be easily seen from the example with growth rate of ion-sound wave instability in a plasma with longitudinal current (Mikhailovskii, 1974)

$$\gamma_s = -\left(\frac{\pi}{8}\right)\omega_s\left\{\frac{(c_{s_i} - u)}{c_{s_i}} + \left(\frac{T_e}{T_i}\right)^{3/2}\exp(-T_e/2T_i)\right\}$$

where the first part is caused by electron decrement/increment and the second one is the ion-sound dissipation by Landau damping of the thermal ions.

2.3 Overheating of Turbulent Regions in the Current Sheet

Turbulent plasma heating by anomalous current dissipation is another reason for the unsteady state of the current sheet (Pustil'nik, 1977) This phenomenon is caused by the fast heating of the plasma during extremely an short time $\tau_{T_e} = \zeta \cdot \nu_{\rm eff}^{-1} \approx 10^{3-4}\Omega_{0_i}^{-1} \approx 1$ ms. This leads to a changing of the current ratio during this time from $\frac{u}{V_{T_e}>1}$ (necessary for plasma wave generation) to $\frac{u}{V_{T_e}} < 1$ with very fast plasma wave dissipation by Landau absorption of plasma waves by thermal electrons (the time is the order of some $\frac{u}{V_{\rm T_e}} < 1$). The result of this heating is the stopping of local plasma turbulence and the transition to a normal high conductivity state. During the next stage this region will cool by the collisionless hot electron thermal front and will turn back into the initial anomalous turbulent state (the anomalous thermoconductivity will restore the turbulent state after short cooling times $\tau_T \approx \xi\left(\frac{l_{\|}}{V_{\rm th}}\right) \approx$ 1–100ms. The next anomalous heating in the turbulent state will repeat these local transitions in the pulsation regime and will create numerous normal and turbulent anomalous regions in the current sheet.

2.4 Splitting of the Current Sheet at the Place of Conductivity Discontinuity

The process of fast plasma wave generation in the turbulent regime leads to the rapid increase of anomalous resistance in the turbulent regime and creates a break of conductivity [σ] at the boundary of the normal-anomalous state (Pustil'nik, 1980).

Since the current and magnetic field structure redistribution caused by the slower diffusion process and at the first stage current is continuous, it leads to a break of the electric field $[E] = \frac{j}{[\sigma]}$. This break of the electric field leads to the diffusion redistribution of current structure with fast decrease of current density in the turbulent region under u_{cr} and to fast increase of the current in the external region up to a value exceeding u_{cr} in the local neighbourhood of the boundary. In the first region with $u \leq u_{cr}$ plasma turbulence will disappear and this local layer turns into the normal state. In the other (external) one we have the opposite result with plasma turbulence and anomalous resistance generation. New breaks of the conductivity arise at the new boundary: normal–abnormal plasma, and it leads to a new splitting of the current sheet. The resulting final state is a dynamic equilibrium in the current sheet which contains numerous compact short-life turbulent and normal regions.

3 UNSTEADY STATE OF A TURBULENT CURRENT SHEET

As we have demonstrated above, the standard steady state of the current sheet is unstable and has to disrupt into numerous local, short-lived and small-scale domains of normal and abnormal plasmas. Current propagation in this state is not free flow, but is more similar to percolation processes through clusters of highly conductive elements in the background of low conductive domains. These domains form numerous clusters from virtual elements and current propagation through the flare current sheet has to be similar to percolation through a stochastic net of good and poor resistors with constant source of electric current. This process was studied in experiments (in superconductive ceramic samples (Vedernikov *et al.*, 1994)), in conductive graphite paper with random holes (Levinshtein *et al.*, 1976; Last and Thouless, 1971), in numerical simulations (Kirkpatrik, 1973) and in theoretical models (Render, 1983). But in the flare's current sheet the nature of this percolation current didn't take into account the model of energy release and particle acceleration. Physical processes in this percolation state are unlike standard current dissipation by the usual electron–ion collisions.

There are some additional effects of the current percolation in our situation – positive and negative feedback between elements caused by currents and dynamic redistribution of thermoconductive fluxes:

(1) Redistribution of the currents in the sheet as a result of permanent stochastic rebuilding of net resistors will change the current density in elements of the net and lead to induced turbulence with switch-on of plasma turbulence in a neighbourhood and switch-off in the initial one. This will lead to permanent transitions of the resistors in the net from the bad state to good and back.

(2) Thermoconductive flux from the heated turbulent elements will escape out into the surrounding cold plasma and will lead to changing of the threshold current value.

This very complex pattern with complex feedback between current propagation and plasma turbulence state in local domains may be described on the basis of elementary transition probabilities in the stochastic resistors net ($w_{1,2}$, $w_{2,1}$) with properties of resistors that depend on the local current value ($\sigma_1 = f(j)$), cross-connections between resistors ($\Sigma j_i = J$), and some delay effect ($\tau_{1,2} \neq 0$). The best approximation to this process is percolation with its characteristic of clusters fractality, dimensions, threshold percolation and infinite cluster disruption. Some general conclusion may founded from first principles of percolation theory (Feder, 1988):

(1) A fundamental property of a percolation process is the threshold dependence of global net conductivity on the density of bad elements and, hence, on current value:

$$\sigma \propto (I - I_{\rm cr})^{-\delta}.$$

The physical basis of this dependence is the condition of non-zero percolation probability P_∞ through an infinite cluster created when the probability of good elements exceeds the critical value

$$p_c \approx \begin{cases} 0.6 & \text{for } n = 2 \\ 0.31 & \text{for } n = 3 \end{cases}$$

where n is the dimension of the space of the cluster. This sharp transition is able to explain the mysterious explosive character of global current sheet rebuilding to the anomalous state – a result of current lock by the first infinite cluster of bad resistors. Another possibility connected with the percolation character of global conductivity is the explanation of the faint preflare heating, observed for many flare processes.

(2) Another general sequence of percolation process (Feder, 1988) is a universal power dependence of the statistical properties in global system on the characteristic of domains (scaling): $N(x) \propto x^{-k}$.

Here x is a parameter of the domain (size, amplitude,...). The exponents δ, k are determined by the fractal dimensions of the clusters, global dimensions of the system n and are

$$\delta = \begin{cases} 0.14 & \text{for } n = 2 \\ 0.4 & \text{for } n = 3 \end{cases}$$

and

$$k = \begin{cases} 1.6\text{–}1.9 & \text{for } n = 2 \\ 2.5 & \text{for } n = 3 \end{cases}$$

If we attempt to compare the general conclusions of a percolation approach with real flare observations in the solar atmosphere and flare stars we will obtain a remarkable correspondence: for all flare stars (red dwarfs of UV Ceti type) (Gershberg and Shahovskaya, 1983) and for different manifestations of solar flares in H_α, microwave bursts and type I metric noise storms (Merceier and Trottet, 1996), and hard X-ray solar bursts (Crosby *et al.*, 1992), there is the same statistical dependence of flare frequency and their energy $f(W)dW \propto W^{-\beta}$ with value of $\beta = 1.7$–1.8, similar to that expected from percolation theories. In the ideal situation we may obtain from this statistical dependence information up to minimal microflare, caused by the spike energy release in the local domain (or cluster of domains). Unfortunately, for the time being our progress in this direction is limited by the sensitivity of the astronomical instruments. The role of the percolation process and the fractal formation in the frequency-energy spectrum formation was successfully considered by Wentzel *et al.* (1992) in percolated active region formation from a convective zone and by Vlahos *et al.* (1995) in the fractal structure of magnetic elements over the active region. Our consideration is a continuation of this approach into the field of energy release in the current sheet itself.

4 ACCELERATION OF PARTICLES IN THE FRAGMENTED TURBULENT CURRENT SHEET

The fundamental property of the flares is the acceleration of the charged particles up to very high energies (Chupp, 1996). The energy spectrum of the accelerated particles is universally a power law $n_\varepsilon \propto \varepsilon^{-\gamma}$ with a slope $\gamma \approx 2$–3.

There are two standard approaches to particle acceleration:

(1) a turbulent boiler with "particle–plasmon" energy exchange (Kaplan and Tsytovich, 1973);

(2) direct run-away of the particles in a DC-field of the current sheet (Spicer, 1982).

The first one is able to explain the power law energy spectrum by turbulent diffusion in momentum space, but needs extremal assumptions about turbulent energy and is not able to explain the maximal observed energies of particles.

The second one may accelerate particles up to very high energy, but meets difficulties in the power spectrum explanation (the typical one for run-away particles is exponential). This approach doesn't take into account the fact that the motion of fast particles in a turbulent plasma is not direct run-away, but space diffusion, caused by effective elastic "particle-plasmon" scattering.

Taking into account the cluster structure of a turbulent current sheet with numerous "bad" resistors (which play the role of plasma double-layers and act as a compact line accelerator in a turbulent plasma) leads to a new possible approach, where "particle-plasmon" interaction and direct energy change in the DC-electric field are combined naturally. This approach leads both to a power energy spectrum and to high energy limits (Pustil'nik, 1978).

The physical reason for the spectrum formation is a universal power dependence of the scattering probability on the particle energy. It leads to a different length of the free path for particles with an opposite velocity direction relative to the electric field. As a result two diffusion fluxes are formed: the first is the standard one from the density gradient and the second is the specific flux caused by variation of kinetic parameters in the medium, similar to the modiffusion. We obtain for the second one that the energy of particles $\varepsilon = eEx$ as well as their number n_ε depend only on the distance x from the point of ejection of particles in a run-away state to the boundary of particle escape. This general connection leads to the "leakage-lifetime" relation with its power law character of the energy spectrum. As shown by Pustil'nik (1978), the resulting spectrum may be estimated from conservation of the diffusion flux

$$J_0 : J_X = D_\perp(\varepsilon_X)\left(\frac{\partial n_\varepsilon}{\partial \varepsilon} + 2\frac{n_\varepsilon}{\varepsilon}\right) \cdot eE = J_0.$$

For a stationary (on the average) state of the current sheet with the simplest geometry this leads naturally to a power law energy spectrum for ejected particles:

$$n_\varepsilon \propto \left(\frac{\varepsilon}{\varepsilon_T}\right)^{-2} e^{-\frac{\varepsilon}{\varepsilon_*}},$$

where ε_T is the thermal energy of the particles, $\varepsilon_* = v_T \cdot \left(\frac{\varepsilon_T^2}{eED_0}\right) \ll \varepsilon_T$, and $D_\perp = D_0 \left(\frac{\varepsilon}{\varepsilon_T}\right)^{5/2}$ is the space diffusion coefficient of a fast particle with energy ε in the field of plasma turbulence. Taking into account the three-dimensional distribution of the electric and magnetic field in the turbulent current sheet will influence the power law slope and may increase it up to $\gamma = 3$.

This means that the fine structure of the turbulent current sheet of clusters may be the basis for understanding not only the threshold regime of flare energy release and its universal statistical properties, but may allow a natural explanation of another property of flare processes – the universal power spectrum of the accelerated particles with a close slope in a wide class of flare objects.

For more progress in the percolation approach to flare energy release we need numerical simulations of the random resistive net taking account of the life-time effect and the high induction of magnetic fields in the normal domains in the sheet.

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