SH.1.5.24

Critical State of Current Percolation, Solar Flare Energy Release, Acceleration and Energy Spectrum

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Abstract

We consider energy release and cosmic ray acceleration in solar flares as result of "phase transition" in turbulent current sheet to the flare state, caused by frustration of current's percolation. We show that numerous plasma instabilities in the flare's current sheet will form random network of resistors, containing clusters from numerous turbulent and normal domains and with current percolation through.

Principal conclusions of the percolation approach are: a) threshold character of energy release, b) universal power character of all distributions in network with cluster size (volume, number), what lead to the natural explanation of power law both for amplitude distribution of flares and energetic spectrum of accelerated particles, c) bursts-precursors near threshold of phase transition (frustration of percolation).

1 Introduction:

Energy release in the solar flares is the old ill problem of the solar physics. Situation is not dramatic at the first sight - we understand many basic processes of flare origin and we are able to describe it in some formal construction. First of all it is role of current sheet as energy engine of flare. The second is conclusion about principal role of the plasma turbulence generation in current sheet as necessary condition of flare itself. Really, giant energy output with rate $P \approx 10^{29 \div 30} erg / sec \propto {j_*}^2 r_*$ requires both very strong currents j_* and very high anomalous resistance r_*. We understand flare phenomena as phase transition in plasma of current sheet with jump-like increasing of the global kinetic coefficients (resistance, in first). This requirement may be satisfied only by sheet with current velocity exceeded waves velocity in plasma (ion sound, for example): $u = j/ne \geq c_s$. Direct sequence of this condition is excitation of strong plasma turbulence in the plasma of current sheet with anomalous resistance caused by current's electrons-plasma waves elastic scattering. Correspondent thickness of the sheet d is order of some Larmor ion radius: $d = \chi \rho_{H_i} = \chi \left(V_{T_i} / \Omega_{H_i} \right) \approx 10^5 \div 10^6 cm$ and is much smaller than its wide and length $d : l : L \cong 1 : 10^4 : 10^5$.

2 Non-Steady State of the Turbulent Current Sheet:

This strong requirement to thickness of the turbulent current sheet is a "hidden" factor of numerous models of flare energy release, what make it vulnerable. In really, analysis of equilibrium of this configuration shows that it will be disrupted immediately into numerous fragments during very short time in result of some chain of instabilities. We list here shortly part of them and describe sequences of its action:

1. Dissipate modes (like to tearing, ripple,) are caused by a field reconnection from opposite sides of current sheet and split initially flat current into numerous longitudinal currents strings (Furth et al., 1963) during time $\tau_d = \tau_A^n \tau_d^{1-n}$ (where n=1/2 1/3 for different modes, τ_A is Alfven time, τ_D is diffusion time). For solar flare conditions $\tau_A \approx 10^{-3}$ sec, $\tau_D \approx 0.1 \div 1$ sec and time of current splitting $\tau_t \approx 0.01 \div 0.1 sec$ much shorter then flare $\tau_{flare} \approx 10 \div 100\, sec$.

2. Formed current strings are in a pinch-like equilibrium and in one's turn they are disrupted by MHD and dissipate instabilities as sausage, kink, helical modes (Kruskal, Shwarzschild, 1954). These instabilities disrupt strings in numerous local regions (with some Alfven time τ_A) into points of current

collapse (with strong plasma turbulence and electrostatic double layers generation). Resulted current structure is changed from any smooth and continuous into many entangled strings with discontinuous distribution of currents in it (see, for example, results of J. Buchner (1988)). This configuration is like to structure of percolated system of currents in random resistor's network (see as example cis-polyacetylene long molecules with conductive (metallic) dopant (see Fig.1,a.)) with its threshold-like behavior of effective resistance of system as whole in dependence on dopant concentration (Fig.1,b).

3. Another reason of fast current and resistance redistribution into local elements with radical change of kinetic properties is threshold character of plasma wave generation by current - it depends on ratio of current velocity to phase velocity of waves (Mikhailovskii, 1975) as: $\gamma \propto \omega_{pl} \cdot (u - v_{pl}) / v_{pl} - \delta$ where $\omega_{pl}, V_{pl} = \omega_{pl} / k$ are plasma waves frequency and phase velocity, δ - decrement caused by influence of background thermal components. This threshold character of increment (and turbulence) leads to diffusion splitting of current sheet into layers of normal and turbulent plasma. Another manifestation of these threshold properties is effect of overheating of turbulent regions in the current sheet (Pustil'nik, 1981) with fast increasing of velocities of thermal electrons V_{T_e} and of plasma waves V_{pl} with decreasing of ratio $\eta = u / V_{pl}$ under threshold value. Following plasma turbulence dissipation by Landau damping leads to transition of the turbulent element to the normal state. Next current redistribution and plasma cooling will return ratio u / V_{pl} to more then critical one and restore plasma turbulence in this local region with next overheating. We see that turbulent current sheet has to be considered as random resistor's network with numerous turbulent and normal. Current propagation in this medium has to be described not as a classical current streaming in uniform matter, but as current percolation through random resistors.

3 Main Properties of Percolated Systems:

Percolation phenomena base on the propagation of any state through array/lattice with random character of bonds between sites (Stauffer, Aharony, 1992). Sites, connected with closest neighbors, form numerous clusters with properties determined by dimensions and geometry of array, and depended on correlation between bonds and sites, bonds and flux, lifetime of bonds. Main parameter, what causes behavior of percolated system is p - relative density (or probability) of sites which are able to conduct the state of propagation. If concentration of active medium is lower than some nonzero threshold value p_c - percolation is impossible. Resistor network with random distribution is typical percolated system and was investigated in this sense last 30 years (see review of Kirkpatrick (1973)). Turbulent current sheet in solar flares is very like to these case and main results of percolation theory may be used here directly.

Main parameter of percolated system is percolation threshold p_C, where p is probability of "good" resistor realization in random site. The percolation threshold p_C is that concentration at which at an infinity network appears in an infinity lattice. It is evident, that global properties of a system as whole change drastically when probability p is chanced in the region of percolation threshold. These aspects of percolation theory are called "critical phenomena". As it shown by numerous investigations (Stanley, 1971; Shklovskii, Efros, 1984; Shauffer, Aharony, 1992), these processes are in the basis of phase transition with change of kinetic properties of system. As it was shown by analytically (for special topological cases) and by numerical simulation for wide classes of dimensions, types of bonds and geometry, percolation near threshold has some universal properties:

1) Average density of points connected with infinity cluster P (percolation probability) depends on p (probability of "good" elements in network) as:

$$P = \begin{cases} = 0 & if\ p < p_C \\ \propto (p - p_C)^n & if\ p > p_C \end{cases}$$

2) All kinetic coefficients (and global conductivity of network) have jumps on the percolation threshold, too. They depend on value p in network as $r \propto r_* (p - p_C)^{-\alpha}$. Concrete value of percolation threshold p_c, critical exponents n and de pend on dimensions of network (2-D, 3-D, or more), geometry of lattices (honeycomb, square, triangular, diamond, Bethe-like with z nearest connections (without loops)), type of percolation (bond percolation or site percolation).

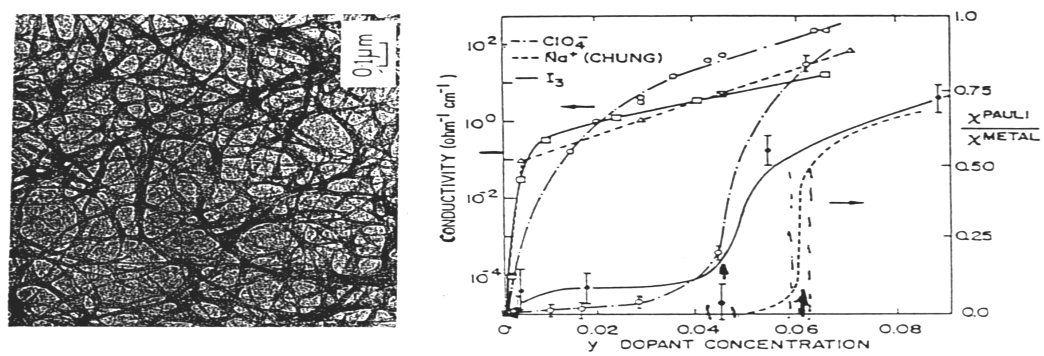
3) Another aspect what is interesting for solar flare application is fractal properties of clusters in random network on the threshold of percolation and above it (Feder, 1988). Effective mass M (number of elements) of cluster depends on its size L for percolated system as universal power law: $M(L) \propto L^D$, where D is fractal dimension (for example $D=91/48=1.89$ for simple square lattice and D 2.52 for cubic lattice). An interaction between sites changes fractal dimension of clusters, too.

4) Next effect of percolation nature of current in the turbulent current sheet what may be interesting for our consideration is divergence of amplitude of fluctuations near percolation threshold (Rammal et al., 1985). It increases to infinity as $A \propto (p - p_c)^{-\chi}$, where χ is new critical exponent and in general case is in the interval $\chi = 1 \div 2$ (for example of square network numerical simulation give $\chi \approx 1.12 \pm 0.02$). This property may be reason of precursor's manifestation near phase transition threshold.

4 Application of Percolation Approach to Turbulent Current Sheet:

What gives for us percolation approach to the current propagation in a turbulent current sheet?

a) First of all it allows us to understand of sudden character of flare in spite of slow preflare evolution of boundary conditions and currents in corona. Since density of turbulent domains ("bad resistors") is caused by current density $p \equiv f(j) = f(\Delta H / 4\pi ne)$, then slow evolution of current up to threshold of percolation will not change effective resistance of current sheet up to last moment. Only after disruption of last "good" bonds from normal plasma domain situation changes drastically with increasing of energy release by Joule heating $Q = J^2 R$ in many orders. Experimental investigations of current percolation through random resistors network were realized with long cis-polyacitelene molecular chains doped by conductive metal including. Fig.1,b show threshold character of dependence of effective resistance on y-dopant concentration with jump on 4 order during very small change of y (like to solar flares).



Some specific of percolation threshold in turbulent current sheet is caused by conservation of full electric current through network (in opposite to standard percolation simulation and experiments with conservation of global drop of electric potential on the boundaries). It will lead to the permanent redistribution of currents in net with avalanche transition of numerous elements into turbulent state near percolation threshold. Numerical simulation of current percolation in these specific conditions is in progress.

b) One of the "strangeness" of flares on the Sun and flare stars is existence of any universal power dependence between number of flares $N(W>W_0)$ with amplitude more then W_0 on its amplitude W_0 (Gershberg, Shahovskaya, 1983) $N(W > W_0) \propto W_0^{-s}$ with slope $s = 0.7 \div 1$. This dependence was discovered both for flare stars and for solar flares themselves (in hard X-ray, in H_α flares, in radio emission of flares (Crosby et al., 1993, Shimuzu, 1995, Kurochka, 1987, Mercie, Trotted, 1997). Our approach to flare energy dissipation as to percolation process on the threshold of percolation allows to explain statistical properties of flares from microflares up to flares itself from unique position of percolated system with "mass" of cluster of resistors depended on its sizes as power law.

From the other side, each "bad" resistor in correspondent cluster of current sheet is a "double layer" with high DC electric field $\vec{E}_i^* = \vec{j}_i r_*$ in it and works as a local accelerator up to energy $\varepsilon_i = eE_i^* a_*$. Resulted energy increase linearly with L-length of the way in E direction through network $\varepsilon = \sum \varepsilon_i \le eE^* L$. Resulted number of the particle with energy ε is caused by the relative number of clusters from turbulent "domains"-double layers, what accelerate particles $\delta N(\varepsilon = eE^* x) \propto \delta N(x) \propto x^{-\lambda} \propto \varepsilon^{-\lambda}$ (where slope γ caused by fractal density) and by diffusion percolation through clusters to boundaries. We see that fractal properties of percolated current sheet lead to power energetic spectrum of accelerated particles, too.

c) Last years observations show burst-like precursors preceded flare itself to 15-30 minutes. These events are observed in the hard X-ray by SMM (Tappin, 1991) and in radio narrow-band microwave emission (Pustil'nik et al., 1999; see SH.1.5.01). These prebursts are not something exotic for flare - as it was formulated by Tappin on the base of large sample of the SMM: "it is found that most (and possible all) X-ray flares are preceded by such bursts". These preflare bursts may be understood naturally as short-life finite fluctuation of global resistance of current sheet's network near threshold of percolation.

5 Conclusions:

Our consideration shows that using of percolation approach allows to understand solar flare phenomena from any universal position as phase transition in percolated random network. Specific of current and turbulence feedback in conditions of current conservation has not analogy in numerical simulations and experimental tests. It is mean that more correct numerical model have to include calculation of currents and voltages in lattice r_{ij} on the base of Kirchhoff's rules $I_i = \sum_j (V_j - V_i)/r_{ij}$; $I_0 = \sum_i I_i = const$ with threshold dependence of conductivity σ_{ij} on current I_{ij} : $\sigma_{ij} = \begin{cases} \sigma_0 & for \ I_{ij} < I_{cr} \\ \sigma_* << \sigma_0 & for \ I_{ij} \ge I_{cr} \end{cases}$.

Output parameter of the model is power of energy release $Q_* = \sum j_{ij}^2 r_{ij}^*$ in the network at whole. At the next step of numerical simulation it is need to take into account finite lifetime $_H$ of turbulent elements caused by its overheating, induction and permanent current redistribution in the net.

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