Pulsating and explosive energy release in solar flares

V.V. Zaitsev[1], S. Urpo[2], and A.V. Stepanov[3]

[1] Applied Physics Institute, Ulyanova 46, N.Novgorod 603600, Russia
[2] Metsähovi Radio Observatory, Metsähovintie 114, FIN-02540 Kylmälä, Finland
[3] Pulkovo observatory, St.Petersburg 196140, Russia

Radio and hard X-ray observations of solar flares reveal various time behaviour of the energy release. Fig.1 presents the time profile of 37 GHz emission of the event of 1991 May 11 observed in Metsähovi (Urpo et al., 1992) which starts from six 10 s pulses with enhanced amplitude at pre-flash phase and then an explosive (non-exponential) energy release occurs. The flux reaches its maximum value of about 530 sfu after four seconds. This event is similar to the flare of 2 November 1991 (Fig.2) observed at microwaves and in hard X-ray emission (Lee & Wang, 1998). Fine time structure, in particular pulse structure, interpreted usually in terms of two colliding current-currying loops (Sakai & de Jager, 1996). However recent X-ray and microwave data suggest that the flares can occur in simple loop. Flare origin in a single loop was considered by many authors (see, e.g. Alfven & Carlqvist, 1967; Zaitsev & Stepanov,1992; Sakai & de Jager, 1996). To explain pulses the MHD-oscillations of a magnetic loop have been used usually and only the influence of the variation of the loop magnetic field on the radiation modulation was considered (non-self-consistent approach). Moreover, such a models don't explain an explosion energy release.

We interpret here both pulsating and explosive energy releases in terms of single current loop and the advanced circuit model (Zaitsev & Stepanov, 1992). In accordance to this model the flare energy release occurs due to the penetration into the loop current channel of partially ionised plasma from the prominence or from the chromosphere. The loop resistance grows by many orders and effective current dissipation leads to the flare. In our self-consistent model the feedback of the magnetic field variations is taking on the energy release rate into account.

Loop Model

Let us consider a coronal magnetic loop with footpoints imbedded into the photosphere in the nodes of supergranulation cells and formed hence by the converging flows. The equivalent electric circuit for such a loop can be represented as three domains. The loop magnetic field and associated electric current are generated in the dynamo-region in the photosphere. In this region $\omega_e \gg \nu_{ea}$, $\omega_i \ll \nu_{ia}$ where ω_e and ω_i are gyrofrequencies of electrons and ions, ν_{ea} and ν_{ia} are the frequencies of electron-atom and ion-atom collisions. Consequently, the electrons are magnetised, and ions are entrained by the neutral component of the plasma. The radial electric field is excited due to charge imbalance, which together with the initial magnetic field B_z generates the Hall current and which, in turn, strengthens B_z. In this region the e.m.f. driven by the photospheric convection exists which supports the electric current flowing in the loop from one footpoint to the other and closes in the photosphere at the level $\tau_{5000} = 1$ where conductivity is isotropic (Zaitsev et al.,1998). In the coronal part plasma beta $\beta \ll 1$ and the loop magnetic field is force-free. The strengthening of the loop magnetic field continues until the field enhancement caused by the converging convective flow is compensated by the magnetic field diffusion due to the finite plasma conductivity in the dynamo-region. The electric currents in a flare loops usually of the order of $10^{11} - 10^{12}$ A and the magnetic field at the loop axis can be as high as 2000 G (Zaitsev et al., 1998).

Temporal dynamics of energy release

Penetration of partially ionised plasma driven by flute instability into the loop current channel gives an effective electric current dissipation caused by ion-atom collisions. Joule dissipation is described based on the generalised Ohm's law and the rate is (Zaitsev & Stepanov, 1992)

$$q = (\mathbf{E} + \frac{1}{c}\,\mathbf{V}\times\mathbf{B})\,\mathbf{j} = \frac{F^2}{nm_i c^2 \nu_{ia}}\,(\mathbf{j}\times\mathbf{B})^2\ \frac{\mathrm{ergs}}{\mathrm{cm^3 s}} \tag{1}$$

where F is the relative density of neutrals. In the steady-state situation the current-carrying coronal magnetic loop is force-free ($\mathbf{j}\times\mathbf{B} = 0$), for example

$$B_{\varphi 0} = \frac{r}{r_0}\frac{B_0}{1 + r^2/r_0^2},\ \ B_{z0} = \frac{B_0}{1 + r^2/r_0^2} \tag{2}$$

and no energy release exists. The flute instability disturbs the force-free situation. As a result the Ampere force appears

$$\frac{1}{c}\,\mathbf{j}\times\mathbf{B} = \frac{B_0^2 r}{2\pi r_0}\frac{e^{4y}(e^{2y}-1)}{(1+\frac{r^2}{r_0^2}e^{2y})^3}\,\mathbf{e_0} \tag{3}$$

where

$$y = -\frac{1}{r_0}\int_0^t (V_0(t') + \frac{F^2\rho}{nm_i\nu_{ia}}\frac{\partial V_0}{\partial t'})dt' \tag{4}$$

is the relative magnitude of the penetrating 'tang' of partially ionized plasma, n is the plasma density. Ampere force in the case of converging plasma flow ($V_0(t) < 0$) pushes the penetrating plasma out the current channel. At the same time as it follows from Eq. (1) the Ampere force produces strong Joule heating inside the current loop. The deviation of gas pressure in a loop is described by the formula

$$\frac{1}{\gamma - 1}\frac{dp}{dt} = \frac{F^2 B_0^4}{nm_i\nu_{ia}4\pi^2}\frac{r^2 e^{8y}(e^{2y}-1)^2}{r_0^4(1+\frac{r^2}{r_0^2}e^{2y})^6} \tag{5}$$

In the case when the velocity of penetrating plasma is small compared to the Alfven velocity ($|V_0| \ll V_A$) for the region of a magnetic flux tube near its axis ($r^2 \ll r_0^2$) we obtain the following equation for y:

$$\frac{\partial^3 y}{\partial\tau^3} + \varepsilon_1\frac{\partial^2 y}{\partial\tau^2} + \frac{\partial y}{\partial\tau} - 2\varepsilon\varepsilon_1 y\frac{\partial y}{\partial\tau} = \varepsilon y^2 \tag{6}$$

Here $t_c = 2(\gamma-1)F^2 \dfrac{n+n_a}{n}\dfrac{1}{\nu_{ia}}$, $t_a = \dfrac{r_0}{2V_A}$, $\tau = \dfrac{t}{t_A}$, $\varepsilon = \dfrac{t_c}{t_A}$, $\varepsilon_1 = \dfrac{\varepsilon}{2(\gamma-1)}$

The ratio of $\varepsilon = t_c/t_A$ is the parameter of the effectiveness of Joule heating and vary in wide interval depending on magnetic field value, tube radius as well as number density, temperature, and ionization rate of the plasma which penetrates into a loop. Parameter ε_1 describes the effectiveness of dissipation of MHD-oscillations of the current channel due to ion-atom collisions. From Eq. (5) it is follows that temporal dynamics of plasma Joule heating determines entirely by the function $y(t)$ which, in turn, determines from the Eq. (6). Depending on parameter $\varepsilon = t_c/t_A$ various regimes of the energy release are possible.

(i) Pulsating energy release. In the case of $y \ll 1$ we can omit the last term εy^2 as well as the term of $2\varepsilon\varepsilon_1 y\partial y/\partial\tau$ in Eq. (6). Supposing that $y = 0$ and the second derivative $\partial^2 y/\partial\tau^2 = 0$ for $\tau = 0$ and $\varepsilon_1 \ll 1$ we can take the integral from Eq. (6) and obtain the oscillating solution $y = A\sin\tau$, where $A = -V_0(0)/2V_A$. For the second approximation we obtain more exact formula:

$$y = A\sin\tau + \frac{\varepsilon A^2}{2}(\tau - \frac{4}{3}\sin\tau + \frac{1}{6}\sin 2\tau) \qquad (7)$$

We see from Eq. (7) that together with the fundamental mode the second harmonic in the oscillations appears. Just in this way we can explain double sub-peak structure observed in the flares on June 7, 1980 (Nakajima et al., 1983). Therewith the period of the fundamental mode is equal to $T = \pi r_0/V_A$.

(ii) Explosive energy release. From Eq. (7) we see that from the moment $\tau > 2/\varepsilon A$ the value of y and consequently gas pressure start grow in time. Physically it means that in the flux tube the gradient of gas pressure is equal to the Ampere force. In this case we can omit the third order derivative in Eq. (6) and rewrite it in the form: $\partial y/\partial\tau = \varepsilon y^2$. This equation has the explosive solution

$$y(\tau) = \frac{1}{(\tau_0 - \tau)\varepsilon} \qquad (8)$$

where $\tau_0 = 1/\varepsilon A$. Hence, characteristic time of explosive energy release is more than two times less then the duration of the pulsating phase as we can see in Fig.1.

Time-dependence of $y(t)$ determines also the temporal dynamics of charged particle acceleration by DC-electric fields in a current loop. It is well known that only the electric field directed along the magnetic field takes a part in the electron acceleration. From generalized Ohm's law one can find $E_\parallel = \bigtriangledown p_e \mathbf{B}/enB$. In vertical axial-symmetric magnetic flux tube with the convective plasma flow converging to the tube axis the we have

$$E_\parallel \approx \frac{1-F}{2-F}\frac{\sigma V_0 B^2}{e^2 nc(1+\alpha B^2)}\frac{B_r}{B} \qquad (9)$$

Here B_r is the radial component of the magnetic field, $B^2 = B_\varphi^2 + B_z^2$, $\alpha = \sigma F^2/(2 - F)c^2 n m_i \nu_{ia}$. For solar flare condition the estimations have shown that the acceleration rate is $\dot{N} \geq 10^{35}$ el/s at $E_D/E_\parallel \leq 26$ (E_D is Dreicer field) which gives $E_\parallel \geq 2\times10^{-3}$ V/cm for 200 keV electrons. From Eq. (9) it follows that such field value generates easily in the current loop with $B_r/B_\parallel \geq 10^{-3}$.

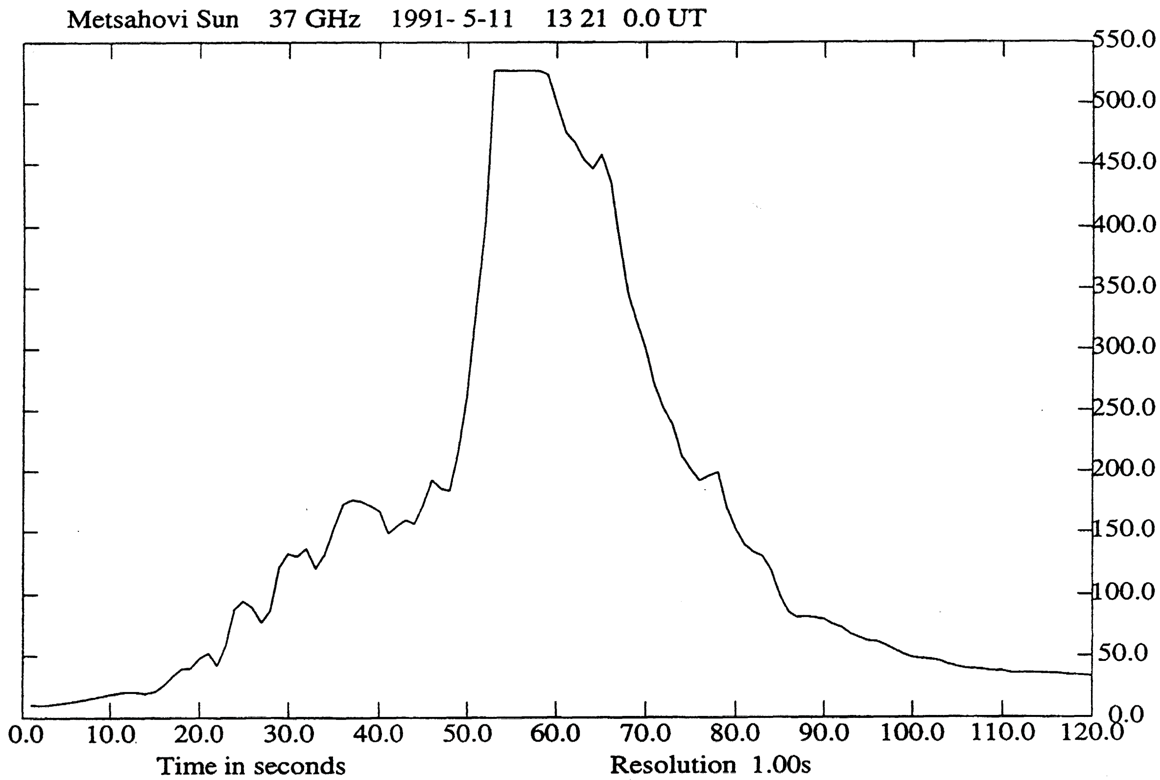

Figure 1: The time profile of 37 GHz emission on 1991 May 11, 1321 UT with enhanced pulses at pre-flash phase followed by the explosive phase.

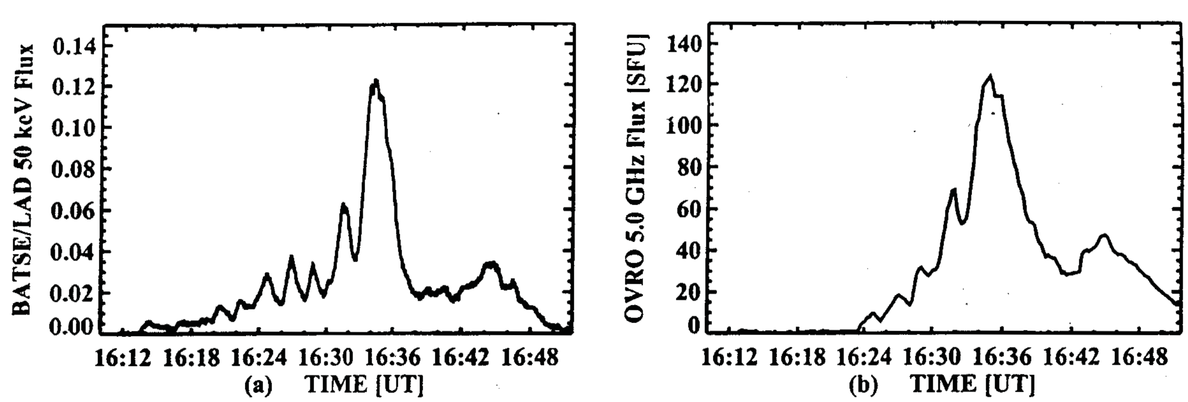

Figure 2: Flare of 2 November 1991, 1612 UT observed in hard X-rays (50 kev) and in 5 GHz radio emission (Lee & Wang, 1998)

Therefore the penetration of partially ionised plasma driven by flute instability into the current channel of a coronal magnetic loop gives simultaneously both plasma heating by Joule dissipation and electron acceleration in sub-Dreicer electric fields. As a result we can see radiation signatures of temporal dynamics of energy release described by Eqs. (7) and (8) in microwaves and in hard X-ray emission.

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