Acceleration of electrons in a large-scale electric field of coronal magnetic loops

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Introduction

The main part of the energy, released during solar and stellar flares, goes on the acceleration of energetic particles. By this the bulk of electrons and ions is accelerated up to the energies 100 KeV and 100 MeV respectively during the impulsive solar flares (Miller, et al., 1997). These values of energy correspond to the observed hard X-ray and γ - ray emissions in lines. Besides, γ - ray emission in continuum and the emission observed sometimes during neutral pions dissociation indicate that the energy of electrons and ions in a flare can reach 10 MeV and 1 GeV respectively. If one will suppose that hard X-ray emission of a flare occurs as a result of bremsstrahlung emission of fast electrons entering the chromosphere (a thick-target non-thermal model) (Emslie, et al., 1981; McClymont and Canfield, 1986; Canfield and Gayley, 1987; Mariska, et al., 1989), then it follows that the impulsive flare should produce energetic electrons with the energies $\varepsilon > 20$ KeV during the time $10 - -100$ s with the production rate of about $\dot{N} = 10^{37}$ s^{-1}. Therefore, the rate of the energy release in this case is about $\dot{\mathcal{E}}_e(\varepsilon > 20 \text{ KeV}) \approx 3 \cdot 10^{29}$ erg $\cdot$ s^{-1} during 100 s. This corresponds to a total energy of electrons $\mathcal{E}_e(\varepsilon > 20 \text{ KeV}) \approx 3 \cdot 10^{31}$ erg and a total number of electrons $N_e(\varepsilon > 20 \text{ KeV}) \approx 10^{39}$. Necessary value of the electrons acceleration rate decreases if one will suppose that the spectrum of hard X-ray emission with the energy $\varepsilon < 30$ KeV is generated by a hot plasma with the corresponding temperature $T \approx 3 \cdot 10^7$ K, whereas the emission of higher energies is produced by fast electrons with a power-law spectrum. This is a hybrid thermal/non-thermal model by Holman and Benka (1992). In this case necessary energetic electrons ($\varepsilon > 20$ KeV) production rate decreases up to $\dot{N} = 2 \cdot 10^{35}$ s^{-1} for the injection time about 100 s. This gives $N_e(\varepsilon > 20 \text{ KeV}) \approx 2 \cdot 10^{37}$, $\dot{\mathcal{E}}_e(\varepsilon > 20 \text{ KeV}) \approx 6 \cdot 10^{27}$ erg $\cdot$ s^{-1} or $\mathcal{E}_e(\varepsilon > 20 \text{ KeV}) \approx 6 \cdot 10^{29}$ erg.

Taking account of a well correlation of impulsive flares with coronal magnetic loops, let us consider acceleration of electrons by a large-scale electric field generated during a convective motion of a photospheric plasma in a coronal magnetic loop's foot-points. A coronal magnetic loop can accumulate an amount of energy (up to $5 \cdot 10^{32}$ erg), sufficient even for the explanation of the energy release of a large flare. This energy is accumulated in a non-potential part of a magnetic field, appearing as a result of a high electric current (up to $3 \cdot 10^{12}$ A), running along a loop from one its foot-point to an other through the coronal part of the loop and upper layers of the photosphere (Zaitsev, et al., 1998). On the red dwarf stars free energy of current-carrying magnetic loops can reach values of $3 \cdot 10^{36}$ erg.

Acceleration region: Chromosphere or Corona

In order to provide the fluxes of fast electrons observed during the flares a large amount of particles should be involved into a regime of acceleration. What could appear to be a source of these particles in the case of the acceleration taking place in a coronal magnetic loop? The total amount of particles in a flaring magnetic loop in the case of its length $(1 \div 5) \cdot 10^9$ cm, cross-section 10^{18} cm^2 and plasma density 10^{10} cm^{-3} inside is $(1 \div 5) \cdot 10^{37}$. If we take into account the fact that any realistic mechanism of acceleration in plasma accelerates only a small part of a total amount of particles, then the number of accelerated electrons appears to be insufficient for the explanation of observed fluxes of energetic particles even in the most suitable case when a hybrid thermal/non-thermal model of hard X-ray emission generation ($N_e \approx 2 \cdot 10^{37}$) is realized. Total amount of electrons in a coronal part of a magnetic loop is insufficient for providing necessary acceleration regime.

For a magnetic loop there exist in principle two important possible sources, providing a sufficient amount of particles for the acceleration process. Firstly, this is a chromospheric part of the loop, where in the heights interval from the temperature minimum up to the transition (chromosphere-corona) region about $5 \cdot 10^{40}$ particles is contained. This estimation is correct for the case of the loop's cross-section near a foot-point about 10^{18} cm^2 or even less, if one will take into account the increase of a magnetic loop's cross-section with a height. For the case of particle acceleration taking place in a chromospheric part of a magnetic loop the total amount of particles is quite sufficient for providing the acceleration rates discussed above. The second possibility of enriching of a magnetic loop with the particles during a flare appears in the case when the said loop interacts with a prominence. In this situation the flare is initiated by a flute instability causing a penetration of a dense plasma of a prominence into the current channel of the loop. The number of particles provided by the prominence during the flare ($t_f \approx 100$ s) can be estimated as $N = 2\pi R_0 r_t n_p V_p t_f$, where $r_t \approx 5 \cdot 10^8$ cm is a thickness of the tongue of prominence plasma penetrating into the current channel, n_p – plasma number density in the prominence, and $V_t \approx V_{Ti} \sim 2 \cdot 10^6 \mathrm{cm} \cdot \mathrm{s}^{-1}$ – characteristic velocity of plasma penetration through the loop's surface into the current channel (this velocity is taken to be equal to the ions thermal velocity in the case of $T = 5 \cdot 10^4$ K). For the above parameters we obtain $N \approx 10^{38}$. This exceeds about an order the value of N necessary for the hybrid (thermal/non-thermal) model, but a few times less then N in the thick-target non-thermal model of hard X-ray emission. Therefore, as a conclusion it follows that to provide particle acceleration mechanisms in the most powerful solar flares with a sufficient total number of particles the most appropriate location of the acceleration region is in a chromospheric part of a coronal magnetic loop. Whereas for the flares of lower energy release the acceleration region can be localized in the vicinity of the top of a loop, and necessary amount of particles can be provided by a plasma of a prominence, penetrating the loop.

Acceleration Mechanism

To explain the appearance of a large amount of fast particles during solar flares a number of concrete mechanisms of particle acceleration was proposed. These mechanisms could be separated on three main classes: 1) stochastic acceleration by waves; 2) acceleration by shockwaves; 3) direct (DC) electric field acceleration. The easiest way to accelerate a particle, probably, is to accelerate it directly in a region of energy release of a flare. This way is called as a DC electric field acceleration. As an accelerating electric field here appear a large-scale electric field **E** of a coronal magnetic loop. By this, in the case of a presence of a magnetic field **B** $(|\mathbf{B}| > |\mathbf{E}|)$ in a plasma particles will be accelerated by a projection of electric field onto a magnetic one $E_{\|} = \dfrac{\mathbf{EB}}{|\,\mathbf{B}\,|}$. If the value of the longitudinal component of the electric field $E_{\|}$ is less then the Dreiser's field: $E_D = \dfrac{e\Lambda\omega_p^2}{V_{Te}}$, then in the acceleration process (runaway) there will be involved only the electrons with velocities $v > (E_D/E_{\|})^{1/2}V_{Te}$, where V_{Te} is a thermal velocity of electrons, Λ – Coulomb logarithm, ω_p – Lengmure electron frequency, e – the electron's charge. Kinetic theory yields the following formula for the runaway production rate (Knoepfel and Strong, 1979):

$$\dot{N}[\text{ s}^{-1}] = 0.35 n\nu_e V_a x^{3/8} exp\left(-\sqrt{2x} - \frac{x}{4}\right), \tag{1}$$

where $\nu_e = \dfrac{5.5n\Lambda}{T^{3/2}}$ is effective frequency of electron-ion collisions, $x = \dfrac{E_D}{E_{\|}}$, V_a – volume of the acceleration region.

In a coronal part of a steady-state magnetic current-carrying loop with $I = 10^{12}$ A, $R_0 = 5 \cdot 10^8$ cm, $n = 10^{10}$ cm^{-3}, and $T = 10^6 \div 10^7$ K the electric field $E_{\|}$ is too small to produce an observable acceleration of particles ($E_D/E_{\|} > 200$). The highest values of electric field are generated in a dynamo-region in the foot-points of a magnetic loop, where charge separation, caused by a convective flow of a photospheric plasma and different interaction of electrons and ions with a magnetic field of magnetic tube takes place. In this case a longitudinal component of the electric field is (Zaitsev and Khodachenko, 1997)

$$E_{\|} = \frac{(1-F)\sigma V_r B^2}{(2-F)enc^2(1+\alpha B^2)}\left(\frac{B_r}{B}\right), \tag{2}$$

where $F = \dfrac{n_a m_a}{(n_a m_a + n m_i)}$ is relative density of neutrals, n – electrons number density, $\sigma = \dfrac{e^2 n}{m_e(\nu_{ei} + \nu_{ea})}$ – Coulomb conductivity, $\alpha = \dfrac{\sigma F^2}{(2-F)c^2 n m_i \nu_{ia}}$, ν_{ia} – effective frequency of ion-neutral collisions, B_r – radial component of the magnetic field, which is assumed to be small ($B_r \ll B$). Therefore in a vertical magnetic tube with a converging radial flow of partially ionized photospheric plasma and $B_r = 0$ there is no a DC electric field acceleration. Acceleration of electrons appears during a flute instability development in a base of a magnetic tube when entering a current channel plasma tongue is inhomogeneous with height. In this case it is possible to show that a radial component of a magnetic field is generated

$$B_r = B\frac{\partial}{\partial z}\int_0^t V(t')dt' \tag{3}$$

and a longitudinal electric field, causing acceleration of electrons, appears.

The electric field $E_{\|}$ increases during the heating of foot-points of a loop, because the heating increases σ and decreases α. By this the relative density of neutrals F decreases too. In the case of a significant heating when an almost complete ionization takes place in the tube ($F \ll 1$) the value $\alpha B^2 \ll 1$, and the formula (2) simplifies:

$$E_{\|} = \frac{1}{2}\frac{V_r}{c}B\left(\frac{\omega_e}{\nu_{ei}}\right)\frac{B_r}{B}, \qquad (\alpha B^2 \ll 1). \tag{4}$$

In the opposite case, when the condition $\alpha B^2 \gg 1$ is realized, formula (2) yields

$$E_{\|} = \frac{1-F}{F^2}\frac{m_i V_r \nu_{ia}}{e}\frac{B_r}{B}, \qquad (\alpha B^2 \gg 1) \tag{5}$$

Note that for $V_r < 0$ the component $E_{\|}$ has a downward direction and accelerates electrons towards the corona, whereas ions are accelerated towards the photosphere.

In the case of a significant heating of the bases of a magnetic tube, when $\alpha B^2 \ll 1$ the ratio of the Dreiser's field to the accelerating one is

$$\frac{E_D}{E_{\|}} = 7.7\cdot 10^{-5}\frac{n^2}{B^2 V_r T^{5/2}}\left(\frac{\Lambda}{20}\right)^2 = 2.6\left(\frac{n}{10^{15}}\right)^2\left(\frac{B}{10^{-3}}\right)^{-2}\left(\frac{3\cdot 10^4}{V_r}\right)\left(\frac{T}{10^6}\right)^{-5/2}\left(\frac{\Lambda}{20}\right)^2\frac{B}{B_r}. \tag{6}$$

An important point is a strong dependence of $\dfrac{E_D}{E_{\|}}$ on the temperature and magnetic field, which can vary widely in a dynamo region. One can see that even for $B_r \approx 0.1B$ a value of the accelerating field can reach the Dreiser's one if the bases are heated up to the temperature $T = 3.5 \cdot 10^6$ K. By this all the electrons appear in a runaway regime, and the electric field reaches the value of 17 V $\cdot$ cm^{-1}. Such a field on a scale $h \sim 10^8$ cm can accelerate particles up to the highest energy of 1 GeV. Some features of electron acceleration in a super-Dreiser fields were considered by Litvinenko (1996). In fact such an extremely high electric field appear in conditions of a maximal possible value of a magnetic field (about 10^3 G) and a significant heating of the photospheric bases of the magnetic tube, which are not always realized. Therefore, the estimations, made above, demonstrate a possibility of an effective particle acceleration in current-carrying magnetic loops.

When acceleration of electrons takes place in chromospheric bases of magnetic loops the fast electrons production rate sufficient for the hybrid thermal/non-thermal model of generation of hard X-ray emission, being higher then 10^{35} s^{-1}, is realized for $n = 10^{11}$ cm^{-3}, $T = 10^5$ K, in the acceleration region, the radius of the tube $R_0 = 10^8$ cm, and a height of the acceleration region $h = 1000$ km. By this, $E_{\|} = 2.15 \cdot 10^{-3}$ V $\cdot$ cm^{-1}, $E_D/E_{\|} = 26$, and the energy of the bulk of accelerated electrons is 200 KeV.

Electric Current of Accelerated Electrons

One more important question is connected with an electric current, caused by the accelerated electrons. If fast electrons production rate during a flare is $\dot{N} > 10^{35}$ s^{-1}, then an electric current, caused by these electrons and having a value $I = e\dot{N} > 1.6\cdot 10^{15}$ A should run. Assuming this current to run in a magnetic loop with a cross-section $S = 10^{18}$ cm^2 one will obtain the corresponding magnetic field $B > 6 \cdot 10^6$ G, which in fact is never observed in coronal magnetic structures.

Usually two ways of solving this contradiction are considered. The first way deals with a hypothesis of the accelerated electrons current filamentation, when a current channel is supposed to be splitted onto many thin current ropes with an opposite current directions in the neighboring ropes. As a result the integral magnetic field of the current channel doesn't exceed an observed value. At the same time it is unclear how such a filamentation can appear. An other way to overcome the above paradox is connected with a formation of a backward current in plasma (Hammer and Rostoker, 1970; Cox and Bennet, 1970; Lee and Sudan, 1971; Lovelace and Sudan, 1971). Let's consider for example a beam of fast electrons, having a radius r_0 and injected into plasma along a z-axis of an external magnetic field. The azimuthal component B_φ of the magnetic field in every fixed point will change during the leading front of the beam passing. The change of B_φ leads to appearance of electric field E_z on the leading front of the beam of fast electrons. This field acts on electrons of the background plasma in such a way that a current, opposite to the current of injected electrons appears. Therefore the total current, and as a result, B_φ and E_z decrease. If the radius of the beam of fast electrons r_0 exceeds a shielding scale $\lambda = c/\omega_p$, then there is no a magnetic field in regions with $r > r_0$. The current of the beam is compensated by the backward current of plasma, which whole runs almost inside the beam. A condition of a total compensation of currents look as the following: $c/\omega_p \ll r_0$, $\nu_{ei}t < 1$, where t is a time of injection. For the times satisfying a condition $\nu_{ei}t \gg 1$ the backward current decays and the currents neutralization gradually disappears. A characteristic time of the backward current decay is determined however by the magnetic diffusion time

$$t_D = \frac{\pi\sigma r_0^2}{c^2}, \tag{7}$$

which for r_0, being of the order of magnitude of a transverse scale of a magnetic loop, exceeds significantly all the characteristic times of flaring processes. Therefore it is possible to assume that the injection of accelerated electrons doesn't change the external magnetic field. The Lentz's law allows the beam of accelerated electrons to penetrate in plasma without losses of energy on a modification of the magnetic field.

Conclusion

In this work the main attention is paid to the important role of the convective motions of plasma in the photosphere and lower chromosphere of the Sun and other stars of later spectral classes for the large scale electric field generation and acceleration of particles. The optimal (with respect to the fast electrons production rate) place of location of the acceleration region is in chromospheric bases of magnetic loops where fast electrons production rates $\dot{N} > 10^{35}$ s^{-1} and average energies of accelerated electrons $\varepsilon > 100$ KeV could be provided. Under the special conditions the maximum value of accelerated electrons energy $\varepsilon \approx 1$ GeV can be reached. Injection of fast electrons into the coronal part of a magnetic loop doesn't lead to a generation of a strong magnetic field. This is caused by the appearance of a backward current in plasma, which compensates the current of accelerated electrons.

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References

Miller J.A., Cargill P.J., Emslie A.G., Holman G.O., Dennis B.R., La Rosa T.N., Winglee R.M., Benka S.G., Tsuneta S., 1997, JGR, 102, 14631

Emslie A.G., Brown J.C., Machado M.E., 1981, Astrophys. J.,246, 337

McClymont A.N., Canfield R.C., 1986, Astrophys. J., 305, 936

Canfield R.C., Gayley K.G., 1987, Astrophys. J., 322, 999

Mariska J.T., Emslie A.G., Li P., 1989, Astrophys. J. Lett., 400, L79

Zaitsev V.V., Stepanov A.V., Urpo S., Pohjalainen S., 1998, Astron. and Astrophys., 337, 887

Knoepfel H., Strong D.A., 1979, Nucl. Fusion, 19, 785

Zaitsev V.V., Khodachenko M.L., 1997, Radiopys. and Quantum Electron., 40, 114

Litvinenko Yu.E., 1996, Astrophys. J., 462, 994

Hammer D.A., Rostoker N., 1970, Phys. Fluids, 13, 1831

Cox J.D., Bennet W.H., 1970, Phys. Fluids, 13, 182

Lee R., Sudan R.N., 1971, Phys. Fluids, 14, 1213

Lovelace R.V., Sudan R.N., 1971, Phys. Rev. Lett., 16, 147