RELATIVISTIC ACCELERATION OF PROTONS IN RECONNECTING CURRENT SHEETS OF SOLAR FLARES

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Abstract. Acceleration of protons in a reconnecting current sheet (RCS), which forms as a consequence of filament eruption in the corona, is considered as a possible mechanism of generation of the relativistic particles during the late phase of solar flares. In order to explain the acceleration of protons and heavier ions up to several GeV in a time of < 0.1 s, the transverse electric field outside the RCS must be taken into account. Physically, this field is always present as a consequence of electric charge separation owing to the difference in the electron and proton masses. The new effect demonstrated in this paper is that the transverse electric field efficiently 'locks' nonthermal ions in the RCS, thus allowing their acceleration by the direct electric field in the RCS. The mechanism considered may be useful in construction of a model for generation of relativistic ions in large gamma-ray/proton flares.

1. Introduction

Generation of charged particles with energies exceeding the thermal energy is known to be a widespread phenomenon in cosmic plasmas. This process, termed particle acceleration, is the subject of a great deal of study. The mechanisms of acceleration, however, still baffle the full theoretical understanding. This is especially true of the particle acceleration in solar flares, because the existing wealth of observations imposes severe restrictions on the models for acceleration. A successful flare model should quantitatively explain the origin and characteristics of energetic particles, both nonrelativistic and relativistic, in solar flares.

Temporal behaviour of various flare emissions suggests that particle acceleration in solar flares frequently occurs in two distinct phases. It was assumed in the past that electrons acquire the energy on the order of 100 keV during the first, impulsive phase (lasting less than several seconds), whereas both electrons and ions become relativistic in the second phase, which can last from several minutes to several hours (for a review of early observations, see Wild, Smerd, and Weiss, 1963). Reconnection in current sheets and shock-wave acceleration were thought to be the physical mechanisms responsible for generation of the relativistic particles.

Later it was discovered that in some flares both electrons and protons acquired energy up to 100 MeV on a time scale of < 1 s (Forrest and Chupp, 1983; Kane *et al.*, 1986), implying that the second phase may be unnecessary for relativistic acceleration. Hence the focus of theoretical research on the high-energy particles

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shifted to the impulsive acceleration. Nevertheless, observations clearly showed that flares with two phases of acceleration, as well as those with a single one, do exist (e.g., Kallenrode and Wibberenz, 1991). This fact has led to the concept of several different mechanisms of acceleration, some of which are fast and some slow. Any of the mechanisms (or all of them) may operate in a particular flare.

According to de Jager (1990), electrons are accelerated by the direct electric field, related to magnetic reconnection, to $\approx$ 10 MeV within 0.1 s; a couple of seconds later protons trapped by shock waves are accelerated to $\approx$ 100 MeV; finally, the protons can be further accelerated to GeV energies by shock waves in open magnetic field lines. This third phase (corresponding to the second one in the usual notation) occurs on a time scale of several minutes. The advantage of such an approach is that it explains the diversity of flares observed, because the relative role of each of the mechanisms varies from flare to flare.

Thus, the largest proton energies observed (up to several GeV) are reached during the last, extended phase of acceleration, which is thought to correspond to the shock-wave Fermi-type acceleration process (for a review, see Bai and Sturrock, 1989). The existence and importance of shock acceleration in strong flares is beyond doubt. Note, however, that there are flares in which shock acceleration seems to be unsuitable for interpretation of the delayed component of gamma-ray emission from neutral pion decay (Akimov *et al.*, 1995). This is because a shock is already too high in the solar corona by the time the delayed component appears. If the protons, which later produced the pions, were accelerated by the shock, they could not reach the chromosphere and produce the gamma-emission (cf., Kahler, 1984). The problem with acceleration rate also exists for the shock mechanism (see below). Therefore, the search for additional mechanism(s) for generation of relativistic ions in flares is still justified.

The purpose of this paper is to determine whether the acceleration of protons during the late phase of large gamma-ray/proton flares to GeV energies can occur in a reconnecting current sheet (RCS), formed behind a rising coronal transient or an erupting prominence. In principle, the electric field, generated in such structures by rapidly changing magnetic field, is the fastest and easiest means of particle acceleration to relativistic energies (Somov, 1981). In practice, however, various effects act both to increase and, mainly, to decrease the acceleration efficiency. That is why one should carefully consider these effects in order to determine correctly the rate of acceleration and the maximum energy of particles. In this respect our paper is a continuation of the previous work. So far it was investigated how the motion of a charged particle in the RCS is influenced by such factors as the transverse (Speiser, 1965) and longitudinal (Litvinenko and Somov, 1993; Litvinenko, 1993) components of magnetic field in the sheet, the magnetic field structure outside the sheet (Shabansky, 1971), and MHD turbulence in the current sheet (Matthaeus, Ambrosiano, and Goldstein, 1984).

A new factor that we introduce below is the transverse (perpendicular to the RCS plane) electric field outside the RCS, arising owing to the electric charge separation

(Harris, 1962). This field will be shown to efficiently 'lock' the protons in the current sheet. In this way the transverse electric field counteracts the transverse magnetic field that tends to eject the particles from the sheet. Hence the protons can gain more energy while moving along the main electric field inside the sheet.

After discussing magnetic field topologies that can give rise to magnetic reconnection and particle acceleration during the late phase of large solar flares (Section 2), we briefly describe the structure and parameters of the RCS, taking care of the transverse electric field outside the sheet (Section 3). Our model for ion acceleration is also presented here. Then we calculate the energy gain rate and the maximum particle energy predicted by the model (Section 4) and compare the results with observations and other models (Section 5).

2. Formation of the Current Sheet in the High Corona

Though the main flare energy release is usually attributed to magnetic reconnection in the low corona or upper chromosphere, an RCS can also form much higher, behind a rising coronal mass ejection (CME) or erupting loop prominence during the late phase of a flare. The existing theoretical models (e.g., Kopp and Pneuman, 1976; Steele and Priest, 1989) assume that the magnetic field loses equilibrium and erupts, this driving reconnection below the prominence. This is because the eruption of the coronal magnetic flux leads to a strong perturbation of the pre-existing magnetic field structure: the field lines, which were closed prior to the flare, become stretched out or even open. Reconnection must occur in order to restore the field to its pre-flare configuration. The perturbed field is envisioned to relax to the initial state through the process of magnetic reconnection in the RCS (Figure 1).

In the simple model described above, the picture of magnetic field lines shown in Figure 1 has to be considered as 2D cross-section of the real magnetic configuration – the arcade of the initially closed loops with a longitudinal magnetic field which makes the process of reconnection to be more complicated than 2D reconnection described below but not forbidden. Anyway, and this is important, reconnection is just a consequence of ejection of a large magnetic loop or 'plasmoid' into interplanetary space during strong flares.

Consider another approach to the problem, according to which the processes of reconnection and ejection are more closely related (Somov, 1991). A coronal streamer can be modelled (also in 2D approximation) as an RCS in which slow magnetic reconnection is driven by the solar wind (Figure 2(a)). Plasma moves upward and brings new magnetic field lines to the sheet, where they reconnect. Reconnection creates plasma downflow below the streamer and upflow above it. A coronal transient or CME can develop in this quasistatic configuration if an instability sets in.

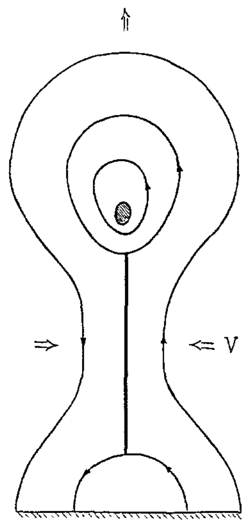

Fig. 1. Two-dimensional model for eruption of the filament through the arcade of closed loops and formation of the RCS below it. Thick arrows show the plasma flows into the region of magnetic reconnection.

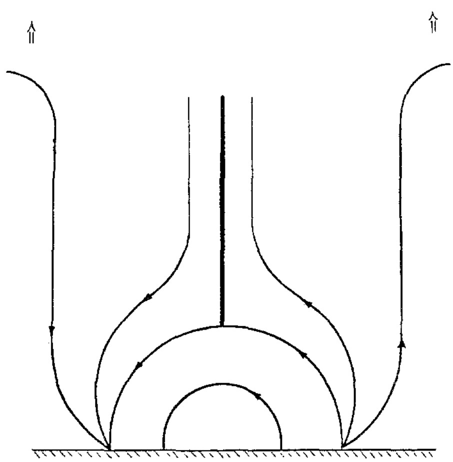

Fig. 2a.

Fig. 2a–b. Large-scale streamer configuration of coronal magnetic field (a) and fast reconnection that causes the CME onset (b).

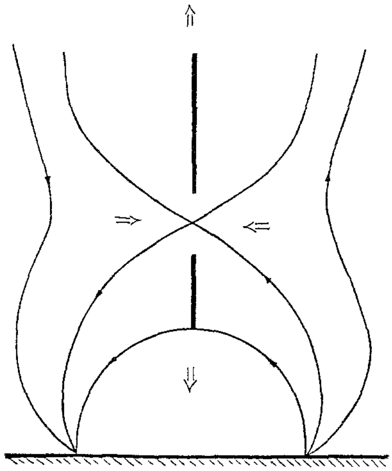

Fig. 2b.

By way of example, consider the current instability. The current velocity of electrons in the RCSI, u, is estimated as in the case of magnetic reconnection driven by solar wind (Somov, 1991):

$$u = \frac{c}{4\pi}\frac{B_0}{nea} = \frac{cB_0}{4\pi ne}\frac{4\pi\sigma V}{c^2} = \left(\frac{V}{c}B_0\right)\frac{\sigma}{en}\,. \qquad (1)$$

Here B_0 is the reconnecting (main) component of magnetic field near the current sheet, a the half-thickness of the sheet, n the particle density in it, σ the electric conductivity, V the speed of plasma inflow into the sheet, and c the speed of light. As the RCS slowly rises, the current velocity increases because n decreases. Thus conditions favourable for the current instability (e.g., the ion-acoustic one) are created. This leads to anomalous resistivity in the RCS and its 'rupture' – the regime of fast reconnection in high-temperature turbulent current sheet (Somov, 1992), the streamer being disrupted simultaneously (Figure 2(b)). This model emphasizes the intimate relation between the processes of magnetic reconnection and mass ejection in the solar atmosphere; we believe that each of the processes can trigger the other one, given favourable initial conditions.

One way or another, the relaxation of magnetic field to its initial state, which takes place after or during the CME launch, is accompanied by a second abrupt energy release, mainly in the form of high-energy particles. The reason for this is a large direct electric field, generated inside the RCS, that efficiently accelerates the charged particles (Somov, 1981). Because the RCS forms very high above the photosphere, the particle density outside the RCS is low and collisional energy losses can be ignored. This fact allows us to explain the efficient generation of relativistic particles in flares of the type considered, in particular, the acceleration of protons to energies on the order of several GeV.

The theoretical picture delineated above seems to be supported by observations, which show that CME launches precede flares, the latter developing much below CMEs (Harrison, 1986). According to Harrison *et al.* (1990), 'the ascending CME structure may destabilize the complex magnetic structures near its footpoints thus producing the conditions for particle acceleration, reconnection and heating'. Note, however, that the assumption of spatial symmetry, usually present in theoretical models, should be abandoned in order to explain the observations.

3. Parameters of the Reconnecting Current Sheet and Mechanism of Acceleration

Some simple estimates confirm the above scenario for particle acceleration in the late phase of large solar flares. A typical CME speed of upward motion equals the Alfvén speed in the corona $V_{\rm A} \approx 1000$ km s^{-1}. A typical speed of plasma inflow into the RCS V is an order of magnitude smaller. Here we assume a fast reconnection regime in the sheet. Such regime is known to be realized in non-neutral current sheets (Somov, 1992, 1994). Taking for illustrative purposes $V = 100$ km s^{-1}, we obtain (under assumption that conductivity of coronal plasma is high enough) a characteristic time of the RCS formation

$$t_f = L/V = 10^2 - 10^3 \text{ s}\,, \tag{2}$$

$L = 10^9$–10^{10} cm being the RCS length- and width-scale; it coincides with the typical expanse of an active region. It is this time that we identify with the delay of the late (extended) acceleration phase with respect to the impulsive one. For a characteristic value of the coronal magnetic field $B_0 = 100$ G, the direct electric field inside the RCS is

$$E_0 = \frac{1}{c} V B_0 = 3 \times 10^{-2}\,\text{CGSE} = 10\,\text{V cm}^{-1}\,. \tag{3}$$

Estimate (3) is compatible with (1) because the electric current density in the RCS is $j = neu = \sigma E_0$. Electric fields of order 10 V cm^{-1} are actually observed in solar active regions, in particular, in erupting prominences (for a review, see Foukal and Hinata, 1991).

The maximum energy gain for a particle accelerated in the RCS is determined by the potential drop along the sheet and equals

$$U = eE_0 L = 100\,\text{GeV}\,. \tag{4}$$

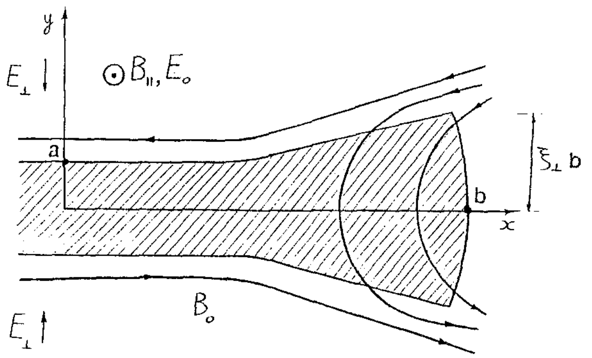

Fig. 3. Sketch of the non-neutral reconnecting current sheet (not to scale). B_0 is the main (reconnecting) magnetic field component, $B_\perp$ is the transverse field, E_0 is the main electric field related to the reconnection process inside the sheet, $E_\perp$ is the transverse electric field outside the sheet due to electric charge separation. (a) is the half-thickness and (b) the half-width of the current sheet.

Clearly this value is amply sufficient for explanation of the extended acceleration phase, though taking care of the magnetic field in the RCS can diminish the actual maximum energy $\mathcal{E}_{\text{max}}$. The question is whether a sufficient acceleration rate and maximum energy can be obtained, given a realistic magnetic and electric field structure in the RCS. In this context, formulas $\mathcal{E}_{\text{max}} = U$ and $\mathrm{d}\mathcal{E}/\mathrm{d}t = ceE_0 = 300$ GeV s^{-1}, ignoring the magnetic field altogether, are too gross overestimates. Thus a more detailed consideration of the RCS structure is necessary.

Speiser (1965) was the first to treat the charged particle acceleration in current sheets, taking into account not only the reconnecting field B_0, but also a small transverse (perpendicular to the plane of the RCS) magnetic field component $B_\perp = \xi_\perp B_0$ (Figure 3). A typical relative value of the transverse field, penetrating into such an RCS, termed *non-neutral*, is $\xi_\perp = 10^{-3}$–10^{-2} (Somov, 1992). In what follows we adopt the value of $\xi_\perp = 3 \times 10^{-3}$ for our estimates. The basic Speiser's result is that both the energy gain $\delta\mathcal{E}$ and the time that the particles spend in the non-neutral RCS δt_{in} are finite. The transverse magnetic field makes the particle turn in the plane of the sheet, and then a component of the Lorentz force expels it from the RCS plane almost along the magnetic lines of force (see Figure 3 in Speiser, 1965). The distance that the particle can travel along the sheet equals the Larmor diameter determined by the transverse field and a typical speed of the particle.

Litvinenko and Somov (1993) generalized the results of Speiser (1965) by including into consideration the longitudinal magnetic field $B_\parallel$ in the sheet. This component, however, while efficiently magnetizing electrons in the RCS, cannot influence the motion of the relativistic protons and heavier ions that are of primary interest to us here. This is because the 'critical' longitudinal field, necessary to magnetize a particle in the RCS, is proportional to the square root of the particle mass (see (22) in Litvinenko and Somov, 1993). Hence we shall use, first, the Speiser's formulas, derived for the case when a particle of mass m and charge e enters the RCS with a negligible velocity:

$$\delta\mathcal{E} = 2mc^2 \left(\frac{E_0}{B_\perp}\right)^2 , \tag{5}$$

$$\delta t_{\text{in}} = \frac{\pi mc}{eB_\perp} . \tag{6}$$

Generalizations of these formulas to particles with nonzero initial velocities are given in the next section.

Thus, on the one hand, electrons acquire the relativistic energy in RCSs with a nonzero longitudinal field $B_\parallel$ (Litvinenko and Somov, 1993). On the other hand, application of Equations (3), (5), and (6) to the RCS, formed behind a rising CME, shows that a nonzero $B_\perp$ radically restricts the energy of heavier particles: $\delta\mathcal{E}$ for protons cannot exceed 20 MeV if a typical value of $\xi_\perp = 3 \times 10^{-3}$ ($B_\perp = 0.3$ G) is assumed. Therefore, the relativistic energies cannot be reached after a single 'interaction' of the particle with the sheet (cf., Martens, 1988). To overcome this difficulty, Martens (1988) conjectured that the relativistic acceleration could take place in RCS regions where $B_\perp \to 0$ (the neutral current sheet approximation), and the protons are freely accelerated by the electric field. This conjecture, however, does not seem to be adequate for actual RCSs, where reconnection always occurs in the presence of a nonzero transverse magnetic field. Though we do expect the latter to vary somewhat along the RCS (Somov, 1992), the region with a vanishing $B_\perp$ is so small that a particle will quickly leave the region (and hence the RCS) before being accelerated. Thus we are led to modify the classic Speiser's model significantly.

We propose that the protons interact with the RCS more than once, each time gaining a finite, relatively small amount of energy. The cumulative effect could be the required relativistic acceleration. Previously Shabansky (1971) considered a similar model in the context of charged particle acceleration in the geomagnetic tail. However, the magnetic field structure of the solar atmosphere is quite different from that of the geomagnetic tail; and conditions are also quite different. Therefore, formulas given by Shabansky (1971) are inapplicable to the problem at hand. For this reason, we have to consider another model in application to the RCS in the solar atmosphere.

The factor that makes positively charged particles return to the RCS is the transverse electric field directed toward the sheet (Figure 3). In an exact self-consistent one-dimensional model of the current sheet due to Harris (1962), this field equals

$$E_\perp = 2\pi\sigma^q , \tag{7}$$

where the magnitude of the electric charge density integrated over the sheet thickness is

$$\sigma^q = \left(\frac{u}{c}\right)^2 nea \; . \tag{8}$$

On substituting (1) and (8) into (7), we obtain

$$E_\perp = \frac{kT}{ea} \; , \tag{9}$$

where the equation $B_0^2/(8\pi) = nkT$ is used, T being the plasma temperature in the RCS.

Physically, the transverse electric field outside the RCS $E_\perp$ is a consequence of electric charge separation. Both electrons and protons are deflected by the magnetic field when they move out of the sheet. The trajectories of electrons, however, are bent to a greater degree owing to their smaller mass. As for much heavier ions, they stream out of the RCS almost freely. Hence the charge separation arises, leading to the electric field that detains the protons in the RCS region (Harris, 1962; cf., Longmire, 1963). This field is directed along the y-axis in Figure 3.

It is not obvious *a priori* that Harris's solution applies to current sheets with nonzero $\xi_\perp$ and finite conductivity σ. It should be valid, however, for small $\xi_\perp$ at least as a first approximation. In fact all we need for our calculations is the electric potential

$$\phi = e \int E_\perp \, \mathrm{d}y \; , \tag{10}$$

which we can safely take to equal kT, the usual value owing to spread of a 'cloud' of charged particles.

The following point is worth emphasizing here. The charge separation that gives rise to the potential ϕ mainly stems from the motion of protons perpendicular to the RCS plane. At the same time, some protons are known to leave the RCS almost along its plane. This property is a characteristic feature of the above mentioned Speiser's mechanism of particle acceleration. It seems obvious that even a modest transverse electric field will considerably influence the motion of these particles because they always move almost perpendicular to this field. Having made this qualitative remark, we now proceed to calculating the energy gain rate and maximum energy for the protons being accelerated in the RCS, taking into account both the main components of electromagnetic field (B_0 and E_0) and the transverse ones ($B_\perp$ and $E_\perp$).

4. Maximum Particle Energy and Acceleration Rate

According to the model delineated above, a positively charged particle ejected from the RCS is quickly 'reflected' and moves back to the RCS. The reason for this is the electric field $E_\perp$, directed perpendicular to the sheet, which always exists outside the RCS (Harris, 1962). It is of paramount importance for what follows that the protons are ejected from the RCS almost *along* the magnetic field lines (Speiser, 1965). The transverse electric field efficiently 'locks' the particles in the RCS because they always move almost in the plane of the sheet. On getting into the sheet again, the particles are further accelerated and the cycle repeats itself.

In order to find the properties of the acceleration mechanism, we need to dwell at some length on the particle motion outside the RCS. Consider a proton leaving the RCS plane with energy $\mathcal{E}$ and momentum p. According to Speiser (1965), the component of momentum perpendicular to the sheet is $p_\perp \approx \xi_\perp p \ll p$ for such a proton. The perpendicular component of the equation of motion for the particle outside the RCS is

$$\frac{\mathrm{d}}{\mathrm{d}t} p_\perp(t) = -eE_\perp \, . \tag{11}$$

Equation (11) allows us to estimate the time spent by the proton between two successive interactions with the RCS,

$$\delta t_{\mathrm{out}} = \frac{2p_\perp}{eE_\perp} \approx \frac{2\xi_\perp p}{eE_\perp} \, . \tag{12}$$

The largest particle energy attainable is determined by the condition that the potential (10) is just enough to prevent the proton from leaving the RCS. In other words, the field $E_\perp$ must cancel the perpendicular momentum. The energy conservation gives

$$\mathcal{E}_{\mathrm{max}} = \sqrt{\mathcal{E}_{\mathrm{max}}^2 - p_\perp^2 c^2} + \phi \, , \tag{13}$$

where

$$p_\perp^2 c^2 = \xi_\perp^2 (\mathcal{E}_{\mathrm{max}}^2 - m^2 c^4) \, . \tag{14}$$

Eliminating $p_\perp$ between (13) and (14), we get the sought-after maximum energy

$$\mathcal{E}_{\mathrm{max}} = \frac{\phi}{\xi_\perp^2} \left[1 + \sqrt{1 - \xi_\perp^2 + \frac{\xi_\perp^4 m^2 c^4}{\phi^2}} \right] , \tag{15}$$

where $\phi \approx kT$. Formula (15) shows that protons can actually be accelerated to GeV energies in the high-temperature RCS (Somov, 1992): for instance $\mathcal{E}_{\mathrm{max}} \approx 2.4$ GeV provided $T = 10^8$ K. Even larger energies can be reached in RCS regions with a smaller transverse magnetic field (cf., Martens, 1988).

We note in passing that if a particle leaves the sheet with the velocity that is perpendicular to the magnetic field lines outside the RCS, the magnetic reflection is very efficient too. In this case it occurs in a time of order the inverse gyrofrequency in the field B_0.

The resulting acceleration rate can be estimated as

$$\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}t} \approx \frac{\langle\delta\mathcal{E}\rangle}{\delta t_{\mathrm{in}} + \delta t_{\mathrm{out}}} \; . \tag{16}$$

Here

$$\langle\delta\mathcal{E}\rangle = 2\mathcal{E}\left(\frac{E_0}{B_\perp}\right)^2 \tag{17}$$

is the relativistic generalization of Equation (5) for the average energy gain (the averaging needs to be introduced because in general a term linear in a component of the particle momentum appears in the expression for $\delta\mathcal{E}$, cf., Speiser and Lyons, 1984). In much the same way

$$\delta t_{\mathrm{in}} = \frac{\pi\mathcal{E}}{ceB_\perp} \tag{18}$$

is the relativistic generalization of Equation (6). The approach using the differential equation (16) is quite justified once the inequality $\langle\delta\mathcal{E}\rangle \ll \mathcal{E}_{\mathrm{max}}$ holds.

Equation (16), with account taken of (12), (17), and (18), can be integrated in elementary functions. To simplify the problem further, we note that

$$\frac{\delta t_{\mathrm{in}}}{\delta t_{\mathrm{out}}} = \frac{\pi E_\perp}{2\xi_\perp B_\perp}\left(\frac{\mathcal{E}}{pc}\right) \approx 10^3\left(\frac{\mathcal{E}}{pc}\right) \gg 1 \; . \tag{19}$$

Hence it is justifiable to ignore the second term in the denominator of Equation (16). The simplified equation is integrated to give the kinetic particle energy

$$\mathcal{K}(t) \equiv \mathcal{E} - mc^2 = \frac{2}{\pi}ceE_0\left(\frac{E_0}{B_\perp}\right)t \, , \tag{20}$$

whence the acceleration time is

$$t_{\mathrm{ac}} \approx 0.03\left(\frac{\mathcal{K}}{1\ \mathrm{GeV}}\right)\mathrm{s} \; . \tag{21}$$

This result clearly demonstrates the possibility of efficient proton acceleration by dint of the direct electric field in the RCS. At the same time, taking care of the actual magnetic field structure has considerably diminished (by a factor of $E_0/B_\perp = V/(\xi_\perp c) \approx 10^{-1}$ the magnitude of the energy gain rate, as compared with the idealized case $B_\perp = 0$.

Alternatively, we could rewrite (20) to obtain the energy $\mathcal{E}$ as a function of the number of particle entries to the RCS, N:

$$\mathcal{E} = mc^2 \exp\left[2\left(\frac{E_0}{B_\perp}\right)^2 N\right] \; . \tag{22}$$

Therefore, the particle must interact with the RCS

$$N^* \approx \left(\frac{B_\perp}{E_0}\right)^2 = \left(\frac{\xi_\perp c}{V}\right)^2 \approx 10^2 \tag{23}$$

times in order to reach a relativistic energy. As was shown above (see Equation (15)), the transverse electric field outside the RCS is actually capable of providing this number of reentries into the current sheet.

Note that, in principle, the protons could leave the RCS along its plane rather than across it. This is not likely, however, because of a very short acceleration time t_{ac}; the distance a proton can travel along the RCS when being accelerated is less than $ct_{\mathrm{ac}} \approx 10^9$ cm, that does not exceed a typical RCS width 10^9–10^{10} cm.

Therefore, we have estimated the efficiency of the acceleration process in the frame of the RCS model which contains several taciturn assumptions. The most important of them is a modification of the steady two-dimensional model for high-temperature turbulent current sheet (see Chapter 3 in Somov, 1992) with account of the Harris type equilibrium across the sheet. Such a possibility does not seem surprising *a priori*, but it certainly has to be considered in detail somewhere else. Another assumption is that the initially assumed conditions of current sheet equilibrium are not changed due to the acceleration, more exactly, during the characteristic time of acceleration of a particle. In fact, we consider the number of particles accelerated to high energies as a small one in comparison with the number of current driving thermal electrons inside the RCS. However, generally speaking, it remains to be seen that this assumption can be well justified without careful numerical modelling of the real plasma processes in the region of magnetic reconnection and particle acceleration.

5. Discussion

We have suggested in this paper that the extended acceleration of protons (and perhaps heavier ions) to relativistic energies during the late phase of large solar flares occurs in reconnecting current sheets (RCSs), where the magnetic field lines are driven together and forced to reconnect. Such RCSs naturally form below erupting loop prominences or coronal streamers. The time of RCS formation corresponds to the delay of the second phase of acceleration after the first, impulsive phase. The mechanism that we invoked – direct electric field acceleration – is quite ordinary in studies of the impulsive phase (e.g., Syrovatskii, 1975; Sakai, 1992). There are good reasons to believe that the same mechanism also efficiently operates during the second phase of acceleration.

First, already early radio observations of solar flares (Palmer and Smerd, 1972; Stewart and Labrum, 1972) were indicative of particle acceleration at the cusps of helmet magnetic structures in the corona. These are exactly the structures where RCSs are expected to form. Note that the acceleration by Langmuir turbulence inside the RCS in the helmet structure, invoked by Zhang and Chupp (1989) to explain the electron acceleration in the flare of April 27, 1981, is too slow to account for the generation of relativistic protons and requires an unreasonably high turbulence level.

Second, gamma emission during large flares consists of separate peaks with a characteristic duration of 0.1–0.3 s, down to 0.04 s (Gal'per *et al.*, 1994). If this behaviour is interpreted in terms of a succession of separate acts of acceleration, then the shock mechanism is also too slow since the acceleration time would be

$$t_{\mathrm{ac}} = 50 \left(\frac{100\ \mathrm{G}}{B_0} \right) \left(\frac{\mathcal{E}}{1\ \mathrm{GeV}} \right) \mathrm{s} \approx 50\ \mathrm{s} \tag{24}$$

(Colgate, 1988). By contrast, the direct electric field inside the RCS provides not only the necessary maximum energy but also the necessary energy gain rate (see Equation (21)). High velocities (up to the coronal Alfvén speed) of erupting filaments and other CMEs imply a large direct electric field in the RCS. This is the reason why the acceleration mechanism considered is so efficient (Somov, 1981). Strong variability of gamma emission may reflect the regime of impulsive, bursty reconnection in the RCS.

An interesting feature of the mechanism considered is that neither the maximum energy nor the acceleration rate depend upon the particle mass. Hence the mechanism may play a role in the preferential acceleration of heavy ions during solar flares.

Recall that Martens (1988) applied the Speiser (1965) model when considering relativistic acceleration of protons during the late phase of flares. However, it turned out necessary to assume an idealized geometry of magnetic field in the RCS, viz., $B_\perp \to 0$, in order to account for the relativistic acceleration. We have shown that the difficulty can be alleviated by allowing for the transverse electric field $E_\perp$ outside the sheet. This field necessarily arises in the vicinity of the RCS (Harris, 1962). So far the influence of the $E_\perp$-field was not considered in the models for particle acceleration in reconnecting current sheets.

To conclude, though MHD shocks are usually thought to be responsible for the relativistic generation of protons during the late phase of extended (gradual) gamma-ray/proton flares (Bai and Sturrock, 1989; de Jager, 1990), another mechanism – the direct electric field acceleration in RCSs – is necessary for explanation of the proton acceleration to the highest energies observed, at least in flares with strong variability of gamma emission. Of course, the same sudden mass motions that lead to formation of RCSs also give rise to strong shock waves, so the two mechanisms of acceleration can easily coexist in a single flare.

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References

Akimov, V. V., Ambrož, P., Belov, A. V., Berlicki, A., Chertok, I. M., Karlický, M., Kurt, V. G., Leikov, N. G., Litvinenko, Yu. E., Maggun, A., Minko-Wasiluk, A., Rompolt, B., and Somov, B. V.: 1995, *Solar Phys.*, submitted.

Bai, T. and Sturrock, P. A.: 1989, *Ann. Rev. Astron. Astrophys.* **27**, 421.

Colgate, S. A.: 1988, *Solar Phys.* **118**, 1.

de Jager, C.: 1990, *Adv. Space Res.* **10**, No. 9, 101.

Forrest, D. J. and Chupp, E. L.: 1983, *Nature* **305**, 291.

Foukal, P. and Hinata, S.: 1991, *Solar Phys.* **132**, 307.

Gal'per, A. M., Zemskov, V. M., Luchkov, B. I., Ozerov, Yu. V., Tugaenko, V. Yu., and Khodarovich, A. M.: 1994, *Pis'ma v ZhETF* **59**, 145.

Harris, E. G.: 1962, *Nuovo Cimento* **23**, 115.

Harrison, R. A.: 1986, *Astron. Astrophys.* **162**, 283.

Harrison, R. A., Hildner, E., Hundhausen, A. J., Sime, D. G., and Simnett, G. M.: 1990, *J. Geophys. Res.* **95A**, 917.

Kahler, S. W.: 1984, *Solar Phys.* **90**, 133.

Kallenrode, M.-B. and Wibberenz, G.: 1991, *Astrophys. J.* **376**, 787.

Kane, S. R., Chupp, E. L., Forrest, D. J., and Share, G. H.: 1986, *Astrophys. J.* **300**, L95.

Kopp, R. A. and Pneuman, G. W.: 1976, *Solar Phys.* **50**, 85.

Litvinenko, Yu. E.: 1993, *Solar Phys.* **147**, 337.

Litvinenko, Yu. E. and Somov, B. V.: 1993, *Solar Phys.* **146**, 127.

Longmire, C. L.: 1963, *Elementary Plasma Physics*, Ch. 5, Interscience Publ., New York.

Martens, P. C. H.: 1988, *Astrophys. J.* **330**, L131.

Matthaeus, W. H., Ambrosiano, J. J., and Goldstein, M. L.: 1984, *Phys. Rev. Letters* **53**, 1449.

Palmer, I. D. and Smerd, S. F.: 1972, *Solar Phys.* **26**, 460.

Sakai, J. I.: 1992, *Solar Phys.* **140**, 99.

Shabansky, V. P.: 1971, *Space Sci. Rev.* **12**, 299.

Somov, B. V.: 1981, *Bull. Acad. Sci. USSR, Phys. Ser.* **45**, No. 4, 114.

Somov, B. V.: 1991, *Adv. Space Res.* **11**, No. 1, 179.

Somov, B. V.: 1992, *Physical Processes in Solar Flares*, Kluwer Academic Publishers, Dordrecht, Holland.

Somov, B. V.: 1994, *Fundamentals of Cosmic Electrodynamics*, Kluwer Academic Publishers, Dordrecht, Holland.

Speiser, T. W.: 1965, *J. Geophys. Res.* **70**, 4219.

Speiser, T. W. and Lyons, L. R.: 1984, *J. Geophys. Res.* **89A**, 147.

Steele, C. D. C. and Priest, E. R.: 1989, *Solar Phys.* **119**, 157.

Stewart, R. T. and Labrum, N. R.: 1972, *Solar Phys.* **27**, 192.

Syrovatskii, S. I.: 1975, *Bull. Acad. Sci. USSR, Phys. Series*, **39**, No. 2, 96.

Wild, J. P., Smerd, S. F., and Weiss, A. A.: 1963, *Ann. Rev. Astron. Astrophys.* **1**, 291.

Zhang, H.-Q. and Chupp, E. L.: 1989, *Astrophys. Space Sci.* **153**, 95.