LARGE-SCALE ELECTRIC FIELDS IN SOLAR FLARE REGIONS

M. I. PUDOVKIN[1], S. A. ZAITSEVA[1], N. O. SHUMILOV[1] and C.-V. MEISTER[2]
[1]*Institute of Physics, St. Petersburg University, St. Petersburg, 198904, Russia*
[2]*Institute for Theoretical Physics and Astrophysics, Potsdam University, 14469, Germany*

(Received 20 November 1996; accepted 2 July 1997)

Abstract. A method of separating electric field in the flare region in the potential and vortex (induced) parts is discussed. According to the proposed model, the motion of flare ribbons from the central line of the flare region is caused by the vortex component of the coronal electric field, while the motion of bright spots within the flare region towards the central line is driven by the potential component of that field. The intensity of both the components of the flare region electric field is estimated to equal approximately $1-3$ V cm^{-1}, which provides the input of the electromagnetic energy into the active region at a rate of about 10^{10} erg cm^{-2} s^{-1}.

1. Introduction

Solar flares are known to be a process in the course of which there is released during a short time a huge amount of energy, or better, energy accumulated in a form invisible for a ground-based observer, rapidly transfers into the energy of visible, UV and X-ray radiation, as well as to the kinetic and magnetic field energy of flare-associated streams in the solar wind. As the source of that energy there have been proposed various physical processes and varied kinds of energy, such as gravitational energy of the chromospheric matter (Sturrock and Coppi, 1966), dissipation of magnetosonic wave energy (Pneuman, 1968), energy of high-energy protons (Elliot, 1969), and others. However, the most popular now, is a magnetic field reconnection hypothesis according to which the energy responsible for the development of the flares is accumulated in the form of magnetic field energy (Parker, 1963; Petschek, 1964; Severny, 1964; Sturrock, 1972). As a matter of fact, the density of the magnetic field energy amounts to a value of 5×10^4 erg cm^{-3} for $B = 10^3$ G, which corresponds in the case of a flare with a characteristic length scale of about 30×10^3 km to the total energy of the flare being about 10^{32} erg, this value being in a reasonable agreement with known estimates of the flare energy.

At the same time, some doubts about the reality of the magnetic reconnection mechanism arise from the fact that the general configuration and the total energy of the magnetic field in the active region do not change in the course of the flare (Mayfield, 1971; Janssens, 1972). However, we believe that this fact may conform with the hypothesis on the magnetic field reconnection mechanism of flares if we suppose that the reconnection proceeds in a steady-state regime. In turn, this is possible only in the case when there exists in the flare region, beside the flare-associated induced electric field, a quasi-stationary or slowly varying large-scale

Solar Physics **178:** 125–136, 1998.

electric field of some external source (e.g., associated with a large-scale convection of the photospheric plasma within and in the vicinity of the flare region).

Electric fields are of great importance, not only from the viewpoint of the magnetic field reconnection model of the flares. They also play a central role in processes of coronal heating, in physics of filament eruption, as well as in generating electric current systems in active regions on the Sun. In this connection, solar electric fields are extensively studied now, and the main regularities of their behaviour are being revealed (see a review by Foukal and Hinata, 1991). So, Foukal, Miller, and Gilliam (1983) have observed in post-flare coronal loops an electric field as high as 170 V cm^{-1}. Even more intensive electric fields (up to 700 V cm^{-1}) were measured by Davis (1977) in a limb flare of importance 2N; the author supposed these fields to be associated with some plasma waves. On the other hand, Foukal, Little, and Gilliam (1987), while analyzing two eruptive events, have found that the total electric field in such structures is less than 10 V cm^{-1}, and about 40 V cm^{-1} in a post-flare loop and in active prominences (Foukal *et al.*, 1986). These results may be supplemented by data by Foukal and Behr (1995) who have found that in quiescent prominences the electric field does not exceed the value of the measurement threshold (5–10 V cm^{-1}), while in flare surges it may amount to a value of $\approx$ 35 V cm^{-1}.

Thus, small-scale electric fields in various coronal structures seem to be studied in detail. At the same time, the results of measurements presented above have certain limitations, the main ones of which are as follows.

(1) Sensitivity of electrographs based on the Stark broadening of hydrogen emissions is such that only relatively intensive ($E >$ 5–10 V cm^{-1}, Moran and Foukal, 1991; Foukal and Hinata, 1991) fields may be detected. At the same time, much less intensive fields may play a significant role in processes developing in active regions. So, Zarro, Mariska, and Dennis (1995) have estimated the intensity of a DC electric field responsible for a pre-flare plasma heating causing strong stationary component of Ca XIX emission to be 10^{-5} V cm^{-1}.

(2) Electrographs based on using the Stark effect detect electric fields in a frame of reference moving with the coronal plasma. Thereby, electric fields perpendicular to the ambient magnetic field which are compensated by the mentioned electric fields are invisible for the observers (see analysis of the problem in Foukal and Hinata, 1991). At the same time, in many problems it is necessary to know the transverse electric field intensity as measured in a motionless frame of reference. First of all, just this electric field determines the rate of the electromagnetic energy input (the Poynting vector flux) into an active region and hence the energetics of subsequent flare processes. Then, as was pointed out by Foukal, Little, and Gilliam (1987) and by Foukal and Hinata (1991), in spite of the fact that transverse electric fields in a moving highly conductive plasma are small, the electrostatic component of those fields, being applied at regions where magnetic field frozen-in conditions are violated, may cause an effective acceleration of particles and heating of the plasma.

Forbes and Priest (1984) proposed a method to estimate those large-scale low-intensity electric fields in flare regions from the velocity of flare ribbons. Kopp and Poletto (1986), with use of that method have estimated electric field intensity within a concrete flare (on 29 July 1973) as 1–1.5 V cm^{-1}, which provides a sufficiently large voltage along the reconnection line.

An analogous method for estimating low-intensity electric fields in the Earth magnetosphere from the equatorward motion of auroral arcs was proposed earlier by Pudovkin, Isaev, and Zaitseva (1970). Kelley, Starr, and Mozer (1971) on applying a similar method to studies of the magnetospheric electric fields, have noticed that the regular motion of auroral arcs is drastically violated during intensive bursts of aurorae (auroral breakups), when a part of the auroral arcs goes on moving equatorward, while the other part is moving poleward. This complicated behaviour of aurorae was explained by Pudovkin *et al.* (1991, 1996) in terms of potential and vortex electric fields which exist in the magnetosphere during auroral substorms.

Bearing in mind a close analogy between the bursts of aurorae and solar flares, we will try to show in this paper that the electric fields in solar flares also consist of potential and vortex components, and we will try to estimate both of them.

2. Model

The supposed configuration of the magnetic field in the flare region is presented in Figure 1 after Sturrock (1972). Energetic electrons which are produced by intensive induced electric field in the vicinity of the reconnection line, precipitate along magnetic field lines onto the photosphere onto points A_1 and A, causing enhancement of the solar luminosity within two regions (two ribbons) located at both sides of the neutral ($B_r = 0$) line. Magnetic field lines located to the right and to the left of the reconnection line are driven by the induced electric field toward the reconnection line, and when the feet of the magnetic lines in the photosphere are fixed (the induced electric field is a local one in its nature), photospheric projections of the reconnection line (or flare ribbons) are moving from the central axis of the flare; knowing velocity of the ribbon motion and the magnetic field intensity, one may estimate the intensity of the vortex electric field in the reconnection region. At the same time, any potential electric field, though it exists in the reconnection region, does not influence the rate of the ribbon motion (Pudovkin *et al.*, 1991). On the other hand, the velocity of the motion of the photospheric projection of plasma clots located on closed magnetic field lines is determined by the intensity of the potential component of the active region electric field and is not affected by the vortex component of the latter (Pudovkin *et al.*, 1991), which makes it possible to distinguish between potential and vortex components of the electric field in the reconnection region by observations of the velocity of the flare ribbons and luminosity irregularities in the active region photosphere. Let us consider this question in more detail (Pudovkin *et al.*, 1991, 1996).

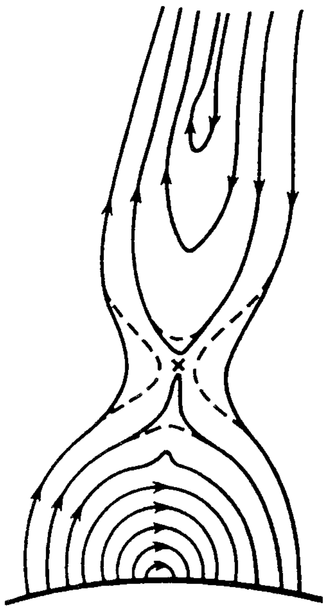


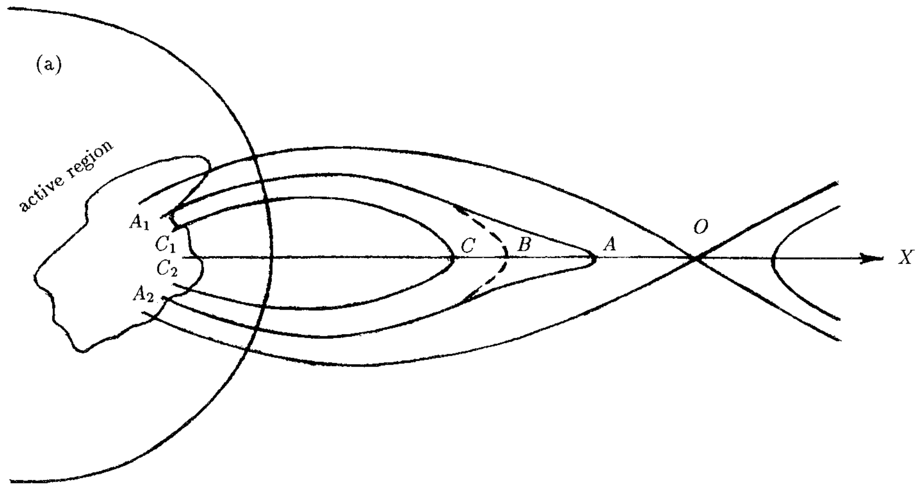
Figure 1. Topology of the magnetic field in a flare region (after Sturrock, 1972).

Let Figure 2(a) represent a cross-section of an active region in a plane perpendicular to the magnetic merging line. For simplicity, we will assume that the gradient of the magnetic field intensity in the direction perpendicular to the merging line is much greater than that along the merging line. In this case, the configuration of the magnetic field in the active region may be considered as quasi-two-dimensional, and the merging line is projected onto the plane of the Figure at a point O.

Let at a moment t_1 a clot of the coronal plasma, heated in the vicinity of the reconnection line, locate at a point A; the magnetic field line passing this point crosses the photosphere at points A_1 and A_2, respectively; energetic particles precipitating from the plasma clot cause an enhancement of the photospheric emissions observed as two relatively bright spots.

During the flare, the configuration of magnetic field lines changes in such a manner that the apex of the magnetic line passing points A_1 and A_2 at the photosphere would locate at a moment $t_2 = t_1 + \Delta t$ at a point B. (Here we assume that the vortex electric field is localized in the reconnection region and does not exist in the photosphere so that magnetic field lines are motionless there.) The velocity of the displacement of the field line apex and the coordinates of the latter may be found from the following consideration.

According to Maxwell's equations, the intensity of an induced (or vortex) electric field $\mathbf{E}^v$ is determined by the equality



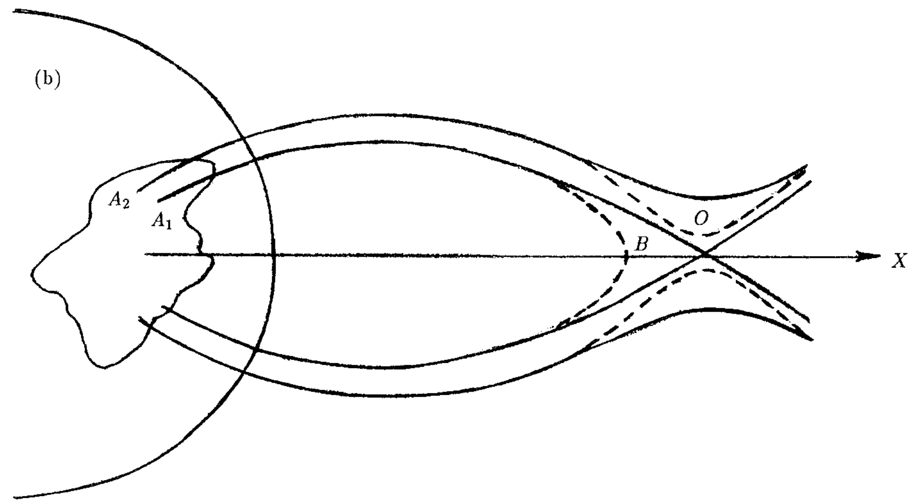


Figure 2. The calculation of the velocity of photospheric emission irregularities and of flare ribbons during solar flares. (a) The source of precipitating particles is located at closed magnetic field lines. (b) The source of precipitating particles is located in the vicinity of the magnetic field merging line.

$$\mathbf{E}^v = -\frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} , \tag{1}$$

where **A** is the vector potential of the magnetic field, and c is the velocity of the light. In the 2D problem under consideration, $\partial \mathbf{A}/\partial t$ may be substituted by

$$\frac{\partial \mathbf{A}}{\partial t} = -\frac{\partial A}{\partial x}\frac{\partial x_a}{\partial t} = -B_c v_a \ ,$$

where B_c is the intensity of the coronal magnetic field, x_a is the apex coordinate and v_a is the apex velocity. Then Equation (1) reduces to

$$\mathbf{E}_c^v = \frac{1}{c} v_a B_c \ , \tag{2}$$

where $\mathbf{E}_c^v$ is the vortex component of the coronal electric field $\mathbf{E}_c$, and B_c is the magnetic field intensity in the corona, and

$$v_a = c\frac{E_c^v}{B_c} \ .$$

Equation (2) allows one to obtain the coordinate x_b of the point B as

$$x_b = x_a + c\frac{E_c^v}{B_c}\Delta t \ . \tag{3}$$

At the same moment, the plasma clot is driven by the total electric field $\mathbf{E}_c = \mathbf{E}_c^v + \mathbf{E}_c^p$, where $\mathbf{E}_c^p$ is the potential component of $\mathbf{E}_c$; correspondingly, the x-coordinate of the point C equals

$$x_c = x_a + c\frac{E_c^v + E_c^p}{B_c}\Delta t \ . \tag{4}$$

Equations (3) and (4) allow one to calculate the distance CB:

$$CB = x_c - x_b = c\frac{E_c^p}{B_c}\Delta t \ . \tag{5}$$

Magnetic field lines A_1BA_2 and C_1CC_2 correspond to a single moment t_2, and hence the figure made by them may be considered to be a cross-section of a magnetic tube. The magnetic flux conservation law may be written for this tube as

$$B_{ph} \cdot A_1C\delta l_{ph} = B_c CB \delta l_c \ ; \tag{6}$$

here B_{ph} is magnetic field intensity at the photosphere; δl_{ph} and δl_c are the widths of the magnetic tube under consideration at the photosphere and in the corona, respectively. The value of δl_{ph} (or δl_c) is quite arbitrary; at the same time, the ratio $\delta l_c/\delta l_{ph}$ is quite certain and is determined by the configuration of the magnetic field in the active region.

Having combined Equation (5) and Equation (6), one obtains the velocity of the photospheric projection of the plasma clot:

$$v_{ph} = \frac{A_1C_1}{\Delta t} = c\frac{E_c^p}{B_{ph}}\frac{\delta l_c}{\delta l_{ph}} \ . \tag{7}$$

It is seen from Equation (7) that the velocity of bright spots in the photosphere is determined solely by the potential component of the coronal electric field E_c^p and is not affected by the vortex component of the latter.

Now we will estimate velocity of the flare ribbons. In this consideration we suppose that the enhancement of the photosphere emissions in the ribbon region is caused by precipitation of energetic particles from the close vicinity of the magnetic reconnection line (Figure 2(b)).

Let the merging line be located at a point O. At moment t_1 this point is projected along the magnetic field line onto a point A_1 at the photosphere. At moment $t_2 = t_1 + \Delta t$ the apex of the field line originated from the same point A_1 at the photosphere is located in point B. At the same time, a new field line (shown by a dashed line in the figure) approaches point O; this field line originates from the photosphere at point A_2, which location may be found from the following arguments.

The magnetic field conservation law for the magnetic tube $A_1B - A_2\,O$ may be written as

$$B_{ph} v_{rb} \Delta l \delta l_{ph} = B_c v_a \Delta t \delta l_c \ , \tag{8}$$

where v_{rb} is the flare-ribbon velocity and all the other symbols are as above. With use of Equation (2) one obtains from Equation (8):

$$v_{rb} = -c \frac{E_p^v}{B_{ph}} \frac{\delta l_c}{\delta l_{ph}} \ . \tag{9}$$

Equation (9) shows that the ribbon velocity is determined by the vortex component of the coronal electric field, and does not depend on the potential component of the latter.

Equations (7) and (9) show that when both components (induced and potential ones) of the reconnection electric field in the corona point in one direction, bright spots and flare ribbons move in opposite directions: the former to the neutral line, and the latter away from it.

Thus, observing the motion of the flare ribbons and of relatively bright spots within the flare region, one can separate the vortex and potential components of the total electric field in the reconnection region, and estimate their intensity.

In the next section of the paper we will apply the proposed methods to the analysis of the electric field in two flare regions.

3. Experimental Data and their Analysis

Figures 3(a–d) show consecutive photographs (negative representation) of a flare which took place at 13:55–15:00 UT on 28 May 1972; the length scale is shown by a bar in the left bottom region of the figures. One can see that beside flare ribbons, we can observe in the flare region two relatively bright spots (framed by a white rectangle) located in the vicinity of the central line of the flare, and the distance between those spots distinctly decreases with time; at the same time, the flare ribbons are moving, as usual, from the central line. Having determined the location of those spots and ribbons at successive moments, one can calculate their velocities, and then estimate the intensity of the potential and vortex components of the electric field in the flare region.

Results of an analysis of that kind are presented in Figure 4, where variation of the distance between the ribbons $(\delta L_r = L_r(t) - L_r(t = 0))$ as well as the distance between the spots $L_s(t)$ during the flare under consideration are shown. As the figure shows, the distance between the ribbons has increased during the flare by about 3000 km for 55 min, which corresponds to a mean velocity of each ribbon of about 0.5 km s^{-1}. If we suppose that the intensity of the magnetic field in the active region equals 10^3 G, the vortex electric field E_{rot} in the reconnection region equals 0.5 V cm^{-1}, which agrees with results by Kopp and Poletto (1986).

At the same time, the distance between the bright spots decreases with time, which means that besides the induced electric field, there exists in the active region a potential electric field E_{pot}; the velocity of the spot approach equals 1.8 km s^{-1} (or 0.9 km s^{-1} for each spot); correspondingly, intensity of the potential electric field in the active region also equals $E_{\mathrm{pot}} \approx 1$ V cm^{-1}. The reconnection rate is determined by the total electric field which is the sum of the vortex and potential fields, that is $E_{\mathrm{tot}} = 1.5$ V cm^{-1}. Then the potential drop along the reconnection line equals $\Delta\Phi = E_{\mathrm{tot}} \times L_{\mathrm{rec}}$, where L_{rec} is the length of the reconnection line, and for $L_{\mathrm{rec}} = 50 \times 10^3$ km, $\Delta\Phi = 10^{10}$ V.

An analogous analysis of flare dynamics has been carried out for a flare on 19 January 1972 (1b; S15 E11). In that case the velocity of the ribbon running away equals 3.2 km s^{-1} ($E_{\mathrm{rot}} \approx 3$ V cm^{-1}), and the spot approaching rate equals 1.5 V cm^{-1}, which is close to the values obtained above.

The existence of the potential electric field in the active region allows us to suppose that some external sources supply that region with electromagnetic energy at the rate $\mathbf{F} = (c/4\pi)\mathbf{E} \times \mathbf{B} \approx 1 \times 10^{10}$ erg cm^{-2} s^{-2}. This source may be associated with large-scale motion of the sub-photospheric plasma in the convection layer. Energy input of that intensity is sufficient for the magnetic field reconnection to precede in a steady-state regime.

4. Conclusions

The use of the methods proposed above has allowed the authors to demonstrate the existence of two kinds of electric fields in active regions during solar flares: a vortex electric field E^v responsible for the flare-ribbon motion from the central line of the active region, and a potential electric field E^p driving bright spots observed within the flare region towards the central line.

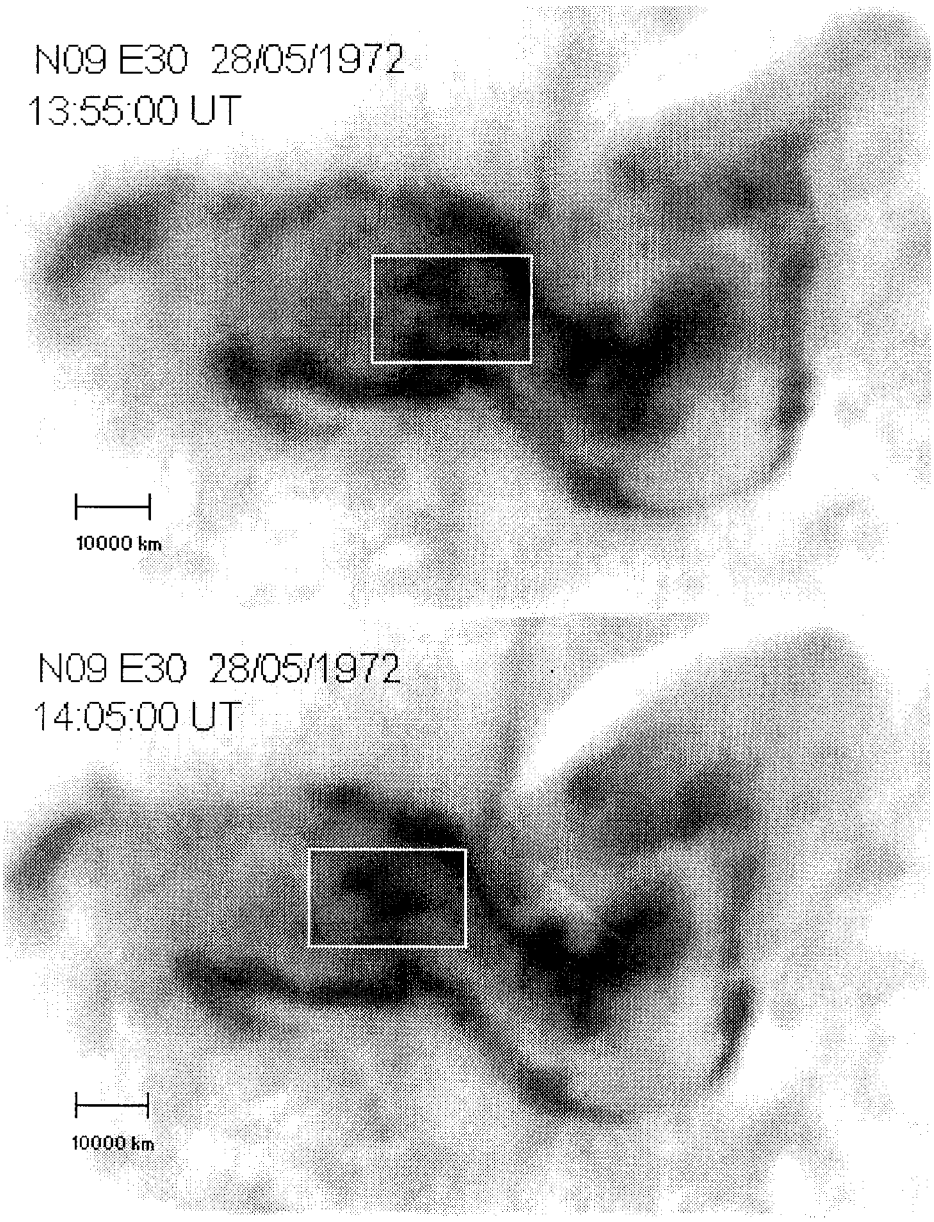


Figure 3a–b.

Intensity of the both components of the electric field is not high and equals approximately 1–3 V cm^{-1}. This intensity is below the threshold of sensitivity of present-day solar electrographs, and much less than the intensity of the solar electric fields discussed in the literature. Nevertheless, the spatial scale of the active region being taken into account, these fields are sufficient to provide the rate of the

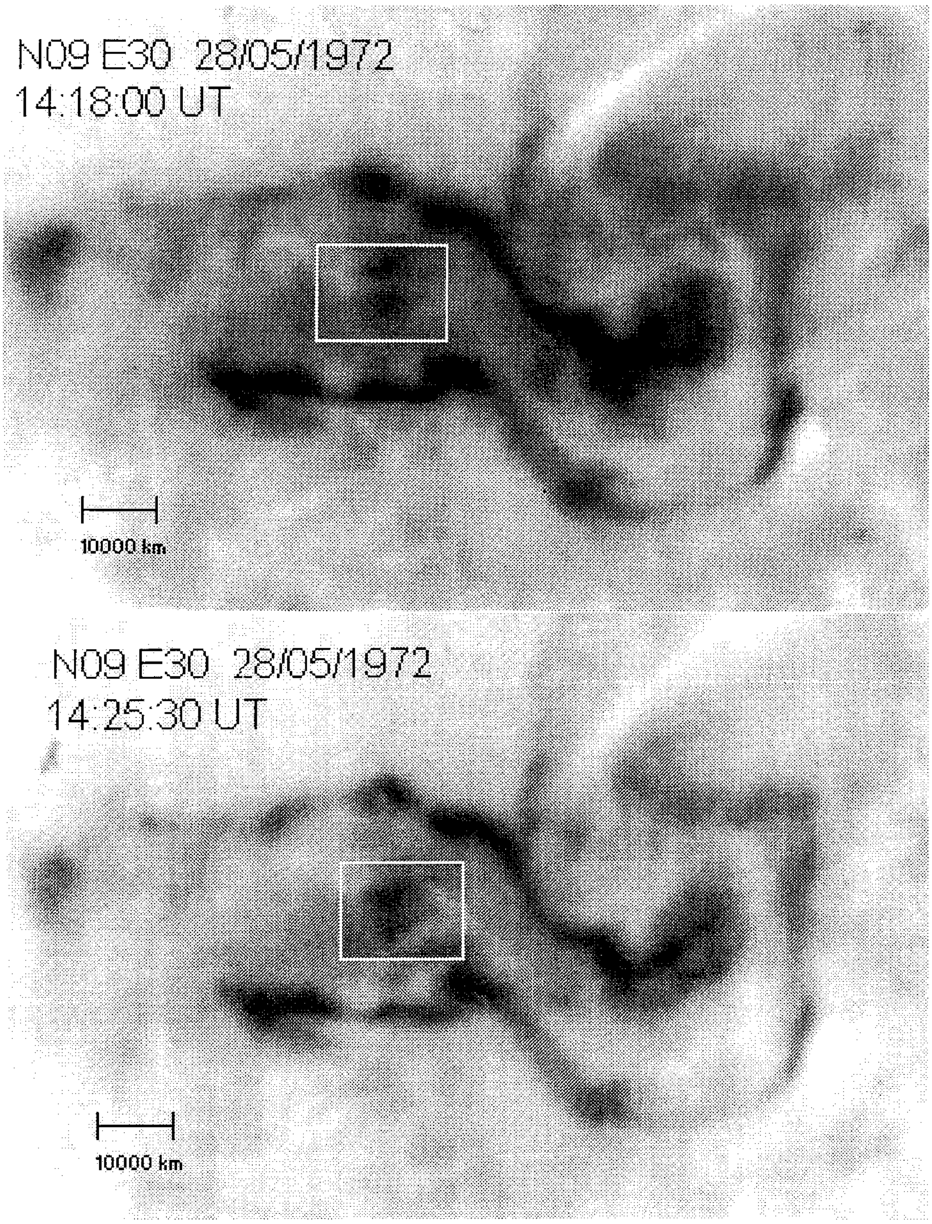


Figure 3c–d. Development of the solar flare on 28 May 1972.

electromagnetic energy input (Poynting vector flux) in the order of 10^{29} erg s^{-1}, and the electric potential drop along the reconnection line in the order of 10^9–10^{10} V, which may explain development of flares in a quasi-steady-state regime, and acceleration of electrons up to energies of some GeV.

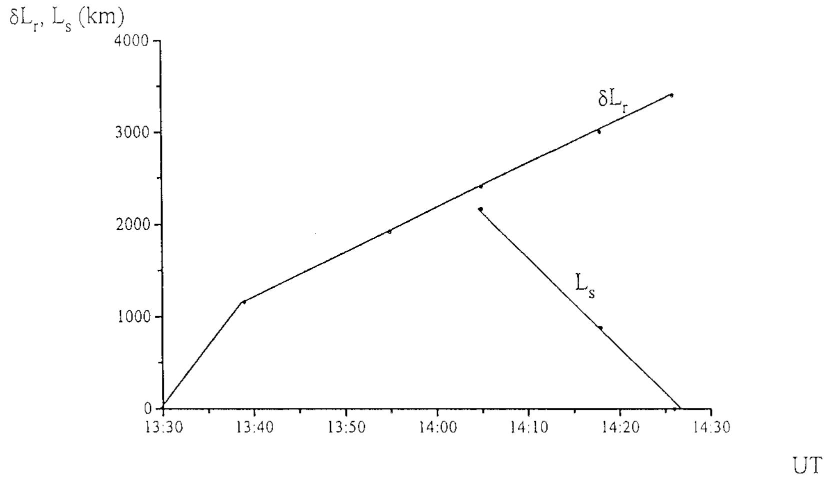


Figure 4. Relative displacement of flare ribbons and of bright spots under consideration during the flare on 28 May 1972.

Besides, if the potential component of the electric field exists also at the pre-flare stage and is of approximately the same intensity, this may explain the formation of current sheets in active regions and the storage of free magnetic energy in amounts sufficient for the development of solar flares.

Acknowledgements

We thank Crimean Astrophysical Observatory and Dr V. Yurchishin for the data of flare observations. This work was supported by the Russian Foundation of Fundamental Research, grants 96-05-00006G and 97-05-64458.

References

Davis, W.: 1977, *Solar Phys.* **54**, 139.
Elliot, H.: 1969, in C. de Jager and Z. Švestka (eds), *Solar Flares and Space Research,* COSPAR Symp., Tokyo, p. 356.
Forbes, T. G. and Priest, E. R.: 1984, in D. M. Butler and K. Papadopulos (eds), *Solar Terrestrial Physics: Present and Future*, NASA Reference Publ. 1120, p. 1.
Foukal, P. and Behr, B. B.: 1995, *Solar Phys.* **156**, 293.
Foukal, P. and Hinata, S.: 1991, *Solar Phys.* **132**, 307.
Foukal, P., Miller, P., and Gilliam, L.: 1983, *Solar Phys.* **83**, 83.
Foukal, P., Hoyt, C., and Gilliam, L.: 1986, *Astrophys. J.* **303**, 861.
Foukal, P., Little, R., and Gilliam, L.: 1987, *Solar Phys.* **114**, 65.
Janssens, T. J.: 1972, *Solar Phys.* **27**, 149.
Kelley, M. C., Starr, J. A., and Mozer, F. S.: 1971, *J. Geophys. Res.* **76**, 5269.
Kopp, R. A., and Poletto, G.: 1986, in *Coronal and Prominence Plasmas*, NASA Conference Publication 2441, p. 469.

Mayfield, E. B.: 1971, in R. F. Howard (ed.), *IAU Symp.* **43** *on Solar Magnetic Fields*, Kluwer Academic Publishers, Dordrecht, Holland, p. 376.
Moran, T. and Foukal, P.: 1991, *Solar Phys.* **135**, 179.
Parker, E. N.: 1963, *Astrophys. J. Suppl.* **8**, 177.
Petschek, H. E.: 1964, in *AAS–NASA Symp. on the Physics of the Solar Flares*, Washington NASA SP-50, p. 425.
Pneuman, G. W.: 1968, *Solar Phys.* **2**, 462.
Pudovkin, M. I., Isaev, S. I., and Zaitseva, S. A.: 1970, *Ann. Geophys.* **26**, 761.
Pudovkin, M. I., Semenov, V. S., Starkov, G. V., and Kornilova, T. A.: 1991, *Planetary Space Sci.* **39**, 563.
Pudovkin, M. I., Brekke, A., Zaitseva, S. A., and Nozawa, S.: 1996, *Proceedings of the Third International Conference on Substorms (ICS-3)*, Versaille, France, May 1996, p. 141.
Severny, A. B.: 1964, *Ann. Rev. Astron. Astrophys.* **2**, 363.
Sturrock, P. A.: 1972, in P. S. McIntosh, and M. Dryer (eds.), *Solar Activity, Observations and Predictions*, 163.
Sturrock, P. A. and Coppi, B. A.: 1966, *Astrophys. J.* **143**, 3.
Zarro, D. M., Mariska, J. T., and Dennis, B. R.: 1995, *Astrophys. J.* **440**, 888.