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Energy conversion of the flare due to direct electric fields from the sheared reconnection

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Abstract

In this paper we present a new mechanism of the main energy conversion of the solar flare. Since a flare inducing prominence (flux tube) rises $V_z \leqslant 300$ km s^{-1}, the plasmas below it cannot continuously eject with Alfvén speeds of $V_A = 3000$ km s^{-1} but probably with $V_z \approx \pm 100$ km s^{-1}. Plasma up and downflows with V_A will within a short duration be blocked between the chromosphere where reconnected flux tubes are piling up, and the slowly rising flux rope. Hence the Petschek slow shock mechanism is difficult to be realized as a major energy converting mechanism.

Adopting a conventional reconnecting morphology, we assume a magnetic component parallel to the photospheric neutral line, i.e. sheared fields of $B_y \neq 0$. Then Gauss's law leads to non-vanishing electric charges σ; $4\pi\sigma = -\mathrm{div}(\boldsymbol{V}\times\boldsymbol{B}/c) \approx B_y \partial V_z/c\partial x$ where the horizontal inflow velocity V_x changes to vertical down-flow V_z (e.g. $B_y \approx B_z = 40$G and $\Delta x \approx 10^4$ km). Then the electric field parallel to the magnetic fields $E_\parallel$ calculated from Coulomb's law from this σ is found to be far greater than the Dreicer field, and accelerates electrons and protons. Thus the horizontally inflowing Poynting energy flux in area S_x is immediately converted to the kinetic energy of electron beams along the magnetic field in area S_z; $B^2 V_x S_x/4\pi = \frac{1}{2} m_e n_{\mathrm{beam}} V_{\mathrm{beam}}^3 S_z$ with $S_x/S_z \approx 4$. The particle beam energy flux cannot exceed the Poynting energy flux however large $E_\parallel$ may be. The total energy can be supplied by 10 keV electrons and $n_{\mathrm{beam}} = 2\times 10^7$ cm^{-3} for $V_x = 40$ km s^{-1}. This inflow velocity V_x, though restricted by the rising prominence speed, explains the short flare duration consistent to observations. The electron beam flux $n_{\mathrm{beam}} V_{\mathrm{beam}}$ will be simultaneously and co-spatially compensated by the slowly back-flowing bulk electrons, avoiding possible enormous charge pile-up.

Instead of the conventional diffusion region, which contains serious difficulties if there is the shear as one should normally expect, we propose a reconnecting small region in the potential magnetic fields. The latter may be created by unwinding motions to erase the shear and to minimize energy, and the time scale is given only from the outside condition free from any diffusive processes such as the anomalous resistivity, because no electric currents may exist.

Keywords: Solar flare; Energy conversion; Direct electric field

1. Introduction

Recently we published a short paper (Hirayama, in press, Paper I) which is essentially the same as this paper. But here we extend some discussions left over. The Petschek mechanism (1964), or its variants consist of two regions; one is the slow shock layers where the main energy conversion is supposed to take place and the other is the so-called diffusion region where the magnetic reconnection in a very small volume is assumed to occur quickly. In Paper I we found that both are difficult to be realized. A basic serious problem in the Petschek(-type) model in the solar flare is that it anticipates that the plasmas should eject with Alfvén speeds of e.g. $V_A \approx$ 3000 km s^{-1}, while a rising prominence, or more generally rising magnetic flux tube (the earlier phase of coronal mass ejections) is often observed in the above with velocities of $\approx$300 km s^{-1} (Hirayama, 1974, Fig. 1a; Kopp and Pneuman, 1976). Below this slowly rising prominence, it is impossible to

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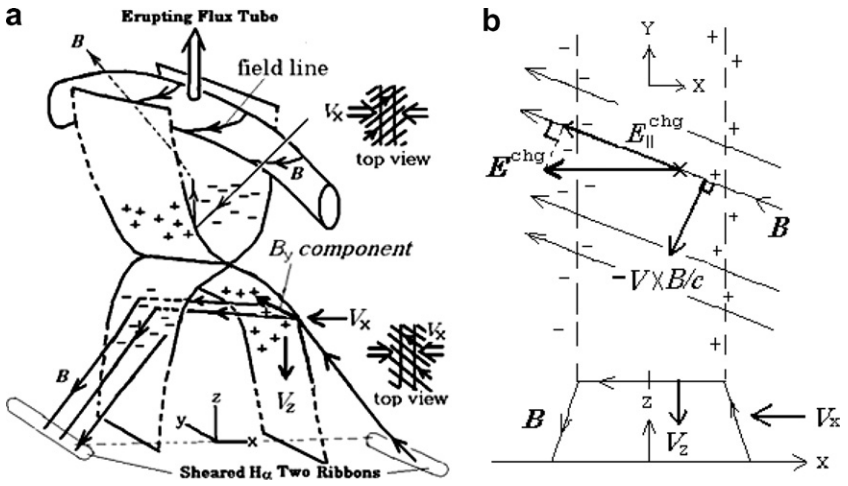

Fig. 1. (a) Charges at large velocity bends. (b) $\boldsymbol{E}_{\mathrm{chg}}$, $\boldsymbol{E}_{\parallel}$, $-\boldsymbol{V}\times\boldsymbol{B}/c$.

maintain 'lasting' ejections with $\pm V_A$ so that there cannot be slow shocks ($2V_A \times 100s \approx R_{\mathrm{sun}}$!). Up and down V_A-flows are blocked between the rising flux tube and the chromosphere below. Priest and Forbes, 2000, p. 344, reviewing a similar situation in the night-side reconnection of geomagnetic disturbances, remark that slow shocks are rarely observed in the earth's side because the earth may act as an obstruct.

Our new model consists of also two regions as the Petschek mechanism. The major energy converting region is nearly in the same geometrical places as the Petschek four slow shocks, but instead of the thin shocks we propose electric charge layers of thickness of a fraction (e.g. 10^4 km) of the total horizonal distance (e.g. 10^5 km). The non-zero charges σ from Gauss's law $4\pi\sigma = \mathrm{div}\,\boldsymbol{E} = \mathrm{div}(-\boldsymbol{V}\times\boldsymbol{B}/c)$ arise if the magnetic shear (i.e. not exactly anti-parallel magnetic field $\boldsymbol{B}$) is present in the layers where the MHD plasma flow velocity $\boldsymbol{V}$ turns from horizontal to vertical directions. These charges produce the electric field parallel to the magnetic field $E_{\parallel}$, and $E_{\parallel}$ accelerates the proper amount of high energy particles within a time scale required from the observations.

For the magnetic reconnecting region, which is conventionally called the diffusion region, we accept a statement by Parker (1963) that unless the merging fields are exactly anti-parallel there is no reconnection. This is because in the neutral line region, the sheared magnetic field component B_y along the neutral line becomes predominant. Namely the second postulate of the Petschek mechanism needs to be reconsidered, since the anti-parallel vertical component $|B_z|$ becomes zero, while B_y does not change as one approaches to the neutral sheet. Since the shear may be observationally unavoidable, we propose a situation where the shear may become zero, i.e. become exactly anti-parallel by unwinding motions due to general tendency of minimizing magnetic energy to a potential magnetic field, provided that the environmental magnetic fields may allow. Thus the magnetic reconnecting region we propose is not a diffusion region which by definition magnetic fields 'diffuse out', but a region of the potential magnetic fields where no-diffusions take place (no electric current is involved). The time scale can take any value determined from the outside condition, which becomes free from the difficult problems so far encountered.

Recently many reconnection simulations of the solar flares have been performed with increasing sophistications (e.g. Shiota et al., 2005; Hesse et al., 2005). See earlier references therein. The latter paper presents a new way of incorporating the 3-dimensional reconnection. However, it is not clear how the field aligned electric fields are generated without invoking the electric charges (they introduced in an ad hoc way a localized E_x which is equivalent to our E_y). Examples of recent magnetospheric reconnection studies include e.g. Birn et al., 2001 and Pritchett and Coroniti, 2004, where a small overall geometrical size of about 10 ion inertial lengths (light velocity divided by the ion plasma angular frequency) initially in the Harris configuration is treated. Although these solar and magnetosperic simulations may be able to reproduce some of the important observed features, how the presumed anomalous resistivity (solar case) is created and how the nonlinear perturbed state (magnetosphere) has started is not yet clearly demonstrated, besides the difficulties of the Petschek type mechanism mentioned above (or is it impossible to adopt other initial conditions than the Harris configuration). Thus the present study, even though primitive, may be of some value.

Both of our proposals, which are rather independent to each other, seem to be new; field aligned electric fields due to 'non-zero charges' and a small reconnection region without electric current created by 'unwinding motions' in initially sheared magnetic fields (new points are in apostrophes). This paper is in particular intended to make clear the basic physics of existence of non-zero charges and the electric fields which are parallel to the magnetic fields, $E_{\parallel}$. Besides, we emphasize an obvious fact that because the horizontally incoming Poynting energy flux is limited, the energy flux of the accelerated particles is limited too, however large the electric fields may be.