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MODELING LARGE SOLAR FLARES

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ABSTRACT

The basic ideas to model the large solar flares are reviewed and illustrated. Some fundamental properties of potential and non-potential fields in the solar atmosphere are recalled. In particular, we consider a classification of the non-potential fields or, more exactly, related electric currents, including reconnecting current layers. The so-called 'rainbow reconnection' model is presented with its properties and predictions. This model allows us to understand main features of large flares in terms of reconnection. We assume that in the two-ribbon flares, like the Bastille-day flare, the magnetic separatrices are involved in a large-scale shear photospheric flow in the presence of reconnecting current layers generated by a converging flow.

INTRODUCTION

A large flare is a complex phenomenon in the solar atmosphere with many different manifestations on which many books have been written. Large solar flares strongly influence interplanetary and terrestrial space by virtue of shock waves, hard electromagnetic radiation and accelerated particles. In this paper the aim is to summarize the large-scale physical processes responsible for accumulation of energy before a flare and for a fast release of this energy during a large flare. (In small flares, we cannot neglect fine structures and small-scale fast processes without a risk to lose an essence.) We begin with a flare energy source, the magnetic fields in the solar atmosphere. They dominate the morphology and energetics of active regions, where flares occur, because the magnetic energy is higher there. Then we focus on the cause of fast energy release in flares. As known, magnetic reconnection does play a key role in solar flares.

After ten years of successful mission of *Yohkoh* we know that the magnetic reconnection is common to impulsive and gradual flares, the gigantic arcade formation, and CMEs. Observations with the Hard X-ray Telescope (HXT; Kosugi et al., 1991) and the Soft X-ray Telescope (SXT; Tsuneta et al., 1991) on board *Yohkoh* have shown that reconnection is responsible for such features of flares as separating ribbons of chromospheric emission, rising arcades of soft X-ray (SXR) loops, with hard X-ray (HXR) emission at their feet and at their summits. However, some important questions related to the flare energetics and dynamics still remain to be clarified from observational and theoretical aspects. For example, magnetic energy conversion by reconnection is relatively well studied in 2D models, but in real three dimensions we are only starting to understand the magnetic topology and the plasma physics involved.

We present the so-called 'rainbow reconnection' model with its properties and predictions. This model allows us to understand main features of large flares in terms of the collisionless 3D reconnection (Somov et al., 1998). We apply the model to the well-observed flare on 14 July 2000, the Bastille-day flare.

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In general, we assume that, in the large two-ribbon flares with observed decrease of HXR footpoint separation, the magnetic field separatrices are involved in a large-scale shear flow in the photosphere, which can be traced by proper motions of main sunspots in an active region, in the presence of a reconnecting current layer (RCL) generated by a large-scale converging flow of the same spots.

POTENTIAL AND NON-POTENTIAL FIELDS

Properties of Potential Fields

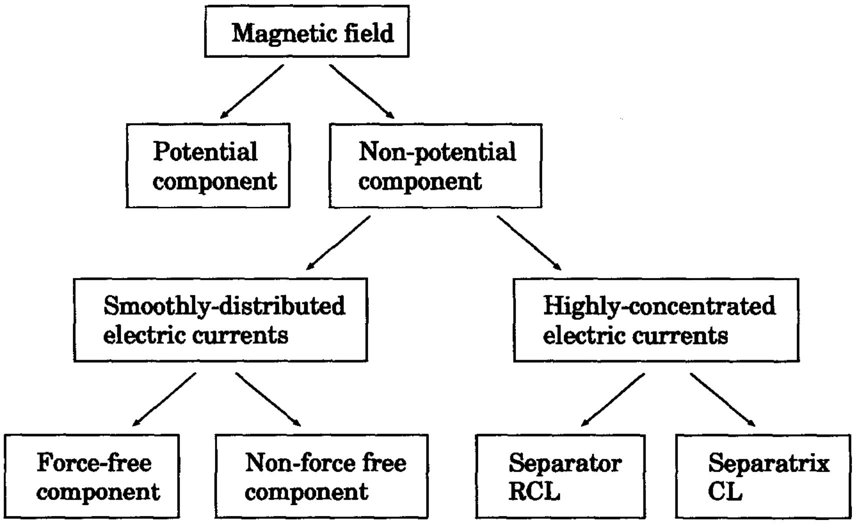

Fig. 1. Main types of the magnetic field in an active region according to their physical properties.

In order to clarify the role of a magnetic field in flares, let us classify the magnetic fields in an active region, as shown in Figure 1. The field is divided broadly into two categories: (a) the potential or current-free part and (b) the non-potential part related to electric currents flowing in an active region. Starting from the photosphere up to some significant height in the corona, the magnetic energy density greatly exceeds that of the thermal, kinetic and gravitational energy of the solar plasma:

$$\frac{B^2}{8\pi} \gg 2nk_{\rm B}T\,, \quad \frac{B^2}{8\pi} \gg \frac{\rho v^2}{2}\,, \quad \text{and} \quad \frac{B^2}{8\pi} \gg \rho g\,. \tag{1}$$

So, the magnetic field can be considered in the strong field approximation (e.g. Somov 2000). This means that the coronal field is mainly potential. At least, it is potential in a large scale, in which the field determines the *global* structure of an active region. However the potential field, which satisfies the given boundary conditions in the photosphere and in the solar wind, has the minimum of energy because the potential field is current-free by definition. Two important consequences for the physics of large flares follow from this fact.

First, being disrupted, for example by an eruptive prominence, the field lines of the potential field are connected back again via reconnection. This behaviour is important for understanding the so-called eruptive flares (Svestka et al., 1992). In the strong field approximation, the magnetic field, changing in time, sets the solar plasma in motion. Such a motion can be described by the set of the ordinary differential equations. They are much simpler than the partial derivative equations of the usual MHD. This is a natural simplicity of the actual conditions in the solar atmosphere. To solve the simplified equations, we have to find the potential field as a function of time. This is not difficult.

Second, since no energy can be taken from the current-free field, the current-carring components have to be unavoidably introduced in the large-flare modeling to explain accumulation of energy before a flare and its release in the flare process. We assume here that the solar flare is the phenomenon which takes its energy during the flare from some volume in the corona.

Classification of Non-potential Fields

The non-potential parts of the field are related to electric currents in the corona. It is of principal importance to distinguish the currents of different origin (Figure 1) because they have different physical properties and, as a consequence, different behaviours in the pre-flare and flare processes. The actual currents conventionally comprise two different types: (a) smoothly-distributed currents that are necessarily parallel or nearly parallel to the field lines, so the field is locally force-free (FFF) or nearly force-free; (b) strongly-concentrated currents like a RCL at separators and a current layer (CL) at separatrices.

It was a question whether or not it is possible to explain the pre-flare energy storage in a FFF, i.e. only with electric currents aligned with the magnetic field lines. This idea never looked too promising, except one suggests that the energy of the FFF can exceed the energy of the 'completely open' field having the same boundary conditions in the photosphere. If this could be true, we would expect an explosive opening of such a configuration with fast release of the excess energy. Aly (1991) has shown that the energy of any FFF occupying a 'coronal half-space' is either infinite or smaller than the energy of the open field. So, *the opening costs energy*, which is not small in fact, and cannot occur spontaneously.

Therefore, to explain the eruptive flares, the initial plasma-field system must have the free energy in excess of the open field limit. Only that excess is available to lift and drive the expelled plasma (Sturrock, 1991). As mentioned above, the coronal fields can be considered as strong (and as a consequence the FFF or potential) only in some range of heights: starting from the photosphere up to a height in the corona where solar wind becomes fast enough to influence the magnetic field. Hence the corona has an upper boundary which is essential for the coronal field structure (Somov and Syrovatskii, 1972). The coronal fields are never completely open or completely closed (Low and Smith, 1993). Their energy is always lower than the Aly-Sturrock limit but higher than the energy of a potential field (Antiochos et al., 1999).

If we recognize the low efficiency of the FFF in eruptive flares, we assume that the currents flowing *across* the field lines allow the corona to have a magnetic energy in excess of some limit (lower than the Aly-Sturrock limit) to drive an eruptive flare. These currents can, in principle, be generated by any non-magnetic force – for example, the gravity force, the gradient of gas pressure or forces of the inertia origin. Two problems arise, however, in this aspect: (a) by virtue of Eq. (1), such forces are normally relatively weak in comparison with the magnetic force in the corona, at least in large scales; (b) the smoothly-distributed currents dissipate too slowly in a low-resistivity plasma. So, the highly-concentrated currents are necessary to explain an extremely high power of energy release in the impulsive phase of a flare. The RCLs may allow an active region to overcome both difficulties.

Reconnecting Current Layers

In a low-resistivity plasma, the thin CLs appear to hinder a redistribution of interacting magnetic fluxes (see the fourth line in Figure 1). They appear at separators in the corona, where reconnection redistributes the fluxes so that the field remains nearly potential. Since resistivity is extremely low, only very slow reconnection proceeds in such a RCL which we call it a slowly-reconnecting RCL. The wider the layer, the larger the magnetic energy is accumulated in the region of the interacting fluxes.

There is a principal difference between the RCL at a separator and the CL at separatrices. It is impossible to consider the RCL as a one-dimensional discontinuity because the plasma coming into the RCL has to be compensated by plasma outflow from it. As for the CL generated at separatrices, it represents the current distribution typical for the MHD tangential discontinuities which are non-evolutionary; they are always spreading out in both directions from separatrix surfaces into surrounding plasma (Somov, 2000). On the contrary, the current density inside the RCL usually grows with time and reaches one or another limit. For example, wave excitation begins and wave-particle interaction becomes efficient to produce high resistivity, or the collisionless dynamic dissipation allows the fast process of collisionless reconnection.

Therefore, we believe that the potential field determines a large-scale structure of the flare-active regions while the RCL at separators together with the other non-potential components of magnetic field determine energetics and dynamics of a large eruptive flare.

Magnetic Reconnection of Electric Currents

Reconnection reconnects field lines together with field-aligned electric currents. This process may play a significant role in flares (Somov, 1994). Hénoux and Somov (1987) considered two systems of coronal currents J_1 and J_2 distributed inside two different magnetic cells interacting along the separator in the corona. Locally, the field-aligned currents modify the equilibrium conditions for the RCL. In this way, they influence the reconnection rate (Somov, 2000).

Reconnection does the same with electric currents as with magnetic field lines, i.e. it disrupts them and connects them in a different way. If reconnection of field lines would create *symmetrical* reconnection of currents, then a current, J_1, should replace another one, J_2, which equals the first current, and no electric field could be induced in such a way. Such coincidence has zero probalility.

In general, the reconnected currents are not equal among themselves; hence the current $(J_1 - J_2)$ is actually interrupted. The simplest but realistic example is shown in Figure 2. Here we neglect one of the currents; e.g., $J_2 = 0$. A new emerging flux (s, n) moves upward together with a current J. The current is disrupted by reconnection in the RCL and appears to be connected into new electric circuits. This process creates an additional electric field at the separator.

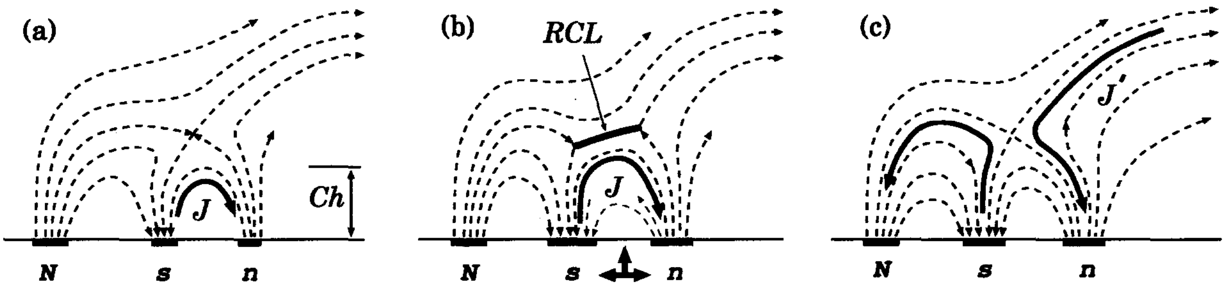

Fig. 2. A reconnecting field with electric current: (a) the initial state is mainly potential but contains a loop of new emerging flux which carries a current J, (b) the *pre-reconnection* (pre-flare) state, (c) the final state after reconnection of the magnetic field lines and field-aligned electric currents.

An important consequence of *non-symmetrical* reconnection of currents is that the current is connected in another electric circuit which, in general, has another self-inductance L. Hence reconnection of this current changes the energy of the current system $W_L = LJ^2/2$ and its inductive time scale $\tau_L = L/R$. A larger circuit implies a larger energy but a longer time. Zuccarello et al. (1987) pointed out that the magnetic energy release in a flare should not be attributed to current dissipation but rather to a change in the current pattern that reduces the stored magnetic energy. They introduced an example of how self-inductance and energy storage can be changed in a sheared FFF. In terms of MHD, the inductive energy W_L is the energy of the azimuthal magnetic field B_φ related to the field-aligned current J.

There is an advantage in the model of reconnecting currents. The topological interruption of large-scale currents flowing along and near separatrices does not require an increase of the total resistivity R everywhere the currents flow but only in the place where these surfaces cross, i.e. along the separator line. The plasma resistivity must be increased, for example by excitation of plasma turbulence, only inside the very thin RCL at the separator. Otherwise reconnection will be too slow and the rate of energy release insufficient for a flare.

Aschwanden et al. (1999) studied in great detail the 3D quadrupolar magnetic reconnection in solar flares. One finding is that, out of ten studied flares, six had the almost collinear reconnecting loops. Another interesting result is that a self-inductance of the largest loop involved in reconnection is relevant for the free magnetic energy in solar flares. The amount of the energy depends on the length of the largest loop and the current ratio J_1/J_2. The angle between interacting current-carrying loops and their relative distance was found to be less important.

RAINBOW RECONNECTION MODEL

Photospheric Vortices and Coronal Separators

The appearance of separators in the solar atmosphere was initially attributed to the emergence of a new magnetic flux from the photosphere into the region where some other magnetic flux already exists (Sweet, 1969). In fact, the presence of separators must be viewed as a much more general phenomenon. Figure 3a shows the simplest model of the uniform distribution of the vertical component B_z of the field in the photosphere (Somov, 1985). The interface between fields with opposite polarity, the neutral line (NL), divides the region of the magnetic field source along the y axis. As is often visible in solar magnetograms, this region is deformed by photospheric flows with the velocity field **v** in such a way that the NL gradually acquires the shape of the letter S as shown in Figure 3b.

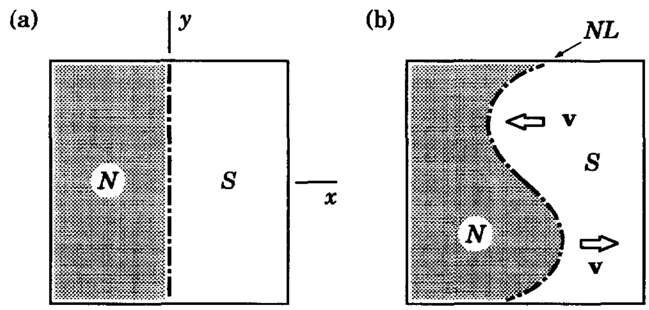

Fig. 3. (a) A model distribution of magnetic field in the photospheric plane. (b) A vortex flow distorts the neutral line NL so that it takes the shape of the letter S.

At a first glance, it seems that the field with such simple sources in the photosphere cannot in principle have any topological peculiarities. A necessary condition for a separator to appear is that the magnetic connectivity becomes discontinuous. The mapping from the positive to negative polarity regions defined by the field lines is discontinuous at a separator. The initial bipole field, shown in Figure 3a, has continuous mapping everywhere. If any smooth flow in the photosphere is applied to this field, such as the vortex flow in Figure 3b, the mapping should remain continuous. However an appearance of the MHD discontinuities and their evolutionarity, continuous transitions between discontinuities are not trivial (see Somov, 2000). In a strong field, following the continuous evolution of the boundary conditions, a neutral (zeroth) point of the magnetic field may appear on the boundary and, if the electric field at this point is not equal to zero (a sufficient condition), it will create a magnetic field discontinuity which prevents a change of the field topology in the approximation of the ideal MHD. In a plasma of finite resistivity, such discontinuity is a RCL of finite thickness.

Creation of the RCL at the neutral point, which appears on the boundary, was used in the model of coronal streamers driven by the solar wind (Somov and Syrovatskii, 1972). The same occurs in the model for interacting magnetic fluxes compressed by the converging flows in the photosphere (Low and Wolfson, 1988). Another case is an appearance of a pair of zeroth points inside the region. This is the case considered here. Beginning with some critical bending of the neutral line NL, the magnetic field begins to contain a pair of the neutral points and a separator appears as shown in Figure 4 (Somov, 1985, 1986). In this figure, the separator X is located above the photospheric NL like a rainbow above a river which makes a bend. The separator is nearly parallel to the NL in its central part. The potential field lines just above the NL are orthogonal to it. This is important to make the simplest 2D models.

At a second glance, the rainbow reconnection seems easy but gives us only a very sketchy account of actual flares. However, both statements are not true. By using the topological model for a potential field above the photosphere, Gorbachev and Somov (1988) showed that the vortices or any other photospheric field changes, creating the S-like shape of the NL, do produce a separator. So, the model reveals a causal connection of

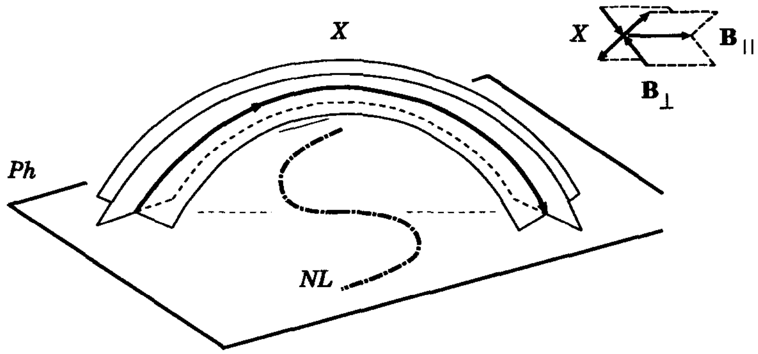

Fig. 4. The separator X above the S-shaped bend of the photospheric neutral line NL. The inset in the upper righthand corner shows the structure of the magnetic field near the top of the separator.

large two-ribbon flares with the S-shaped bend. Moreover, it naturally explains the arrangement and shape of the flare ribbons in the chromosphere, the SXR structures like intersecting loops, and the early appearance of bright kernels on the flare ribbon ends (Gorbachev and Somov, 1989, 1990).

The model by Gorbachev and Somov had reproduced the observed features of the 1B/M4 flare of 1980 November 5. In general, the S-shaped structures (sigmoids), observed in SXR (e.g. Pevtsov et al., 1996; Moore et al., 2001) or in Hα-line, are usually interpreted in favour of non-potential fields. The shapes of coronal loops are considered as a signature of the helicity of their magnetic fields. However, the S-shaped SXR structures in the flare of 1980 November 5 result from the computations of the ordinary potential field. A potential field may look as a strongly non-potential one, this is related to the field structure near the separator.

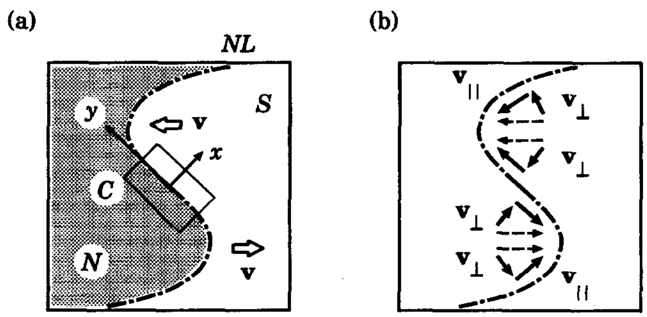

Fig. 5. (a) A photospheric vortex flow distorts the neutral line. (b) A schematic decomposition of the velocity field $\mathbf{v}$ into the components parallel and perpendicular to the NL.

As another consequence of the rainbow reconnection, Figure 5 illustrates a character of the photospheric velocity field. The vortex flow generates two components of the velocity: parallel to the NL and directed to the NL. The first component of the velocity field provides a shear of magnetic field lines above the photospheric NL. The second one tends to compress the photospheric plasma near the NL and in such a way it can drive magnetic reconnection in the corona and photosphere.

RCL in the Global Structure without Shear

At first, we shall discuss only an influence of the *converging* photospheric flows on reconnection at the separator. To demonstrate it in the simplest way, we shall consider only a central region C in the vicinity of the S-shaped NL in Figure 5a. In this region, we put the y-direction along the NL. So, the separator is parallel to NL as shown in Figure 4.

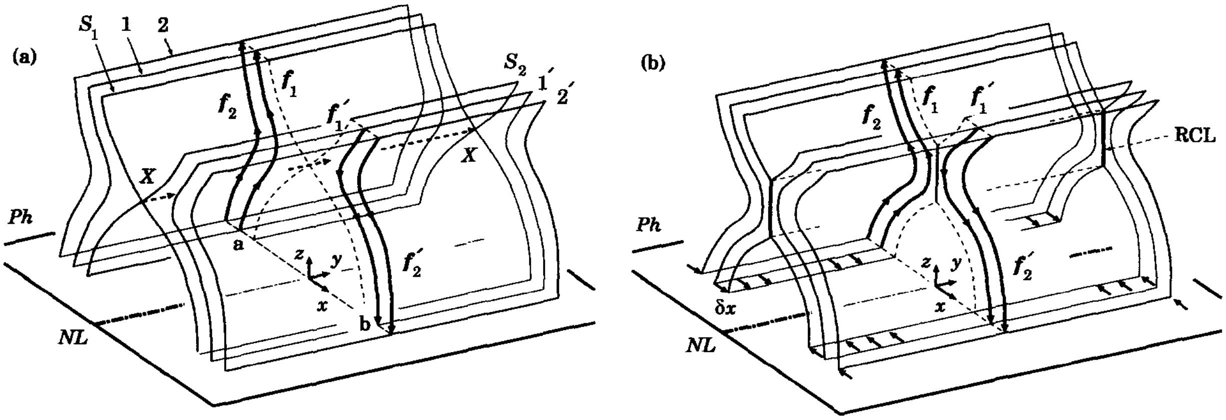

Fig. 6. (a) An initial state of magnetic field. (b) The converging flows in the photosphere induce a reconnecting current layer (RCL) in the corona.

To clarify notation let us start from the classical 'reconnection in the plane'. In this case, illustrated by Figure 6a, the straight line NL is the neutral line in the photospheric plane (x, y). Above this plane, six magnetic surfaces are shown to discuss the reconnection model. We do not introduce the magnetic surfaces in usual schemes which are sufficient to describe plane reconnection. We simply consider reconnection of field lines just in one plane, the 'reconnection plane' (x, z), i.e. $y = 0$. And we 'remember' that, in all other planes with $y \neq 0$, we have the same process. This is not true, however, in 3D configurations of the magnetic fields in active regions. So, it is instructive to introduce the magnetic surfaces.

The magnetic surface 1 consists of the field lines which are similar to the line f_1 starting at the point a. The surface 2 consists of the field lines similar to f_2. For the sake of simplicity, we consider a symmetrical case with the symmetry plane $x = 0$. So, the field lines f_1', f_2' etc have the vertical component B_z of the opposite sign with respect to the similar lines on the opposite side of NL. Among the magnetic surfaces, two are topologically important: separatrices S_1 and S_2 cross at the separator straight line X, which is parallel to NL. The separator separates the interacting magnetic fluxes by the separatrices. The interacting fluxes are reconnected across the separator so that the field would tend to remain potential, if there were no plasma.

Let Figure 6a describe an 'initial state' of the magnetic configuration in evolution. Starting from this state, let us introduce the converging flow of the photospheric footpoints. This is illustrated by the displacement vector δx related to the velocity component $\mathbf{v}_\perp$:

$$\delta x = v_\perp \times \tau \,, \tag{2}$$

where τ is a duration of a pre-reconnection stage in the active region evolution. We make the assumption that reconnection goes so slowly that we can neglect it. Some part of magnetic fluxes, δA, should be reconnected across the separator X, if our assumption did not hold. Here A is the y-component of the vector potential $\mathbf{A}$ defined by relation $\mathbf{B} = \operatorname{curl} \mathbf{A}$. In a plasma of low resistivity, like coronal plasma, the slowly-reconnecting current layer (RCL in Figure 6b) is developing and growing (we may call this process a 'pile-up regime') to hinder the redistribution of interacting fluxes. This results in an excess energy being stored in the form of magnetic energy of the RCL.

Pre-flare Structure with Shear

As in the previous Section, a converging flow creates the RCL along the separator in the corona as shown in Figure 7b. In addition, now a shear flow is superposed on the converging flow in the photosphere. So, the separatrices S_1 and S_2 are involved in the shear flow together with nearby surfaces 1, 2 and 1′, 2′. When a field line, for example f_1, moves in direction to NL, it becomes longer along the NL under action of the shear. Figure 7b shows only the field lines which were initially in the plane (x, z) as shown in Figure 7a. Under action of the shear, these lines move out of the plane (x, z), except for an upper corona boundary,

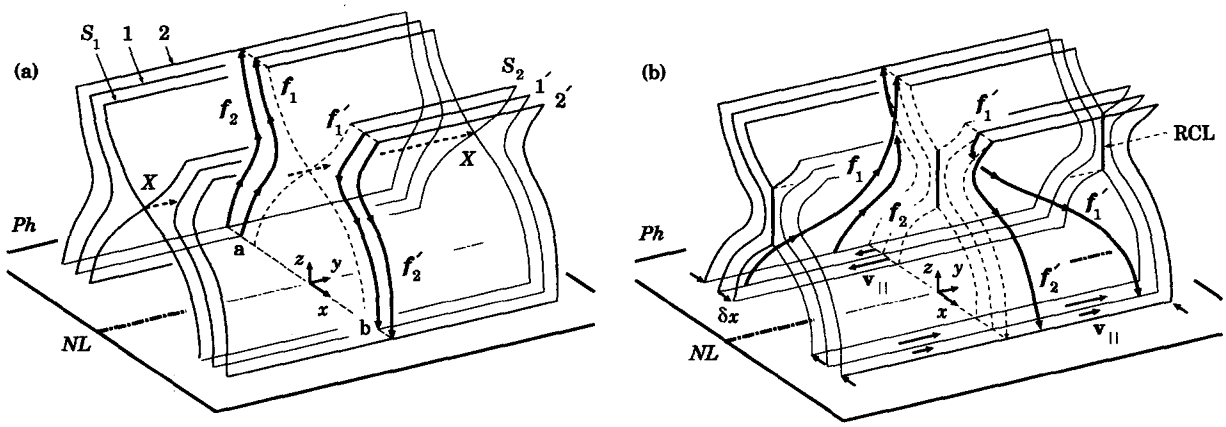

Fig. 7. (a) The initial configuration of the field is the same as in Figure 6. (b) The converging flow creates the RCL. In addition, the shear flow in the photosphere makes the field lines longer, increasing the energy in the magnetic field.

which is assumed, for the sake of simplicity of illustration, not to be affected by the photospheric shear.

The shear flows add to the energy of the pre-flare state an additional energy. This is the energy of magnetic tension generated by the shear because of the 'freezing-in' property of the solar plasma. The photospheric flows work on the field-plasma system, making the field lines longer. This is always true, even if there are neither a separator nor separatices. In this case, the currents responsible for tension are smoothly distributed in a coronal volume above a region of photospheric shear. If the pre-flare configuration contains separatrices, then these flows induce current layers extending along the separatrices, with the concentrated current flowing parallel to the orthogonal field $\mathbf{B}_{\perp}$ (see Somov, 2000). The origin of this current lies in the discontinuity of the longitudinal component $B_{\|}$ on the separatrices. Dissipation of the current during a flare leads to a decrease of the discontinuity. We call such a process the 'shear relaxation'.

So, if the magnetic force dominates all the others, the potential field is a solution of the MHD equations in the approximation of a strong field. Such a field, changing in time according to the boundary conditions, sets the solar plasma in motion. The field remains mainly potential but accumulates the non-potential components related to electric currents: (a) slowly-reconnecting current layers which are highly-concentrated currents flowing parallel to the separator, (b) smoothly distributed currents which are responsible for magnetic tension generated by the photospheric shear flows, (c) concentrated currents at the separatrices, also generated by the shear flows. As for the fast reconnection which tends to release these excesses of energy during a flare, now a longitudinal magnetic field is present inside and outside the RCL. Hence, we shall have a three-component reconnection at the separator.

Flare Energy Release and CMEs

The fast reconnection stage of a flare, i.e. its impulsive phase, is illustrated by Figure 8. As in the case of plane reconnection, only two pairs of the reconnecting field lines are shown. Figure 8a differs from Figure 7b in one important respect. These figures show the same magnetic surfaces but different field lines. An additional assumption made here is that the physical conditions along the y-direction are not uniform any longer. It is assumed that the fastest reconnection place is located in the vicinity of point $y = 0$ in the RCL at the separator. For this reason, those field lines are selected which have the nearest distance to the RCL under condition $y = 0$. Just these lines will reconnect first and quickly.

In 3D models, the place of fast reconnection is usually chosen at the top of the separator. This is assumed, for example, in the model for the flare of 1980 November 5 (Gorbachev and Somov, 1989, 1990). As a consequence of the three-component reconnection, the upward-moving lines take a twisted shape, which may correspond to a helical part of a CME. In general, the upward disconnection plays a central role in observed expansion of arcade loops into the upper corona and interplanetary space by creating helical fields which may still be partially connected to the Sun (Gosling et al., 1995; Crooker et al., 2002). In this paper

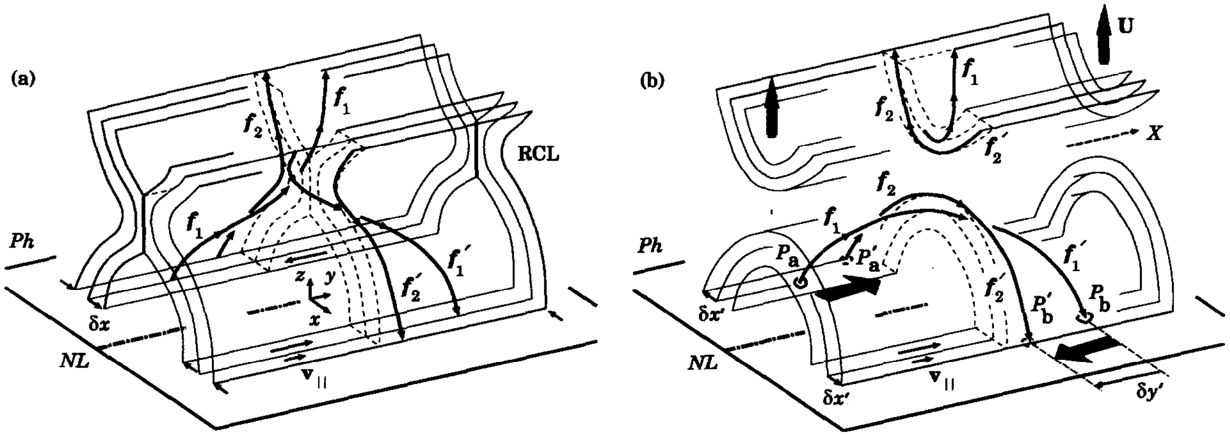

Fig. 8. (a) A pre-reconnection state of the magnetic field in an active region with the converging and shear flows in the photosphere. (b) Rapidly decreasing footpoint separation during the 'more impulsive' Sakao-type flares.

we shall not consider the upward-moving reconnected field lines. They are only indicated in Figure 8b by a velocity vector **U**. On the other hand, the low-lying, SXR arcade events associated with CMEs are interpreted as the consequent brightening of the newly formed arcade (Crooker et al., 2002). In terms of our model, the reconnected field lines below the separator shrink to form magnetic arcade loops. This part is discussed below.

Flare and HXR Footpoints

Reconnection at the separator causes energetic particles to stream down field lines and collide with the chromospheric plasma. The quickest release of energy at the top of the separator creates, at first, the pair of the chromospheric brightest points P_a and P_b related to the *first* reconnected line $f_1 f_1'$ shown in Figure 8b. Later on the field lines f_2 and f_2', being reconnected at the point $y = 0$ in the RCL, create the field line $f_2 f_2'$ with the pair of the bright footpoints P_a' and P_b'. The apparent displacement of the footpoints, from P_a to P_a' and from P_b to P_b', now consists of two parts: $\delta x'$ and $\delta y'$. The first one has the same meaning as in the classical 2D reconnection. δx equals a distance between the magnetic surfaces 1′ and 2′ which is proportional to the reconnected magnetic flux.

The apparent displacement $\delta y'$ equals a distance along the y axis between footpoints of the reconnected field lines $f_1 f_1'$ and $f_2 f_2'$. This value is related to an increase of the length of the field lines on two different magnetic surfaces, generated by the photospheric shear flow along these surfaces before a flare. Therefore, the displacement $\delta y'$ during a flare represents the effect of relaxation of the non-potential component of the magnetic field related to the photospheric shear.

The rainbow reconnection predicts the existence of the converging and shear flows in the central region under the separator. In this region, the converging flow generates the RCL above the photospheric NL. The shear flow creates the longer magnetic loops which must be reconnected by the RCL. Such loops, being reconnected first, provide the bright footpoints, flare kernels, with a large footpoint separation. Later on, the bright footpoints with shorter separation appear. In this way, the *more impulsive* (MI) Sakao-type flares (see definitions and properties of two sub-classes, *more impulsive* (MI) and *less impulsive* (LI) flares, in Sakao et al. 1998) with a decreasing footpoint separation can appear in active regions.

THE BASTILLE-DAY FLARE

On 14 July 2000 near 10:10 UT, the 3B/X5.7 flare occurred near disk center in the active region NOAA 9077. The event revealed bright emission throughout the electromagnetic spectrum, the eruption of a giant twisted filament, an extended Earth-directed CME, and a large enhancement of accelerated particle flux in interplanetary space. This well-observed flare was called the 'Bastille-day' flare.

The *Yohkoh* satellite observed an early phase and some of the impulsive phase from ~10:19 UT. The SXT observed a large arcade; the width and length of the arcade were ~30 000 km and ~120 000 km, respectively. The HXT clearly showed a two-ribbon structure that corresponds to footpoints of the SXR arcade (Figure 9).

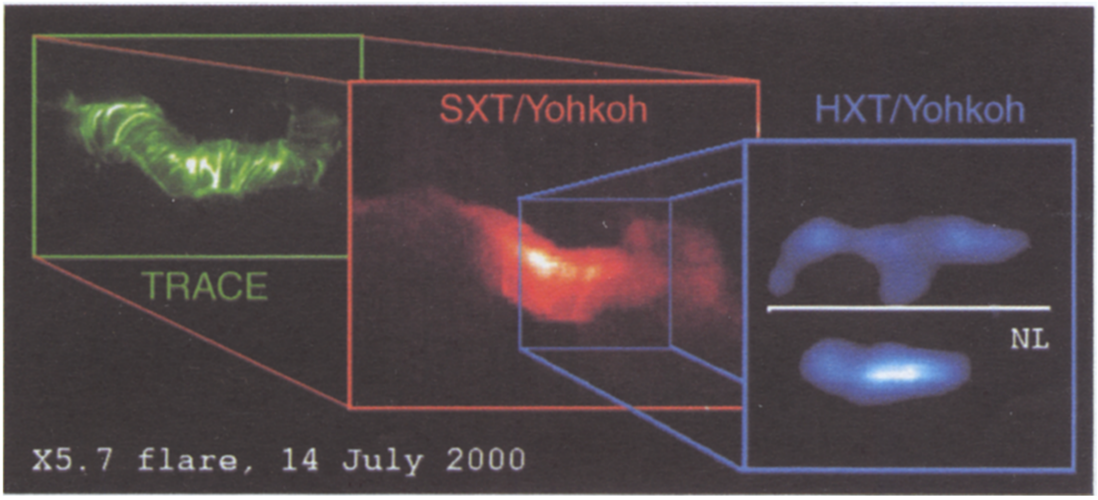

Fig. 9. TRACE and Yohkoh observations of the Bastille-day flare. The right panel shows HXR (53-93 keV) sources aligned along the flare ribbons, which lie at the feet of the arcade loops in the center of the left panels.

Flares often exhibit a two-ribbon structure observed, e.g. in Hα. In the Bastille-day flare, the two ribbons were well seen in Hα. Fletcher and Hudson (2001) described the EUV ribbons as seen in SOHO, TRACE, and *Yohkoh* data. The two-ribbon structure, however, had never before been observed so clearly in HXR (Masuda et al., 2001). Two ribbons were most clearly observed in the first HXR burst. Moreover, the bright kernels in HXR were observed along the ribbons, separated by the simplified neutral line NL in Figure 9. Masuda et al. analyzed the motions of the kernels in the ribbons. Even without accurate overlay of the HXR images on the magnetograms, Masuda et al. concluded that 'bright kernels are footpoints of newly reconnected loops' and that 'lower loops, reconnecting early, are highly sheared; the higher loops, reconnecting later, are less sheared'.

This key guess supports the idea of the rainbow reconnection. However, to make a judgement about it we investigated possible relationships between the HXR kernels and the photospheric magnetic field. It appeared that the observed displacement of the brightest kernel during the first HXR spike was directed nearly anti-parallel to the displacement of the strongest positive spot during the two days between two largest flares (Somov et al., 2002). Presumably, before the Bastille-day flare, the bases of separatrices are moved by the large-scale photospheric flows of two types. First, the shear flows, parallel to the photospheric NL, increase the length of field lines in the corona and, in this way, produce an excess of magnetic energy. Second, the converging flows, directed to the NL, create the pre-flare current layers in the corona.

During the flare, both excesses of energy are released completely or partially. In the Bastille-day flare, the rainbow reconnection model predicts two kinds of apparent displacements. An increase of a distance between the flare ribbons. The effect results from reconnection in a coronal current layer. The second effect is a decrease of the distance between the kernels moving to each other as a result of shear relaxation. Both features are typical for the MI flares (Sakao et al., 1998).

DISCUSSION

Why does the footpoint separation increase in the LI Sakao-type flares? Is it the case when the velocity of the photospheric shear flow decreases near the polarity reversal boundary NL? If so, the second field line f_2 arrives to the separator with a stronger longitudinal field than the first, i.e. $B_{\|2} > B_{\|1}$. This can make reconnection slower, because the longitudinal field makes the plasma less compressible, and the flare less impulsive. However, the longitudinal field does not have an overwhelming effect on the parameters of the RCL and the reconnection rate (Somov, 2000), especially if the compression of the plasma inside the RCL is not high since its temperature is very high.

What seems to be more efficient is the following. In LI flares, after reconnection, the reconnected field line f_2 will be longer than the line f_1. It means that the energy of a longitudinal component of magnetic field becomes larger after reconnection of the shear-related currents. On the contrary, in MI flares reconnection tends to decrease both excesses of energy: (a) the magnetic energy which comes from the converging flows in the photosphere, i.e. the magnetic energy of RCL, and (b) the energy taken by coronal magnetic fields from the photospheric shear flows. This circumstance can make the MI flares more impulsive.

Presumably, in the large-scale two-ribbon flares with observed decrease of footpoint separation, like the Bastille-day flare, the magnetic field separatrices are involved in a large-scale shear photospheric flow (which can be traced by proper motions of main sunspots in an active region) in the presence of an RCL generated by a large-scale converging flow of the same spots. These two conditions are *sufficient* ones for the active region to produce a huge flare similar to the Bastille-day flare. Other realizations of large flares are possible, of course, but this one is the most plausible situation. At least, in addition to the flare HXR ribbons and kernels, it allows us to understand formation of the long twisted filament prominences along the photospheric neutral line before, during and after the flare as a result of on-going reconnection in the photosphere. This prediction of the rainbow model, however, has to be investigated separately.

The same conclusion concerns the fine structure of large flares, not considered in this paper. For example, in the Bastille-day flare, the observations show more than 100 flare loops distributed along the entire neutral line, not only at the mid-location of the S-shape (Aschwanden and Alexander, 2001). What role does the S-shape of the photospheric neutral line play in the flare on its periphery? In this paper, we have considered only a central part of the S-shape. How is the large-scale separator reconnection related to the much more complicated fine structure of the flare? The actual magnetic field configuration presumably contains many places where reconnection occurs. These important questions should be answered by more detailed modeling of the Bastille-day flare and other large solar flares.

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