MODELING LARGE SOLAR FLARES: PRINCIPLES AND PRACTICE

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ABSTRACT

The basic ideas to model the large-scale solar flares are reviewed and illustrated. The so-called 'rainbow reconnection' model is applied to the observations of flares with the HXT and SXT on board *Yohkoh*, the MDI instrument on the SOHO, the TRACE satellite, and the Solar Magnetic Field Telescope of the Beijing Astronomical Observatory. This allows us to improve a theory of large solar flares. In particular, the well-observed Bastille-day 2000 flare is interpreted. Main features of this flare in large-scale structure and dynamics can be explained in terms of the collisionless three-dimensional reconnection.

INTRODUCTION

A large flare is a complex phenomenon in the solar atmosphere with many different manifestations on which many books have been written (e.g. Svestka, 1976; Zirin, 1988; Svestka et al., 1992). 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 an element of risk to lose an essence.) We begin this brief review with a flare energy source, the magnetic fields in the solar atmosphere. They dominate the morphology and energetics of solar active regions, where large flares occur, because the magnetic energy density is higher there. Other possible sources are completely inadequate. Then we focus on the cause of fast energy release in large flares. As known, magnetic reconnection does play a key role in solar flares (Giovanelli, 1946; Dungey, 1958; Syrovatskii, 1962; Priest, 1982).

The reconnection is responsible for such features of flares as separating ribbons of chromospheric emission, a rising arcade of soft X-ray (SXR) loops, with hard X-ray (HXR) emission at their feet and at their summits. There are the observational facts of our days after ten years of successful mission of *Yohkoh* (Ogawara et al., 1991; Acton et al., 1992). 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 the magnetic reconnection is common to impulsive and gradual flares, the gigantic arcade formation, and CMEs. However, some important questions related to the large solar-flare-type event 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 two-dimensional (2D) models, but in real three dimensions we are only starting to understand the magnetic topology and the plasma physics involved.

We apply the so-called 'rainbow reconnection' model to the observations with the HXT and SXT on board *Yohkoh*, the MDI instrument on the SOHO (Domingo et al., 1995), the TRACE satellite, and the Solar Magnetic Field Telescope (SMFT) of the Beijing Astronomical Observatory. This allows us to improve a theory of large solar flares (Somov, 2000). In particular, the well-observed flare on 14 July 2000, the Bastille-day flare, is interpreted. It is shown that the main large-scale structure and dynamics of this flare is explained in terms of the collisionless 3D reconnection model by Somov et al. (1998).

The paper is organized as follows. First, we recall the fundamental properties of potential and non-potential fields in the solar atmosphere. In particular, we consider a classification of the non-potential fields or, more exactly, related electric currents. Among them, the reconnecting current layers (RCLs) are responsible for a fast dynamics of the large solar flares. Second, we explain the rainbow reconnection model, its properties, and predictions. Then we apply this model to the Bastille-day flare. Conclusions are formulated in the last Section.

POTENTIAL AND NON-POTENTIAL FIELDS

Fundamental Properties of Potential Fields

In order to clarify the role of a magnetic field in flares, let us classify the magnetic fields in a flare-active region according to their physical properties, as shown in Figure 1.

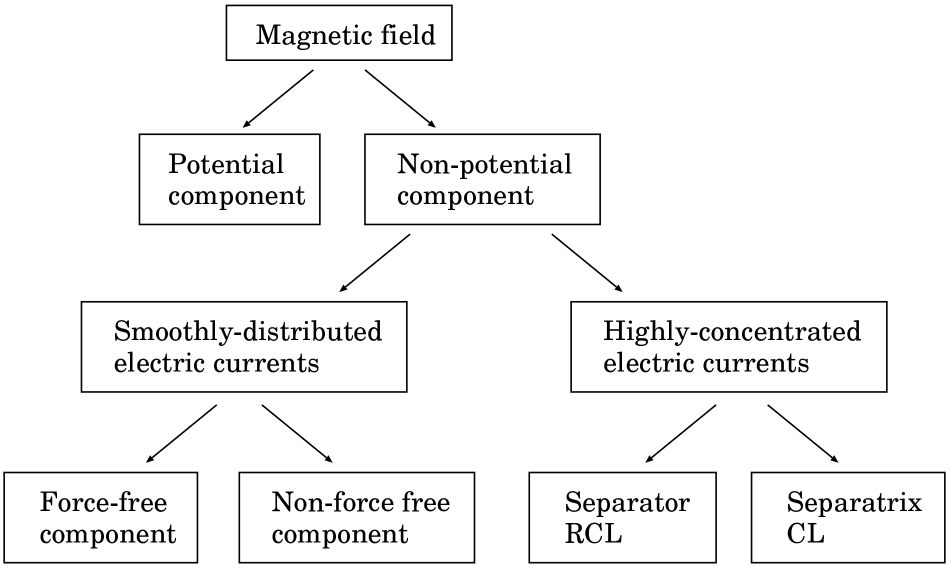

Fig. 1. Main types of the magnetic field in an active region.

The field can be 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 some small height in the chromosphere upto some significant height in the corona, $h \sim 0.5 - 0.7\ R_{\odot}$, the magnetic energy density greatly exceeds that of the thermal, kinetic and gravitational energy of the solar plasma:

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

So, the magnetic field can be considered in the strong field approximation (e.g. Somov 2000). This means, in fact, 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 photoshere and in the solar wind, has the absolute 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 somewhere and somehow (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 observed flare dynamics, more exactly, for the so-called eruptive flares (Svestka et al., 1992; Priest and Forbes, 2002). 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 (e.g. Somov, 2000). They are much simpler than the equations of the usual MHD in partial derivatives. We shall not forget about this fact since we do not want to lose a natural simplicity of the actual physical conditions in the solar atmosphere in favour of the standard MHD computer codes. However, to solve the simplified equations of motion, 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. It means that, during a relatively short time of the flare, we neglect an income flux of energy from the photosphere.

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 absolutely different physical properties and, as a consequence, different behaviours in the pre-flare and flare processes. The actual currents in the solar atmosphere 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 or nearly force-free; (b) strongly-concentrated currents like a RCL at separators or 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 force free field (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 condition in the photosphere. If this could be true, we would expect an explosive opening of such an FFF 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. This means that *the opening costs energy*, which is not small in fact, and cannot occur spontaneously.

Therefore, to explain the energetics of eruptive flares the initial plasma-magnetic 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). Note, however, as we mentioned above, the coronal magnetic fields can be considered as strong (and as a consequence the force-free or potential) only in some range of heights: starting from the low chromosphere upto 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 and dynamics (e.g., Somov and Syrovatskii, 1972). The coronal fields are never completely open or completely closed (Low and Smith, 1993). So, their energy is always lower than the Aly-Sturrock limit but higher the energy of a potential field (see also discussion in Antiochos et al., 1999).

If, following Aly and Sturrock, we recognize the low efficiency of the FFF in global eruptive events, we should assume that the electric currents flowing *across* the field lines allow the corona to have a magnetic energy in excess of the Aly-Sturrock limit or of some other lower limit to drive an eruptive flare or a CME. 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. Presumably, the RCLs allow an active region to accumulate the energy which is necessary to open closed coronal fields or, more exactly, to drive the coronal plasma upward.

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 specific locations called separators, where the magnetic reconnection should redistribute the fluxes so that the field could remain potential or nearly potential (e.g. Somov, 2000). In this way the RCLs appear at the separators in the corona. Since resistivity is extremely low, only very slow reconnection proceeds in such a RCL which we call it a slowly-reconnecting (or non-reconnecting) RCL. The wider the current layer, the larger the magnetic energy can be 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 (see Somov, 2000).

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 or CME.

RAINBOW RECONNECTION MODEL

Photospheric Vortex Flows 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 another magnetic flux already exists (Sweet, 1969; Syrovatskii, 1982). In fact, the presence of separators must be viewed as a much more general phenomenon. Figure 2a 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 $\mathbf{v}$ in such a way that the NL gradually acquires the shape of the letter S as shown in Figure 2b.

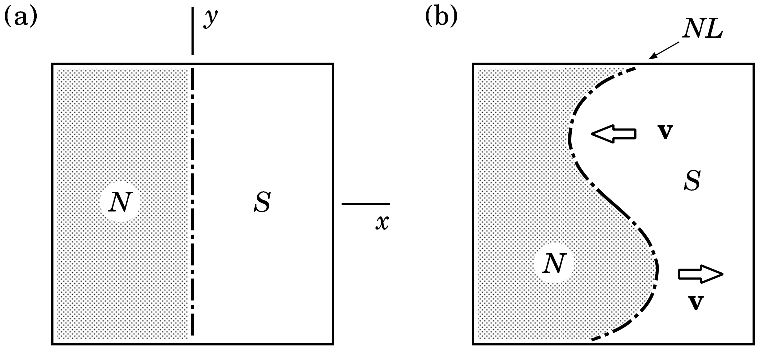

Fig. 2. (a) A model distribution of magnetic field in the photospheric plane. (b) A vortex flow distorts the neutral line NL so that it takes the shape of the letter S.

At a first glance, it seems that the magnetic field with such simple sources in the photosphere cannot in principle have any topological peculiarities. However this is not so. Beginning with some critical bending of the NL, the field calculated in the potential approximation begins to contain a separator as shown in Figure 3. In this figure, the separator X is located above the photospheric NL like a rainbow above a river which makes a bend (Somov, 1985, 1986). Note that 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 consider the properties of the magnetic field and the reconnection process in the simplest 2D model.

At a second glance, the rainbow reconnection model seems easy but gives us only a very sketchy (if any) account of actual solar flares. However, both statements are not true. By using the topological model (see Somov, 2000) for the potential field above the photosphere, Gorbachev and Somov (1988) showed that the vortex flows or any other photospheric magnetic field changes, creating the S-like shape of the photospheric NL, do produce a separator above the photosphere. They also showed that the rainbow model can explain some reliably established properties of two-ribbon flares. First, the model reveals a causal connection of large two-ribbon flares with the S-shaped bend of the photospheric NL. Second, the rainbow reconnection model

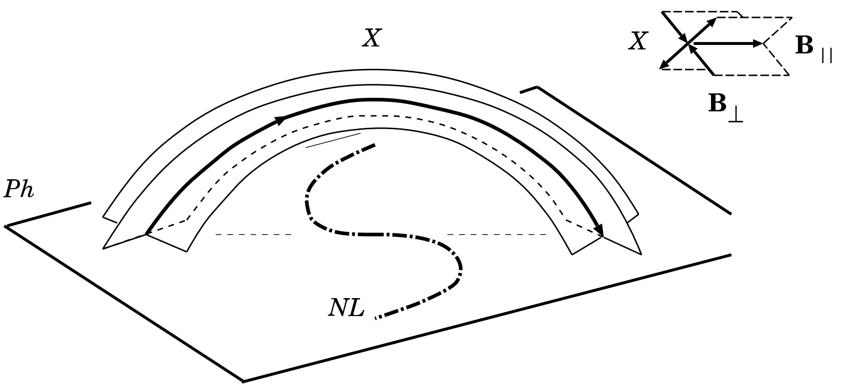

Fig. 3. The separator X above the S-shaped bend of the photospheric neutral line NL. The inset in the upper righthand corner shows the structure of the magnetic field near the top of the separator.

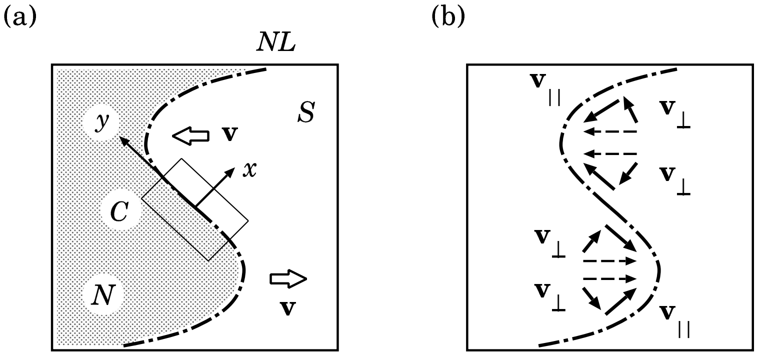

Fig. 4. (a) A photospheric vortex flow distorts the neutral line. (b) A schematic decomposition of the velocity field $\mathbf{v}$ into the components parallel and perpendicular to the NL.

explains a flare development simultaneously in regions of different photospheric magnetic field polarities. Moreover, it naturally explains the arrangement and shape of the flare ribbons in the chromosphere, the structure observed in SXR bands like intersecting loops, and the early appearance of bright kernels on the flare ribbon ends (Gorbachev and Somov, 1989, 1990).

For the first time, the model by Gorbachev and Somov (1989, 1990) had reproduced the observed features of the M4/1B flare of 1980 November 5. Note that the well-known S-shaped structures, observed in SXR (e.g. Figure 2 in Pevtsov et al., 1996) or in Hα-line, are usually interpreted in favour of non-potential fields. In general, the shapes of coronal loops are signature of the helicity of their magnetic fields. S-shaped loops match flux tubes of positive current helicity, and inverse S-shaped loops match flux tubes of negative current helicity (Pevtsov et al., 1996). However, the S-shaped SXR structures in the flare of 1980 November 5 result from the computations of the ordinary potential field in the frame of the topological model. Not surprisingly, the potential field may be even more complicated and may look as a strongly non-potential field. This is related to the magnetic field structure near the separator.

Consider another consequence of the rainbow reconnection model. Figure 4 illustrates a character of the photospheric velocity field which deforms the NL. We see that the velocity components $\mathbf{v}_{||}$ and $\mathbf{v}_{\perp}$ are parallel and perpendicular to NL. So, the vortex-type flow generates two components of the velocity field: parallel to NL and directed to 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 (see next Section) and in the photosphere.

RCL in the Global Structure without Shear

At first, we shall discuss only an influence of the *converging* photospheric flows on the reconnection process in the RCL 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 4a. In this region, we put the y-direction along the NL. So, the separator is nearly parallel to NL as was shown in Figure 3. We believe that in actual flares this 'central part' can be long enough to be considered in the 2D approximation.

To clarify notation let us start from the classical example of 'reconnection in the plane'. This means that all the unknown functions do not depend of the coordinate y and, in addition, there is no magnetic field component B_y. In this case, illustrated by Figure 5a, the straight line NL is the neutral line in the photospheric plane (x, y). Above the photospheric plane, six magnetic surfaces are shown to discuss the reconnection model. In usual schemes, that are sufficient to describe plane reconnection, we do not introduce the magnetic surfaces. We simply consider reconnection of field lines just in one plane, the 'reconnection plane' (x, z), that is $y = 0$. And we 'remember' that, in all other planes with $y \neq 0$, we have the same process. This is not necessarily true, however, in general and never true in reality, in 3D configurations of the magnetic fields in solar active regions. So, it is convenient and instructive to introduce the magnetic surfaces even in the trivial situation considered here.

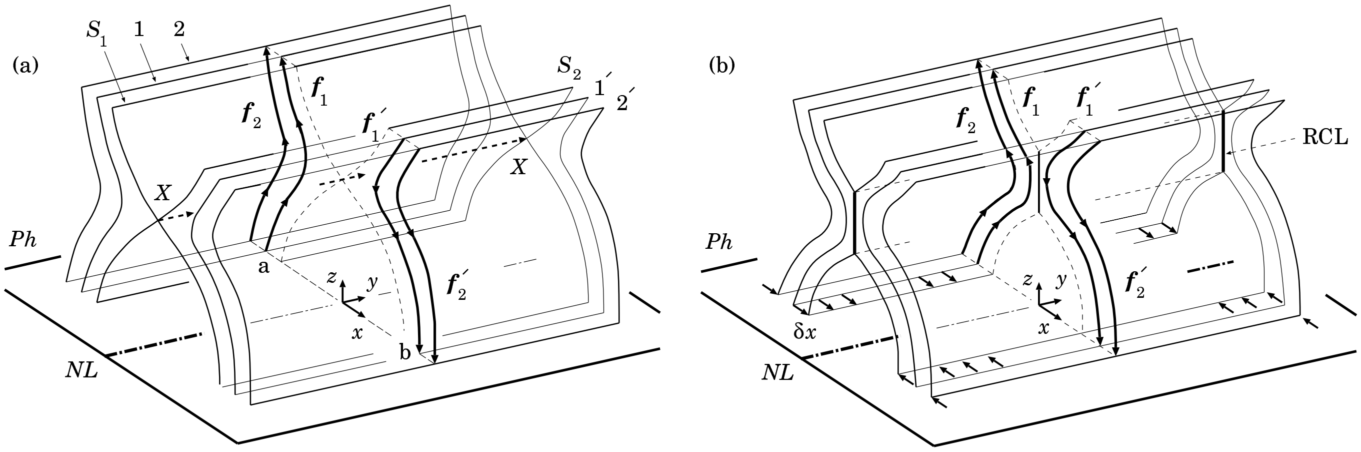

Fig. 5. (a) An initial state of magnetic field. (b) The converging motions in the photosphere induce a reconnecting current layer (RCL) in the corona.

The magnetic surface 1 in Figure 5a consists of the field lines which are similar to the line f_1 starting at the point a with coordinates $x = x_a$, $y = 0$, $z = 0$. 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 field 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. In addition, it is across the separator that the interacting fluxes are redistributed (more exactly, reconnected) so that the field would tend to keep a minimum energy, to remain potential, if there were no plasma.

Let Figure 5a 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 Figure 5b 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 the reconnection process 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 $\mathbf{B} = \mathrm{curl}\,\mathbf{A}$. In a plasma of low resistivity, like coronal plasma, the slowly-reconnecting current layer (see RCL in Figure 5b) is developing and growing (we may call this process a 'pile-up regime') to hinder the redistribution of interacting magnetic fluxes. This results in an excess energy being stored in the form of magnetic energy of a RCL.

RCL in the Global Structure with Shear

As in the previous Section, a converging flow is present in opposite sides of the photospheric NL and creates the RCL along the separator in the corona as shown in Figure 6b. 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 large-scale shear photospheric flow together with nearby magnetic surfaces 1, 2 and $1'$, $2'$. When a field line, for example the line f_1, moves in direction to NL, it becomes longer along the NL under action of the shear flow. Figure 6b shows only the field lines those were initially in the plane $(x,\, z)$ as shown in Figure 6a. Under action of the shear flow, these lines move out of the plane $(x,\, z)$, except for an upper corona boundary, which is assumed, for the sake of simplicity of illustration, not to be affected by the photospheric shear. Naturally, before reconnection, all the field lines remain on their initial magnetic surfaces.

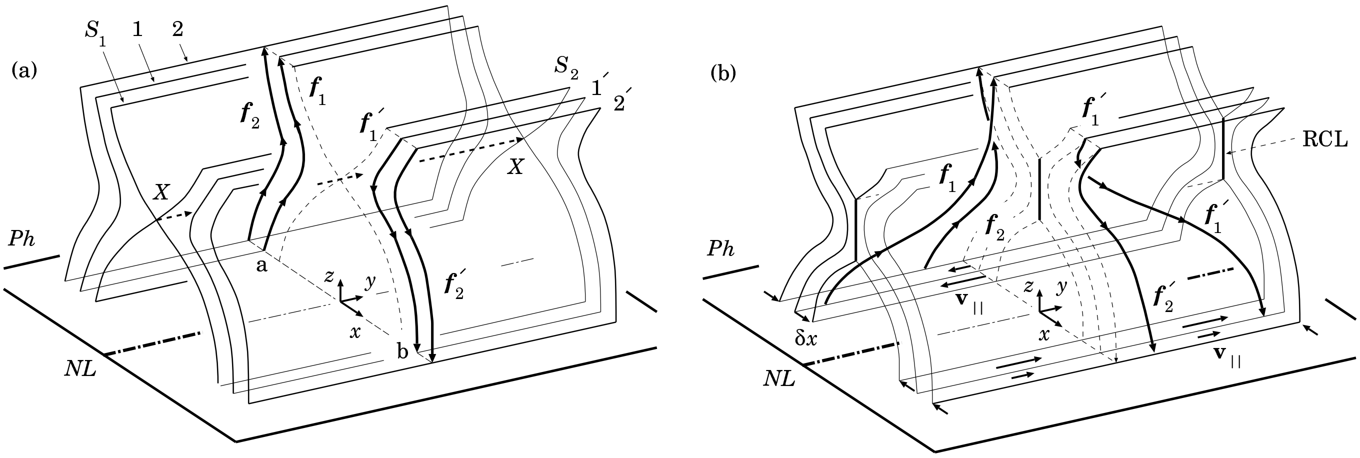

Fig. 6. (a) The initial configuration of the magnetic field is the same as in Figure 5. (b) The converging photospheric flow creates the RCL. In addition, the shear flow in the photosphere makes the field lines longer, increasing the energy in the magnetic field.

Again the reconnection is too slow to be important yet. We call this stage of the magnetic field evolution the 'pre-reconnection state'. It means that, at this stage, coming between the initial and final one, the magnetic field sources in the photosphere have been displaced to their final pre-flare positions, but the field lines have not started to reconnect yet because the plasma conductivity still can be considered as infinite. Therefore, the RCL along the separator protects the interacting fluxes from reconnection. The energy of this interaction is just the energy of the magnetic field of the current layer, as in the canonical case discussed in previous Section.

Photospheric shear flows add to the magnetic energy of the pre-reconnection 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 flow works 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 electric currents responsible for magnetic tension are smoothly distributed in a coronal volume above a region of photospheric shear. In addition, if the pre-flare magnetic-field configuration contains the separator and separatrices, and if the bases of the separatrices are involved in the large-scale photospheric shear flows, then the shear flows induce current layers extending along the separatrices, with the concentrated current flowing parallel to the orthogonal field $\mathbf{B}_{\perp}$ (see Sections 22.3 and 22.4 in Somov, 2000). The origin of this current lies in the discontinuity of the longitudinal component $B_{||}$ on the separatrices, created by the photospheric shear flows in the presence of the separator in the corona. A complete or partial dissipation of this current (as well as its decrease because of the magnetic reconnection) during a flare leads to a decrease of the longitudinal field discontinuity. We shall call such a process the 'shear relaxation'.

From a mathematical point of view, if the magnetic force dominates all the others, the potential or force-free field is a solution of the set of MHD equations for an ideal medium in the approximation of a strong field (see Chapter 9 in Somov, 2000). Such a field, changing in time according to the boundary conditions, sets the chromospheric and coronal plasma in motion. The field remains mainly potential but still accumulates the non-potential components related to electric currents: (a) slowly-reconnecting current layers which are highly-concentrated electric 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 process 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 in the RCL at the separator.

Flare Energy Release and CMEs

The fast reconnection stage of a flare, that is its impulsive phase, is illustrated by Figure 7. As in the case of plane reconnection, in Figire 7a only two pairs of the reconnecting field lines are shown. Note that Figure 7a differs from Figure 6b in one important respect. These figures show the same magnetic surfaces but different field lines. An additional assumption made and used here is that the physical conditions along the y-direction are not uniform any longer. More exactly, 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 line are selected which have the nearest distance to the RCL under condition $y = 0$. Just these field lines will reconnect first and quickly.

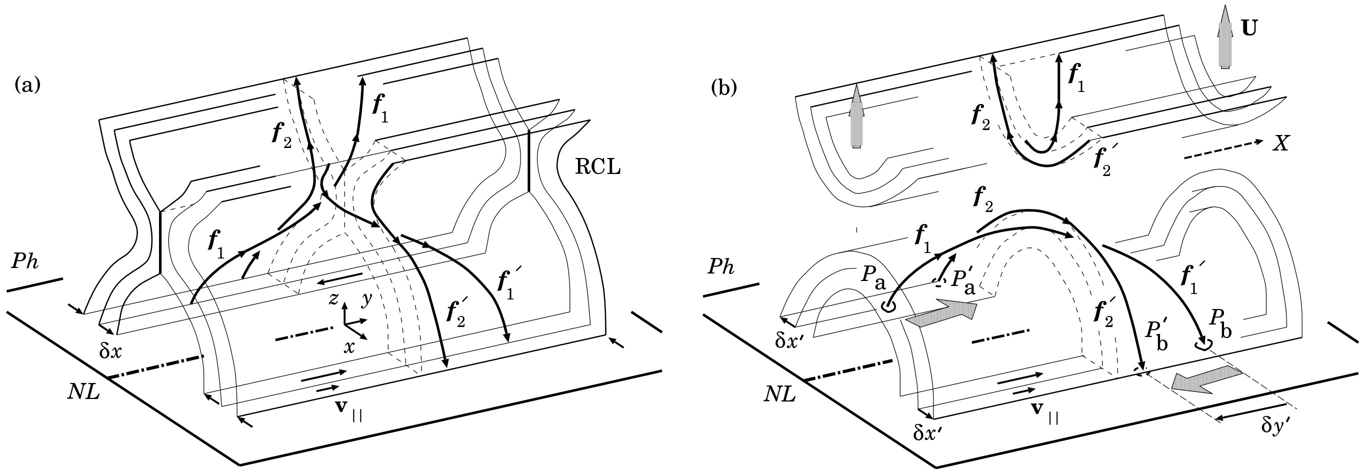

Fig. 7. (a) A pre-reconnection state of the magnetic field in an active region with the converging and shear flows in the photosphere. (b) Rapidly decreasing footpoint separation during the 'more impulsive' Sakao-type flares.

Usually, in 3D topological models, the place of fast reconnection is chosen at the top of the separator. This is assumed, for example, in the model for the well-studied flare of 1980 November 5 (Gorbachev and Somov, 1989, 1990; Somov, 2000). As a consequence of the three-component reconnection at the separator, the upward-moving lines may take a twisted-flux-tube shape, which may correspond to a central 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 we shall not consider the upward-moving reconnected field lines. They are only indicated in Figure 7b 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 (e.g. Crooker et al., 2002, Figure 2). 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

The magnetic 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 $P_{\rm a}$ and $P_{\rm b}$ related to the *first* reconnected line $f_1 f_1'$ shown in Figure 7b. 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 $P_{\rm a}'$ and $P_{\rm b}'$. The apparent displacement of the footpoints, from $P_{\rm a}$ to $P_{\rm a}'$ and from $P_{\rm b}$ to $P_{\rm b}'$, 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 part of 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 flow. In the case under consideration, the pre-flare magnetic field contains the separator, and the bases of the separatrices are involved in the photospheric shear flows. These flows induce current layers extending along the separatrices, with the concentrated current flowing parallel to the orthogonal field $\mathbf{B}_{\perp}$. The origin of this current lies in the discontinuity of the longitudinal component $B_{||}$ on the separatrices, created by the shear flows. Dissipation of this current, as well as its decrease because of the magnetic reconnection (Somov, 2000), during a flare leads to a decrease of the longitudinal field discontinuity. We call this process the shear relaxation.

The rainbow reconnection model predicts the existence of the converging and shear flows in the central region under the top of the separator. In this region, the converging flow generates the RCL in the corona above the photospheric neutral line. 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. This is consistent with the model by Somov et al. (1998) for the Sakao-type flares.

THE BASTILLE-DAY 2000 FLARE

On 14 July 2000 near 10:10 UT, a large solar flare with X-ray importance of X5.7 occurred near disk center in the active region NOAA 9077. The event comprised a 3B flare as revealed by 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 the corona and interplanetary space. This well-observed huge flare is often called the ‘Bastille day 2000’ flare. The *Yohkoh* satellite observed an early phase (∼10:11 - 10:13 UT) and some of the impulsive phase (from ∼10:19:40 UT) of this flare classified as a long duration event (LDE). 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. This structure corresponds to a series of footpoints of the SXR arcade (Figure 8).

Solar flares often exhibit a two-ribbon structure in the chromosphere, observed for example in Hα (see Svestka, 1976; Zirin, 1988), and this pattern becomes especially pronounced for LDEs of the type often associated with CMEs. In the Bastille-day flare, the two ribbons were well seen in Hα and Hβ (Yan et al., 2001, Liu and Zhang, 2001). Fletcher and Hudson (2001) describe the morphology of the EUV ribbons of this flare, as seen in SOHO, TRACE, and *Yohkoh* data. The two-ribbon structure, however, had never before been observed so clearly in HXR as presented in Masuda et al. (2001). Two ribbons are most clearly observed in the rising phase and the decay phase of the first HXR burst S1. Moreover, the bright compact kernels in HXR are observed along the ribbons separated by the simplified magnetic neutral line NL which

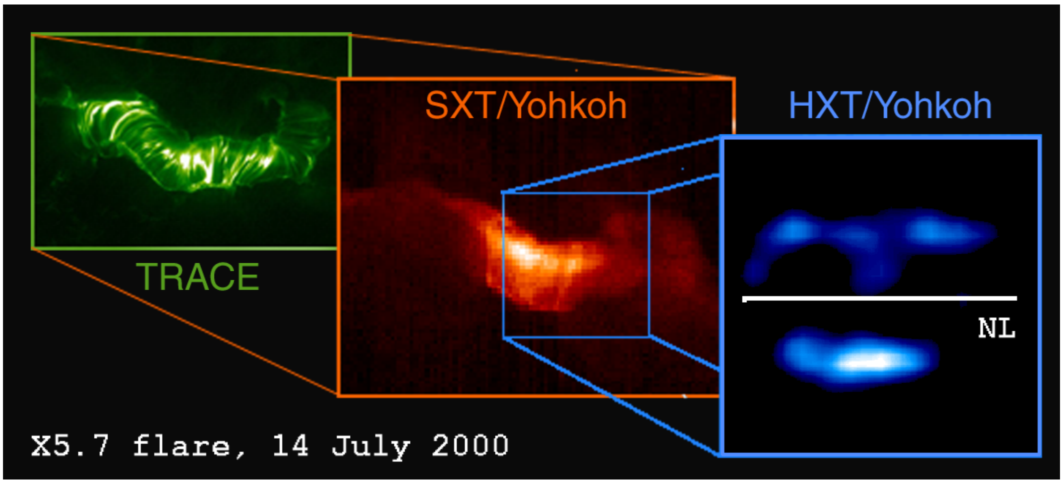

Fig. 8. (a) TRACE and Yohkoh observations of the Bastille-day flare. The right panel shows HXR (53-93 keV) sources aligned along the flare ribbons, which lie at the feet of the arcade loops in the center of the left panels. (Courtesy by S. Akiyama)

is almost exactly aligned in the E-W direction as shown in Figure 8.

Masuda et al. (2001) analyzed in detail the motions of bright HXR kernels in the two ribbons of the Bastille day flare during the first and second bursts (S1 and S2) of emission in the energy ranges: 23-33, 33-53, and 53-93 keV. Even without accurate overlay of the HXR images of the flare on the photospheric magnetograms, Masuda et al. speculated that 'these 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 well supports the idea of 3D reconnection in the corona at a separator with a longitudinal magnetic field as predicted by the rainbow reconnection model. However, to make a judgement about it we need to investigate possible relationships between the HXR kernels (their appearance positions and further dynamics) and the photospheric magnetic field (its structure and evolution). With the aim of finding such relations, we overlaid the HXR images of the flare on the MDI/SOHO and SMFT magnetograms. This allows us: (a) to identify the most important MDI sunspots with the SMFT spots, whose properties, morphology and evolution have been carefully studied; and (b) to examine the relationships between the HXR kernel behavior during the impulsive phase of the Bastille-day flare and the large-scale displacements of the most impotant sunspots during the two days before the flare, based on precise measurements of the proper motions (Liu and Zhang, 2001).

It appears that the observed displacement of the brightest HXR kernel during the first HXR spike S1 is directed nearly anti-parallel to the displacement of the strongest positive spot P1 during the two days between two largest flares. We suggest (for more detail see Somov et al., 2002) that, before the Bastille-day flare, the bases of magnetic separatrices are moved by the large-scale photospheric flows of two types. First, the shear flows, which are parallel to the photospheric neutral line, increase the length of field lines in the corona and, in this way, produce an excess of magnetic energy. Second, the converging flows, i.e. the flows directed to the neutral line, create the pre-flare current layers in the corona and provide an excess of energy sufficient to produce the flare.

During the flare, both excesses of magnetic energy are released completely or partially. In the Bastille-day flare, the rainbow reconnection model predicts two kinds of apparent displacements of the HXR kernels. An increase of a distance between the flare ribbons together with the HXR kernels inside the ribbons. The effect results from fast 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 so-called 'more impulsive' Sakao-type flares (Sakao et al., 1998).

DISCUSSION and CONCLUSIONS

Why does the footpoint separation increase in the *less impulsive* (LI) Sakao-type flares? This may be the case when the velocity of the photospheric shear flow decreases near the polarity reversal boundary NL in the photosphere. Hence, 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 the reconnection process slower, because the longitudinal field makes the solar plasma less compressible, and the flare less impulsive. However, the longitudinal field does not have an overwhelming effect on the parameters of the current layer and the reconnection rate (see Section 17.2 in Somov, 2000). This might be especially true if the compression of the plasma inside the current layer is not high since its temperature is very high.

What seems to be more obvious and perhaps more efficient is the following. In LI flares, after reconnection, the line f_2 will be longer than the line f_1 as illustrated by Figure 5a in Somov et al. (1998). It means that reconnection proceeds in the direction of a stronger shear in the LI flares. So, the energy of a longitudinal component of magnetic field becomes larger after the magnetic reconnection of the shear-related currents. On the contrary, in MI flares the reconnection process tends to release 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. Presumably this circumstance is a more important reason why the Sakao-type MI flares are more impulsive.

In summary, we assume that 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 seem to be *sufficient* ones for the active region to produce a huge solar flare similar to the Bastille day flare. Other realizations of large solar flares are possible, of course, but this one seems to be the most plausible situation. At least, in addition to the flare HXR rebbons 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 (Somov et al., 2002). This prediction of the rainbow model, however, has to be investigated separatelly.

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