Earth Planets Space, **53**, 483–490, 2001

Three-dimensional reconnection on the Sun

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(Received May 1, 2000; Revised November 1, 2000; Accepted November 1, 2000)

A brief review is given of the theory of magnetic reconnection in three dimensions. The key elements of a three-dimensional null point are its *spine* and its *fan*, which consist, respectively, of a field line and a surface of field lines that pass through the null. The fans of two nulls intersect in general in a field line called a *separator* that joins the nulls. Several different types of reconnection have been proposed, namely: spine reconnection, fan reconnection, separator reconnection and quasi-separatrix layer reconnection. In addition, a new exact solution for reconnective annihilation has been recently discovered. A summary is also given of the impressive evidence of reconnection at work on the Sun provided by a range of observations from the Yohkoh and SOHO satellites, both of solar flares and of coronal heating events.

1. Introduction

Two-dimensional magnetohydrodynamic reconnection is now fairly well understood. The classical Sweet-Parker and Petschek regimes have been generalised to give an Almost-Uniform family (Priest and Forbes, 1986) and a NonUniform family (Priest and Lee, 1990; Strachan and Priest, 1994) of regimes which depend partly on the boundary conditions and partly on whether the magnetic diffusivity is uniform or nonuniform. Recently, Terry Forbes and I have completed a monograph (Priest and Forbes, 2000) that describes these models in detail, as well as models for unsteady and three-dimensional reconnection and their application to the magnetosphere, the Sun, astrophysics, the laboratory and particle acceleration.

There are also few exact solutions of the MHD equations. For magnetic annihilation (Sonnerup and Priest, 1975) the magnetic flux function is

$$A = A_0(x)$$

and the stream function is

$$\psi = v_{ex} x y$$

and one can impose the values of the inflow speed (v_{ex}) and inflow magnetic field (B_{ye}) at an inflow point $(x, y) = (1, 0)$, say. More recently, Craig and Henton (1995) suggested a solution

$$\begin{aligned} A &= A(x) + v_{xe}\frac{v_{ye}}{B_{ye}}xy \\ \psi &= xy + A(x) \end{aligned}$$

in which they were also able to impose $v_y = v_{ye}$ at $(x, y) = (1, 0)$. Recently, Priest *et al.* (2000a) have discovered much more general reconnective annihilation solutions of the form

$$\begin{aligned} A &= A_0(x) + A_1(x)y \\ \psi &= \psi_0(x) + \psi_1(x)y \end{aligned}$$

in which one can also impose B_x at $(1, 0)$ and there is an additional free parameter. Also, it is currently being extended into three dimensions.

In this brief review we first of all describe some of the attempts to extend ideas about two-dimensional reconnection into three dimensions and then we summarise some of the recent evidence for the presence of reconnection of work in the Sun's corona. We consider only reconnection at null points where the magnetic field vanishes, although there are other regimes that occur in the absence of null points (Schindler *et al.*, 1988). Also, we focus on the MHD aspects of reconnection, which apply to collisional environments such as the solar photosphere. In regions such as the solar corona where the diffusion region is collisionless, the MHD models still play an important role in providing the macroscopic environment within which the microscopic collisionless processes are at work. Indeed, a proper linking of the MHD and collisionless aspects is an important matter for future research.

2. Three-Dimensional Magnetic Reconnection

When we go from two dimensions into three dimensions, there are many new features that are currently being studied (Sato, 1985; Hesse and Schindler, 1988; Lau and Finn, 1990; Shibata *et al.*, 1996; Longcope and Cowley, 1996; Priest and Titov, 1996; Ugai and Wang, 1998). For example, the definition itself is no longer obvious. The structure of the null points is different. The global topology of the field is much more complex, and there are several different types of magnetic reconnection. In particular, it was Axford (1984) who stressed that a change of magnetic connectivity is the key to a definition of three-dimensional reconnection and Schindler *et al.* (1988) who proposed a notion of general magnetic reconnection.

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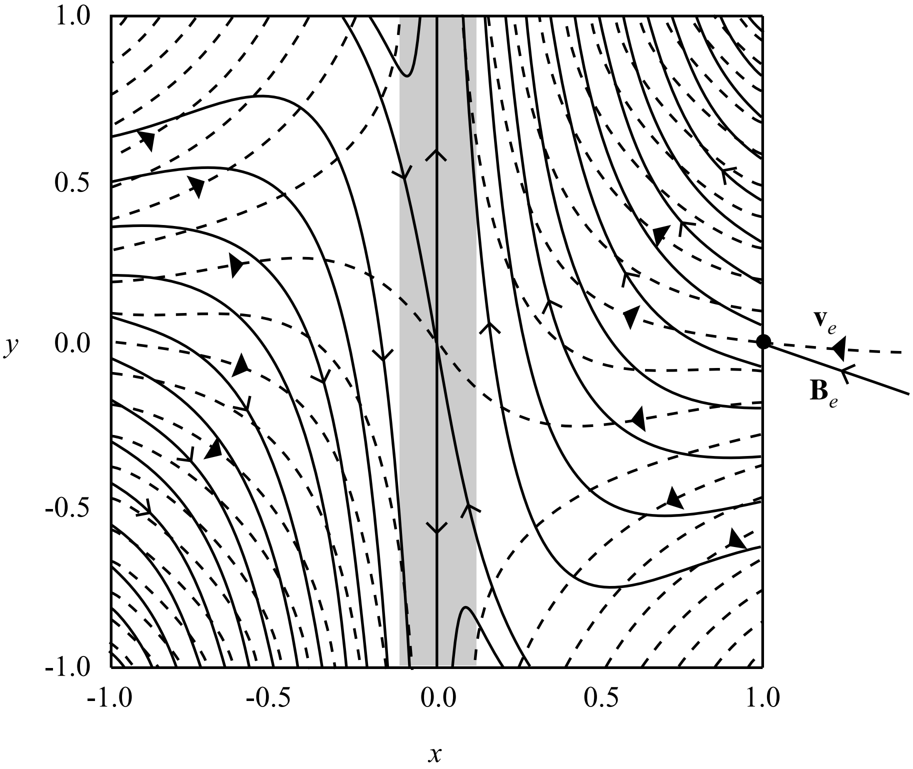

Fig. 1. Magnetic field lines and streamlines for reconnective annihilation (Priest *et al.*, 2000a).

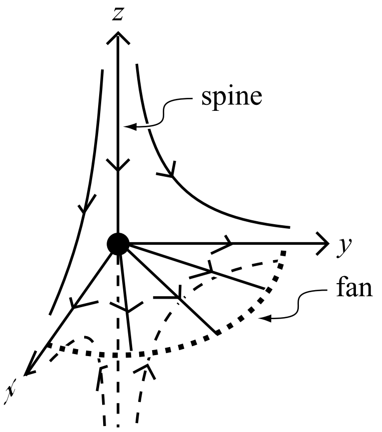

Fig. 2. Magnetic structure of a three-dimensional null point.

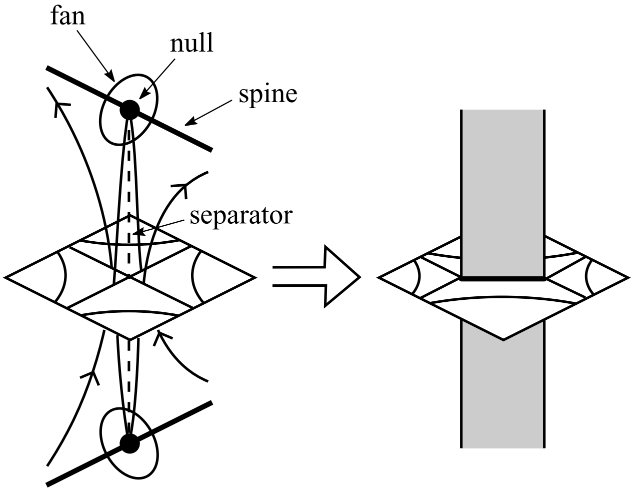

Fig. 3. Separator reconnection due to the collapse of a separator.

2.1 Structure of a null point

The simplest magnetic null in three dimensions has magnetic field components

$$(B_x, B_y, B_z) = (x, y, -2z),$$

which satisfy $\nabla \cdot \mathbf{B} = 0$. The resulting magnetic field lines have the structure shown in Fig. 2, in which there are two families of magnetic field lines through the null point. A *spine* approaches the origin from above and below along the z-axis. Also, a fan of field lines leaves the origin in a surface (the xy-plane). More generally, the field near a linear null always possesses a spine and a fan, but the field lines in the null may spiral or touch an axis and the spine may be inclined to the fan at some other angle than $\frac{1}{2}\pi$ (Parnell *et al.*, 1996).

2.2 Types of reconnection

At a magnetic null point, three different types of reconnection have been discovered. In *spine reconnection* the current is concentrated along the spine (Priest and Titov, 1996). It may be driven by continuous footpoint motions across the fan of a null point. In *fan reconnection* the current concentrates along the fan, and it may be driven by continuous footpoint motions across the spine of a null (Priest and Titov, 1996). The result is a rapid counter-flipping of magnetic field lines above and below the fan, which has been observed

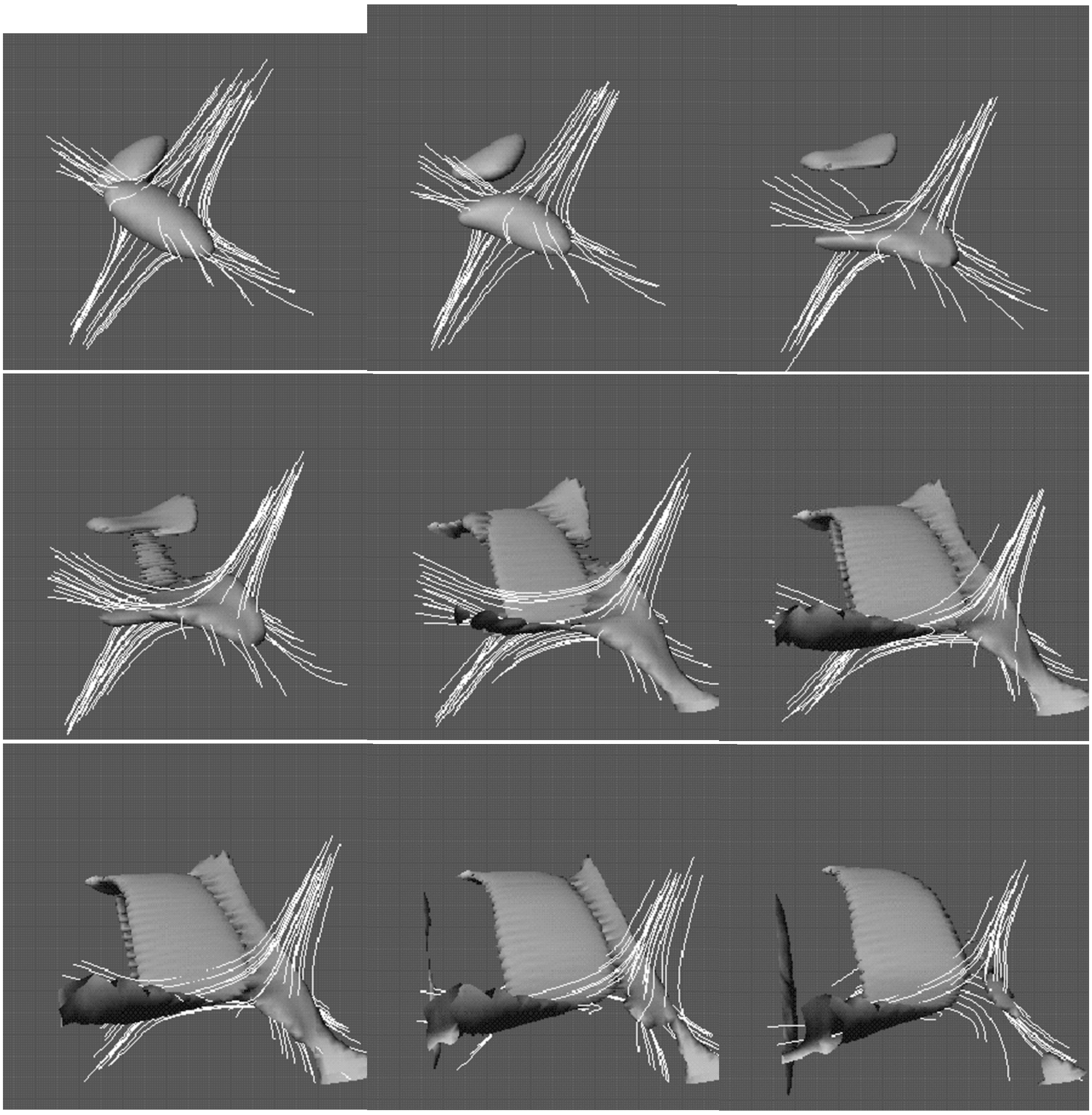

Fig. 4. Numerical experiment with an initial configuration of 8 null points, showing the local collapse of one of the nulls and the development of a strong current joining a nearby null due to separator reconnection (Galsgaard and Nordlund, 1997).

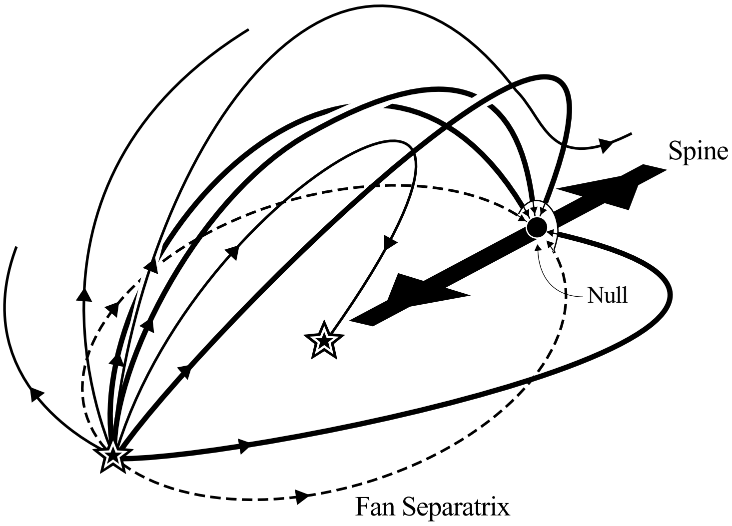

Fig. 5. The skeleton of two unbalanced sources (stars) in an ambient magnetic field, namely a null (a large dot) a spine (thick solid curve) and a separatrix fan that intersects the horizontal plane in a dashed curve.

in the solar atmosphere by the TRACE satellite (Priest and Schrijver, 1999).

In *separator reconnection* (Fig. 3) the current is concentrated along a separator, which is the intersection of the fans of two nulls and so is the magnetic field line that joins one null to another (Priest and Titov, 1996; Longcope and Silva, 1998). Reconnection may also occur in the absence of nulls at so-called quasi-separatrix layers, where the gradient of the mapping from one boundary to another is very large (Priest and Demoulin, 1995; Hornig and Rastätter, 1998; Titov *et al.*, 1999). Indeed, Demoulin *et al.* (1996) have demonstrated that noneruptive flares are often located along quasi-separatrix layers.

These different three-dimensional mechanisms have been analysed both in the kinematic approximation and in the strong magnetic field approximation of the full MHD equations and also numerically.

For example, Galsgaard and Nordlund (1997) started with a magnetic field consisting of eight null points in force-free equilibrium and then sheared the footpoints and watched what happened in a three-dimensional resistive MHD experiment. The nulls collapsed and reconnected by separator reconnection with strong current sheets joining nearby nulls (Fig. 4).

2.3 Complex magnetic topology

In two dimensions there are *separatrix curves* that separate the plane up into topologically distinct regions, and a pair of separatrices intersects in an X-type neutral point where the magnetic field vanishes. In three dimensions *separatrix surfaces* divide up the volume into topologically separate regions and separatrices intersect in a special field line known as a *separator*, which ends either at null points or on the boundary. In the Sun's surface there is a multitude of flux sources, and so the topology of the overlying coronal magnetic field is extremely complex. However, it can be described in terms of its *skeleton*, namely, a set of null points, a network of spine curves and a collection of separatrix fan surfaces. Its building blocks are the fields due to two, three and four sources. For two sources there is a null, with its

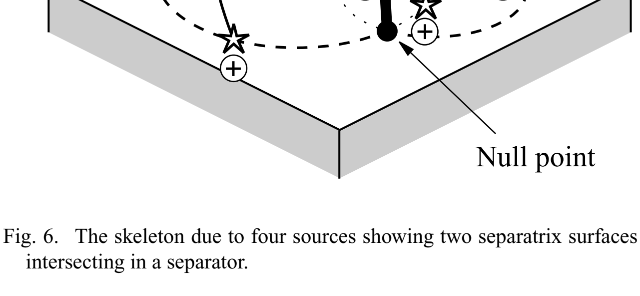

Fig. 6. The skeleton due to four sources showing two separatrix surfaces intersecting in a separator.

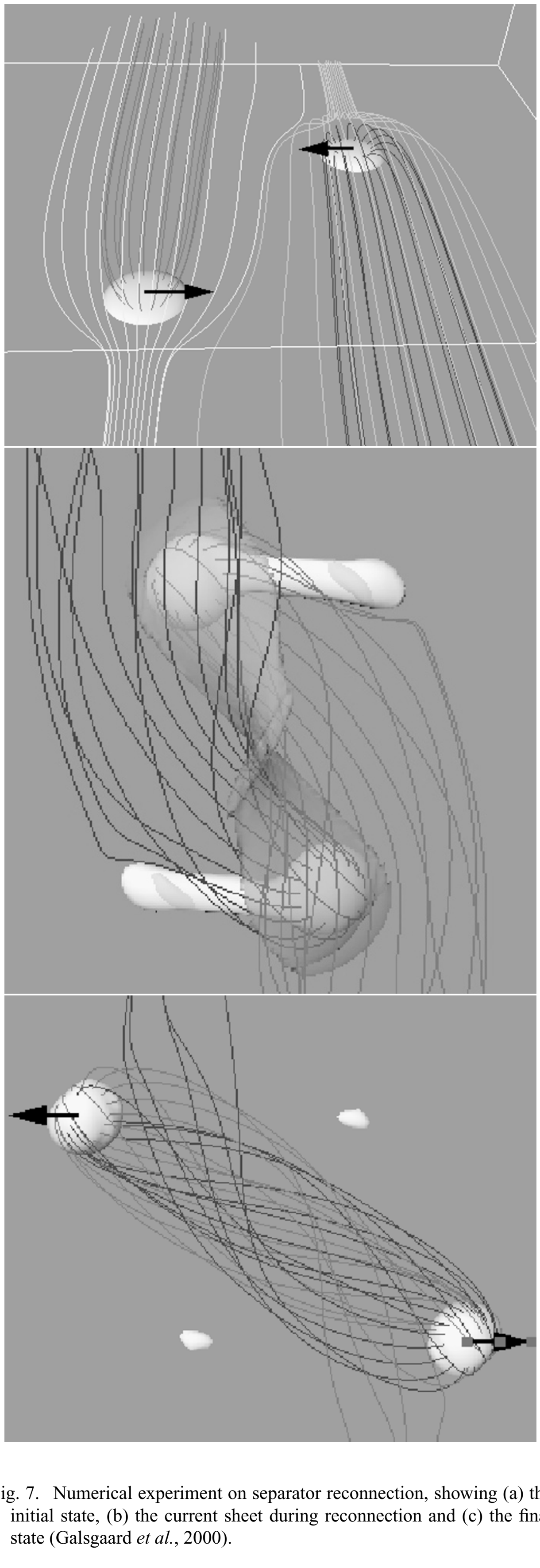

Fig. 7. Numerical experiment on separator reconnection, showing (a) the initial state, (b) the current sheet during reconnection and (c) the final state (Galsgaard *et al.*, 2000).

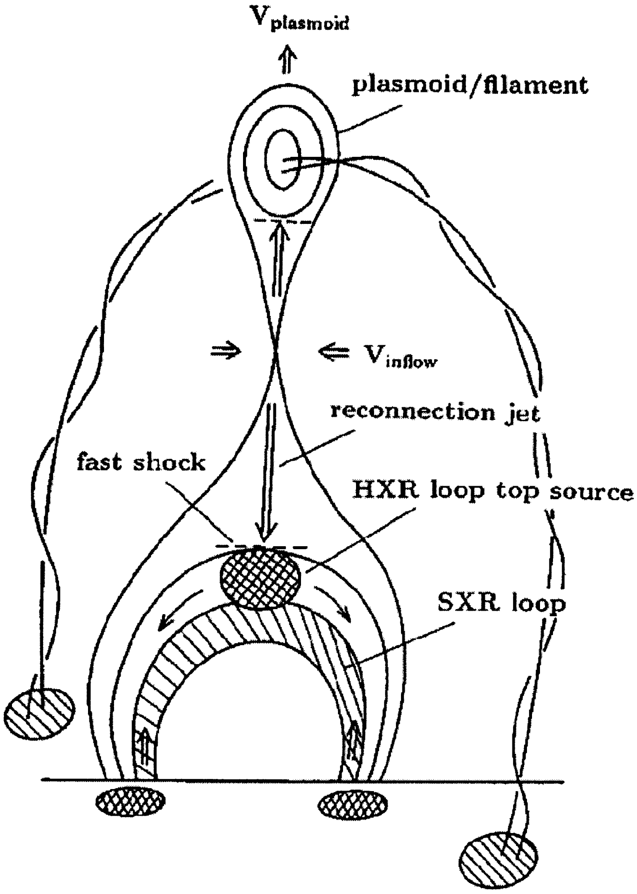

Fig. 8. Shibata's model of a solar flare.

spine and separatrix surface that intersects the solar surface in the dashed curve shown in Fig. 5. For three sources the structure is surprisingly rich, with six different topological states when two sources are of the same sign and differ in sign from the third source. Transfer from one state to another is by local or global bifurcations (Priest *et al.*, 1996).

So what is the effect on the corona of motions of magnetic

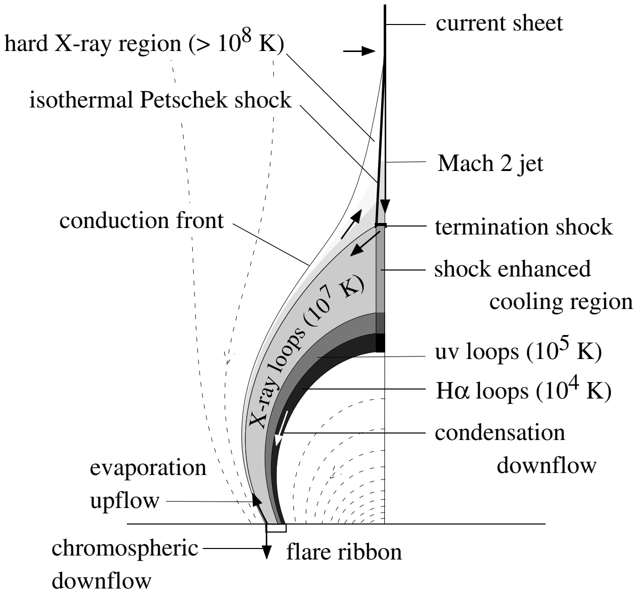

Fig. 9. The structure of flare loops created by reconnection (Priest and Forbes, 2000).

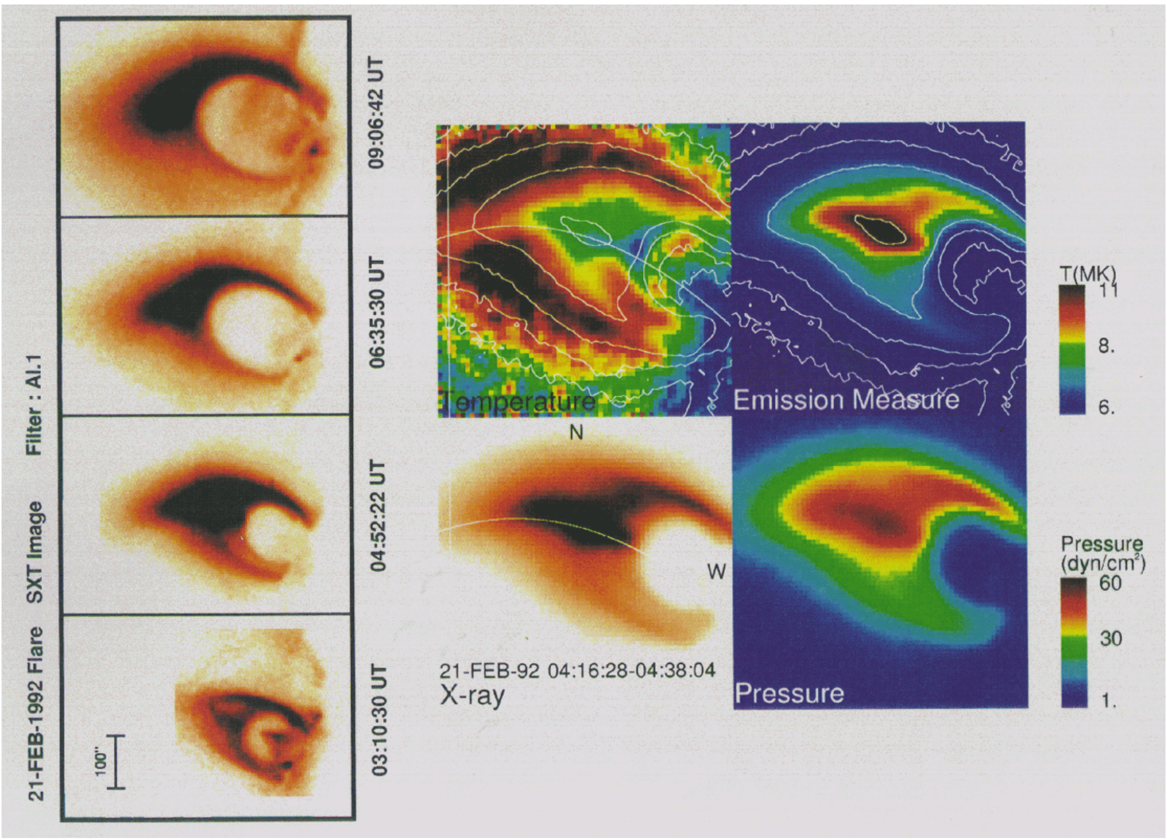

Fig. 10. The structure of the Tsuneta flare.

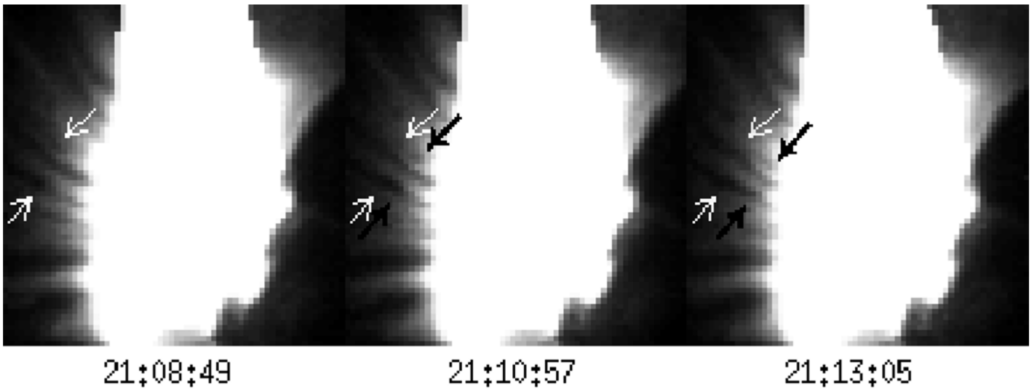

Fig. 11. Spikey current sheet above a flare loop system (McKenzie and Hudson, 1999).

flux sources in the solar surface? It drives three-dimensional reconnection and therefore heating. There are two main elements of this process, depending on whether the fundamental interaction is between a pair of sources or between three or more sources. First of all, the relative motion of a pair of sources in an ambient field (Fig. 5) produces heating by *binary reconnection* (Priest and Schrijver, 1999). Just as in a gas, the binary collisions between pairs of particles dominates, so in the corona the effect of the interactions of pairs of photospheric magnetic flux sources may dominate the resulting heating that is driven in the corona. As the sources move around, the flux joining them is preserved, but individual magnetic field lines are reconnected since they may either lie below the separatrix dome or above it, depending on the orientation of the sources. The resulting heating is focussed on the separatrix surface and along the field lines that have just crossed it. The second element is an effect of the interaction of three or four sources, namely, *separator reconnection* when their separatrix surfaces intersect (Priest and Titov, 1996; Longcope, 1998). As such sources move, there is now a change of flux in each region as flux is transferred from one to another, and the heat is concentrated along the separatrices and especially along the separator (Fig. 6).

Galsgaard *et al.* (2000) have recently set up a numerical experiment for a scenario proposed by Longcope (1998) for the interaction between two flux sources in an ambient field. Initially, the sources are not connected magnetically (Fig. 7(a)). As they move, separator reconnection occurs and produces a twisted current sheet along the separator (Fig. 7(b)). After reconnection has occurred, the two sources are joined by a twisted flux tube, which has been created by the conversion of mutual magnetic helicity in the initial state to the self-helicity of the flux tube.

3. Recent Observational Evidence for Reconnection

There is now a host of indirect evidence in favour of reconnection from the Yohkoh and SOHO satellites, especially in solar flares and coronal heating events. Much of it has been produced by Tsuneta and Shibata and their coworkers (e.g., Shibata *et al.*, 1990; Kusano *et al.*, 1995).

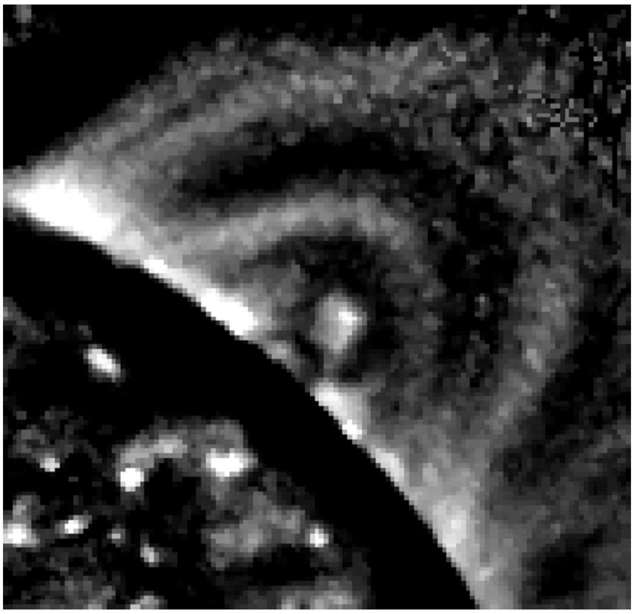

Fig. 12. Large-scale coronal loop whose heating may well be turbulent reconnection.

3.1 Solar flares

For example, after the large-scale magnetic field has been opened up in a coronal mass ejection, it closes back down by reconnection and produces below the reconnection point a rising cusp-shaped arcade that shows up in Yohkoh images. In a large eruptive solar flare, there is a similar magnetic process, where an arcade erupts because of a MHD catastrophe (Priest and Forbes, 1990; Amari *et al.*, 2000) and then drives reconnection (Fig. 8). The reconnection-produced flare loops have a structure deduced from numerical experiments (Fig. 9) that agrees with many aspects of the observations. For example, the famous Tsuneta *et al.* (1992) flare has a set of rising soft X-ray loops (Fig. 10) with a temperature and pressure structure that agrees qualitatively with the models. Also, the equally famous Masuda *et al.* (1994) flare exhibits hard X-rays at the loop top and at its feet. Furthermore, McKenzie and Hudson (1999) have discovered above the flare loops a spikey current sheet (Fig. 11) containing dark voids moving down at 200 km/s that may possibly be

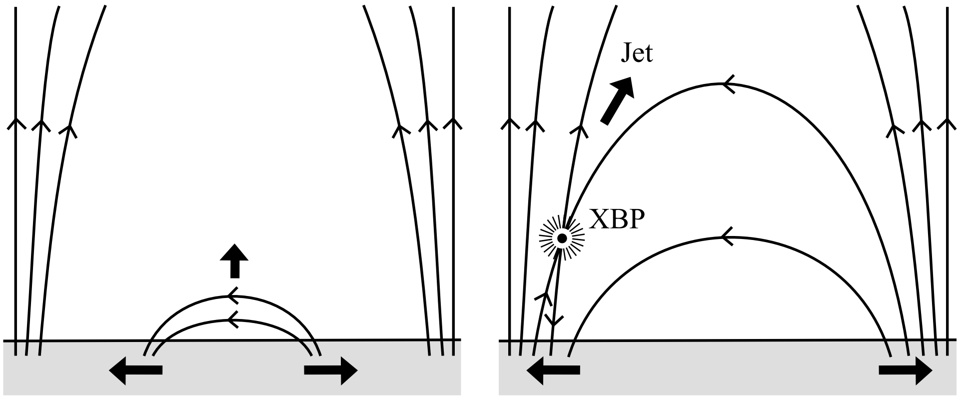

Fig. 13. Converging Flux Model.

produced by impulsive bursty reconnection (Priest, 1987).

3.2 Coronal Heating

Many examples of reconnection have been found in coronal heating events. The temperature profile measured along large-scale loops in Yohkoh images (Fig. 12), for instance, has been found to be consistent with heating by Parker braiding or turbulent reconnection (Priest *et al.*, 1998, 2000b).

With Yohkoh too Yoshida and Tsuneta (1996) have shown that the hottest loops are either cusp-shaped or are interacting loops, both of which may be produced by reconnection. Furthermore, Shibata *et al.* (1996) has observed many x-ray jets produced by reconnection which have been simulated in a most impressive manner (Yokoyama and Shibata, 1997).

On SOHO the MDI instrument has shown that the surface of the Sun is covered with a magnetic carpet, in which magnetic fragments are continually emerging, fragmenting, merging and cancelling (Schrijver *et al.*, 1997). Indeed, this is such an efficient process that the magnetic flux at the surface in the Quiet Sun is replaced not every 11 years, but every 40 hours.

The basic idea of the Converging Flux Model (Priest *et al.*, 1994) is that new flux emerges in a supergranule cell, moves to the boundary and reconnects (Fig. 13), where it can in large events create an X-ray bright point and accelerate an X-ray jet. Furthermore, with the EIT instrument on SOHO, Falconer *et al.* (1998) have found that most bright points lie above oppositely directed magnetic fragments. With TRACE Parnell and Jupp (2000) have found that most nanoflares also lie above the supergranule boundaries.

So what is the effect of the magnetic carpet on coronal heating? I would like to suggest the following scenario. The evolution of magnetic flux on the solar surface has three stages. First of all, a bipolar ephemeral region is born once every few days in a supergranule cell of typical diameter 15 Mm (Fig. 14(a)). This drives global reconnection with the overlying field which becomes visible as an X-ray bright point. Then each polarity of the ephemeral region moves towards the boundary over about 8 hours and fragments into typically 10 network elements (Fig. 14(b)). This drives internal reconnection between the network elements and also provides a fibril magnetic structure within which MHD waves driven by granulation may dissipate efficiently. Thirdly, over the next 22 hours, the network elements move

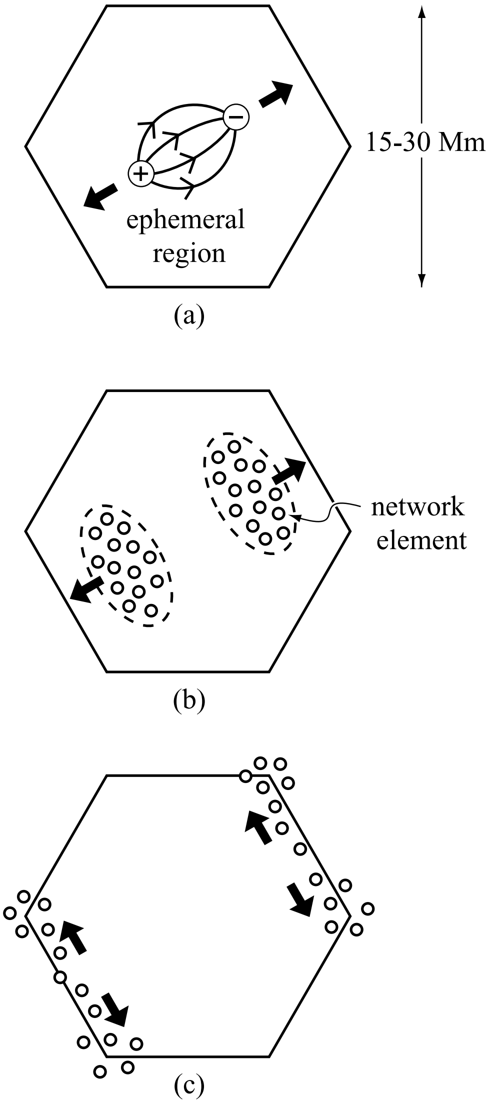

Fig. 14. The evolution of magnetic flux in the quiet Sun.

along the boundary of the cell and undergo merging, fragmentation and cancellation (Fig. 14(c)), which also drive reconnection within the network and in the overlying field. The elementary heating events in this model are: binary reconnection between flux pairs, separator reconnection by the interaction of three or more sources, internal Parker braiding and dissipation of waves driven by granular buffeting.

4. Concluding Comment

In summary, there are two main points to this review: the theory of three-dimensional reconnection is developing rapidly; and SOHO and Yohkoh have produced much evidence of the consequences of reconnection. However, for a detailed understanding of the connection between the surface of the Sun and its corona, we eagerly await the Solar-B Mission.

Acknowledgments. I am most grateful to the Symposium organisers and the UK Particle Physics and Astronomy Research Council for financial support and to our Japanese hosts for the care with which they have organised a most stimulating meeting.

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