INTRODUCTORY OVERVIEWS

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Solar Flares

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Abstract: There are many types of solar flare, but the classic type is a two-ribbon flare with three phases – a preflare phase, a rise phase and a main phase. The properties of these phases are described, together with some recent observational advances in understanding the conditions for solar flares. Such flares are thought to be caused by an eruptive MHD instability which drives reconnection and therefore energy conversion. A review is given of our current understanding of the nature of this instability and the resulting reconnection process, including a recent attempt to describe its three-dimensional nature.

1 Description of typical large flare

Perhaps the most interesting flare star in the Universe is the Sun. However, the subject of solar flares is an enormous one, which I cannot hope to cover adequately in such a short review. It has been studied at many previous conferences (e.g. Sturrock 1980, Kundu et al. 1989, Schmieder & Priest 1991, Svestka et al. 1992, Uchida et al. 1991) and has been covered in several books (e.g. Svestka 1976, Priest 1981, Tandberg-Hanssen & Emslie 1988, Somov 1992). My aim here is simply to give a simple description of a typical large flare and to attempt to answer the two key questions that are addressed by MHD, namely: how is the energy converted in such a flare and how does the eruptive instability that drives it occur?

A large flare has three phases:
(i) the *preflare phase*, which lasts for about half an hour and during which there is a slight rise in soft X-ray emission; at the same time, an active-region prominence in a complex sunspot group starts to rise slowly;
(ii) the *rise phase*, for between 5 min and 1 hr, when there is a steep rise in intensity of soft X-ray and Hα emission; here the prominence undergoes a sudden rapid eruption and two Hα ribbons form in the chromosphere; at the same time, there are impulsive high-energy effects in the form of hard X-ray spikes, impulsive EUV and microwave bursts and type III and type II radio bursts;
(iii) the *main phase*, for an hour or up to 1 or 2 days, during which the intensity declines slowly; the Hα ribbons move apart and are joined by a rising arcade of cool loops which an enormous amount of downflowing plasma (more than would

fill the entire corona); the velocity of separation and rise is at first very rapid (up to 50 km s^{-1}) but it declines to much slower values later in the event (0.5 km s^{-1}); the density and temperature are 10^{17} m^{-3} and 40×10^6 K early on, falling to 10^{16} m^{-3} and 5×10^6 K later.

It may be noted that the typical energy in a flare is a few times 10^{25} J (10^{32} ergs), and flares only occur in complex active regions: complexity seems to be a necessary pre-requisite for a flare, probably because it helps the triggering and release of stored energy (Priest 1992). However, large quiescent prominences far from active regions can also erupt and have associated soft X-ray emission (and a coronal mass ejection): here the process is magnetically very similar, but the magnetic field is much weaker and so usually the high-energy aspects are absent.

Several new features of flares have been discovered by space satellite observations from Skylab (1973 – 1974), Solar Maximum Mission (1980 – 1989) and the Japanese *YOHKOH* mission (1990 – present):

(a) The density in the corona increases by one or two orders of magnitude by the following mechanism: fast particles are accelerated and heat is generated at the flare site up in the corona and they then propagate down to the chromosphere; there they heat the plasma which expands up into the loop by a process known as *evaporation*; subsequently, the loop plasma cools by conduction and radiation and drains back down to the feet of the magnetic fieldlines (e.g. Antiochos & Sturrock 1978, Peres 1989, Canfield et al. 1991);

(b) the high-temperature flare in the main phase consists of an arcade of hot X-ray loops that are located above the cool Hα loops (e.g. Pallavacini et al. 1977);

(c) the hard X-rays have been imaged and are found to come often from the footpoints in the impulsive phase (e.g. Hoyng et al. 1981);

(d) often a pre-existing coronal streamer overlying the flare erupts as a bubble, starting in the preflare phase; it is known as a *coronal mass ejection* (e.g. Hildner 1977);

(e) γ-ray lines and continua imply that the ions are accelerated to typically 100s of MeV (sometimes several GeV) and the electrons to 100s of keV within a few seconds (Chupp 1990, Forrest & Chupp 1983);

(f) narrow-band radio spikes imply a fragmentation of the acceleration site with a timescale of 0.01 sec (Benz 1994).

Another necessary condition for a flare (in addition to complexity) is shear up in the corona, because of the associated storage of free magnetic energy in excess of potential. One indication of this is the presence of a prominence and another is the presence of photospheric shear as revealed in vector magnetograms (e.g. Hagyard 1990, Canfield et al. 1991).

2 Basic magnetic reconnection process

2.1 Two-dimensional reconnection

The key process whereby magnetic energy is converted into other forms at the core of a flare is believed to be magnetic reconnection, whose two-dimensional MHD aspects are now fairly well understood (Priest 1990, Scholer 1991).

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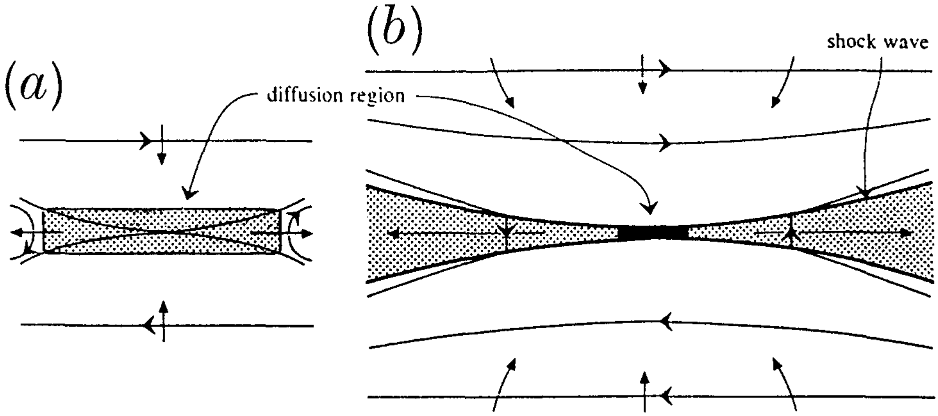

Fig. 1. The classical energy conversion mechanisms of (a) Sweet-Parker and (b) Petschek

Classical Regimes. The Sweet-Parker regime (Fig. 1) consists of a simple diffusion layer of length $2L_e$ between oppositely directed magnetic fields. The speed (v_i) with which magnetic energy is carried in and converted is called the reconnection rate and is written in dimensionless form in terms of the Alfvén speed (v_A) as

$$M_i = \frac{1}{R_{mi}^{1/2}}, \tag{1}$$

where $M = v/v_A$ and $R_m = L_e v_A/\eta$ is the magnetic Reynolds number. Since R_m is typically 10^8 or more, this gives an extremely slow reconnection rate, much too slow to explain flare energy release.

Petschek (1964), however, was able to set up a sufficiently rapid mechanism by making the diffusion region very small and having four slow-mode shock waves propagating from its ends and standing in the flow. Most of the energy release occurs at the shocks as magnetic energy is carried slowly in from large ("external") distances at a speed v_e and is converted at the shocks into the heat and kinetic energy of two hot fast streams of plasma. The maximum reconnnection rate (i.e. the dimensionless value of v_e) is now

$$M_e = \frac{\pi}{8 \log R_{me}}, \tag{2}$$

which is typically between 0.01 and 0.1.

New Generation of Fast Regimes. Now a new generation of fast reconnection regimes has been set up. First, there is an *Almost-Uniform Family* (Priest & Forbes 1986, Jardine & Priest 1990) which, like Petschek's mechanism, possesses weakly curving inflow magnetic fields (Fig. 2). The key point here is that a variety of different boundary conditions may be imposed on the inflow boundary and these produce a family of different regimes with different properties such as

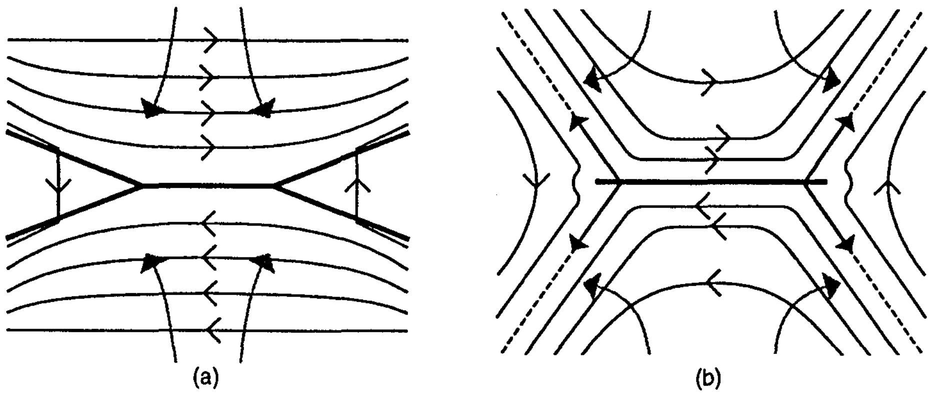

Fig. 2. Examples of members of the (a) Almost-Uniform and (b) Non Uniform regimes

sheet lengths and reconnection rates. Petschek's mechanism is one particular regime in this family.

Secondly, a *Non-Uniform Family* of regimes has been set up by Priest & Lee (1990), in which the inflow fields are now highly curved and there are jets of plasma expelled from the central current sheet along the separatrix field lines.

These two families have been used by Priest & Forbes (1992) to understand and explain results from some numerical experiments on reconnection (Biskamp 1986) and have also been carefully reproduced in other numerical experiments (Yan et al. 1992, 1993).

Reconnection in a Flare. In a large solar flare, the overall picture (Fig. 3) is that during the preflare phase a flux tube (containing a prominence) and an overlying arcade rises slowly because of some kind of eruptive instability. Then at the flare onset the rapid eruption is initiated by the beginning of reconnection in the stretched out field lines. During the main phase the reconnection continues and creates the hot flare loops and ribbons as the field closes down: the loops rise and the ribbons separate as the reconnection point rises.

This process of reconnection has been studied numerically by Forbes & Priest (1983), Forbes & Malherbe (1991) who start with open field lines which are line-tied at the base and then they watch them close down. Slow shocks develop, as in the Almost-Uniform family, and a new feature is that the stream of plasma flowing down from the reconnection site is slowed down by a fast shock where it meets a magnetic obstacle in the shape of closed loops attached to the solar surface.

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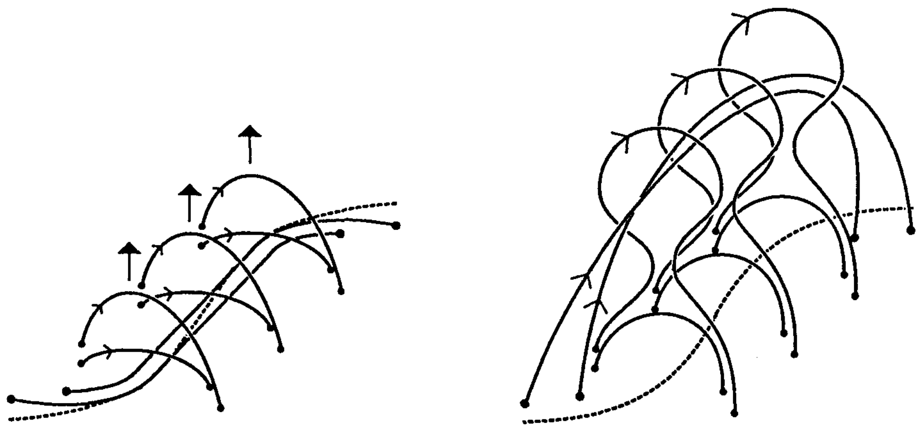

Fig. 3. The overall scenario for a large flare

Our present understanding for what is happening during the main phase (Fig. 4) is that the slow shock splits into a conduction front and an isothermal subshock. Plasma is evaporated up from the Hα ribbons to fill the hot loops with a marked cusp at their summits. The cool loops are loops which have cooled down from a previously hot state. A startling discovery from *YOHKOH* (Uchida 1993) is the presence in many flares of the cusp-shaped hot loops which had previously been suggested on theoretical grounds (e.g. Priest 1982).

2.2 Magnetic reconnection in three dimensions

Introduction. In two dimensions the global skeleton of a complex field consists of *separatrix curves* (Fig. 5) which separate the plane into topologically distinct regions in the sense that all the field lines in one region start at a particular source and end at a particular sink. The separatrices intersect in an X-type neutral point, where reconnection can take place as flux is transferred from one region to another.

In three dimensions the skeleton consists of *separatrix surfaces*, which divide the volume into topologically distinct regions (Fig. 5). They intersect in a curve known as a *separator*, which is a special field line that joins two null points.

Demoulin et al. (1993) have used the observed normal field component in the photosphere to calculate the overlying three-dimensional (potential or force-free) coronal magnetic field. They then determine the location of the separatrix surfaces and the curves in which they intersect the chromosphere (shown as dark solid curves in Fig. 6). What they find is that the resulting flare ribbons and

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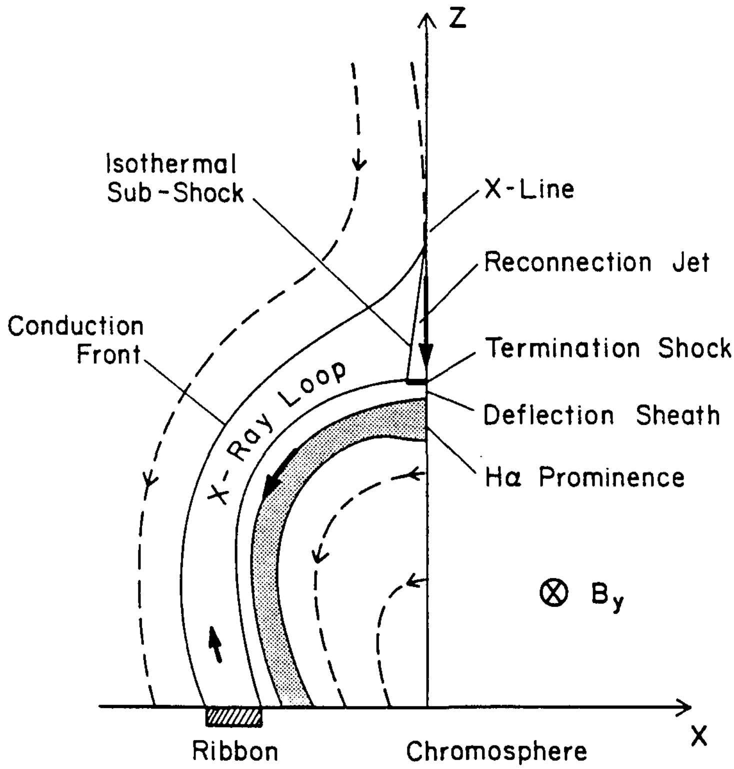

Fig. 4. Schematic of creation of flare loops and Hα ribbons

kernels are always located on or near the separatrices, which is clear confirmation of the role of reconnection at the separatrices.

It turns out that many flares posses no true null points (Demoulin et al. 1994) and no separatrices (Schindler et al. 1988), but nevertheless a theory has been developed for reconnection in such configurations at *quasi-separatrices* (Priest & Demoulin 1995).

Theory of 3D Reconnection (Priest & Titov 1995). The question then arises: how does reconnection occur at a null point in such a 3D configuration? This question is only just beginning to be tackled (Schindler et al. 1988, Lau & Finn, 1990). The simplest null point in three dimensions has field components $(B_x, B_y, B_z) = (x, y, -2z)$, so that $\nabla \cdot \mathbf{B} = 0$. There are two families of field lines through the null point at the origin (Fig. 7). The *null spine* along the z-axis is isolated, with neighbouring field lines forming two bundles around the z-axis which splay out as they approach the xy-plane. Also the *null fan* is a surface (the xy-plane) consisting of field lines which spread out from the origin.

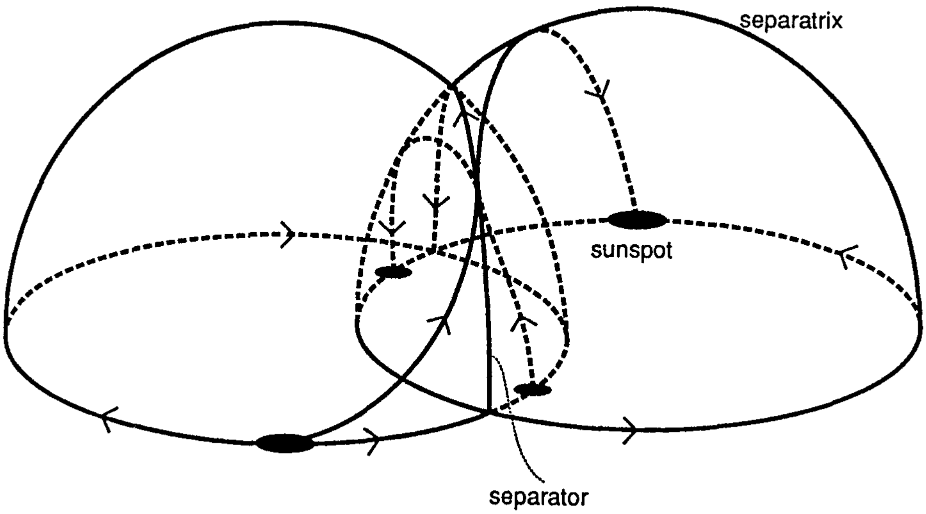

Fig. 5. The separatrix topology above four sunspots

Priest & Titov (1995) have studied the kinematic aspects of steady reconnection by solving the equations

$$\nabla \times \mathbf{E} = 0 \quad , \quad \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$$

subject to appropriate boundary conditions. They have discovered two distinct types of reconnection. In *spine reconnection* (Fig. 8) continuous footpoint motions are imposed on a surface, such as a cylinder, which encircles the spine and crosses the fan. Two flux surfaces come in, touch at the null and then reconnect at the null, unfurling from the spine like a bubble. Singular flows are driven at the spine. In *fan reconnection*, on the other hand, continuous footpoint motions are imposed on the top and bottom of the cylinder crossing the spine. Then singular swirling flows are driven at the fan.

3 Cause of eruptive behaviour

The other major question for MHD theory is: why does the prominence erupt? Why does the flare start? In theory, you may imagine this could be answered by solving the MHD equations numerically for evolution of the coronal field through a series of force-free equilibria in response to footpoint motions. Many such attempts have been made in two dimensions and a few in three dimensions, but it has proved remarkably difficult to produce an eruption.

One promising solution has been proposed by Priest & Forbes (1990), Demoulin & Priest (1988), Forbes & Isenberg (1991). They suggest that converging

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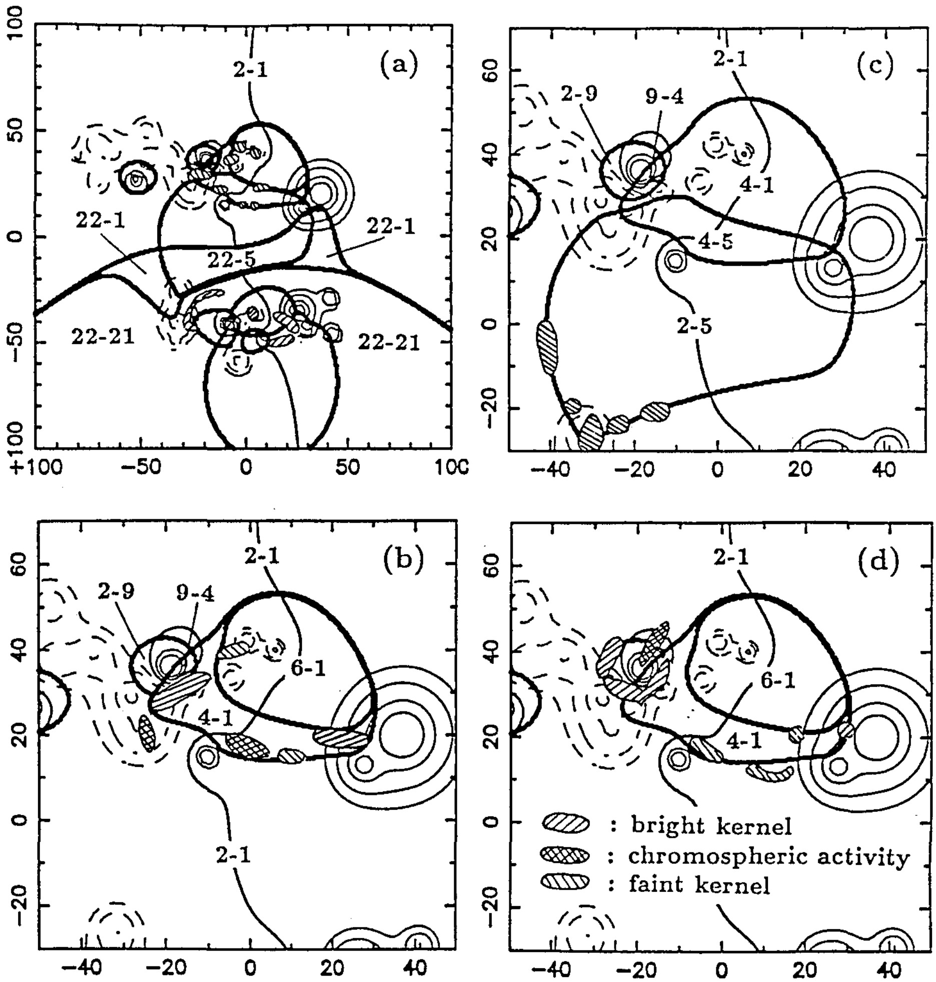

Fig. 6. Trace of the separatrices and flare features on the chromospheric plane showing (a) the general view and (b)–(d) a close-up for three flares (from Demoulin et al. 1993)

flow builds up the energy and flux in the magnetic field, so that, in a plane perpendicular to the arcade axis, a magnetic island is formed (Fig. 9), where a prominence can form. As the magnetic energy increases so the height of the prominence rises slowly. Eventually, however, a critical catastrophe point is reached, beyond which there is no neighbouring equilibrium. The imbalance in forces is upward and the prominence erupts, driving the formation of a current sheet and reconnection below the rising prominence. A simple model for this idea has been complemented by a detailed numerical experiment which elegantly explains many features of the observations.

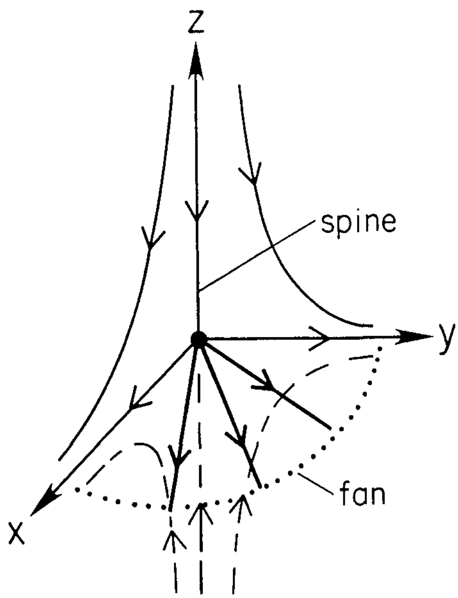

Fig. 7. The structure of a 3D null point

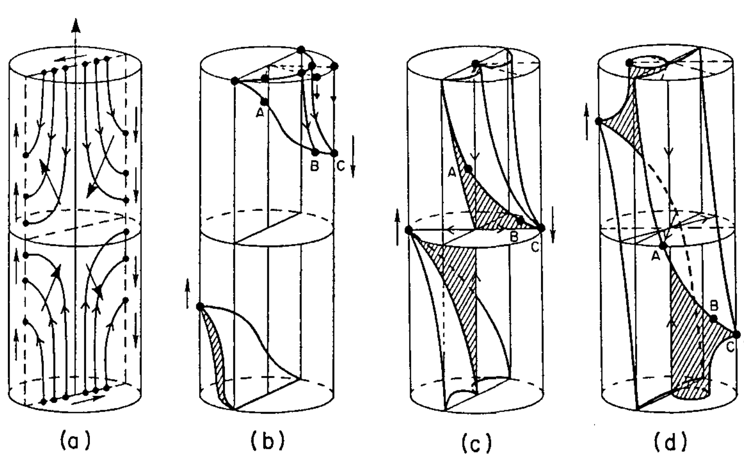

Fig. 8. Motion of field lines and flux surfaces in spine reconnection

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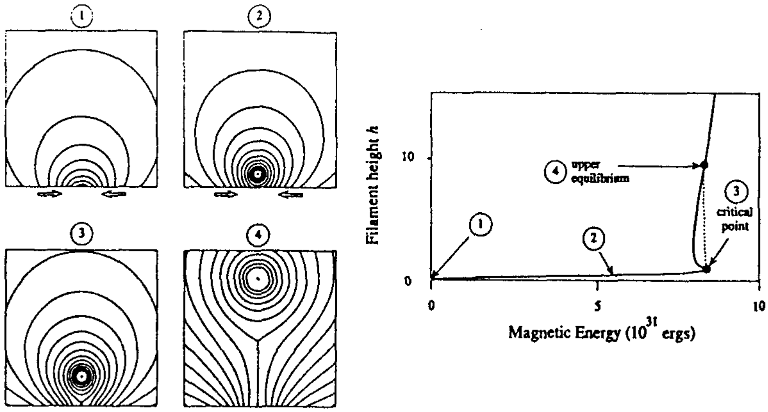

Fig. 9. A catastrophe model for prominence eruption

4 Conclusion

It is now well established that the energy release in a flare is by magnetic reconnection and it is likely that this is driven by an eruptive catastrophe. In future we expect progress from: three-dimensional understanding of reconnection; plasma theorists as they study the consequences of the MHD environment for microscopic processes such as particle acceleration; and finally comparisons with energy release processes under different parameter regimes in different parts of the universe.

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J. van Paradijs: What determines the direction of magnetic flux transport across a separator?

E.R. Priest: If the sources of magnetic flux (such as sunspots or photospheric magnetic fragments) move, this flux will be driven across the separatrix surfaces from one regime to another, so the direction of flux transport will depend on which sources move and the direction in which they move. Also it is possible to twist up or shear the field in each region and then for it to lose equilibrium and drive flux across the separatrices from the region where most energy is stored.

P.B. Byrne: What drives the converging flow at the footpoints of pre-flare loops?

E.R. Priest: The photospheric motions of footpoints are essentially due to convecture flows and general active region evolution. It has been observed by Sara Martin that under prominences photospheric magnetic fragments approach the prominence and cancel, thereby increasing the flux in the overlaying prominence field.