SESSION IV

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CURRENT SHEETS IN SOLAR FLARES

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ABSTRACT Until recently magnetic reconnection in solar flares was discussed simplistically in terms of either a spontaneous tearing mode instability or a driven Petschek mode. Now the subtle relationship between these two extremes is much better understood. Current sheets may form and reconnection may be initiated in many different ways. There are also a variety of nonlinear pathways from a reconnection instability and several types of driven reconnection.

In solar flares current sheets may be important as new flux emerges from below the photosphere and also as a magnetic arcade closes down after being blown open by an eruptive instability. Numerical simulations of these sheets will be described, including new features such as the presence of a fast shock in Petschek's mechanism and impulsive bursty reconnection due to secondary tearing and coalescence.

1. INTRODUCTION

The collapse of the magnetic field near an X-point to form a sheet of intense current is a universal phenomenon in a cosmic plasma. Such current sheets are important as sites where the magnetic energy may be converted to kinetic energy, heat and fast particle energy. Also, they allow the global topology of the magnetic field to be changed as magnetic field lines break and reconnect.

A few years ago the emphasis in laboratory plasmas was on the tearing mode instability, whereby time-dependent linear reconnection grows spontaneously. The emphasis in cosmic plasma research was instead on the Petschek regime, in which steady nonlinear reconnection is driven at a fast rate. Now, however, we have entered an age of sophisticated numerical experimentation on time-dependent nonlinear reconnection. This has linked the two previous strands of thought and has produced many unexpected results.

In the next two sections my aim is to summarise some of the lessons

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learnt while preparing a major review of the MHD of current sheets (Priest, 1984) and also to mention some of the distinctive properties of current sheets in solar flares.

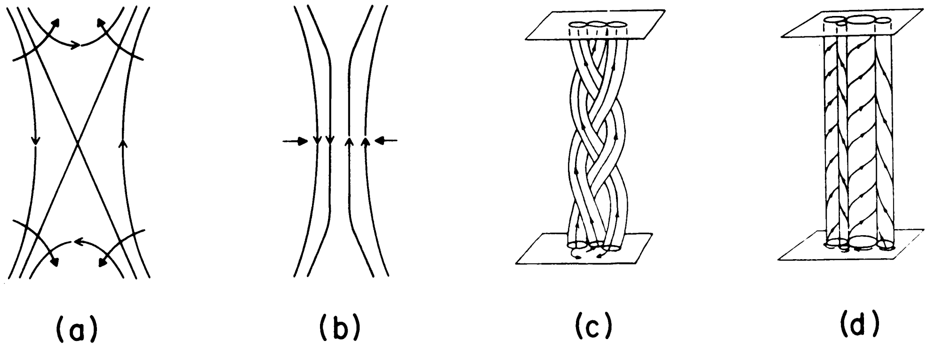

Figure 1. Current sheet formation.

2. GENERAL PROPERTIES OF MAGNETIC RECONNECTION

2.1. Current sheets may form in different ways.

Because the magnetic Reynolds number (vL/η) is so large throughout most of a cosmic plasma, where η is the magnetic diffusivity, the magnetic field is frozen very effectively to the plasma except in intense concentrations of current such as sheets. These may form if the region near an X-point (or separator) collapses (Dungey, 1953; Syrovatsky, 1966), which occurs when, for example, topologically separate flux systems are pushed towards one another (Figure 1a, b). Also, Parker (1972, 1983) has pointed out that a closely packed set of flux tubes will tend to create sheets. When the tubes are braided (Figure 1c) he conjectures that no equilibrium is possible so that magnetic nonequilibrium ensues (Syrovatsky, 1978; Tsinganos, 1982; Rosner and Knobloch, 1982). When the tubes are twisted (Figure 1d) with neighbouring tubes possessing the same sense of twist an equilibrium does exist but there is a current sheet at the interface between them.

Current sheets may also be created by ideal magnetic instabilities such as the classical kink instability (Figure 2a) studied in the solar context by Raadu (1972), Hood and Priest (1979), Van Hoven *et al*. (1981) and, in its nonlinear regime, by Sakurai (1976). Other ideal modes are the eruptive instability (Figure 2b, §3.3) and the coalescence instability (Finn and Kaw, 1977; Pritchett and Wu, 1979), which drives neighbouring magnetic islands together in a tearing layer (§3.3).

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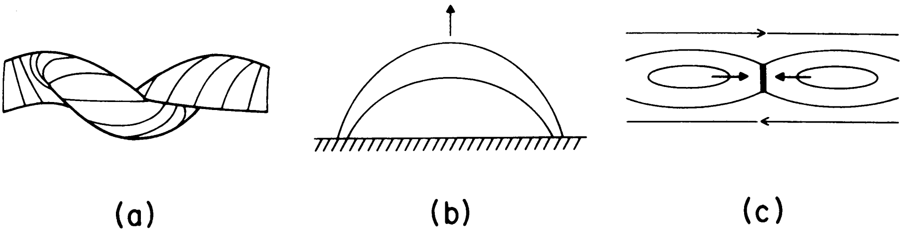

Figure 2. Ideal magnetic instabilities.

2.2. Reconnection may be initiated in different ways

Magnetic reconnection in a current sheet may occur spontaneously by a resistive instability such as a tearing mode (Furth et al. 1963). Alternatively, it may be driven locally by a sudden enhancement of the magnetic diffusivity (η) due to, for example, the onset of microturbulence (Ugai and Tsuda, 1977). Furthermore, reconnection may be driven from outside when topologically separate flux systems are pushed together (Sato and Hayashi, 1979).

2.3. Regimes of driven reconnection

When separate flux systems are forced together at a steady speed v (at large distances from the neutral point), the resulting type of reconnection depends on the value of v. If the reconnection rate is smaller than the overall diffusion speed, i.e.

$$v < \frac{\eta}{L} ,$$

where L is the overall length-scale of the system, we have a state of very slow (vacuum) reconnection (Figure 3(I)), in which the field diffuses through a series of potential fields. If instead

$$\frac{\eta}{L} < v < \frac{v_A}{R_m^{1/2}} ,$$

where $v_A = B/(\mu\rho)^{1/2}$ is the Alfvén speed at large distances and $R_m = Lv_A/\eta$ is the large-scale Lundquist number, the result is a slow (Sweet-Parker) mode (Figure 3(II)) with a narrow diffusion region (shaded) of length L where the magnetic field slips through the plasma.

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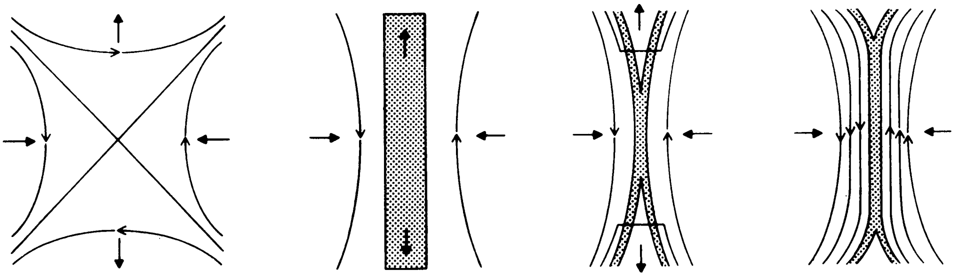

Figure 3. Reconnection regimes: (I) very slow, (II) slow, (III) fast, (IV) supercritical.

When the distant inflow speed (v) lies in the range

$$\frac{v_A}{R_m^{\frac{1}{2}}} < v < v_{max} \quad ,$$

where $v_{max} = \pi v_A/(8 \log R_m)$ lies typically between 0.01 v_A and 0.1 v_A, one finds fast (Petschek) reconnection, in which the current sheet bifurcates into a pair of slow magnetoacoustic shock waves (Figure 3 (III)). The central diffusion region is just a Sweet-Parker current sheet, which is insignificant energetically but acts as a source for the slow shocks. The shocks create hot fast jets of plasma with typically $\frac{3}{5}$ of the inflowing magnetic energy being converted into kinetic energy and $\frac{2}{5}$ into heat. They form simply because the inflow is supersonic with respect to the slow-mode speed.

When the inflow speed is so large that

$$v_{max} < v$$

a fast steady state is impossible and we have supercritical reconnection with flux pile-up (Figure 3 (IV)). The magnetic flux is being brought in faster than it can reconnect and so it piles up outside the diffusion region, gradually increasing its length until there is no room for the slow shocks. This is a highly time-dependent regime with fast-mode waves propagating back towards the source and must not be confused with the Sweet-Parker mode.

In practice the nonlinear development of a tearing mode in a cosmical plasma is likely to lead to regime III (§3.1), unless reconnection is inhibited by severe constraints. For example, in a tokamak

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there is a strong magnetic field component along the X-line as well as conducting walls and restrictions on the wavelengths that can fit in the torus, with the result that the tearing soon slows down to a simple diffusion (the Rutherford regime). Ideal magnetic instabilities, on the other hand, (Figure 2) occur on Alfvénic times and are likely to drive very fast reconnection in regime IV, which needs to be explored in more detail.

3. SOLAR FLARES

3.1. Important extra effects in the solar atmosphere

Steinolfson and Van Hoven (1983, 1984) have stressed that the Lundquist number ($S = a\, v_A/\eta$) and dimensionless wavelength (λ/a), where a is the current sheet width, are both much larger in the solar atmosphere than is normally considered in tearing mode calculations. For $S \gtrsim 10^6$ they find that at $\lambda/a=2$ the tearing has the usual linear growth rate ($\sim S^{2/5}$) and the nonlinear growth is very slow (at "constant-ψ"). However, at larger wavelengths ($\lambda/a=20$) the linear tearing is much faster ($\sim S^{2/3}$) and the perturbation extends far from the sheet with a much faster non-linear growth than before (at non-constant-ψ).

Another feature of modelling the solar atmosphere is that a realistic energy balance should be employed including optically thin radiation. For the Sweet-Parker or Petschek mechanism this leads to a beta-limitation, since a steady-state diffusion region becomes impossible when the plasma beta is too low (Milne and Priest, 1981). Furthermore, the tearing mode becomes coupled to the faster radiative mode, which exhibits a surprisingly high level of reconnection and magnetic energy conversion (Van Hoven *et al.*, 1983).

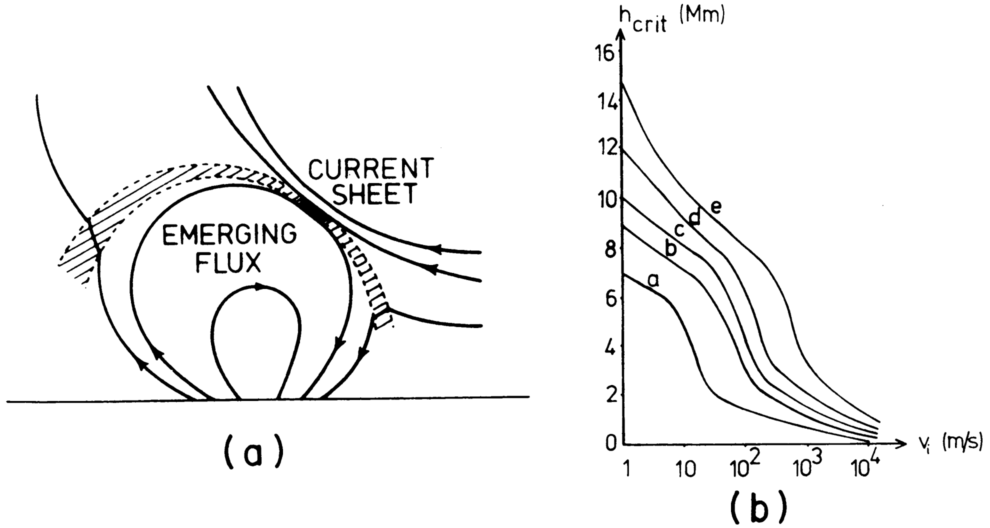

Figure 4. (a) Flux emergence, (b) Critical sheet height.

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Finally, it is important to incorporate the stablising effect of photospheric line tying, since the footpoints of coronal magnetic field lines are usually anchored in the dense photosphere. It has been suggested that this may even make the resistive modes completely stable in a loop (Mok and Van Hoven, 1982) or an arcade (Hood, 1983) unless there is a reversal in the axial field component.

3.2 Emerging flux

According to the emerging flux model (Heyvaerts et al., 1977), as new magnetic flux emerges from below the photosphere it creates a current sheet at the interface with the overlying field at a height h (Figure

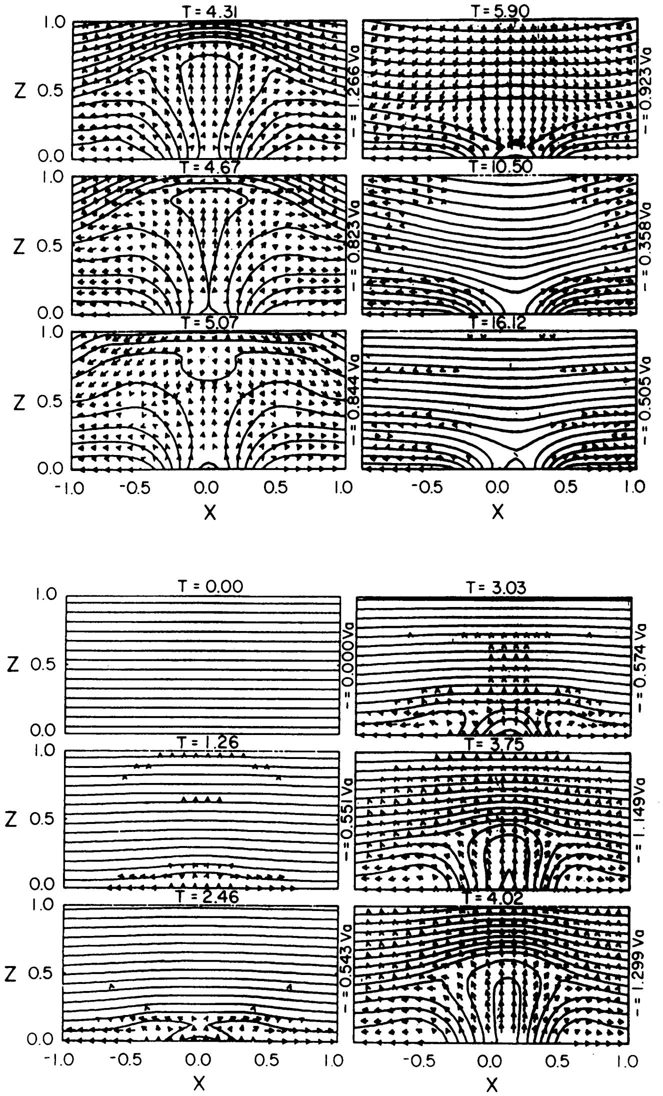

Figure 5. Numerical simulation of emerging flux (Forbes and Priest).

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4a). The type of flare depends on the magnetic environment into which the new flux emerges. Usually, an X-ray bright point is produced or a small flare if a lot of flux emerges. If the emergence is near the sheared magnetic field of an active-region (or plage) filament, a large two-ribbon flare may result, with the emerging flux triggering the release of energy stored in the overlying sheared field. The model also applies to horizontal (rather than vertical) motion of the new flux (e.g. satellite sunspots), because all that is needed to produce current sheets is a relative motion of the two flux systems. It is suggested that the onset of the flare occurs when the sheet reaches a critical height h_{crit} such that the current density becomes large enough to trigger microturbulence. Its variation with emergence speed (v) and field strength (B) is calculated by solving the energy balance in the sheet (Heyvaerts and Priest, 1976; Tur and Priest, 1978; Milne and Priest, 1981) as shown in Figure 4b, where a,b,c,d,e refer to field strengths of 10^3, $10^{2.5}$, 10^2, $10^{1.5}$ and 10 Gauss, respectively.

Some preliminary results of a numerical experiment on emerging flux by Forbes and Priest are shown in Figure 5, with time measured in units of the Alfvén travel time over unit distance and the initial magnetic field being horizontal. The boundary conditions are free-floating on the sides and top, whereas on the base an emerging flux region of oppositely directed field is modelled by imposing the normal magnetic field component and the mass flux normal to the field lines. For this case the magnetic Reynolds number of 400 and the emergence speed is rather large (one eighth of the Alfvén speed). In the first six frames it can been seen how the flux emerges and reconnects. Even though no more new flux is forced through the base after t = 4, the flux continues to rise

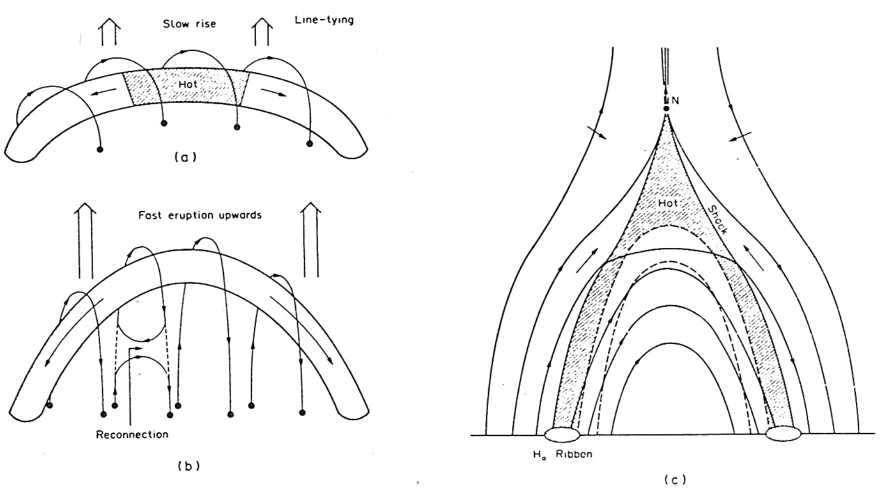

Figure 6. Overall behaviour of large flare.

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through its own inertia. In the second six frames the flux pinches off near the base and tears to form a plasmoid which is ejected upwards out of the top of the box. By the last frame the configuration has quietened down to an almost potential state. As well as being important in solar flares, the formation and acceleration of plasmoids may be occuring in X-ray bright points and EUV Brueckner jets, and it has even been speculated that they may represent a large part of the solar wind (Pneuman, 1983).

3.3 Large (two-ribbon) flares

For most major flares one observes in the preflare phase a large flux tube (active-region filament) starting to rise slowly for typically half an hour (Figure 6a). This slow rise may be caused by an ideal eruptive instability (Hood and Priest, 1980; Migliulo and Cargill, 1983) or it may be the result of magnetic nonequilibrium when the flux tube can no longer remain in equilibrium under the combined action of magnetic tension and magnetic buoyancy (Parker, 1979; Browning and Priest, 1983).

As the flux tube rises it stretches out the overlying arcade of magnetic field lines until they start to reconnect by the tearing mode, thereby no longer holding down the tube. This represents the flare onset and the beginning of a much more rapid eruption (Figure 6b). During the main phase the filament has disappeared from view and the reconnection continues, as shown in a section across the arcade in Figure 6c. As the open field closes back down the neutral point and the Petschek shocks rise, creating hot rising loops of plasma ($\simeq 10^7$K) with two separating ribbons of emission at their footpoints (Kopp and Pneuman, 1976; Cargill and Priest, 1982).

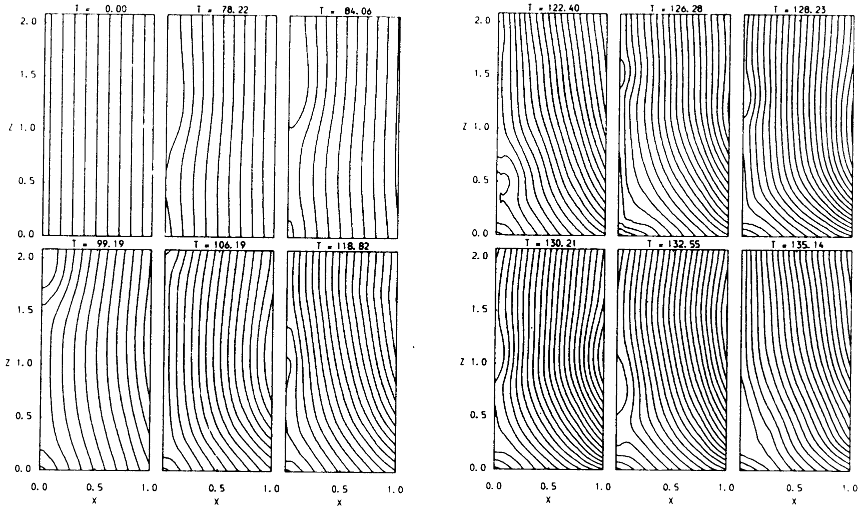

Figure 7. Line-tied reconnection (Forbes and Priest, 1983).

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A numerical simulation of this reconnection process in stretched-out field lines has included the line tying of the footpoints at the base of the numerical box (Forbes and Priest, 1982a, 1983). Boundary conditions along the upper and right-hand edges are free-floating and along the left-hand edge they are symmetry conditions, since only the right-hand part of the configuration is shown in each frame of Figure 7. The initial state just consists of vertical field lines and the magnetic Reynolds number ($R_m = v_A\ a/\eta$) is 300, while the ambient plasma beta is 0.1 and the width (a) of the initial vertical current sheet is 0.1 of the box width. A flux-corrected algorithm is used with a variable grid and time is measured in units of the Alfvén travel time (a/v_A).

For the first three frames of Figure 7 the behaviour was as expected. The sheet tears near the base and in the nonlinear development the magnetic field continues to close down while the X-type neutral point rises and a plasmoid is ejected. From a single frame during this development (Figure 8a, for $R_m = 10^3$) the presence of two slow Petschek shocks can be seen extending up and down from the neutral point. They show up much more clearly in the current density or plasma velocity plots than in the magnetic field line sketches. A new feature is the presence of a fast magnetoacoustic shock wave, as predicted by Yang and Sonnerup (1976). It rapidly slows down the jet of plasma that is being squirted down towards the obstacle of closed magnetic field lines near the base and therefore degrades some of the kinetic energy released in the Petschek mode further into heat.

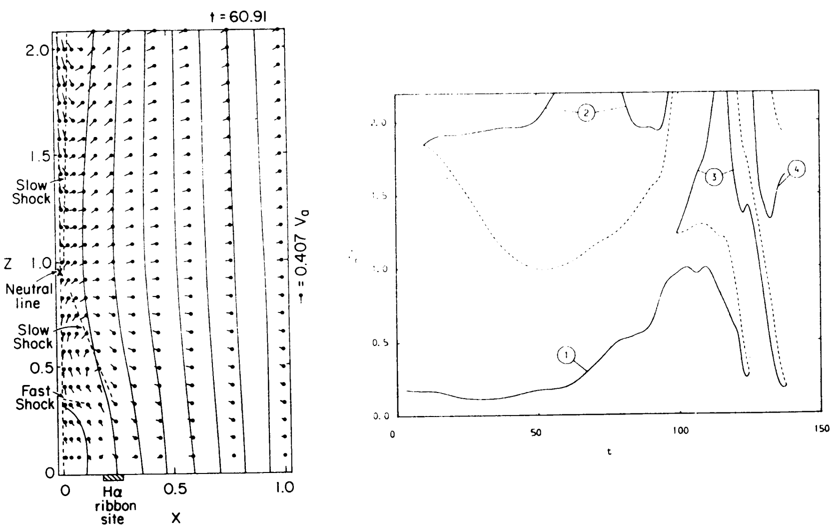

Figure 8(a). Magnetic field lines and flow velocity vectors.
(b). Creation and annihilation of neutral point pairs. (Forbes and Priest, 1983.)

The subsequent development (t>90) was a surprise. The current sheet thins and tears again, creating a pair of X- and 0-points. Recon-

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nection at the upper X dominates and the O is shot down and coalesces with the lower X extremely rapidly by the coalescence instability. Meanwhile a new pair of neutral points is created and the process repeats. This relatively slow secondary tearing and much faster coalescence produces an impulsive bursty mode of reconnection and is found to occur more easily as R_m , β^{-1} and the box width are increased.

4. CONCLUSION

It is important to increase greatly the contact (both theoretical and observational) between those working on reconnection in the laboratory, the magnetosphere and the solar atmosphere, so that we can understand better the fundamental behaviour of current sheets. In so doing, we should seek to recognise the distinctive properties of reconnection in these diverse plasmas in order to discover the real similarities and differences rather than being over-prejudiced by our own speciality (see e.g. Forbes and Priest (1982b) for a comparison of geomagnetic substorms and solar flares). It will be especially interesting to continue the present crop of numerical experiments on reconnection and to compare with analytical models so as to appreciate more of the basic physical mechanisms at work in this beautiful process. Clearly, current sheets will continue to intrigue and surprise us in years to come.

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DISCUSSION

Vasyliunas: In your Figure 3, there should be an additional regime IIIa, between III and IV, which might be called the Sonnerup regime, where plasma is being pushed together faster than v_{max} but is also being sucked out the sides, creating a slow-mode expansion ahead of the reconnection region and allowing steady reconnection of essentially arbitrarily high rates. This could occur, for example, at the dayside of the earth where the flow goes both toward and around the magnetosphere.

Priest: I agree that one can have a slow mode expansion Petschek (or Sonnerup) mode or a fast mode expansion Petschek mode. Indeed, it is possible to have a modified Petschek mode with both slow and fast mode expansion effects in the inflow region and with a quite different scaling from the normally quoted value.

It is the inflow boundary conditions that determine which of these modes occurs. However, if reconnection is driven locally by a resistivity enhancement or by a tearing mode, I would expect the fast mode expansion Petschek regime to be the relevant one. There are great difficulties comparing numerical experiments with the Petschek or Sweet-Parker modes. For example, in numerical simulations the magnetic field may not be steady or uniform at large distances; there may be external sources of waves and currents; numerical diffusion may be so high that it smooths out the shocks over large regions. Just comparing with the η scaling is too simplistic, and it is preferable to use the presence of slow mode shocks as the criterion for the Petschek mechanism - such shocks are best detected in maps of the current density contours rather than magnetic field line plots.

Migliuolo: What is the width of the current sheet in the simulation by Forbes and Priest?

Priest: The width (a) of the current sheet (within regions of uniform field) has been varied from 0.5 to less than .03 of the width (w) of the numerical box. The interesting feature is that the new regime of impulsive bursty reconnection is absent at low values of magnetic Reynolds number (R_m) or w/a or high values of external plasma

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beta (β). But, as R_m, w/a or β^{-1} are increased the impulsive bursty regime becomes more evident. In this regime the reconnection rate (as measured by the electric field at the dominant X-point) is significantly higher. Also, this new regime could develop in theory from either regime II, III or IV when the sheet length becomes large enough for tearing (Bulanov et al., 1978).

Migliuolo: Why is diffusion in neutral sheets limited by the value of β?

Priest: When the plasma beta is too low the optically thin radiation can no longer be balanced by the other terms in the energy balance. It arises because of the maximum in the radiative loss curve.

Van Hoven: What is the vertical scale in the line-tied reconnection plots (Fig. 7)?

Priest: The numerical box is twice as high as it is wide.

Van Hoven: Would you clarify the effects of the distance to the free boundaries on the "bursts" of X- and O-point movement?

Priest: The "free" boundary conditions (setting e.g. $\partial\rho/\partial n = 0$, $\partial v/\partial n = 0$) are freer than fixed conditions (ρ = const, v = const), but they are still not completely free since they do inhibit reconnection to a certain extent. Therefore, as the boundaries are taken further away from the sheet the impulsive bursty reconnection becomes more possible.

Drake: In the case in which the inflow velocity initially exceeds the Alfvén velocity, it seems to me that the magnetic flux will simply build up (increasing local B) until the Alfvén velocity exceeds the inflow velocity so that the Petschek model can be applied to the whole process.

Priest: When $v > v_{max}$ (not v_A) I agree that the propagation of fast mode waves in the inflow region will tend to increase B, but the result is a subtle interaction between these waves and the sources of magnetic field. This highly time-dependent process has just not been looked at in detail yet.

Drake: In all simulations of resistive instabilities with high magnetic Reynolds numbers, the magnetic reconnection rate is never as large as the Petschek rate. The maximum reconnection rates are seen in simulations of the coalescence instability and kink mode (ideal modes) in which the Sweet-Parker model seems to describe the scaling (Biskamp and Park et al.). Petschek reconnection rates have only been seen when a constant velocity external driver has been imposed from the outside. In my opinion the real question is whether the plasma itself can ever internally generate reconnection rates as fast as predicted by Petschek.

Priest: The important feature is the assumed boundary conditions. If these are free-floating, as in our simulations or those of Tsuda, for instance, then the tearing mode does develop nonlinearly into the Petschek mode. If instead you impose fixed or periodic conditions, then it evolves much more slowly into the Rutherford regime. In my view the solar flare is likely to be caused by an ideal instability (such as the kink or eruptive mode) which then drives fast reconnection.

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