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Flare models and radio emission

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Abstract

Flare-associated radio emissions, specifically microwave bursts, type III bursts and type III-like bursts, provide information on the spectrum of suprathermal electrons accelerated in a flare, and on the location of the acceleration region. They can also be used to map out both closed and open magnetic structures. The radio data also suggest that the energy release process in flares is highly structured in space and time, and provides indirect evidence that the corona is highly inhomogeneous on a finer scale than can be resolved. Of the many flare models proposed two are now favored by observational data. There is indirect evidence for the open field model from Yohkoh data, and there is strong evidence in favor of an emerging flux model from vector magnetogram data. The evidence that the emerging flux is already twisted implies that the energy released in a flare is already stored in the associated current system in the emerging flux, so that this energy is transported into the corona as the emerging flux loop rises. A specific emerging flux model, in which reconnection between two current-carrying flux loops releases magnetic energy, is reviewed briefly.

Key words: Solar flares — radio emission — flare models

1. Introduction

Flare-associated radio emission provides information primarily about the particles accelerated in a flare, plus secondary information about the location and time evolution of the energy release. The radio data at metric and decimetric wavelengths imply that the energy release process, leading to particle acceleration in a flare, is highly structured in space and time. Multifrequency radio observations, especially at microwave frequencies, can map out the structure of a flaring region in a way that no other observations can. The data at different wavelengths are complementary for formulating flare models. While soft X-ray images are excellent for showing active region loops, they are sensitive to a limited temperature range and to the densest loops and they can miss magnetic structures that are involved in a flare. Hard X-ray observations either identify the regions of hottest plasma in flares or the regions where suprathermal electrons impinge on denser plasma in the chromosphere or perhaps near the tops of flaring loops. Vector magnetograms provide information which in principle can be used to construct models for the coronal magnetic field, but in practice the construction requires additional assumptions and the results are sensitive to the assumptions. Only the radio observations can provide a comprehensive mapping of the coronal magnetic field and sensitivity to energetic electrons throughout the flaring region. Radio emission is discussed further in section 2.

A flare model is an attempt to explain the observational data in terms of some general principles, with strong emphasis on the location and nature of the stored energy and on the energy release mechanism. Although there is wide agreement that magnetic energy is released in a flare, the details remain uncertain. Magnetic energy release requires some form of dissipation, and the radio and other data suggest that in a flare this dissipation involves energy transfer to the accelerated particles with relatively high efficiency. Existing flare models are classified and discussed in section 3, and a new type of flare model is discussed in section 4.

2. Flare-associated radio bursts

Solar radio bursts separate naturally into short and long wavelengths, with the transition at wavelength $\lambda \sim 10\,\mathrm{cm}$ or frequency $f \sim 3\,\mathrm{GHz}$. Microwave bursts (cm-λ) are due to gyrosynchrotron emission from higher energy ($\gtrsim 100\,\mathrm{keV}$) electrons accelerated in the flare and trapped in closed magnetic structures associated with the flaring region. Gyrosynchrotron emission is an incoherent process, and one can deduce information on the energy of the electrons and the strength of the magnetic field directly from observations. Moreover, propagation effects are relatively unimportant so that the structure of the source can be inferred directly from radio images. Recently (Lee

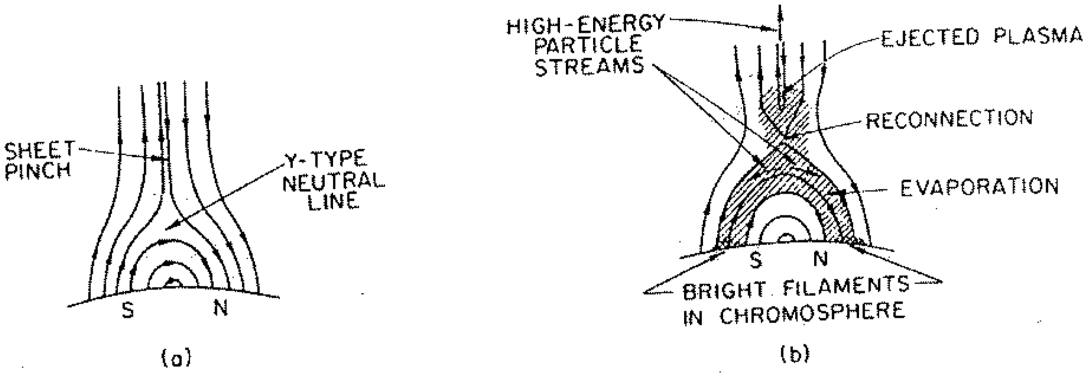


Fig. 1.. Open field line model for solar flares; (a) the preflare configuration with open field lines, (b) reconnection leading to acceleration and chromospheric heating [after Sturrock (1980)].

et al. 1998) microwave data have been used to infer a direct link between electric currents and coronal heating, and this may well be indicative of the role played by currents in the more extreme examples of heating and acceleration involved in flares. Microwave bursts are reviewed in another paper at this meeting, and are not discussed further here.

Radio bursts at longer wavelengths are associated with plasma instabilities, with the most familiar being type III (and type III-like) bursts which are due to a beam or streaming instability (e.g., Melrose 1980, 1986) in which Langmuir waves are generated, with the observed radiation resulting from secondary processes that produce emission at the fundamental (F) or the second harmonic (H) of the plasma frequency, f_p. At the highest frequencies (dm-λ) at which they are detected, type III-like bursts are the most direct available signatures of the flaring process (Benz 1986; Bastian et al. 1998).

2.1. Type III bursts

The most important flare-associated m-λ radio emissions are type III bursts. For many small flares the only evidence of nonthermal particles are X-ray footpoints, attributed to precipitating $\gtrsim 10\,\mathrm{keV}$ electrons, and type III bursts. Type III bursts are due to streams of electrons which can propagate through the corona into the solar wind, where in situ observations provide information on their energy spectrum. Such data are consistent with the type III electrons and the hard X-ray producing electrons originating from a single population. The type III electrons accelerated in the flare clearly have access to open field lines. The simplest interpretation is that magnetic reconnection in the energy release region of flares leads to a fraction of the magnetic field lines becoming open or already being open.

In the two favored flare models discussed below, the energy release occurs in a magnetic reconnection region which separates open and closed magnetic field lines. In the open field model illustrated in Figure 1, the type III electron streams escape along the field lines that remain open after the reconnection. The situation is similar in the emerging flux model illustrated in Figure 2. The main difference between these models from the viewpoint of the radio data is that the reconnection site is higher in the open field model, where it is above the initial flux loop, than in the emerging flux model, where is is below the main initial flux loop.

For the coherent emission processes involved in type III emission, the relation between the particles and the escaping radiation is rather indirect and the radio data do not provide reliable quantitative information about the properties of the particle beams. Moreover, propagation effects are important for m-λ bursts. The sources observed with a heliograph appear to be scatter-images, rather than the actual sources. There is strong evidence that the radiation is ducted (Duncan 1979) from the actual source to a much higher apparent source from where it escapes freely. The required ducts need to have special properties, having relatively large contrasts between the overdense and underdense regions, and being nearly radial but on a much smaller scale than is apparent from coronal rays in eclipse photographs.

Other flare-associated m-λ bursts are type II bursts (Nelson, Melrose 1985) and the flare continuum (cf. Robinson

1985). Type II bursts are associated with shock waves excited by flares. They sometimes exhibit a 'herring-bone' structure in which type III-like bursts emerge from a 'backbone' of type II emission. This suggests that the acceleration of type III-like electrons is not confined to flares. A clearer example of this is a similar acceleration in a related non-flaring context. In type I–III storms (e.g., Kai et al. 1985) the type III bursts (with lower electron energies, $\lesssim$ few keV, than in flare type III bursts) propagate up along open field lines and the type I bursts appear to be confined to closed field lines. The energy release on the boundary between them appears sometimes to be triggered by a disturbance propagating at about the Alfvén speed. These radio observations suggest that the copious acceleration of electrons can occur in a variety of contexts in the corona, and that when this does occur it involves many localized bursts of acceleration.

2.2. Type III-like bursts

The observed properties of dm-λ bursts (e.g., Benz 1986) are reviewed in another paper at this meeting. The bursts may be separated into two major classes, conveniently called spike bursts and type III-like bursts. Spike bursts are thought to be produced by electron cyclotron maser emission (ECME). They provide clear evidence of fragmented energy release (Benz 1986). Accepting the simplest version of the ECME hypothesis (e.g., Melrose 1986, p. 194), the emission frequency is equal to the cyclotron frequency, f_B, which provides direct information on the strength of the magnetic field in the energy release region. Moreover, the simplest form of ECME requires $f_p \lesssim 0.3\, f_B$, giving a further constraint on the plasma parameters in this region. However, significant uncertainties remain in the interpretation of spike bursts because the problem of how the ECME can escape through the second harmonic ($f = 2f_B$) absorption layer (Melrose, Dulk 1982) has yet to be overcome satisfactorily.

Type III-like bursts are interpreted as electron beams close to the site of the energy release in the corona (e.g., Benz et al. 1992). The relatively high frequency of these type III-like bursts, assuming that they are at $f \approx 2f_p$, implies electrons densities $\sim 10^{10}\,\mathrm{cm}^{-3}$. These bursts appear to be the most direct signatures of the energy release in solar flares. Some of the bursts propagate to higher frequency and some propagate to lower frequency, suggesting that the acceleration of the electrons occurs near a boundary between open and closed field lines. This is indicative of acceleration in a localized region of magnetic reconnection involving both open and closed field lines, analogous to that inferred for type I–III storms.

Another inference from type III-like bursts arises from the fact that it is difficult for radiation to overcome free-free absorption to escape from regions as dense as is inferred. This suggests that the radiation is generated in overdense regions and escapes initially into neighboring underdense regions in which it can be ducted to much greater heights before escaping freely. This suggests that the corona is highly inhomogeneous on a small scale, and supports other radio evidence for this, most notably from the depolarization of m-λ bursts (e.g., Melrose et al. 1995) and the directivity of type I emission (Bougeret, Steinberg 1977).

3. Flare models

Flare models differ primarily in the way energy is stored and released. In reviewing flare models, Sturrock (1980) discussed six specific models: the Gold-Hoyle model (Gold, Hoyle 1960), the Alfvén-Carlqvist model (Alfvén, Carlqvist 1967), closed current sheet models (Syrovatskii 1969), open field models (Carmichael 1964; Hirayama 1974), emerging flux models (e.g., Heyvaerts et al. 1977), and loop-flare models (Spicer 1977; Colgate 1978). To Sturrock's list one could add the discharge theory of Giovanelli (1946), the photospheric dynamo models (e.g., Sen, White 1972) and Alfvén wave models (e.g., Piddington 1974; Uchida 1987), in which the energy is stored in flow motions and wave fluxes, respectively, near the photosphere. Giovanelli's model is of historical interest because it stimulated criticism by Piddington (1953) and Cowling (1953), and this led Dungey (1958) to respond to Cowling's criticism by suggesting what we now recognize as the basic model for reconnection at an X-type neutral point. The Gold-Hoyle model requires a specific configuration of two neighboring current-carrying magnetic loops, with the currents parallel, leading to an attractive force between the loops ('like currents attract') and antiparallel axial magnetic fields which annihilate when the flux loops come together. This model is not usually considered as viable because the required combination of current and magnetic configuration is not found in flares. It is of interest as one of the few models in which the force between currents is taken into account explicitly; other examples are the Kuperus, Raadu (1974) model for prominences and the Anzer (1978) model for coronal transients.

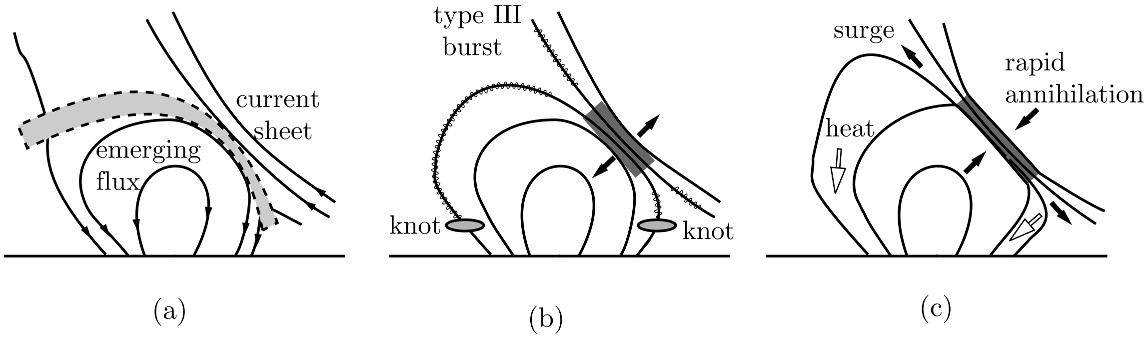


Fig. 2.. Emerging flux model for solar flares: (a) during the preflare phase the emerging flux begins to reconnect with the overlying field; (b) during the impulsive phase the onset of turbulence in the current sheet causes a rapid expansion and rapid energy release; (c) during the main phase the reconnection rate reaches a new steady state [after Heyvaerts et al. (1977)].

3.1. Open field models

An open field model for solar flares is illustrated in Figure 1. The important feature is that the field lines are drawn out by the solar wind so that there is a neutral line (or sheet) that separates regions of opposite magnetic polarity. In this case the magnetic energy is stored in stresses associated with the outflowing solar wind driven by coronal heating. This is favorable for the familiar Petschek (1964) model of magnetic reconnection in two dimensions. Such reconnection relaxes the magnetic stresses, converting some open field lines into closed field lines, moving the boundary (shaped like an inverted-Y) between the closed and open regions to a lower height. Two-dimensional models for reconnection require that there be an inflow toward the neutral line, transporting magnetic field of opposite polarity into a reconnection region. The reconnected field lines and hot plasma are ejected along the neutral line. The downward directed hot plasma can result in a shock wave when it impinges on the top of underlying closed magnetic structure (Forbes et al. 1989).

Sturrock (1980) discussed some of the difficulties associated with this model. One difficulty that he identified is that in order for the solar wind to draw out the magnetic field into an open structure, the gas pressure must exceed the magnetic pressure. Sturrock argued that this limits the height at which the cusp in the inverted-Y geometry can occur, and this is too high to account for compact flares. Stresses imposed by the solar wind in drawing out the coronal magnetic field into a more radial structure are thought to be relaxed in coronal mass ejections (e.g., Low 1994), and some flares are associated with coronal mass ejections. However, there is no compelling evidence for open magnetic field structures playing an important role in compact flares, for which the most plausible location for the storage of the energy release is in the flaring flux loop itself. A second difficulty raised by Sturrock is that the model is not compatible with homologous flares. A third difficulty arises from the radio data discussed above: the radio data suggest that the primary energy release occurs in closed field regions, involving only a small fraction of open field lines.

Open field models have received considerable support from Yohkoh data (e.g., Masuda et al. 1994). The X-ray data often show the cusp-like, or inverted-Y, geometry implied by the open field model. The appearance of a hard X-ray source above the closed loop structures evident in soft X-rays (Masuda et al. 1994) can be explained in terms of shock acceleration as the downflowing hot plasma is deflected at the interface with the closed-field region (Tsuneta, Naito 1998). Quantitatively the model seems capable of accounting for the energetics in a flare. A definitive test of an open field model involving reconnection high in the corona follows from the required inflow of plasma into the reconnection region; there is no compelling evidence that this occurs.

One can conclude that an open field model can account for an important class of flares in which the energy release appears to occur high in the corona. However, the difficulties raised by Sturrock remain, and suggest that the model in its simplest form is missing some important ingredient, for example, the reconnecting region might be part of a larger magnetic structure that is dynamically important (Uchida 1980). There is no direct evidence that an open field model is relevant to compact flares where the energy release appears to occur much lower in the corona.

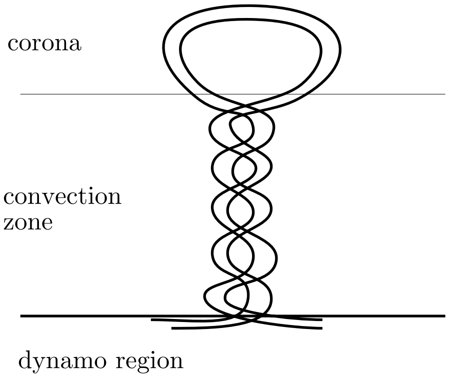


Fig. 3.. Flux tube extending from below the base of the convection zone into the corona; the current path is along the entire length of the flux tube.

3.2. Emerging flux models

Newly emerging magnetic flux appears in the form of magnetic bipoles, and as an emerging flux tube rises it can impinge on an existing magnetic structure in the corona. If the newly emerging flux has reverse magnetic polarity, and it impinges on existing magnetic structures with normal polarity, then field lines of opposite polarity are pushed together and magnetic reconnection should occur. This is the basis for the emerging flux model (e.g., Heyvaerts et al. 1977), as illustrated in Figure 2. In this case the magnetic reconnection is three dimensional, with the magnetic flux being transferred from one magnetic loop to another, which can lead to new magnetic connections between the footpoints. One simple model for the connectivity between footpoints, called magnetic charge topology (e.g., Longcope 1996), is based on treating the footpoints as magnetic monopoles. Despite the obviously unphysical nature of this model, it does provide useful insight into how flux can be transferred between footpoints in three-dimensional reconnection.

More recently there has been renewed interest in emerging flux models because of evidence that the emerging flux is pre-stressed. In fact, there has long been evidence that magnetic structures emerging from below the photosphere are already twisted (Weart 1972), and more recently the evidence (from vector magnetograms) has become compelling (e.g., Lites et al. 1995; Leka et al. 1996). One implication is that the magnetic energy stored in the corona is simply transported into the corona as the stressed magnetic flux loops rise up through the photosphere.

Another implication of the vector magnetogram data is that they involve a large-scale current flowing in the magnetic flux loop before it emerges from below the photosphere. This current flows from one footpoint to the other, with no systematic evidence for a return current in the corona. The direction of current flow relative to the magnetic field defines the handedness for the twist or the helicity of the magnetic field. Observationally there is strong evidence for a characteristic helicity (e.g., Rust, Kumar 1994), which is left hand in the northern hemisphere and right hand in the southern hemisphere, irrespective of the solar cycle. McClymont, Fisher (1989) argued that this current must close deep in the solar atmosphere, as illustrated in Figure 3, and presumably it is associated with the solar dynamo. An attractive feature of an emerging flux model based on such pre-stressed fields is that the energy budget is explained in a simple way: the ultimate source of the energy is the solar dynamo and the energy available in the corona is transported there by rising, current-carrying flux tubes. A specific version of the emerging flux model is discussed in the next section.

3.3. Current-interruption models

The Alfvén-Carlqvist model involves energy release due to current interruption. The coronal stresses are described in terms of a coronal current that flows from one footpoint to the other along the flaring flux loop, and closes deep in the solar atmosphere. The energy release is postulated to occur when a dissipation region is turned on in the solar corona and effectively stops the current flowing. The specific dissipation process invoked is a double layer. This model is amenable to a simple description in terms of an electrical circuit. The current, I, is assumed to be generated by an EMF, V, deep in the solar atmosphere, and prior to the flare to flow around a circuit with a resistance, $R = V/I$, and an inductance, L. During the flare an additional resistance, $R_c \gg R$, is assumed to be turned on in the coronal portion of the circuit. The power dissipated in the corona, $R_c I^2$, is identified as the power

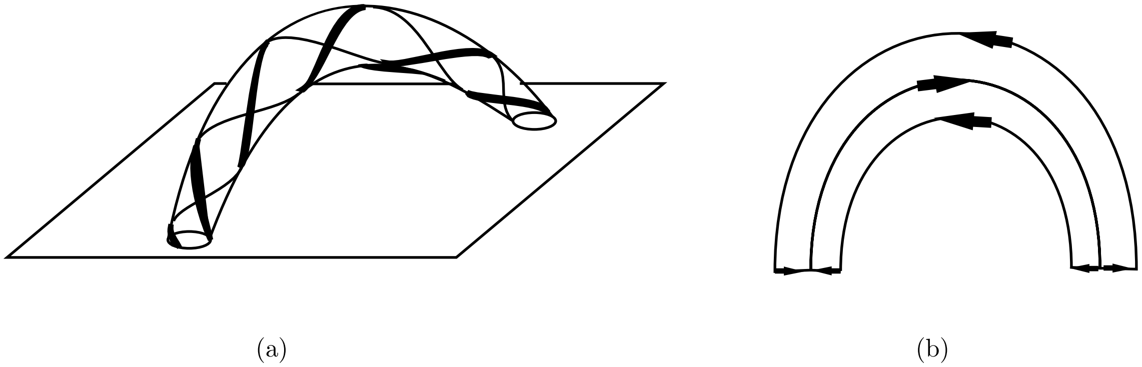

(a) (b)

Fig. 4.. (a) A twisted magnetic loop and (b) the associated current pattern (solid arrows) when the twist is assumed to be generated by a line-tied vortex motion in the photosphere.

released in the flare.

There are several major objections to this model. A basic objection is that it is inconsistent with an MHD description of the coronal and subphotospheric plasma. In particular, there is no Alfvén speed in the model, so that the speed of energy propagation around the circuit is infinite (technically it is the speed of light but as in a circuit made of wire the light propagation time around the circuit is neglected). This implies that all the magnetic energy stored around the circuit, and not just that in the coronal portion of the circuit, propagates into the dissipation region over the inductive time, $(R+R_c)/L \approx R_c/L$. This is inconsistent with the fact that magnetic stresses propagate at the local Alfvén speed in an astrophysical plasma. One can include a capacitance, C, in the circuit and identify the time $1/(LC)^{1/2}$ as the Alfvén propagation time around the circuit, but this does not correctly model energy propagation at the Alfvén speed. A related objection is that the underlying circuit model is valid only on a time scale long compared with the energy propagation time around the circuit (e.g., Melrose 1992), which is much longer than the time scale of a flare. A separate objection is that turning a dissipation region on in the corona causes part of the current to deviate around the dissipation region, with the net coronal current being unchanged (e.g., Melrose 1992), and this effect is precluded by the assumptions in the model.

For these and other reasons, a current-interruption model is untenable. However, the current-based model does raise an important point that is ignored in other magnetic-field-based models. This is that the boundary conditions need to treat the current correctly. An acceptable model should be consistent with both the magnetic (MHD) viewpoint and the current viewpoint, and the Alfvén-Carlqvist model is not consistent with the magnetic viewpoint. These points were the subject of a recent controversy (Parker 1996; Melrose 1996).

3.4. Flare-loop models

One feature of flare-loop models is the assumption that the magnetic energy is stored in the coronal magnetic field by photospheric (or subphotospheric motions) twisting or shearing the coronal magnetic field. The idea is that such motions cause the magnetic stresses to build up relatively slowly prior to a flare, with these stresses released explosively during a flare. However, this type of model is based on an unjustifiable photospheric boundary condition.

There has been a long tradition of treating the photosphere, or some other subphotospheric layer that plays the role of a lower boundary, as a resistive surface with a large inertia, and assuming that the coronal magnetic field is tied to this surface. This 'line-tying' assumption requires that the coronal currents close across the surface, as illustrated in Figure 4. However, this implies a current flowing across magnetic field lines, and the associated $\mathbf{J}\times\mathbf{B}$ force accelerates the plasma. Assuming this boundary condition at $t=0$, Wheatland, Melrose (1994) showed that the cross-field current propagates away below the photosphere at the Alfvén speed. The implication is that the line-tying boundary condition is valid only for times short compared with the Alfvén propagation time.

The line-tying assumption is valid during a flare because the Alfvén speed below the photosphere is relatively slow compared with the Alfvén speed above the photosphere. Let the Alfvén time be L/v_A for propagation of a disturbance across a region of size L at the Alfvén speed, v_A. The time scale of a flare, 10^2–10^3 s, is longer than the Alfvén time for a coronal magnetic loop, which is a few seconds. Hence, during a flare coronal magnetic stresses can be relaxed down to the photospheric boundary. As a result of the changed coronal stresses, a $\mathbf{J}\times\mathbf{B}$ force is imposed

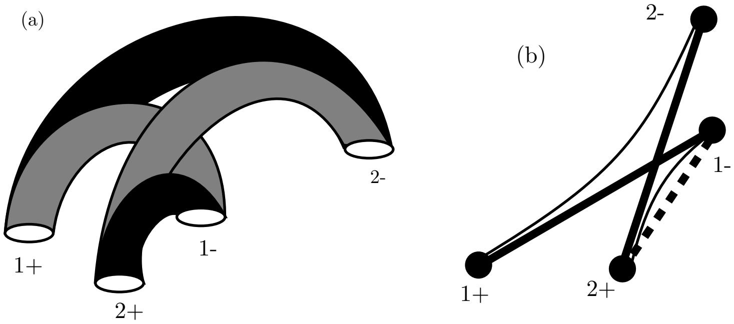


Fig. 5.. Idealized model for reconnection between two flux loops. (a) Initial magnetic flux loops (in gray) before reconnection plus additional flux loops (in black) resulting from reconnection. (b) Line drawing of same model projected onto the photosphere.

on the photosphere. However, due to the slow Alfvén speed below the photosphere, this cross-field current has insufficient time to propagate much deeper into the solar atmosphere so that it remains localized to the photospheric regions on the time scale of the flare. Thus line tying is a reasonable assumption on this time scale.

However, line-tying is not valid over the much longer time scales, of order a day or so, over which the coronal magnetic stresses are assumed to build up due to subphotospheric motions. On this time scale stresses can propagate between the photosphere and the bottom of the convection zone (McClymont, Fisher 1989). Suppose a slow twisting or shearing motion is imposed on a magnetic flux tube that extends from the base of the convection zone to the photosphere, through the corona and back to the base of the convection zone, as illustrated in Figure 3. On a sufficiently long time scale, specifically longer than the Alfvén propagation time from one end of the flux tube to the other, any such twisting or shearing applies to the entire flux tube. Line-tying at the photosphere artificially confines any imposed twist or shear to the coronal portion of the flux tube. However, this boundary condition is unjustifiable on the time scale of days over which the stresses are assumed to build up.

A model in which the coronal stresses are attributed to line-tying and photospheric motions implies that the currents must close entirely within the corona and this surface. If magnetic stresses were created in this way, then every coronal current would have a return current in the corona (e.g., Melrose 1991, 1996). Thus the model is inconsistent with vector magnetogram data which show that the current flows from one footpoint to the other (e.g., Leka et al. 1996).

It follows that models involving magnetic energy storage due to stresses imposed by photospheric or subphotospheric motions are unacceptable because they are based on an unjustifiable boundary condition, specifically, 'line-tying' at the photosphere over a time scale of many hours to days. Photospheric dynamo models are unacceptable for similar reasons, further compounded by other difficulties (Melrose, Khan 1989).

3.5. Alfvén-wave models

Alfvén wave models involve an energy flow into the flaring flux loop in the form of Alfvén waves during a flare (Piddington 1974; Uchida, Shibata 1988). An obvious requirement is that there be an actual or potential flux of Alfvén waves below the photosphere that becomes available to release energy in the flaring flux loop during a flare. It might be remarked that, assuming an adequate of Alfvén waves is available, its access to the corona is affected by the impedance matching between the flux tubes above and below the photosphere, and a turning on of a dissipation region in the flux tube in the corona can alter its impedance to match that required for Alfvén waves to propagate freely into the dissipation region. However, although this is an interesting model in principle, there is no clear evidence for an adequate flux of Alfvén waves to power a large flare.

4. A flare model involving large-scale currents

Observationally, there is strong support for an emerging flux model in which the emerging flux is already twisted. The suggests a model in which the energy available for release in a flare is transported into the corona as the current-carrying flux tube rises. There is no need to find an additional source of magnetic stress to set up a coronal current system; the coronal current system involves the currents already flowing in the emerging flux tubes, and the

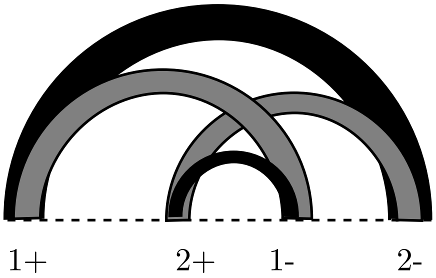


Fig. 6.. Two-loop reconnection model for collinear, overlapping flux tubes; it is energetically favorable for the two initial loops (in gray) to reconnect into a longer loop and a shorter loop (in black).

ultimate source of these currents is presumably the solar dynamo. A model that takes the current system associated with the twisted emerging flux into account and involves reconnection between two current-carrying flux loops is outlined here.

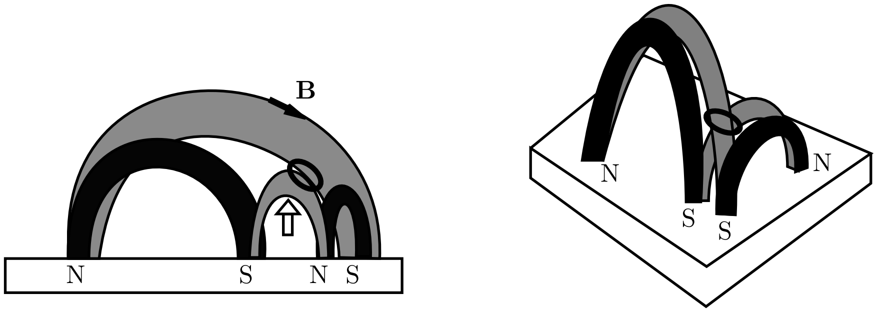
4.1. Reconnection between two current-carrying loops

The model involves a rising current-carrying flux loop impinging on a higher current-carrying flux loop so that the two intersect allowing magnetic flux and current to be transferred from one to the other (Melrose 1997; Hardy et al. 1998). An important ingredient in the model is the boundary condition at the photosphere, which needs to take account of the fact that the current at each footpoint has insufficient time to change during the flare. This implies that the appropriate boundary conditions during a flare are that neither the magnetic flux nor the current crossing the photosphere changes at any of the four footpoints of the two flux loops. In principle, magnetic energy can be released even in an isolated flux loop through a change in the current profile or path (Melrose 1992), but a more plausible type of model involves transfer of flux and current between two loops. In the model (Melrose 1997) it is assumed that a transfer of an amount $\Delta\Psi$ of magnetic flux is accompanied by a transfer of current ΔI, with the ratio $\Delta I/\Delta\Psi$ fixed by the characteristic value of the helicity. In this model the magnetic energy is effectively separated into two types. One is that associated with the magnetic fluxes which are defined to include only the vertical component of the magnetic field at the photosphere. This part of the magnetic energy is regarded as the counterpart of what is usually called the potential field and it is assumed not to change during a flare. The other part of the magnetic energy is that stored in the current system, and a reduction in this magnetic energy is identified as the energy released in the flare.

The model is indicated schematically in Figure 5. Initially there are two flux tubes, labeled 1 and 2, connecting footpoints labeled 1+, 1− and 2+, 2−, with magnetic fluxes Ψ_1, Ψ_2 and currents I_1, I_2. Transfer of $\Delta\Psi$, ΔI, changes the fluxes to $\Psi_1 - \Delta\Psi$, $\Psi_2 - \Delta\Psi$ and the currents to $I_1 - \Delta I$, $I_2 - \Delta I$, and creates two new flux tubes, labeled 3 connecting 1+ to 2−, and 4 connecting 2+ to 1−, each with fluxes and currents $\Delta\Psi$, ΔI. It is assumed that the reconnection proceeds if it is energetically favorable to do so, and the magnetic energy released is identified as the energy in the flare. Thus one needs to identify the change in the magnetic energy and determine the conditions under which there is a net reduction.

4.2. Favorable configurations for magnetic energy release

This model implies energy release only for favorable orientations of the two flux tubes. A particularly simple geometry (which is not directly relevant for flares) is one in which the four footpoint are collinear and such that the two flux loops are overlapping so that reconnection is possible. Suppose the footpoints are in the sequence 1+, 2+, 1−, 2−. In this case the sign of $\Delta\Psi$ and ΔI required to release magnetic energy is such that it is energetically favorable to form a flux loop connecting 1+, 2−, as illustrated in Figure 6. This suggests a way in which long flux loops connecting separate active regions may be formed by sequential reconnections involving ephemeral flux loops (Melrose 1997). More generally it is found that a favorable configuration for energy release is when two of the footpoints are close together, as illustrated in Figure 7. There is observational evidence that such a configuration is favorable for flares (Nishio et al. 1997; Hanaoka 1997). Quantitatively, a relatively modest current change $\Delta I \sim 10^{11}$ A suffices to provide an energy change of order $\sim 10^{24}$ J, which is adequate to account for the energy released in a modest to large flare. On the basis of this model there is another prediction that may be tested



(a) (b)

Fig. 7.. The configuration inferred by Nishio et al. (1997) for a flare; this configuration is favorable for maximum energy release in the two-loop reconnection model.

(Hardy et al. 1998): for flares that occur in parasitic geometries, the model implies a strong correlation between the energy released and the ratio of the currents in the interacting loops. Currents $\sim 10^{11}$ A are of order the present limit of resolution of vector magnetograms, and a further lowering of this observational limit significantly should lead to definitive tests of this model.

5. Discussion and Conclusions

Radio data provide information on flares that complements data at other wavelengths. Microwave data provide information on the suprathermal electrons accelerated in the flare and trapped in closed magnetic structures. Type III bursts show that there is magnetic access to open field lines from the acceleration region in a flare. Type III-like bursts suggest that the energy release site is in a relatively dense region, with electron number density $\gtrsim 10^{10}\,\mathrm{cm}^{-3}$. These radio data also indicate that the energy release process in flares is highly structured in space and time.

Of the various flare models that have been proposed, only two are considered viable here, an open flux model and an emerging flux model. Two other models are discussed critically. The Alfvén-Carlqvist models fails to take account of the fact that energy propagates at the Alfvén speed in a magnetized fluid, and this leads to a number of seriously misleading features in the model. Flare-loop models in which the energy is stored by twisting or shearing motions are based on an unjustified assumption: line tying at the photosphere over the time scale in which the magnetic stresses are assumed to be stored in the corona. Line tying is valid over the time scale of a flare, but is not valid over the longer time scale required for the postulated storage, in the sense that the stresses cannot be confined to the corona for the requires times of a day or so. There is now strong evidence, from vector magnetograms, in favor of an emerging flux model in which the emerging flux is already twisted and the energy available for release in a flare is stored in the associated current system. The energy released in a flare is transported into the corona in association with this current system as the twisted flux tube rises into the corona.

A specific model is reviewed in which a rising current-carrying flux loop impinges on an existing current-carrying flux loop leading to reconnection. Both magnetic flux and current are transferred together, with the ratio fixed by the characteristic helicity of solar magnetic fields. The reconnection forms two new flux loops. It is assumed that the reconnection proceeds if the magnetic energy associated with the final current system is less than the initial magnetic energy associated with the initial current system, with the energy difference identified as the energy released in a flare. When the flux loops are nearly collinear it is energetically favorable to form a longer and a shorter loop from two loops of intermediate length. Configurations favorable for a flare involve two loops at oblique angles, so that they have opposite polarity (but the same helicity), with two footpoints close together, and there is observational support for flares occurring in such configurations.

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