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Solar Flares: Current Dissipation or Magnetic Annihilation?*

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Abstract

Solar flares involve the explosive release of energy, 10^{22}–10^{25} J in 10^2–10^3 s, in the solar corona. A substantial fraction of this energy goes into energetic ($\approx$10 keV) electrons, and these produce most of the familiar signatures of flares, such as Hα emission, hard X-ray bursts and type III radio bursts. Solar flares occur in magnetic flux tubes in which the fields are highly stressed with associated large currents, $I \gtrsim 10^{12}$ A, flowing into the corona. Despite the enormous variety of detailed data on solar flares, there is no wide consensus on the essential theoretical ingredients in an acceptable flare model. Since the first detailed flare models were proposed in the 1940s, there have been two competing types: models based on an electric-current viewpoint and models based on a magnetic-field viewpoint. In principle these are equivalent, but in practice they have led to different and seemingly incompatible models. In this paper the theory of solar flares is reviewed, comparing and contrasting these two viewpoints. It is argued that all models, as presently formulated, contain serious deficiencies. One feature that is unsatisfactory is the treatment of energy propagation into a flare kernel. A specific model for such energy propagation is outlined.

1. Introduction

Solar flares are the most energetic events that occur in the solar system. Flares, which are explosions that occur in magnetic loops in the solar corona above magnetically active regions, are of practical importance due to their direct effect on the Earth: this includes interference with radio communications (due to their effect on the ionosphere) and dangers to manned space flights (due to the flux of solar energetic particles released by a large flare). The energy release occurs in a so-called flare kernel, located in the relatively hot (10^6–10^7 K), low density (10^{16}–$10^{18}\,\mathrm{m}^{-3}$) plasma in the solar corona (e.g. Švestka 1976). In this paper the physical ideas proposed for the interpretation of flares are discussed critically. It is argued here that, despite over three decades of theoretical work, the theory of solar flares remains in an unsatisfactory state. An acceptable model for an explosive event such as a flare should contain the following features:

(1) an identification of the ultimate source of the energy,
(2) a mechanism for transport of energy from its source to the energy release site,
(3) an energy storage mechanism that allows a metastable configuration,

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(4) a mechanism that leads to the energy release, and
(5) a trigger for an instability that allows energy release to become effective.
There is wide (but not universal) agreement only on feature (3): the energy released in a flare is stored in the coronal magnetic field. More specifically, the energy is stored in a nonpotential component of the coronal magnetic field or, equivalently, in a coronal current system. (Here a potential magnetic field means a field due to currents flowing in the denser regions of the solar atmosphere below the corona.) It is assumed that in a flare some of this stored magnetic energy is released. An implication is that as the result of a flare the magnetic field in the corona should become closer to a potential field, with an associated reduction in the electric currents in the corona. However, there is no direct observational support for this, and there is indirect evidence against it from the existence of homologous flares, which are essentially identical flares occurring at the same locations. Moreover, as discussed below, there are theoretical difficulties with this idea of relaxation of a stressed magnetic field and reduction in the current: in essence, an argument based on Lenz's law suggests that it cannot occur, at least in the simple sense usually assumed.

Flare models may be separated into those based on an electric-current viewpoint, called circuit models here, and those based on a magnetic-field viewpoint, called coronal storage models here. In the literature on flares these two viewpoints are often regarded as competing, and there are few examples where a synthesis of the two has been attempted. However, they should be regarded as complementary. For example, on the one hand, a circuit model readily allows one to describe coupling between remote parts of the circuit, and the existence of such coupling is obscured when the magnetic-field viewpoint is adopted; on the other hand, a coronal storage mode readily allows one to include the magnetohydrodynamic (MHD) coupling between the plasma and the magnetic field, and the neglect of such coupling is a major weakness in circuit models. An acceptable flare theory should incorporate the important features of both types of model. To illustrate how the two viewpoints come into conflict, consider feature (1) above. From the magnetic-field viewpoint one seeks to identify motions that lead to twisting or shearing of the coronal magnetic field, and so one identifies the ultimate source of the energy as a fluid motion that can twist or shear the field. From the electric-current viewpoint one seeks to identify the dynamo that generates the current. These two viewpoints are not in conflict in principle because a dynamo in a magnetised fluid is associated with relative motions between regions that are threaded by the same magnetic field lines. However, in practice those that adopt the magnetic-field viewpoint concentrate on the motions that can be seen on the solar surface, and so attribute the storage of magnetic energy to twisting or shearing by subphotospheric motions, and those that adopt the electric-current viewpoint tend to attribute the current to the known solar dynamo, which must be much deeper in the solar atmosphere. These two possible ultimate sources of the energy are different and the differences have important implications for the energy storage and release. As a result, models based on these two viewpoints are not readily compatible.

Another notable difference between the two types of model concerns the energy release mechanism. From a magnetic-field viewpoint one describes the energy release in terms of *magnetic annihilation.* Generally, magnetic fields are frozen in to plasmas, such that magnetic field lines may be regarded as comoving with the fluid velocity. This precludes any change in the magnetic topology, and hence any significant release of magnetic energy. Significant release of magnetic energy must involve *magnetic reconnection* at specific sites where the frozen-in condition breaks down and allows the magnetic topology to relax from a more stressed to a less stressed configuration. From an electric-current viewpoint one regards energy release in terms of *current dissipation.* Locally this requires some form of resistivity, η, such that the power released per unit volume is ηJ^2, where $\mathbf{J}$ is the current density. Integrated over the energy release site, this implies a power RI^2, where R is the corresponding resistance and I is the total current. The classical resistivity (also called the Spitzer resistivity, due to Coulomb interactions between electrons and ions) of the coronal plasma is negligible in the present context, and effective energy release requires an anomalous form of resistivity in regions of high current density. In principle these two energy release mechanisms are different aspects of the same phenomenon: negligible resistivity implies the frozen-in condition, and magnetic reconnection occurs only in resistive regions where the magnetic field lines diffuse relative to the plasma flow lines. However, in practice the energy dissipation mechanisms in the two types of model are described in quite different ways: in terms of magnetic reconnection and annihilation, and in terms of anomalous resistivity or potential double layers, respectively.

It is argued here that one specific aspect that is not treated in an acceptable way in either magnetic-storage or circuit models is energy propagation into the flare kernel, that is, feature (2) above. In magnetic models the only relevant form of energy propagation included is the flow of frozen-in magnetic flux at the fluid velocity, and in circuit models energy propagation occurs on the inductive time scale. Neither of these is acceptable in explaining the actual energy propagation into a flare kernel during a flare: the former neglects an essential energy inflow from remote parts of a circuit, and the latter is inconsistent with MHD theory.

A review of some relevant observational aspects of solar flares is given in Section 2. Flare models based on the electric-current and the magnetic-field viewpoints are reviewed in Sections 3 and 4, respectively, loosely following their historical developments. Emphasis is given to criticism of the early models, as most of these criticisms remain relevant today and underlie some of the objections to contemporary models. A model for energy propagation into a flare kernel is presented in Section 5. Some remarks on future directions of flare theories are presented in Section 6.

2. Observations of Solar Flares

In this section a brief review of the properties of flares is presented. Further details may be found in extensive reviews of the literature (e.g. Švestka 1976; Priest 1982; Dulk *et al.* 1985). First, however, it is appropriate to describe some relevant properties of the solar atmosphere.

The Solar Corona

The photosphere is the visible disk of the Sun, above it is the chromosphere, and above the chromosphere is the solar corona. The corona is much hotter ($>10^6$ K) than the underlying regions, cf. Fig. 1. The corona is not gravitationally bound, and it expands with speed increasing steadily with radial distance, eventually

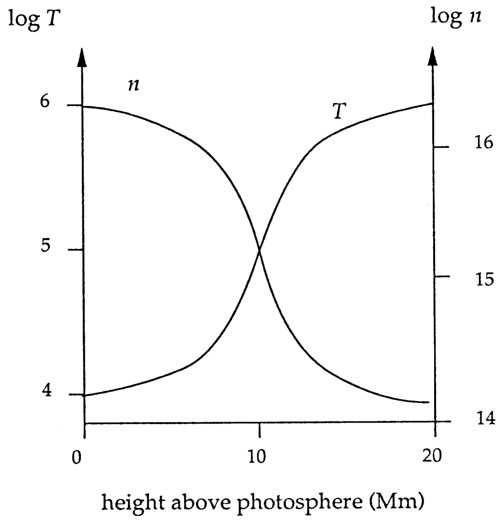


Fig. 1. The logarithm of the temperature, T, in kelvin and the electron number density, n, per cubic metre plotted as a function of height above the photosphere.

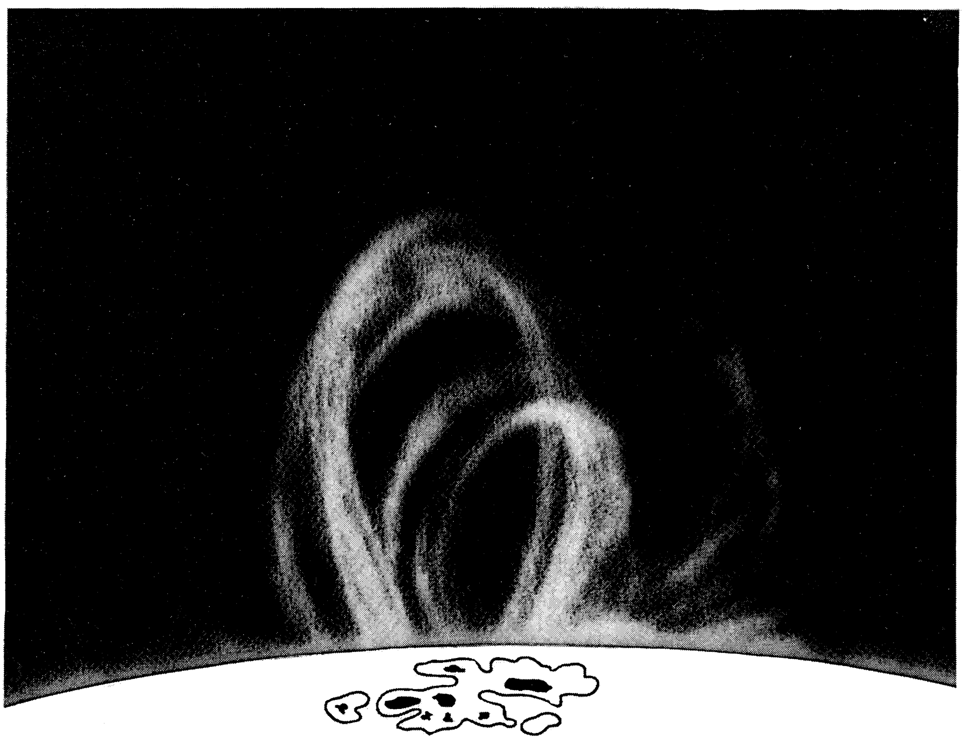


Fig. 2. Nested magnetic flux tubes shown over a complex sunspot region (Bray *et al.* 1991).

becoming the solar wind. The structure of the corona is dominated by the magnetic field, which emerges through the photosphere in magnetic pores, where the field is relatively strong ($\approx 0 \cdot 15$ T). The magnetic field emerges preferentially in relatively long-lived, so-called active regions. A given active region may contain several sunspots. Spots emerge in pairs and form so-called bipolar magnetic configurations. A pair of spots of opposite polarity is separated on the solar surface by a neutral line where the vertical component of the field vanishes. Magnetic loops connect regions of opposite polarity across a neutral line. Flares occur preferentially in complex magnetic regions with newly emerging magnetic flux.

The solar corona itself may be regarded as consisting of closed and open magnetic regions. The magnetically closed regions consist of collections of nested magnetic flux tubes, overlying magnetically active regions, and connecting different active regions, cf. Fig. 2. Different flux tubes have different temperatures, densities, lengths and magnetic fluxes.

The solar corona must be heated by a non-radiative flux of energy from below the photosphere, but the details are still unclear. Part of the extra heat is transported back to the chromosphere by thermal conduction, and part is transported outward by the solar wind. An increase in the heating rate causes an increase in the rate that cool ($\lesssim 10^4$ K) plasma boils off the chromosphere to become coronal plasma, and a decrease in the heating rate causes coronal plasma to condense back to chromospheric temperatures. (Such boiling off is referred to either as evaporation or as ablation.) Heat transport into some higher regions, near the top of an arcade of loops, can sometimes be ineffective, so that coronal condensations of $\lesssim 10^4$ K plasma form. These are seen as dark *filaments* on the solar disk, or as *prominences* on the solar limb, cf. Fig. 3. Filaments align along magnetic neutral lines and are supported magnetically by an arcade of loops. Filaments can erupt and move outward through the corona as coronal mass ejections (CMEs). There is an association between CMEs and flares, but the association is not adequately understood: it is not one-to-one and it is not a simple cause and effect.

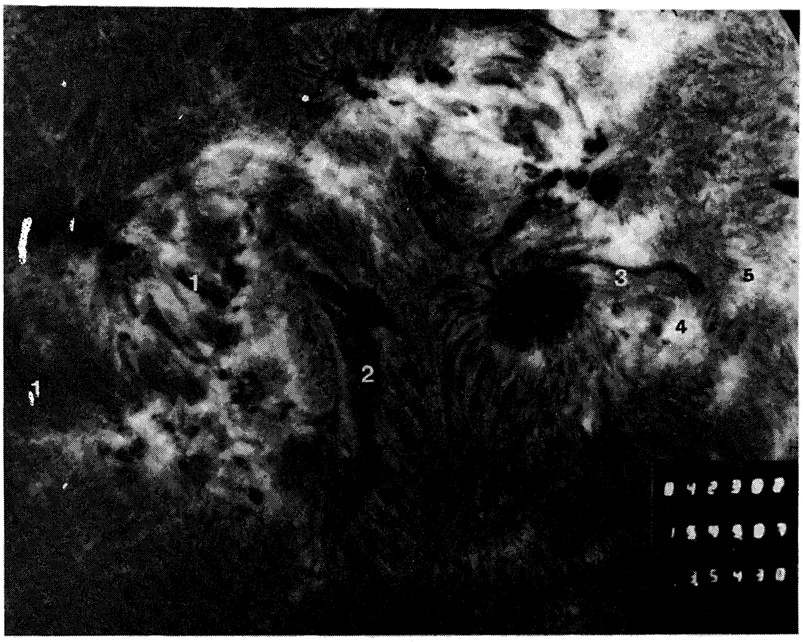


Fig. 3. An active region showing (1) arches, (2) and (3) filaments, and (4) and (5) regions of opposite magnetic polarity (Zirin 1988).

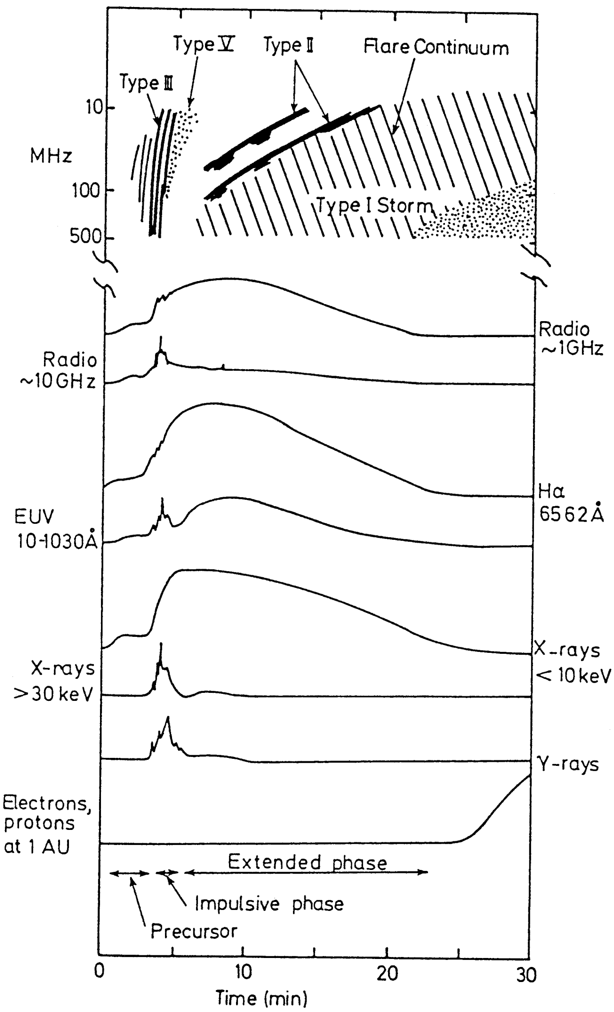


Fig. 4. The impulsive phase of a flare appears as a spike of emission lasting for a few minutes and is most prominent in type III bursts, Hα and hard X-rays (Dulk *et al.* 1985).

Flare Observations

The earliest observations of a flare to be reported in the scientific literature were of a flare in 1859 seen in white light. White-light flares visible to the naked eye are rare, occurring about once per solar cycle of 11 years. Systematic observation of flares did not begin until early this century, after the invention of the spectroheliograph allowed observation in Hα. Flares are classified according to the area that brightens in Hα, and this area is roughly proportional to the energy released in the flare. The frequency of occurrence of flares increases steeply with decreasing total energy released, so that the integrated energy is dominated by the weakest flares. The smallest flares seen in Hα also produce type III radio bursts and hard X-ray bursts; type III bursts and bright points in hard X-rays are now regarded as the basic signatures of a flare. Type III bursts from flares are due to beams of $\approx$10 keV electrons escaping outward through the solar corona; these electrons are observed regularly by spacecraft in the interplanetary medium. The hard X-ray bursts are produced by $\approx$10 keV electrons precipitating into the denser regions of the chromosphere. The precipitating electrons lose their energy through Coulomb interactions with ions, and part of the energy loss is through bremsstrahlung emission. The cross section for bremsstrahlung has a peak, as a function of energy of the emitted photon, at an energy approximately equal to the initial kinetic energy of the electron. It is found that an electron with energy ε has a probability of about 10^{-5} of emitting an X-ray photon with energy $\approx\varepsilon$. Hence, hard X-ray emission (energies $\approx$10 keV) provide a direct signature of the precipitating electrons, and the observed photon flux at the Earth may be used to estimate the precipitating electron flux directly. Moreover, in situ observations of the electrons that generate type III bursts in the interplanetary medium show that they have the energies expected on the basis of the hard X-ray data, supporting the suggestion that both the hard X-ray emitting electrons and the type III emitting electrons originate from the same population of accelerated electrons.

Other phenomena are observed only for the more energetic flares. A large flare has several distinguishable phases, cf. Fig. 4. The primary energy release occurs in the so-called impulsive phase, which is characterised by the brightening in Hα, hard X-ray bursts and type III bursts. The discussion here concentrates on this phase. Besides Hα, hard X-rays and type III bursts, a variety of other phenomena are associated with the impulsive phase of a large flare. These include the following (e.g. Wild and Smerd 1971; Švestka 1976; Dulk *et al.* 1985):
(1) a shock wave that produces type II radio bursts, that can be seen as a Moreton wave as its intersection sweeps across the chromosphere, and that can be observed directly in the interplanetary medium,
(2) microwave bursts due to $\lesssim$100 keV electrons trapped in magnetic loops near the flare site,
(3) radio spike bursts (e.g. Benz 1986) thought to be produced by the primary electrons close to the point of their acceleration,
(4) soft X-ray bursts due to hot, $\gtrsim 10^7$ K, plasma rising into the corona, having been ablated from the chromosphere due to excess heating by the precipitating electrons,
(5) gamma-ray lines produced by $\gtrsim$40 MeV per nucleon ions and a gamma-ray continuum produced by relativistic electrons, both accelerated within a second or so of the onset of the flare.
In addition to these and other phenomena in the impulsive phase, large flares are often associated with CMEs and with solar energetic particle events.

Flares are classified in a variety of ways. One classification is that in terms of the area that brightens in Hα. Another classification is into thermal and nonthermal flares. In thermal flares the electrons accelerated in the impulsive phase have a characteristic temperature, typically $\lesssim 10^8$ K $\approx$ 10 keV, and in nonthermal flares the electron spectrum cannot be described in terms of a Maxwellian distribution, and is better approximated by one or more power laws in energy. Flares are also classified according to their geometry. Large flares can have a characteristic

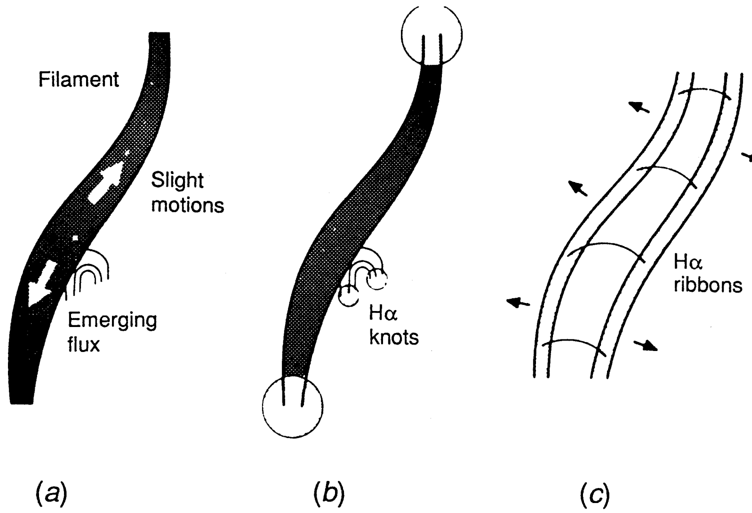


Fig. 5. An idealised model for a two-ribbon flare illustrated schematically. In (a), a newly emerging bipolar region impinges on a filament, and (b) Hα brightenings occur at the footpoints of the newly emerging flux loop. In (c) the filament has lifted off and Hα ribbons have formed along the footpoints of the magnetic arcade that initially supported it (Sturrock 1980).

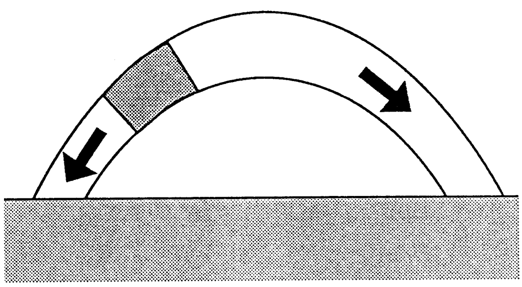


Fig. 6. Energy released in a flare kernel, indicated by the shaded region, in a magnetic flux tube. The energy goes into energetic electrons, most of which precipitate, indicated by the solid arrow, producing hard X-rays, optical and UV radiation, and heat the ambient plasma so that hot plasma rises into the corona and emits soft X-rays.

two-ribbon geometry, as illustrated in Fig. 5. Such flares are associated with eruption of a filament, and the two ribbons trace out footpoints of the flux tubes that thread the filament. There are also compact flares that appear to occur in a simple geometry, with no evidence for an associated filament.

Properties of Flares

The energy release in a flare occurs in a flare kernel, as illustrated schematically in Fig. 6. A large fraction, estimated to be $\gtrsim 20\%$ (Duijveman *et al.* 1982), of the energy goes initially into electrons with energies in the range $\gtrsim 10$ keV. In the impulsive phase of a large flare, the power released is typically in the range 10^{21}–10^{22} W; this lasts for 10^2–10^3 s giving a total energy of 10^{23}–10^{25} J. (This does not include the kinetic energy of a CME, which can be an order of magnitude larger.) The electrons precipitate into the chromosphere at a rate that can exceed $10^{36}\ \mathrm{s}^{-1}$, with up to 10^{39} electrons precipitating during the impulsive phase. This number may exceed the number of electrons initially in the flare kernel; however, this does not pose an insurmountable problem because an upward flow of cold electrons from the chromosphere is required to maintain current balance, and the electrons in this return current can resupply those lost from the flare kernel.

The onset of a flare is very sudden, and can occur on a time scale as short as can be resolved ($\lesssim$100 ms). There is evidence from time variations in hard X-ray and microwave bursts that subsequent acceleration of electrons varies on several time scales, down to the shortest that can be resolved.

Magnetic Structures and Current Systems

As already stated, flares tend to occur near neutral lines in magnetically active regions, especially where new magnetic flux is emerging from below the photosphere into an existing magnetically complicated structure. They also favour regions where the magnetic field is strongly sheared (e.g. Machado *et al.* 1988), as indicated by the orientation of spicules, which are bright local protrusions of chromospheric plasma into the corona along field lines. Strong shearing implies a large current flowing along coronal magnetic field lines. The complete vector magnetic field can be estimated from observations of all three Zeeman components, and given the three components of the magnetic field, one may use the integral form of $\mathbf{J} = \mathrm{curl}\,\mathbf{B}/\mu_0$ to estimate the current flowing into the corona (e.g. Moreton and Severny 1968; Hagyard 1989; Canfield *et al.* 1991). There is observational evidence that flare kernels do correlate with regions where large currents ($\gtrsim 10^{12}$ A) flow into the corona (e.g. Lin and Gaizauskas 1987). The observations imply that the currents flow up on one side of the neutral plane and down on the other. As discussed below, this appears incompatible with flare models in which the current, or the associated shearing, is produced after the magnetic field has emerged from below the photosphere.

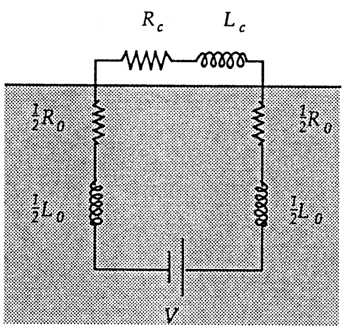


Fig. 7. A circuit model, with the shaded area denoting the subphotospheric region. The coronal resistance is assumed to increase sharply at the onset of a flare.

3. The Electric-current Viewpoint

The earliest models for the energy release in solar flares were based on ideas closely related to a circuit model, as illustrated in Fig. 7. In its simplest form, the idea is that a current, I, flows in the energy release site, and dissipation occurs there due to some effective resistance, R, giving a power RI^2. By Ohm's law, there is a potential drop Φ across the dissipation region, and this potential is available to accelerate fast particles; in modern language, runaway electrons are produced. The earliest model based on such ideas was criticised in detail, and fell into disfavour. However, the arguments both for and against these ideas remain relevant today. Here the ideas are introduced in a roughly historical sequence, with the relevance to contemporary ideas mentioned at each stage.

Giovanelli's Discharge Theory

In a series of papers Giovanelli (1946, 1947, 1948, 1949) developed a 'discharge theory' for solar flares. The theory is based on two ingredients. In terms of contemporary terminology, these are that (a) electrons can run away in an electric field that exceeds an appropriate threshold, and (b) relative fluid motions can lead to parallel electric fields that satisfy the requirement for such runaway. Giovanelli envisaged the acceleration occurring in the chromosphere, from where the Hα emission originates, whereas it is now accepted that the energy release occurs in the corona, and the chromospheric emission is a secondary phenomenon.

Giovanelli argued that if there is a parallel electric field of sufficient strength, then electrons can overcome the slowing down effect of collisions and be accelerated to high energy. [This idea became familiar in the plasma physics literature as 'runaway' acceleration about a decade after Giovanelli's work (Dreicer 1959, 1960).] The threshold electric field required in Giovanelli's theory is $E \approx 1\ \mathrm{V\,m^{-1}}$ (Cowling 1953). The parallel electric field is attributed to two regions in a magnetised plasma that (a) are in relative motion and (b) are linked by a magnetic field line. There is then a potential drop along this field line. The electric field is determined by $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$, where $\mathbf{v}$ is the relevant fluid velocity. By way of illustration, for a relative motion at $v = 10^3\ \mathrm{m\,s^{-1}}$, which is typical of photospheric motions relative to the magnetic flux tubes, and a field $B = 10^{-1}$ T, the electric field is $E = 10^2\ \mathrm{V\,m^{-1}}$, which is well above Giovanelli's threshold field, so that one expects runaway to occur. Despite the arguments against it, as discussed below, runaway acceleration has remained a possible ingredient in flare theories and continues to be invoked in contemporary theories (e.g. Holman 1985).

Cowling's Criticisms of the Discharge Theory

Cowling (1953) criticised the discharge theory on two grounds. Both criticisms are based on regarding the flow of electrons as an electric current, and both remain relevant today.

One criticism is that the region in which the current flows must be very narrow. Cowling estimated a thickness of 5 m, and remarked that this 'cannot by any stretch of the imagination be regarded as a possible thickness of the flare layer.' A more recent version of the argument is as follows (e.g. Chiuderi 1981, 1983; Melrose and McClymont 1987). Suppose that the total current, $I = AJ$, is fixed, where A is the cross section of the current channel and J is the current density. The power dissipated per unit volume is ηJ^2, where $\eta = 1/\sigma$ is the electric resistivity and σ the conductivity of the plasma. The total power released in the flare volume, $V = A\ell$, where ℓ is the length along the current lines, is then RI^2 with the resistance given by $R = \eta\ell/A$. The classical resistivity can lead to a moderately large resistance only for a very small value of the cross-sectional area, A, and a correspondingly high current density for a fixed current $I = AJ$. However, to account for the observed power release in terms of the classical resistivity requires a current density that is so high that it involves electrons streaming relative to ions at in excess of the ion sound speed (e.g. Melrose and McClymont 1987); such a current is unstable to a current instability that causes the resistivity to increase greatly, which is referred to as *anomalous resistivity*. One is forced to conclude that the current channels in which the dissipation actually occurs must be microscopically thin compared with a coronal flux tube. Both current filamentation into thin channels and the onset of some form of anomalous resistivity are required to account for the power released (e.g. Chiuderi 1981, 1983; Melrose and McClymont 1987).

Cowling (1953) emphasised the point concerning a microscopically thin current channel (the concept of anomalous resistivity is much more recent) and argued that this invalidated Giovanelli's model. Although Cowling (1953) presented this argument as one against the discharge theory, it is more general. In fact it is an argument that *all* forms of current dissipation or magnetic annihilation require that the current flow in a narrow channel with a high current density. This should not be regarded as an argument against any specific model, but rather as imposing the requirement of thin current channels on *any* model for a solar flare.

The other argument presented by Cowling (1953) against the discharge model is that any process that tends to set up a current is strongly opposed by the plasma, as implied by Lenz's law. As a consequence, the required electric field should be shorted out so that no change occurs to the net current. In circuit language, the argument can be expressed in terms of the inductive time scale for a circuit. Let L be the inductance of the circuit in which the current flows: I cannot change significantly on a time scale shorter than the inductive time, L/R. Cowling concluded that 'a discharge due to increased conductivity takes too long to initiate.' More recent authors have reached the same conclusion (e.g. Hoyng 1977; Spicer 1983; Holman 1985). However, the implications of this conclusion on flare models is still not widely appreciated. It implies that the *total* current flowing through the corona cannot change substantially as the result of a flare. On the other hand, the language used in describing flare models tends to suggest the contrary; for example, 'current dissipation' and 'current interruption' tend to suggest that the current decreases, and 'magnetic annihilation' tends to suggest the reduction of the current that produces the nonpotential magnetic field. The argument that currents can change only on the inductive time scale, and that this is longer than the time scale for energy release in a flare, seems to be a criticism of most contemporary flare models.

Dungey (1958) responded to Cowling's criticisms and defended the discharge theory. Concerning the small thickness of the dissipation layer, Dungey pointed out that there is no observational evidence against dissipation in small regions. An implication is that dissipation must occur in many small localised regions, so that dissipation on a macroscopic scale should be regarded as a sum over very many microscopic dissipation events. Dungey (1958) also accepted Cowling's argument related to Lenz's law. However, Dungey argued that the electric field required in the discharge theory could be set up near a neutral point in the magnetic field, as illustrated in Fig. 8. Thus, according to Dungey, one might expect magnetic energy release to be effective near a neutral point. This became, and remains, the most widely favoured mechanism for energy release in flares, and is now referred to as magnetic reconnection. New magnetic field lines can be created or destroyed only at (X-type or O-type) neutral points, and the presence of an X-type neutral point (in the magnetic field components in one plane) is an essential ingredient in all magnetic annihilation or reconnection mechanisms.

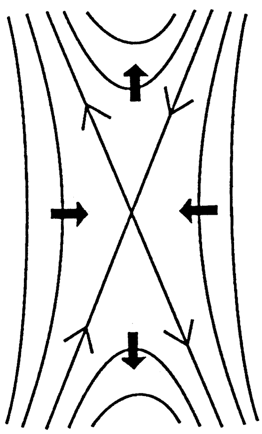


Fig. 8. An X-type neutral point of the form suggested by Dungey (1958). The solid arrows indicate the direction of plasma flow when reconnection occurs.

The Available Potential Drop

One other aspect of this earlier discussion that warrants further investigation concerns the role of a parallel potential drop that can appear as a result of reconnection. For example, Dungey (1958) remarked that it is well known that potentials of order 10^{10} V are available due to footpoint motions, and similar remarks were made by Sweet (1958) and much earlier by Swann (1933). An interesting implication is that when reconnection occurs, the reconnecting magnetic field lines are likely to be at different potentials, so that the potential difference between the field lines suddenly appears as a parallel potential drop along the reconnected field line. The implications of this do not seem to be considered in contemporary flare theories based on magnetic reconnection.

The Current Interruption Model

From the mid 1950s the main emphasis in flare theory shifted to the alternative magnetic viewpoint, as discussed below. However, models based on the current viewpoint continued to be pursued, especially by a group associated with Alfvén.

A *current interruption* model was proposed by Jacobsen and Carlqvist (1964) and developed further by Alfvén and Carlqvist (1967). The central idea is that the energy release in a flare may be regarded as analogous to the energy release when a circuit is shorted. In a short-circuit a large resistance is switched on in a circuit carrying a current, and the inductive (magnetic) energy stored around the circuit is dumped into the resistance. This model is amenable to a description in terms of circuit parameters (e.g. Boström 1974; Alfvén 1977), and is the archetypal *circuit model*. Classical resistivity is inadequate for the short circuit and the dissipation process was assumed to be due to a potential double layer (e.g. Carlqvist 1969; Raadu 1989).

Cowling's two criticisms also apply to the current interruption model. To overcome the first of these criticisms one needs to appeal to a current flowing in many narrow channels. A variant on the model involves many weak double layers in series along many current channels in parallel (Khan 1989). As already remarked, the argument related to Lenz's law seems to exclude the sudden change in the current implied by a literal interpretation of 'current interruption'. This point is discussed further below.

Deficiencies with Circuit Models

There is a further criticism that applies to any circuit model for a flare. This is particularly the case for models that involve only a resistance, R, and an inductance, L. There is then only one time scale, L/R, in the model. Consider the energy propagation speed in such a model. The only speed that can be identified in the model is $v_0 = \ell/(L/R)$. The dependence $L = \mu_0\zeta\ell$, where ζ depends only on the current profile, implies that v_0 depends only on the total resistance, R, of the circuit. The implication that energy propagates at v_0 in any circuit is incompatible with the seemingly compelling arguments that magnetic energy cannot propagate faster than the Alfvén speed, v_A, in a magnetised plasma. This incompatibility becomes slightly less clear-cut if a capacitance, C, is included in the circuit, such that the time $(LC)^{1/2}$ is identified as the Alfvén propagation time ℓ/v_A (e.g. Ionson 1985). However, this modification only allows v_A to be included as a parameter in the model, and it does not allow propagation of energy at v_A. A more general circuit model, involving transmission lines, is required to allow propagation of Alfvén waves (e.g. Scheurwater and Kuperus 1988). The major modification required to allow energy propagation at the Alfvén speed has not been included in any existing circuit model for a flare. Consequently, existing circuit models are incompatible with MHD theory in that they do not allow magnetic energy to propagate at the Alfvén speed.

4. The Magnetic Annihilation Viewpoint

Following the criticisms of the discharge model, the emphasis in the modeling of solar flares turned to magnetic annihilation models. Technically, this involves only a change in viewpoint—from the current system to the magnetic field that it generates. However, the constraints imposed by the presence of a highly conducting medium make it conceptually difficult to relate these two viewpoints.

Gold and Hoyle's Model

An early model for magnetic annihilation was proposed by Gold and Hoyle (1960), cf. Fig. 9. The basic idea is that if two neighbouring flux tubes carry currents in the same direction, then the current–current interaction provides an attractive force between them. If the magnetic fields in the two flux tubes are in opposite directions, then when the two flux tubes come together the magnetic fields annihilate, releasing magnetic energy. The annihilation actually involves magnetic reconnections in which one magnetic field line from each flux tube reconnects, as illustrated in Fig. 9.

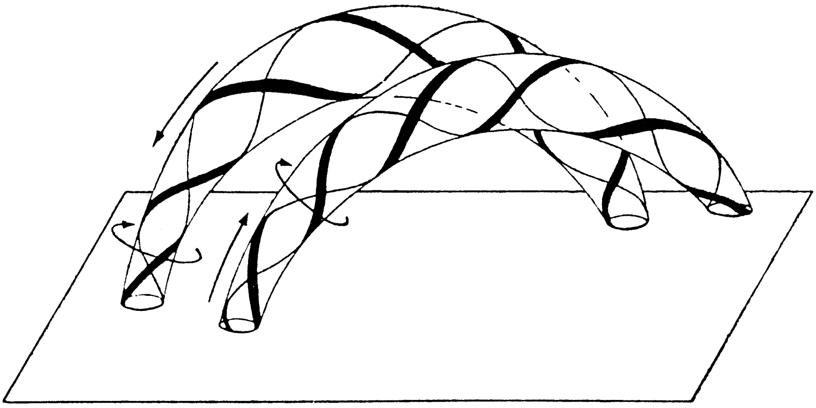


Fig. 9. Gold and Hoyle's model for a solar flare. The arrows indicate the directions of the axial and azimuthal magnetic fields in the two flux tubes. The currents, not shown, are similarly directed so that the two flux tubes are attracted to each other.

A notable feature of the model of Gold and Hoyle is that a magnetic interaction between two different current-carrying magnetic loops is invoked. In the contemporary solar physics literature it is usually assumed, albeit implicitly, that flux tubes are magnetically isolated from each other. This requires that there be a surface current on the flux tube that confines the magnetic field to the interior of the flux tube, as in a solenoid. If the flux tube carries a net current, then by implication there must be a neutralising, equal and opposite, surface current in order for the interior current to produce no magnetic field outside the flux tube. It is only in the absence of such a neutralising current that the magnetic interaction envisaged by Gold and Hoyle (1960) can occur. There are relatively few solar models that invoke such current–current interactions. Two other examples are the model for a filament of van Tend and Kuperus (1978), and the model for a coronal mass ejection of Anzer (1978).

In circuit language the magnetic interaction between the two flux tubes in the model of Gold and Hoyle (1960) may be described in terms of a mutual inductance between two circuits representing the two flux tubes. The circuit description involving mutual inductances has been given relatively little attention (cf. Spicer 1982; Martens 1986 however), although it is clearly the simplest way to introduce a coupling between two otherwise unrelated current-carrying systems.

The Rate of Magnetic Reconnection

Once the magnetic viewpoint is adopted, one refers to magnetic energy dissipation, rather than to current dissipation, and one describes the changes in the topology of the magnetic field in terms of magnetic reconnection. Early reviews of theories based on magnetic reconnection were by Parker (1963) and Sweet (1969). As emphasised by Dungey (1958), reconnection occurs only at special sites corresponding to magnetic neutral points.

A major difficulty with early models (e.g. Sweet 1958) concerns the speed at which reconnection can occur. From Maxwell's equations, neglecting the displacement current, and Ohm's law in the form $\mathbf{J} = \sigma[\mathbf{E} + \mathbf{v} \times \mathbf{B}]$, one obtains an equation for the evolution of the magnetic field:

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{curl}\,(\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}\,. \tag{1}$$

The first term on the right-hand side describes the effect of transport of magnetic field lines frozen into plasma moving with velocity $\mathbf{v}$, and the final term describes diffusion of the magnetic field lines. For magnetic reconnection to occur, oppositely directed field lines need to diffuse together and annihilate, releasing the magnetic energy. According to (1), the time scale required for diffusion over a characteristic distance x over which $\mathbf{B}$ changes is $t_{\mathrm{diff}} = \mu_0 \sigma x^2$. Sweet (1958) argued that the energy release time may be estimated by identifying x as being of order the thickness of a flaring flux tube; however, the resulting time is absurdly long, as emphasised by Parker (1963). Sweet (1969) estimated $t_{\mathrm{diff}} \approx 3 \times 10^{14}\,\mathrm{s}$.

This difficulty with time scales is closely related to Cowling's first criticism of the discharge theory, expressed from the magnetic rather than the electric-current viewpoint. In effect, dissipative processes are too slow to allow energy release on the time scale of a flare unless the size of the region is very small, and then the amount of energy released is necessarily small. As in circuit models, one is forced to appeal to dissipation in a large number of very small regions.

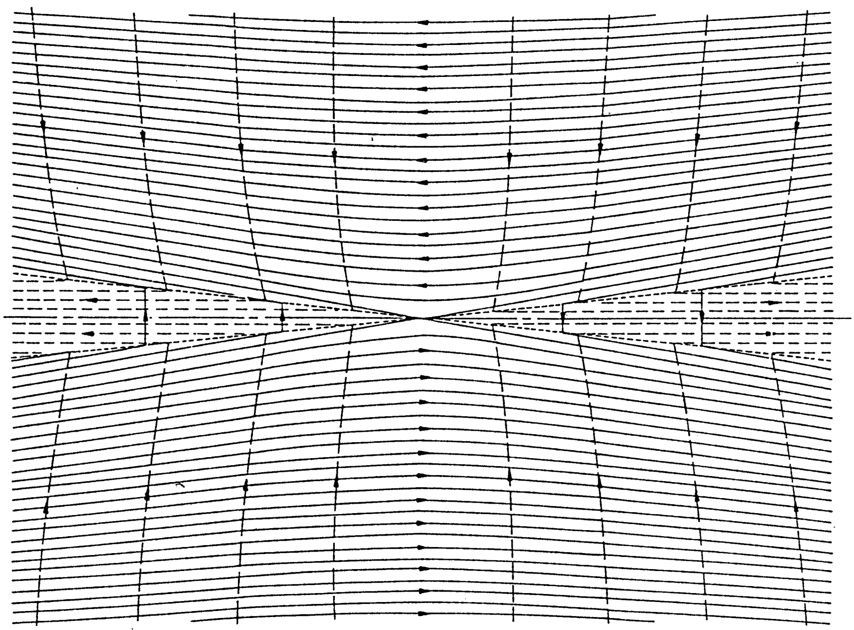


Fig. 10. Petschek's model: the magnetic field lines are denoted by solid lines and plasma flow lines by dashed lines; the slow mode shocks separate the regions of inflow and outflow (Vasyliunas 1975).

Petschek's Model

The difficulty with the removal of plasma and the speed of reconnection was overcome by Petschek (1964). As illustrated in Fig. 10, the idea is to remove the plasma by outflow essentially at the Alfvén speed along separatrices. The time scale for reconnection, $t_{\rm rec}$, is reduced from that implied by Sweet's (1958) early model according to (e.g. Sweet 1969)

$$t_{\rm rec} = \begin{cases} t_{\rm diff} & \text{Sweet (1958)}, \qquad \mathrm{t}_{\rm diff}=\mu_0\sigma\ell^2\,, \\ t_A \ln(t_{\rm diff}/t_A) & \text{Petschek (1964)}, \qquad \mathrm{t}_A=\ell/\mathrm{v}_A\,, \end{cases} \tag{2}$$

where ℓ is an appropriate length scale. Other reconnection models that differ in details from Petschek's model were developed by subsequent authors, and such models were reviewed by Vasyliunas (1975).

Coronal Storage Models

For the past three decades or so, the most widely favoured models have been coronal storage models (e.g. Sturrock 1980). The main ingredients in these models are the following. (a) Magnetic energy is stored in the corona, due to twisting or shearing of coronal field lines due to subphotospheric motions, or due to new magnetic flux emerging and stressing the coronal magnetic field (e.g. Heyvaerts *et al.* 1977). (b) This energy is released due to explosive magnetic reconnections. The energy release is often attributed to the eruption of a filament, and quite detailed MHD models have been developed and analysed (e.g. Mikic *et al.* 1988).

However, there has been ongoing criticism of coronal storage models on a variety of grounds. Indeed almost all aspects of the model have been criticised. In discussing the criticisms here, emphasis is placed on aspects concerned with the current.

Small-scale and Large-scale Dissipation Regions

One point that is clear from the discussion here is that the dissipation must occur in many thin current channels. For example, although the model of Petschek (1964) solves the difficulty with the rate of magnetic reconnection, it does so by identifying the regions of dissipation as thin reconnection regions. These local regions in which reconnection occurs are microscopic compared to the size of a flare kernel. It is useful to define two scale lengths: one that is characteristic of the individual regions where dissipation occurs, and a macroscopic scale characteristic of the flare kernel itself. The small scale is sensitive to the detailed assumptions made, but the specific value is not important in the present discussion; Cowling's (1953) estimate of a few metres is reasonable. The important point is that this is many orders of magnitude smaller than the several hundred kilometres characteristic of a flare kernel. A realistic model must include a description of how the small-scale energy release sites couple together to produce a macroscopic model for energy dissipation.

Deficiencies with Reconnection Models

One deficiency in existing discussions of reconnection models is the lack of attention to the necessary coupling between the small-scale regions and the macroscopic coronal current system. In considering this coupling it is relevant to note a difference between models based on the magnetic and the electric-current viewpoints concerning the direction of current flow. In small-scale regions of magnetic reconnection, the important current flows perpendicular to the local magnetic field lines, whereas in circuit models the current is assumed to flow essentially along the field lines. The distinction between such current systems was emphasised by Spicer and Brown (1980). The evidence from observation is that the large-scale current system associated with flares is flowing into the corona along field lines (cf. Melrose 1991). In reconnection models, this parallel macroscopic current system must connect to the small-scale perpendicular currents in localised dissipation regions. The lack of discussion of the connection between the small-scale currents and the global current system is a deficiency in existing models. No such difficulty occurs for a circuit model: assuming that the macroscopic currents break up into many small-scale current filaments, the dissipation in each filament may be attributed to multiple weak double layers (e.g. Khan 1989).

A related question concerns the closure of the coronal current system. In the corona, currents large enough to be relevant in solar flares must flow virtually along field lines, so that the force per unit volume, $\mathbf{J} \times \mathbf{B}$, is small due to $\mathbf{J}$ and $\mathbf{B}$ being nearly parallel. Somewhere the currents must close by flowing across the field lines, and this must occur where $\mathbf{J} \times \mathbf{B}$ can be balanced by an available pressure gradient. (An exception is in an Alfvénic front, as discussed in Section 5, when $\mathbf{J} \times \mathbf{B}$ is balanced by plasma inertia.) Based on this requirement that the plasma stresses be adequate to balance the magnetic stresses, one concludes that closure of any coronal current system of relevance in a flare must occur well below the photosphere, and then only where adequate pressure gradients are available. McClymont and Fisher (1989) considered where closure could occur, and argued against it occurring significantly above the base of the convection zone. The important point is that when discussing the current one should not ignore the subphotospheric portions of the current circuit.

An implication of including the subphotospheric portions of the circuit is that the coronal current is then only a small portion of a much larger current circuit, and the inductive time scale for the complete circuit is much longer than one would estimate for the coronal portion alone. The inductive time scale for a circuit extending to the base of the convection zone is at least several days, and so is much longer than the time scale for energy release in a flare. It follows that if the coronal current decreases due to magnetic dissipation in reconnection regions, then the current must decrease everywhere around the *actual* current circuit. Such a decrease would release magnetic energy everywhere around the circuit, with this energy propagating into the dissipation region, that is, into the flare kernel. Simple estimates, based on the ratio of the size of a flare kernel to the length of the total circuit, suggest that much more energy is released in remote regions of the circuit than locally in the flare kernel. However, this energy release could not occur on the time scale of a flare. A careful discussion of how magnetic energy is released around the circuit and how it flows into the flare kernel is needed. Another deficiency in existing models based on magnetic reconnection is the neglect of energy propagation into the flare kernel during a flare. It is usually simply assumed that the only energy released is the magnetic free energy in the plasma that is processed through the reconnection region, but the foregoing arguments imply that this is not correct. Energy inflow into the energy release site must be included in any realistic flare model.

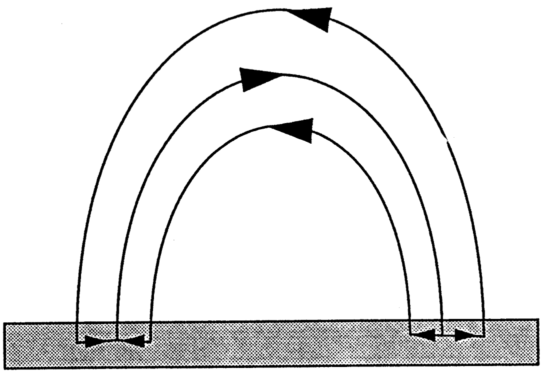


Fig. 11. The current path in an isolated, line-tied magnetic loop: the current flows from the left to the right footpoints in the body of the flux tube (central line), across the field lines in the shaded region where the line tying occurs, and the return current flows back on the surface of the flux tube (outer lines).

As mentioned above, nearly all ingredients in coronal storage models have been criticised. One criticism is that a coronal flux tube can expand at the Alfvén speed and so can relax stresses rather than store them (van Tend and Kuperus 1978; Spicer 1982). Another criticism concerns the amount of energy that can be stored in the corona and whether or not it is adequate to account for the energy released in a flare; this is controversial, with different authors reaching different conclusions (e.g. Xue and Chen 1983; Yang *et al.* 1983). Discussion of coronal storage involves a calculation of the structure of a twisted coronal flux tube or of a sheared arcade of flux loops, and in either case the assumed boundary conditions are important. The commonly assumed boundary condition, called 'line tying', is itself questionable in that it implies current closure across the field lines where the line tying occurs, and this is inconsistent with the electrical properties of the photospheric plasma (e.g. Melrose and Khan 1989). However, perhaps the most serious criticism of the coronal storage model is that the current profile implied by the assumed generation through twisting or shearing motions is inconsistent with the vector magnetic field observations: the observations imply that the currents flow up on one side of the neutral line and down on the other, whereas twisting or shearing of an existing magnetic flux tube or magnetic arcade implies equal currents flowing up and down on each side of the neutral line (Melrose 1991), as illustrated schematically in Fig. 11.

An argument against the energy-release stage of coronal storage models concerns explosive magnetic reconnection (e.g. Akasofu 1984). Magnetic reconnection is a *driven* process in both the laboratory and the terrestrial magnetosphere, and it is questionable to invoke it as the *driving* mechanism for solar flares (Spicer 1982). This criticism concerns what is cause and what is effect in the energy release. In models based on explosive magnetic reconnection it is implicit that the *cause* of the flare is the onset of reconnection allowing the system to relax explosively to one of lower energy. In models for coronal heating, attributed to currents generated by subphotospheric motions on a time scale less than about five minutes, reconnection is assumed to allow rapid dissipation (e.g. Low 1985). It seems inconsistent to assume that currents generated on a longer time scale lead to storage of magnetic energy building up to a flare. Reconnection should occur continuously and prevent the stresses from being stored; that is, the system should relax due to reconnection at a rate that adjusts to the rate the stress is imposed. Thus, this argument against reconnection models is that magnetic reconnection should occur rapidly and so should prevent the assumed build up of stored magnetic energy.

Despite these criticisms of coronal storage models, these models continue to be favoured. This may be attributed to the widely held opinion that coronal storage models are more consistent with observations than other models. However, the criticisms of these models are unlikely to go away, and a rethinking of the basic interpretation of the energy release in flares is needed. A more convincing model will need to have self-consistent magnetic and current structures, realistic boundary conditions that show explicitly how the important current closes, a mechanism for energy inflow from remote parts of the circuit, and a realistic model for energy release within a flare kernel.

5. An Idealised Model for Energy Propagation into a Flare

As just remarked, a realistic flare model must include energy propagation from remote parts of the circuit into the flare kernel. Some progress has been made recently in formulating a model for the energy propagation into a dissipation region (Melrose 1992; Nicholls 1992), and although the existing model is highly idealised, it provides some insight into how this energy propagation must occur and what its implications might be.

Releasing Magnetic Energy by Changing the Current Profile

Before describing this model, an important preliminary point concerns the changes in the coronal current pattern that could occur during a flare. As already emphasised, the fact that the inductive time scale for the circuit carrying the current is longer than the time scale for a flare places a severe restriction on the change that can occur in the total current (Cowling 1953; Hoyng 1977; Spicer 1983; Holman 1985). The implications of this restriction are simply ignored in the current interruption model and in magnetic reconnection models, and this leads to serious doubts (at least in the mind of this author) as to the viability of the widely favoured models for energy release in flares. Suppose that one takes the opposite viewpoint and, instead of ignoring the restriction on the change in I, assumes that I does not change at all during a flare. This does not preclude magnetic energy release, as may be seen by noting that the stored magnetic energy is represented by $\frac{1}{2}LI^2$ in a circuit model, and magnetic energy release can be due to a decrease in I or due to a decrease in the inductance L. A change in the inductance without a change in the current implies a change in the current profile or the current path. A decrease in the length of the current path leads to a reduction in L and hence to magnetic energy release, as suggested by Zuccarello *et al.* (1987).

Release of magnetic energy can also occur due to a change in the current profile, as discussed by Khan (1990). A simple idealised model that illustrates this effect is a cylindrical flux tube, of radius r_0, with a strong axial magnetic field, B_z, carrying a current that is weak in the sense that the azimuthal magnetic field, B_ϕ, generated by it is much weaker than B_z. Suppose that the current density is uniform initially, that is, suppose that initially $J = I/\pi r_0^2$ is independent of the radial coordinate, r. Then one has $B_\phi = \mu_0 Ir/\pi r_0^2$. The magnetic free energy density inside the cylinder is $B_\phi^2/2\mu_0$. Now consider an extreme case in which the current profile changes such that the current becomes a surface current on the cylinder. Then one has $B_\phi = 0$ inside the cylinder. Hence, this change releases all the magnetic free energy in the interior of the cylinder. This energy release occurs, in this idealised case, without any change in I, and it may be attributed to a decrease in the inductance L.

Thus, although at first sight the assumption that the total current does not change at all during a flare may seem extreme and excessively restrictive, nevertheless it still allows one to account for a substantial energy release. However, the mechanism for energy release would then be different from the mechanisms envisaged in the more familiar flare models.

Propagation of Energy into a Flare Kernel

The idealised model proposed for energy propagation into a flare kernel during a flare (Melrose 1992) is based on two ideas.

One idea is from the magnetospheric literature. When a disturbance in the outer magnetosphere causes a motion across magnetic field lines at a velocity $\mathbf{v}$, the required electric field $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$ is set up due to a charge separation across the moving mass of plasma. The associated charges tend to drain from one side of this mass to the other by flowing along magnetospheric field lines to the ionosphere, across the ionospheric field lines due to the Pedersen conductivity of the ionosphere, and back to the other side of the mass along magnetospheric field lines. The idea invoked here is that this current system is set up, after the initial disturbance is assumed to be turned on impulsively, due to Alfvénic fronts (e.g. Scholer 1970; Goertz and Boswell 1979). An Alfvénic front is set up by the initial switching on of the disturbance, and this front propagates back and forth between the ionosphere and the source point in the magnetosphere. (An Alfvénic front is technically a tangential or rotational discontinuity; it has shock-like properties, in the sense that there is a discontinuity in the magnetic field at the front, but there is no entropy generation.) At the front there is a current flow across field lines, with the associated $\mathbf{J} \times \mathbf{B}$ force balanced by plasma inertia. In a cylindrical model the current in the front is radial, corresponding to a deflection of part of the current in the body of the cylinder onto the surface of the cylinder at the front, and the associated acceleration causes a rotational motion of the plasma to be set up as the front passes. Once generated, the Alfvénic front bounces back and forth between the source region and the ionosphere, and it slowly dissipates through ohmic losses, due to the Pedersen conductivity of the ionosphere. A steady current system is set up on the time scale over which the Alfvénic front dies away due to this dissipation.

The other idea was proposed originally in a model for solar surges (Carlqvist 1979), and subsequently to energy release in a flare (Raadu 1989). When a dissipative region is turned on impulsively in a current-carrying coronal flux tube, as presumably must be the case in a flare, Alfvénic fronts are launched (e.g. Raadu 1989). This idea was proposed specifically in connection with dissipation at a double layer (Raadu 1989), but the essential idea is independent of the actual dissipation mechanism. Whenever enhanced dissipation is turned on in a local region in a coronal flux, this sets up an electric field across the field lines that thread that region, and the associated voltage pulse launches the Alfvénic front.

The idealised model (Melrose 1992) envisaged here is illustrated in Fig. 12. A resistance, R_c, is turned on at time $t = 0$ in a cylindrical flux tube carrying a current I_0 due to a current density independent of $r < r_0$. This cylinder is intended to model the flaring flux tube, with R_c modeling the dissipation in the flare kernel. In the region $r > r_0$ outside the flux tube there is assumed to be no current, or rather no change in the profile of any current flowing there, so that the magnetic field at $r > r_0$ does not change. The switching on of R_c launches Alfvénic fronts. At each front the current inside the cylinder, at $r < r_0$, is partially deflected onto the surface, $r = r_0$, of the cylinder (Raadu 1989). At the Alfvénic fronts magnetic energy is released due to the decrease in B_ϕ, as discussed above. The energy released goes partly into a Poynting flux that implies a flow of energy into R_c where it is dissipated, and partly into kinetic energy of a rotational motion of the plasma inside the cylinder behind the front.

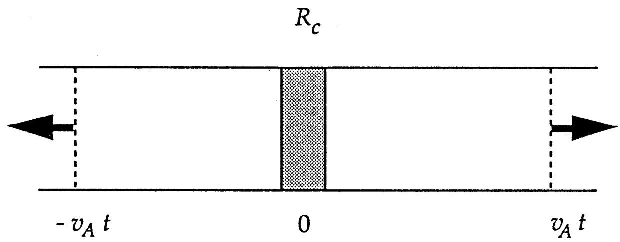


Fig. 12. When dissipation is turned on suddenly, described here by the switching on of the resistance R_c at $t = 0$, a voltage pulse is generated and propagates away as two Alfvénic fronts (rotational discontinuities). Magnetic energy is released at each front and an energy flow, as a Poynting vector, back toward R_c is set up.

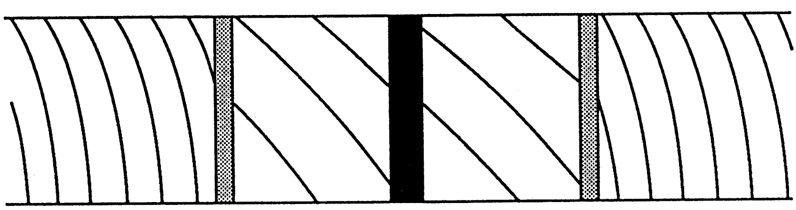


Fig. 13. The unwinding of the magnetic field lines by advancing Alfvénic fronts, cf. Fig. 12.

Physically, the rotational motion may be interpreted as the unwinding motion of the magnetic field, as illustrated in Fig. 13. The unwinding motion behind the front reduces the twist associated with B_ϕ. The fraction of the current that is deflected onto the surface of the flux tube is determined by the following requirement. The current, I_1, after the front has passed and which flows into R_c giving the power dissipated, $R_c I_1^2$, must be such that this power matches the rate magnetic energy is released at the Alfvénic fronts. This requirement gives the ratio

$$\frac{I_1}{I_0} = \frac{R_A}{R_c + R_A}, \qquad R_A := \frac{\mu_0 v_A}{4\pi}, \tag{3}$$

which depends only on R_c and an Alfvénic impedance, R_A. Provided R_c does not change, the energy release continues at the rate $R_c I_1^2$ until the Alfvénic front returns to R_c after being reflected.

Reflections at the Photospheric Boundary

Appropriate boundary conditions need to be imposed to describe what happens to the Alfvénic fronts at the photospheric footpoints of the coronal flux tube. At each footpoint the Alfvénic front is partially reflected back into the coronal portion of the flux tube and partially transmitted to the subphotospheric portion of the flux tube. Two idealised boundary conditions have been considered. One is the same as the boundary condition at the ionosphere in the corresponding magnetospheric model (Goertz and Boswell 1979). Specifically, the photosphere is represented by a resistance, R_0, which allows no transmission. An interesting implication of this model is that after many reflections from both R_0 and R_c, the current approaches $I_\infty = I_0 R_0/(R_0 + R_c)$. This corresponds to the prediction of a simple circuit model in which the current is driven by an EMF $\Phi = I_0 R_0$: when the total resistance in the circuit is increased from R_0 to $R_0 + R_c$, the current reduces from I_0 to $I_\infty = I_0 R_0/(R_0 + R_c)$ on the inductive time scale for the circuit.

However, a resistive boundary is unrealistic for the photosphere and a more appropriate boundary condition is an abrupt decrease in Alfvén speed, from v_{A1} in the corona to v_{A2} below the photosphere. The Alfvénic fronts are partially reflected and partially transmitted from such a boundary. The evolution of the coronal current is qualitatively similar to the case of a resistive photosphere. However, the presence of a transmitted front introduces an important qualitative new effect: the transmitted Alfvénic front, which propagates down the magnetic field lines below the photosphere, releases magnetic energy there and this energy flows back into the coronal portion of the flux tube and then into the flare kernel. Thus this provides an energy flux into the corona, and thence into R_c from below the photosphere. This subphotospheric energy release may not be important in the impulsive phase of a flare: with $v_{A2} \ll v_{A1}$, the power inflow from below the photosphere is only a small fraction of the power released in R_c. However, this energy inflow into the corona may play a crucial role in resupplying magnetic energy to the corona after the flare ends. (The end of a flare may be described by a switching off of R_c in this idealised model.) Specifically, the energy inflow allows the current profile to relax back toward its initial configuration.

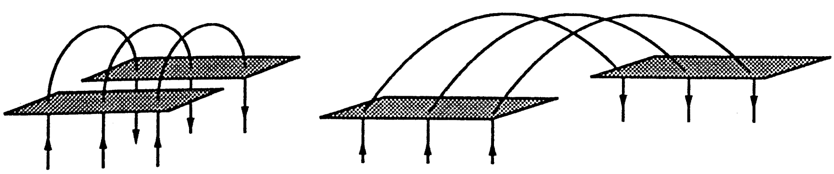
This model allows repetitive identical flares, separated by the time required for the energy inflow to resupply the corona. This is a particularly attractive feature of the model in that so-called 'homologous flares' are often observed (e.g. Martres 1989), and are inconsistent with a reconnection model that implies a change in the magnetic topology. The Alfvénic front below the photosphere propagates down toward the base of the convection zone, continuously releasing stored magnetic energy which flows back to the corona as a Poynting vector. Ultimately, the front may reach the base of the convection zone but the time scale for this is at least several days and so is too long to be of relevance in a model for flares.

6. Future Developments of Flare Models

The idealised model for energy propagation outlined in the previous section is not in itself a realistic flare model. However, it does suggest an alternative to circuit models and to magnetic reconnection models that avoids the serious objections to such models.

Complementarity of the Current and Magnetic Viewpoints

Both the electric-current and magnetic-field viewpoints have advantages and disadvantages, and a realistic model needs to incorporate the advantages and avoid the disadvantages of both. A serious disadvantage of the current viewpoint, at least in the existing treatments, is that it does not allow a description of energy propagation at the Alfvén speed. As discussed above, such energy propagation is an essential ingredient in an acceptable model. A serious disadvantage of reconnection models, and all models developed within an MHD framework, is that the global current system is not considered, and yet it is the global current system that couples different parts of the system together. For example, this neglect of the global circuit precludes discussion of the propagation of energy from remote parts of the circuit into an energy release site. In MHD models the energy dissipation is local, and the MHD model needs to be complemented to describe energy release in the global circuit. This neglect arises from the traditional procedure in MHD theory of regarding $\mathrm{curl}\,\mathbf{B} = \mu_0 \mathbf{J}$ as implying that the current density is completely determined by the magnetic field, so that the current need not be considered. However, $\mathrm{curl}\,\mathbf{B} = \mu_0 \mathbf{J}$ gives information only about the local value of the current density and provides no information on where the currents close.



(*a*) (*b*)

Fig. 14. The effect of line tying on (*a*) an unsheared arcade of loops when (*b*) shearing is caused by relative motion of the footpoints, indicated schematically by the shaded plates. The magnetic field below the surface is assumed to be fixed in the plates, so that the field at the surface develops a kink.

Remarks on the Photospheric Boundary Condition

The remark made above about current closure being obscured in traditional MHD theory has a particularly relevant illustration in the traditional photospheric boundary conditions for models of coronal magnetic flux tubes. A standard boundary condition is referred to as line tying (e.g. Priest 1982, p. 393). Line tying is equivalent to assuming that the surface of the Sun acts like a superconducting plate, so that field lines below the surface are held fixed. Any motion of the field lines above the surface then cause a kink at the surface, as illustrated in Fig. 14. This implies a surface electric current across the kinked field lines. From an MHD viewpoint the line-tying assumption appears plausible: the large inertia of the photospheric plasma implies that the footpoints should not move. From a current viewpoint the line-tying assumption corresponds to closure of the current across the field lines at the postulated boundary, as illustrated in Fig. 10. However, this assumption is not supported by detailed estimates (e.g. Melrose and Khan 1989), which imply that the photosphere is highly conducting and that currents flow unimpeded through the photosphere along magnetic field lines. From this viewpoint, the line-tying assumption is valid only on a time scale of order the Alfvén propagation time, and not on the much longer time scales involved in the postulated stressing of the coronal magnetic field.

A realistic model for a current-carrying coronal flux tube must allow coupling between the coronal and subphotospheric portions of the flux tube through the current. The line-tying assumption excludes this coupling and so is inconsistent with a net current flow from one footpoint to the other, as implied by observational evidence on the current flowing into the corona (e.g. Melrose 1991).

7. Conclusions

The electric-current and magnetic-field viewpoints should be regarded as complementary rather than as competing alternatives. The current viewpoint is the more appropriate when considering dissipation and when discussing coupling (through currents) between remote parts of the system. The magnetic viewpoint is needed when discussing the geometry in which dissipation occurs and is also needed to treat the coupling between magnetic fields and fluid motions.

The theory of solar flares remains in an unsatisfactory state, in the sense that there is no model which combines a realistic magnetic structure and a complete current circuit, and which shows how these evolve during a flare. To illustrate these points, let us return to the five features listed for an acceptable model in the Introduction and discuss them separately.

(1) The ultimate source of the energy in coronal storage models is usually assumed to be subphotospheric motions (e.g. Sturrock 1980). However, energetic arguments (McClymont and Fisher 1987) imply that an adequate source must be located deep in the solar atmosphere, perhaps near the base of the convection zone. The fact that the important currents in flares appear to be unneutralised, in the sense defined by Melrose (1991), seems to preclude these currents being generated after the flux tube has emerged, suggesting that they are generated in the solar dynamo region.

(2) Magnetic energy transport must occur through a Poynting vector. A specific model for this energy propagation into a flare kernel during a flare is described in

Section 5. Another feature relating to energy storage and propagation that has not been discussed adequately is the shielding of currents. In most treatments based on the magnetic-field viewpoint it is implicit that the magnetic flux tubes are magnetically isolated structures. This requires that the structures have surface currents, but these implied surface currents are not discussed explicitly. For example, two magnetically isolated flux tubes that are pushed together should interact initially though their surface currents. On the other hand, if the currents are unneutralised, different flux tubes interact magnetically, and such interaction could be incorporated into a circuit model by including several different circuits with mutual inductances between them.

(3) Energy storage in a coronal flux tube, from the magnetic-field viewpoint, is attributed to twisting or shearing of the coronal field. However, the line-tying assumption obscures an important aspect of the physics in that it precludes propagation of the twist or shear to below the photosphere in the form of Alfvén waves. Any estimate of the amount of free energy available (e.g. Low 1985; Aly 1991) depends on the boundary conditions, and as argued above, the line-tying assumption is unacceptable in this context.

(4) The instability associated with the energy release in a flare has not been identified satisfactorily in either coronal storage or circuit models. The argument that the inductive time scale is too long to allow the current to change in magnitude imposes a severe limit on the energy that can be released during a flare, and presumably also on acceptable instabilities that lead to energy release. This constraint needs to be incorporated into any realistic model.

(5) The trigger for a flare has not been identified. It seems that there must be instabilities on the two scales introduced in Section 3. On a macroscopic scale, one requires a transition from one configuration to another due to a change in the current profile that reduces the magnetic energy. On a small scale, the energy release requires anomalous resistivity in reconnection regions, weak double layers, or some other form of local dissipation of a current.

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