Solar Flares: Implications of the Circuit Model (Invited Paper)

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Abstract: A review is given of recent developments in the interpretation of the structure and heating of the solar corona, and of solar flares. An electric circuit model for a flaring magnetic loop is introduced, and used to discuss the closure of the current pattern. It is argued that cross-field current flow cannot be set up after a flux tube has emerged above the photosphere. The energy dissipated in a flare is attributed to a change in the inductance of the flaring loop, with the current remaining approximately constant. Emphasis is placed on the value of the resistance of the flaring loop, and on the associated inductive timescale.

1. Introduction

Over the last decade or so there has been an enormous increase in detailed observational data on the solar corona in general and on solar flares in particular. These data come primarily from spacecraft designed specifically for solar observations, such as Skylab, SMM and Hinotori, supported by systematic monitoring of the Sun in Hα, at radio wavelengths and by magnetographs. The new results have led to changes in our picture of the solar corona, which is now regarded as a collection of magnetic flux loops with footpoints at magnetic knots in photospheric active regions. These more recent observations have also led to a better qualitative understanding of solar flares, particularly of when flares are most likely to occur, and of the details of the time, space and spectral characteristics of the energy released. However, even some quite basic questions remain poorly determined or controversial. Opinions differ on the preconditions required for a flare to occur, e.g., on whether flares occur only in complicated or interacting loops and whether a filament eruption necessarily occurs, or whether flares can occur in simple loops (as sometimes seems to be the case). Also it is not clear how (and when) the energy is transported to the corona, where it is stored and how it is released rapidly in a flare.

In this paper I review some of these recent observational advances, and concentrate on their interpretation in terms of an electric circuit model. The idea that a flaring flux loop may be regarded as an electric circuit is not new (e.g., Alfvén 1977, Spicer 1977), but some of the implications have not been widely recognized. It is more conventional to regard a flaring flux loop as a magnetic structure that is relaxing by relieving its magnetic stresses. These alternative viewpoints are complementary, but in practice they lead to quite different emphases; the one based on the magnetic field emphasizes the geometric structures, and the circuit model emphasizes the current system. In particular the problem of current closure tends to be overlooked when the magnetic viewpoint is adopted, and is highlighted when the circuit approach is adopted. The main points emphasized in the present paper are current closure, the resistance R of a flaring coronal loop and relevant L/R and RC timescales and their implications.

Recent ideas on the structure and heating of the solar corona are reviewed in Section 2. An overview of solar flares is presented in Section 3, concentrating on the energy release in the impulsive phase. Difficulties with the favoured interpretation in terms of the explosive release of energy stored in nonpotential magnetic fields are outlined in Section 4. The circuit model is introduced in Section 5 and its implications are discussed in Section 6.

2. The Structure and Heating of the Corona

Two observations have led to a major change in our views on how the solar corona is heated. One resulted from photographs of the corona in the far UV taken during the Skylab mission: these showed the corona to consist of a collections of magnetic flux loops, e.g., Rosner, Tucker and Vaiana (1978). The other is from magnetograph observations, which show that the magnetic field emerges through the photosphere in knots or pores, usually identified with emerging flux loops.

Photospheric Magnetic Knots

The observable solar magnetic field emerges from below the photosphere in knots of a range of sizes, some of which may be smaller than our current resolution threshold. However, the magnetic field strength $B \approx 0.1\text{-}0.2\mathrm{T}(1\mathrm{T} = 10^4\mathrm{G})$ is approximately independent of the size of the knot, and is much stronger than the mean solar field $B \approx 10^{-4}\mathrm{T}$. The strong field in knots has important implications on the dynamical interaction of the magnetic structures and the plasma. This is usually described in terms of the so-called plasma beta

$$\beta = P/(B^2/2\mu_0), \qquad (1)$$

where P is the gas pressure. For $\beta > 1$ the gas drags around the magnetic field, and for $\beta < 1$ the field drags around the gas. Also, to within a factor of order unity, one has $\beta \approx (c_s/v_A)^2$, where v_A is the Alfvén speed and c_s is the sound speed. Sound waves transmit stresses for $v_A << c_s$, and Alfvén waves transmit stresses for $v_A >> c_s$. One has $\beta < 1$ in the knots, and $\beta > 1$ outside the knots.

From the late 1940s for about three decades it was widely accepted that the corona is heated by sound waves, generated by the convective (granular) motions in the photosphere. More recently it has been recognized that, in view of the small value of β in the knots, the energy must be transported along the magnetic field through the photospheric knots in the form of Alfvén waves. The idea that the corona is heated by such waves is now widely accepted, e.g., the reviews by Kuperus, Ionson and Spicer (1981) and Ionson (1985a).

Electric Currents

There is another idea for the heating of the corona involving static currents. One refers to AC models, which are based on dissipation of Alfvén waves, and to DC models based on dissipation of a steady current flowing through the corona (Heyvaerts and Priest 1984, Ionson 1985a, b). Steady currents probably play a central role in transporting energy to flaring flux loops.

Observational determination of the current is possible using vector magnetographs, which allow one to measure all three components of the magnetic field. The electric current flowing into or out of the photosphere along the magnetic field lines turns out to be several times 10^{11} A (Moreton and Severny 1968). Such currents are near the maximum possible coronal current, cf. equation (9) below. The electric currents must be force free, and this implies that the current lines are parallel to the magnetic lines, i.e., **J** must satisfy

$$\mathbf{J} \times \mathbf{B} = 0. \qquad (2)$$

Such a current generates a magnetic field such that the net field in a magnetic loop has a twist or shear. The available free energy is in the current or, equivalently, in the twist or shear in the magnetic field.

Heating of Loops by Alfvén waves

Let me return to the heating of coronal flux tubes. The coronal loops are linked magnetically to the photospheric knots, and hence the waves relevant for transport of mechanical energy are Alfvén waves. The idea that the corona is heated by Alfvén waves has become widely accepted only over the past decade or so. Until then it was thought that Alfvén waves are ineffective in heating the corona because they are so weakly damped in hot plasmas. Several effective damping mechanisms are now recognized, e.g., the reviews by Kuperus, Ionson and Spicer (1981) and Ionson (1985a). Two favourable mechanisms are as follows:

(1) The frequency of the waves matches the resonant frequency for propagation of Alfvén waves along the flux tube through the corona, so that the flux tube acts as a high-Q resonator for the waves; the rate of energy dissipation in a high-Q resonator is independent of the details of the dissipation mechanism (Ionson 1978).

(2) Plasma instabilities cause enhanced scattering of particles and hence enhanced resistivity and enhanced dissipation (e.g., Kuperus 1976, Heyvaerts, Priest and Rust 1977, Galeev *et al.* 1981, Duijveman, Hoyng and Ionson 1981).

This dissipation deposits energy directly in the corona. A balance is reached between the resulting heating and energy losses due to radiation and due to conduction of the energy back to the chromosphere. This model accounts well for many of the observed properties of coronal loops (Rosner, Tucker and Vaiana 1978).

A viewpoint that I favor is that a solar flare may be attributed to a situation in which the heating is so rapid that

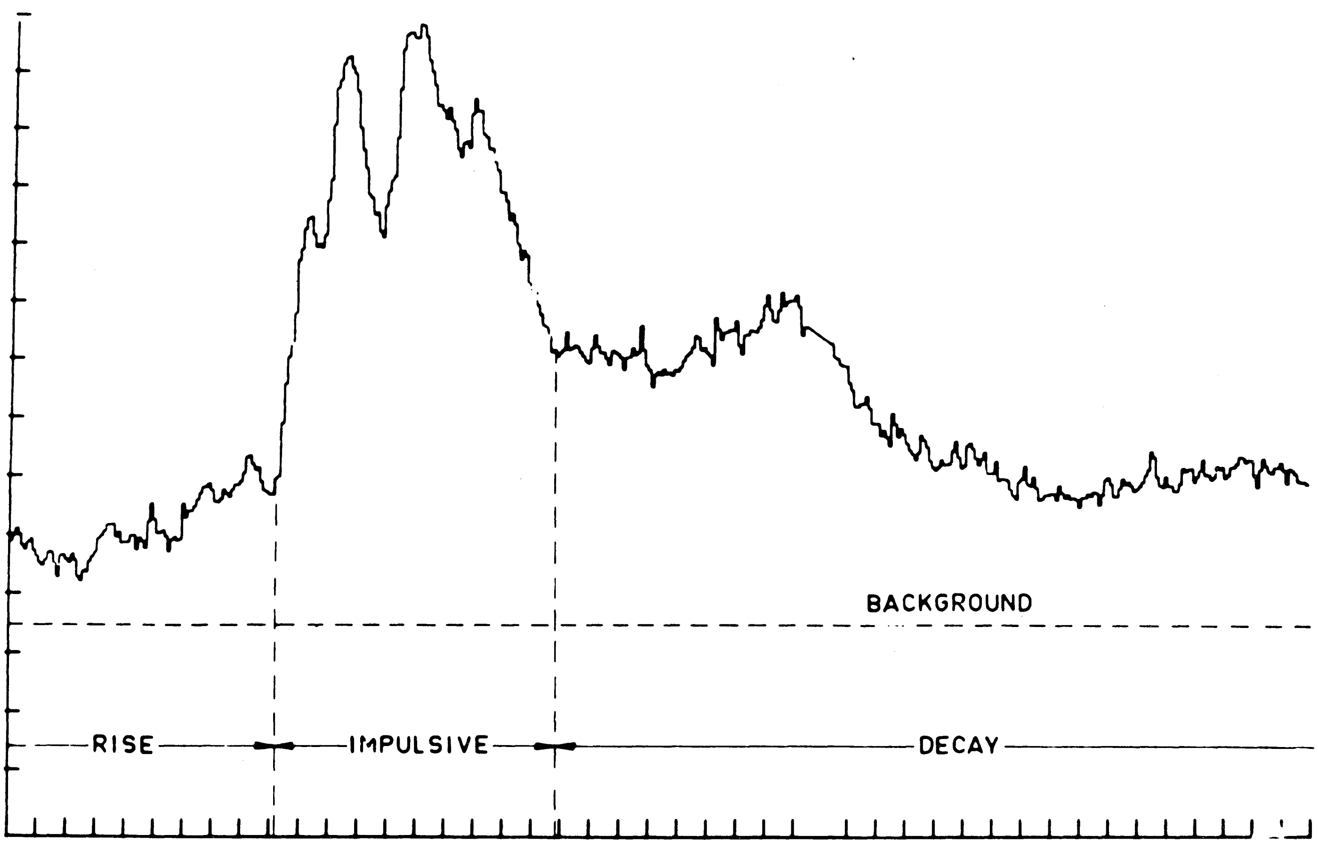

Figure 1 – The time evolution of an impulsive hard X-ray burst. The horizontal axis denotes time in seconds, and the vertical axis denotes X-ray count rate (1 unit ≈ 1020 s^{-1}). The impulsive phase last ≈9.5 s and is superimposed on a gradual rise and fall over a much longer period. (Kane *et al.* 1980).

thermal conduction becomes incapable of balancing it. The system then has to find a more effective way of transporting the energy out of the flux loop, and it can do so only by accelerating energetic electrons, which carry away the energy as they propagate down to the chromosphere. Before discussing possible interpretations of flares further, let me summarize their properties.

3. The Phases of a Flare

It is conventional to describe the development of a solar flare in terms of phases. A large solar flare has three phases: a precursor phase, an impulsive phase, and a gradual phase. These are illustrated in Figure 1, which shows the evolution schematically in hard X-rays. The precursor and gradual phases could be interpreted as one continuous phase (Sturrock *et al.* 1984) with a gradual rise and fall over an hour to a few hours. The impulsive phase is much shorter, and consists of spiky bursts of energy release.

The impulsive phase last for a few minutes (10^2 to 10^3 s). It involves radiation across the spectrum from radio to γ-ray frequencies. The emission shows rapid variations over timescales as short as can be resolved (<100 ms), with such variations correlated in γ-rays, hard and soft X-rays, and in microwave and metrewave radio emissions. There is an enormous range of data relevant to the energy release in the impulsive phase. The important features may be summarized as follows.

(1) The energy release is spiky. There are peaks in the emission on a timescale ≈ 1 s called 'elementary flare bursts' (EFBs) (van Beek *et al.* 1974), and there are peaks on a shorter timescale ≈ 10 to 100 ms (e.g., Sturrock *et al.* 1984).

(2) The energy release in EFBs occurs in flare kernels which are small regions with diameter ≈ 300 km (de Jager and Kuijpers 1987), which may be near the top of the flux loop or just above the transition zone (de Jager and Kuijpers 1987).

(3) A large fraction of energy released goes into 2 to 20 keV electrons (e.g., Lin 1985).

(4) The $\lesssim 10$ keV electrons deposit their energy in the corona; the $\gtrsim 10$ keV electrons precipitate into the chromosphere, leading to the hard X-ray emission, and the observed optical and ultraviolet emissions from a narrow region at the top of the chromosphere.

(5) The energy deposited by these electrons causes an explosive evaporation of the chromosphere, and the hot gas ($>10^7$K) that boils off into the corona produces the observed soft X-ray emission.

(6) A small fraction of these energetic electrons escape along open field lines, producing metrewave type III radio bursts.

(7) A high-energy tail of up to 100 keV electrons produce microwave radio bursts through gyro emission.

(8) Promptly accelerated >30 MeV/nucleon ions precipitating into the chromosphere produce the γ rays.

The release of energy continues at a reduced rate during the gradual phase, with further heating and acceleration of both electrons and ions. However the most spectacular energy released is in the impulsive phase.

4. Difficulties with the Twisted Flux Loop Model

One of the favoured models for the energy release in flares is as follows (e.g., Sturrock 1977, 1980). A flare involves storage of energy in the coronal loop through a twisting-up of the magnetic field lines due to photospheric motions, followed by a rapid release of the energy due to untwisting of the flux loop in explosive magnetic reconnection. (Conceptually, this model may be likened to a toy aeroplane powered by a rubber band connected to the propeller: energy is stored in the rubber band by slowly winding it up through the propeller, and is then released rapidly by releasing the propeller and allowing the rubber band to unwind.) There are two stages in this model, specifically the storage and the release. The storage and release has been described in terms of loading and unloading (Akasofu 1981). The energy release is usually assumed to be much more rapid than the energy storage, although an exception is in 'dynamo' models in which the loading and unloading times are approximately equal (Kan, Akasofu and Lee 1983, de Jager 1986). However, the models have been criticized because of the storage of energy in the corona, as discussed below, and serious doubt has been expressed concerning the existence of explosive magnetic reconnection (e.g. Akasofu 1984).

The storage has been criticized on two grounds. On the one hand, it has been argued that the coronal loop should expand as more energy is stored in it (e.g., van Tend and Kuperus 1978, Spicer 1982), preventing storage at the required energy density. A specific model was analysed by Xue and Chen (1983), who emphasized the importance of the boundary conditions; they estimated the total energy that can be stored to be much less than that released in a flare. Spicer (1982) concluded that it is impossible to store an adequate energy in a coronal loop, and argued for storage near or below the photosphere. The second criticism is that the energy supplied to the corona through motions of the footpoints should be dissipated rapidly, leading to heating rather than to energy storage (e.g., van Ballegooijen 1985). There is an apparent inconsistency between the requirements of rapid dissipation to account for coronal heating and for storage rather than dissipation to account for flares. This inconsistency was recognized by Low (1985), who referred to small-scale non equilibrium (rapidly dissipated motions) and large-scale equilibrium (stored magnetic stresses), but made no attempt to justify this distinction.

A further difficulty with this type of model becomes apparent when one adopts the circuit viewpoint. This concerns the closure of the current, and is discussed in Section 6. The viability of models based on storage of magnetic energy in the corona remains a matter of controversy. My opinion is that the arguments that such models are untenable have not been refuted.

5. An Electric Circuit Model

In an electric-current model a flaring coronal loop (Alfvén 1977, Spicer 1977, 1982, Chiuderi 1982) is described by lumped circuit parameters, the resistance R, inductance L and capacitance C, and is assumed to carry a current I driven by an e.m.f. which provides a potential drop Φ.

The importance quantities in a model for a flaring loop are L and R. The inductance of a current element of length ℓ is

$$L \approx \mu_0 \ell, \tag{3}$$

and is only weakly dependent on the current profile. The resistance R is related to the resistivity η by

$$R = \eta \, \ell / A, \tag{4}$$

where A is the cross-sectional area of the loop, and where the current is assumed to be uniform across A. The resistivity is an intrinsic property of the material through which the current is flowing. For a thermal plasma interparticle collisions result in the so-called 'Spitzer resistivity', given by

$$\eta = 1.3 \; 10^3 \; T^{-3/2} \; \Omega\mathrm{m}, \tag{5}$$

which depends only on the plasma temperature T (in kelvin).

Constraints

There are several constraints on the circuit parameters for an electric circuit model of a flare. If the current I is uniform across an area $A = \pi r^2$, where r is the radius of the loop, it is related to the current density J and the area A by

$$I = JA. \tag{6}$$

The current density may be written

$$J = - nev_D, \tag{7}$$

where n is the number density of electrons, $-e$ is their charge, and v_D is the drift speed of the electrons relative to the ions. Three plasma instabilities that can limit v_D are the ion sound, ion cyclotron and Buneman instabilities (e.g., Duijveman, Hoyng and Ionson 1981). Assuming the ion sound instability to be relevant v_D is limited to $\approx v_s$, where v_s is the ion sound speed ($v_s \approx V_E/43$, where V_E is the thermal speed of electrons). One then requires

$$I < nev_s A. \tag{8}$$

The requirement that the self field must not exceed the net field places a further restriction on I:

$$I < 2\pi r B \tag{9}$$

where B is the net field (in tesla). In a solar flux loop this limit typically requires $I << 10^{12}$ A. A current $I = 3 \times 10^{11}$ A is assumed here.

Energetics

The power dissipated P is identified as ΦI. The resistance R may be introduced or defined through Ohm's Law relating the potential and the current:

$$\Phi = IR. \tag{10}$$

The power dissipated then becomes

$$P = RI^2. \tag{11}$$

The power P is identified here with the power released in the impulsive phase of a flare, so that R is the resistance of the flaring loop. The fact that the energy release is greatly enhanced during the impulsive phase requires either that I or R be greatly enhanced. It is argued below that I cannot change significantly on the impulsive timescale. Hence, a flare theory must involve an explanation for the greatly enhanced R for the region in which the energy is released. Two ways of enhancing R are to appeal to 'anomalous' η due to plasma turbulence, and to appeal to filamentation of the current. It is argued below that one needs to appeal to both, and even then it is difficult to account for the required large value of R.

Current Filamentation

Filamentation of the current has two consequences that may be important in a flare. These are that it makes free energy available, and that it increases the resistance.

The energy stored in the coronal non potential magnetic field is represented by the inductive energy $LI^2/2$. It is usually assumed that the energy released during the current dissipation is due to the value of I decreasing. This is not necessarily the case; the current profile can change and make free energy available by reducing the inductance L (Spicer 1981). To see this consider an idealized model in which a current that is initially uniform over a cross-section A breaks up into N equal currents δI each over an area δA. We require

$$\delta I = I/N. \tag{12}$$

A filling factor for the area may be defined by

$$f = N\delta A/A. \tag{13}$$

Quite generally, the inductive energy for a collection of N circuit elements, labelled $i = 1$ to N, with the ith element carrying a current I_i is

$$E = \sum_{ij} M_{ij} I_i I_j / 2, \tag{14}$$

where the M_{ij} are the mutual inductances for $i = j$ and the self inductances for $i = j$. Here all the currents are set equal to I/N. In one extreme limit, suppose the current elements are close enough together so that all the M_{ij} may be approximated by $\approx \mu_0 \ell$, cf. (3). Then E, as given by (14), reduces to the value $LI^2/2$ for a uniform current profile. In the opposite extreme, when the current elements are well separated, the mutual inductances are negligible, and only the self inductances contribute in (14). In this extreme case E reduces to $1/N$ times $LI^2/2$ and most of the magnetic energy is released. Thus free energy becomes available when the current profile breaks up into filaments, and no reduction in the net current is required for the release of this energy.

Current filamentation increases the net resistance. Suppose the resistivity η does not change. Then the resistance of each filament is given by (4) with A replaced by δA. These resistances add in parallel, and hence the net resistance is $1/N$ times the resistance of each, i.e.,

$$R = \eta \ell / N\delta A = f^{-1} (\eta \ell / A), \tag{15}$$

where the filling factor is defined by (13). Thus filamentation increases the resistance, compared to a constant current profile, by the inverse of the filling factor. However the enhancement is limited due to the current density and the drift speed v_D also both increasing by the inverse of the filling factor. The limit $v_D < v_s$ restricts the possible enhancement to a factor

$$f^{-1} < I/neAv_s. \quad (16)$$

6. Implications of the Circuit Model

The power released in the impulsive phases of flares varies between about 10^{20} and 10^{22} W. The assumed value $I = 3 \times 10^{11}$ A in $P = RI^2$ gives a power in this range for $R = 10^{-3}$ to 10^{-1} Ω. This is an extremely large resistance. For comparison, consider the value of R estimated from (4) with the collisional resistivity (5), by inserting values ($\ell \approx 10^7$m, $r \approx 10^6$m, $T \approx 10^6$K) appropriate to a flux tube in the corona. One finds $R \approx 10^{-11}\Omega$. Current filamentation can enhance R by the inverse of the filling factor. However, the limit (16) becomes $f^{1} \lesssim 10^5$ (for the parameters chosen above and $n = 10^{17}$ m^{-3}), and this enhancement factor is inadequate.

It follows that collisional effects are inadequate in causing the required dissipation, and one is forced to conclude that the dissipation process is collisionless. Dissipation due to anomolous ion sound ressistivity may be a viable mechanism (Kuperus 1976). In this case the resistivity is

$$\eta \approx 10^{-2}\mu_0 \, c^2/\omega_p, \quad (17)$$

where is the plasma frequency $\approx 2 \times 10^{10}$ s^{-1} here. The implied value of R is then of order $10^{-2}\Omega$. A possible alternative collisionless dissipation mechanism involves a collection of double layers (e.g., Smith 1985).

Inductive Timescales

In a circuit model changes in the current pattern and the magnetic field occur on the inductive timescale

$$t_I = L/R. \quad (18)$$

Consider this timescales for the flaring loop as a whole. With $\ell \approx 10^7$m, (3) gives $L \approx 10$ H, and then with $R \approx 10^{-2}$ one finds $t_I \approx 10^3$ s. This corresponds to the observed timescale for the impulsive phase of a flare. This agreement may be interpreted as independent support for the circuit model in that it provides an independent estimate of R. That is, there is a consistency between the estimates of R made by equating I^2R to the power dissipated and by setting t_I equal to the impulsive timescale.

Other relevant timescales may be interpreted in terms of inductive timescales. These include the timescale between homologous flares (10^5 to 10^6 s), that for EFBs (1 to 10 s) and that for spikes (10^{-1} to 10^{-2} s). The longer timescale requires either a larger ℓ, i.e., a larger circuit, or a smaller resistance, and the shorter timescales require either shorter circuits or larger resistances. The idea of interpreting the observational timescales in this way looks promising, but has yet to be explored in detail.

An important implication of the fact that the inductive timescale is not negligibly small was pointed out by Spicer (1983), and also by Holman (1985). Large potentials, $\Phi \approx 10^8$ to 10^{10} V, are required to account for the power dissipated. A seemingly attractive simple idea is that the energetic particles are accelerated simply by falling through the potential drop. Spicer argued that if the curent is written $I = eN$, then $\dot{N}$ cannot change significantly on the inductive timescale. A current of 3×10^{11} A corresponds to $\dot{N} = 2 \times 10^{30}$ s^{-1}. It follows that no more than a few times 10^{30} electrons per second can be accelerated in this way. This is to be compared with the 10^{37} to 10^{39} 2 to 20 keV electrons estimated to be accelerated in a flare. This simple idea on how electrons might be accelerated is untenable.

Capacitive Timescales

The capacitive timescale RC is relevant in at least two contexts. When R and C are taken to correspond to a footpoint, or rather to one scale height of plasma below a footpoint, the RC time may be interpreted as the inertial timescale for acceleration of the plasma due to any $\mathbf{J} \times \mathbf{B}$ force. This time has been called the line-tying time (e.g., Sato 1985). The other capacitive time which is relevant is for a coronal filament. A filament may be represented in the circuit by a capacitor C, and $C\Phi^2/2$ then corresponding to the kinetic energy of the filament. Eruption of the filament corresponds to its charging up, with the velocity identified with the $\mathbf{E} \times \mathbf{B}$ drift resulting from the cross-field potential Φ. The acceleration time for the filament is then its RC time.

These ideas have yet to be developed in detail. However simple estimates based on observational data on erupting filaments suggest a value of Φ of the same order ($\approx 10^9$V) as the potential inferred by equating RI^2 to the power in a flare.

Generation of the Coronal Current

The most widely favoured idea on how the current required to power a flare is generated (e.g., Sturrock 1980) is that it is due to motions of the footpoints of the flux tubes and that the energy is stored in non potential magnetic fields in the corona. This model encounters a difficulty in connection with the closure of the current. Consider a current generated by the motion of one footpoint; it must flow upwards along one set of field lines and downwards along another set of field lines and hence it must close by flowing across the field lines in or below the photosphere (e.g., Spicer 1982, Kuperus 1983). A possible current pattern is illustrated in Figure 2. This cross-field flow implies a $\mathbf{J} \times \mathbf{B}$ force which must be balanced by a pressure force, by a frictional force, or by an inertial force. No adequate horizontal pressure gradient is available.

A balance of the $\mathbf{J} \times \mathbf{B}$ force with a frictional force corresponds to closure due to the finite resistivity of the photosphere associated with this frictional force. This closure mechanism seems to be implicit in some models for storage of energy in twisted or sheared fields. (The question of current closure is usually ignored so that it is not clear what mechanism is implicitly assumed.) Current closure due to the cross-field resistivity of the weakly ionized photosphere is explicit in so-called 'dynamo' models for flares (Heyvaerts 1974, Kan, Akasofu and Lee 1983). However, it can be shown that the timescale to set up the current is too long by a large factor for the process to be effective (Melrose and McClymont 1987). Current closure due to the cross-field resistivity of the photosphere seems to be untenable.

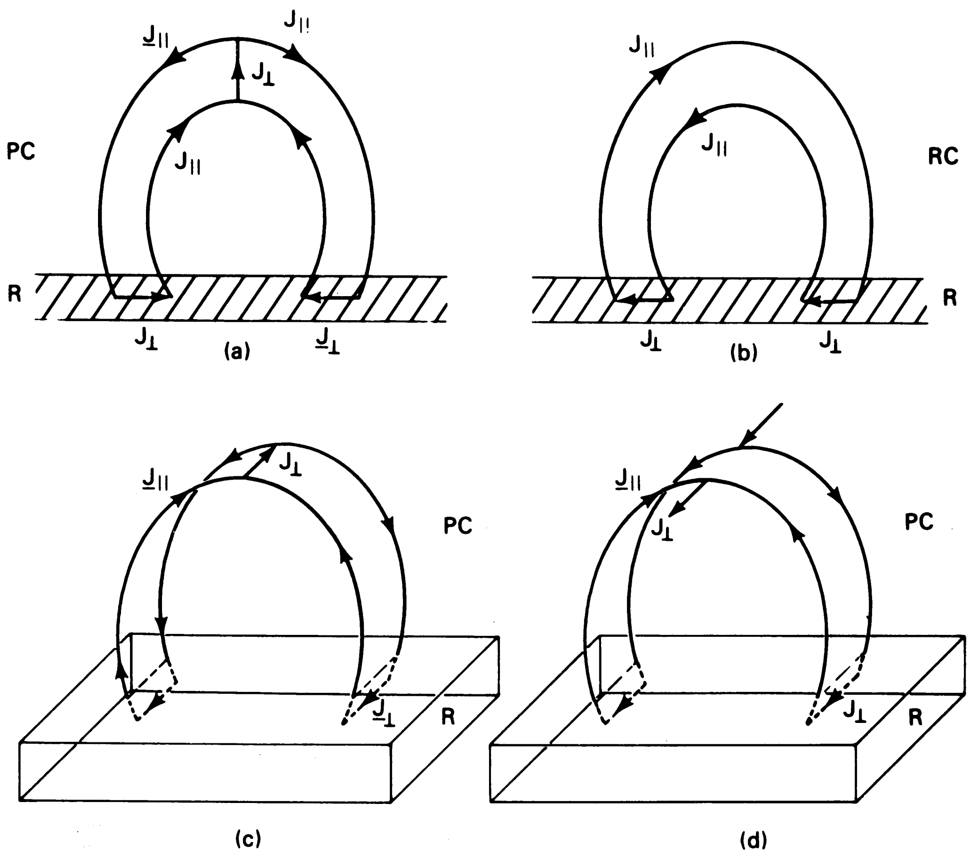

Figure 2—Four suggested ways (a) to (d) of closing parallel currents ($J_{\parallel}$) flowing through the perfectly conducting (PC) corona by cross-field currents ($J_{\perp}$) in the resistive (R) photosphere. (Spicer 1982). It is argued in the text that such cross-field current closure is not viable, and that the current in the corona must close deep in the solar atmosphere.

The only remaining possibility for current closure involves an inertial force which may be interpreted in terms of an Alfvénic wavefront. An inertial force persists only as long as the plasma is being accelerated. The relevant time is the line-tying or RC time (e.g., Sato 1985). This time becomes long enough (say 10^5 s) to be relevant to the storage of currents in the corona only when the Alfvénic wavefront reaches the depth at which the propagation time for an Alfvén wave through a scale height is of order 10^5 s. A model based on current closure at this height is being investigated; it seems to encounter serious difficulties and is probably not viable.

It seems that there is no acceptable mechanism for cross-field current closure in the photosphere or just below it. One is forced to conclude that the current must close deep in the solar atmosphere. An implication is that the current relevant to a solar flare is already flowing in the flux loop when it emerges through the photosphere.

7. Discussion

The circuit model for a flaring magnetic flux loop provides a view which is complementary to that in terms of magnetic structures. There are three aspects of flare models for which the advantages of the circuit viewpoint are evident.

First a circuit viewpoint highlights the requirement that the current close. A favored view is that the currents are generated by photospheric motions. In such models the current flows along one set of coronal field lines and returns along another, requiring cross-field current closure in or below the photosphere. It seems that there is no acceptable way of balancing the implied $\mathbf{J} \times \mathbf{B}$ force. Granted this, models based on such current closure are untenable, and such models include all those involving energy storage by twisting or shearing the coronal loop after it has emerged through the photosphere, and also 'dynamo' models.

An implication is that the current required to power a flare is present when the flux tube emerges, and that this current does not change significantly during a flare. Such a current can close in a much larger circuit, maybe even around the Sun. In a model based on this alternative the energy release must be attributed to a change in the inductance rather than to a change in the current.

Second, the circuit model provides a way of relating the power released in a flare to the local dissipation mechanism for the current in the corona. This is in terms of the resistance required for a flaring coronal loop. The resistance ($\approx 10^{-2}\Omega$) is much greater than the estimates based on classical resistivity allow, even when the maximum possible enhancement due to current filamentation is taken into account. One must invoke enhanced or anomalous dissipation in thin current sheets with high current densities. An alternative is that the potential drop driving the current forms across a collection of 'double layers' (Smith 1985). A related implication of the circuit model is that a large potential, $\Phi = 3 \times 10^8$ to 3×10^{10} V, is required, cf. Heyvaerts (1974), Colgate (1978) and Holman (1985). It is not widely recognized that such a large potential is unavoidable in virtually all models.

Third, the circuit model provides estimates for the timescales on which energy can be transferred from one component to another in the circuit. The inductive timescale L/R is relevant to the storage and release of magnetic energy, and the capacitive timescale RC (sometimes called the 'line-tying' time) is relevant to the kinetic energy of plasma motion. Possible implications of the identifications of these timescales with relevant observed timescales have yet to be explored in detail. One notable result of the inductive timescale being non-negligible is that the acceleration of the very large number of mildly relativistitic required ($\approx 10^{37}$ to 10^{39}) cannot be explained in terms of direct acceleration through the potential drop Φ (Spicer 1983, Holman 1985).

The circuit model has limitations which should not be understated. It involves describing a complicated system in terms of bulk parameters and simple (circuit) equations. Clearly many important details are excluded. However this can be regarded as the main advantage of the circuit approach; it provides a simple global model that allows analysis of the coupling between various parts of the total system. The viewpoints based on the circuit or current model, the magnetic structures, and the microphysics of dissipation processes are complementary. Of the three the circuit approach has received the least attention, and its profound implications have yet to be widely recognized.

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