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THE CURRENT PROFILE AND ENERGY RELEASE IN SOLAR FLARES

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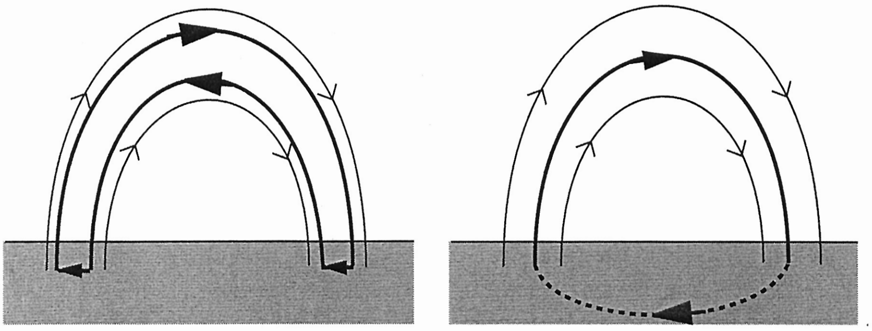
Abstract

The currents, $I \sim 10^{12}$ A, that are important in solar flares must close deep in the solar atmosphere, and be flowing in solar flux tubes when they emerge through the photosphere. Photospheric motions cannot be the primary cause of the coronal storage of magnetic energy released in a flare, nor of the large potential $\Phi \sim 10^{9}$ V required. The large inductive time scale of the circuit implies that the total current in the corona cannot change significantly during a flare; ways in which magnetic energy might be released at constant current are identified.

1. Introduction

Three aspects of the energy release in solar flares are discussed in this paper: the closure of the large-scale currents associated with flares; the potential differences before, during and after flares; and the allowed changes in the current that can account for the energy release in a flare. The power released, P, can always be written in terms of the volume integral, over the energy release region, of the energy source term $\mathbf{J} \cdot \mathbf{E}$, where $\mathbf{J}$ is the current density and $\mathbf{E}$ is the electric field strength. In this paper it is assumed that this integral is of the form $P = I\Phi$, where I is the current through the energy release region, and Φ is the potential difference across this region along the current path. It is assumed that the current involved is that inferred from vector magnetograms ($I \sim 10^{12}$ A) to flow through the photosphere into the corona, and to correlate with the sites of flare kernels (e.g., Moreton and Severny 1968; Lin and Gaizauskas 1987; Hagyard 1989; Romanov and Tsap 1990; Leka et al. 1993). It is argued in section 2 that these currents must close deep in the solar atmosphere and must be flowing when the flux tube emerges from below the photosphere. To produce a power $P \sim 10^{21}$ W in a flare with $I \sim 10^{12}$ A, requires $\Phi \sim 10^{9}$ V across the energy release site. The origin of such a Φ is discussed briefly in section 3. The large current path implied by closure deep in the solar atmosphere implies that I cannot change during a flare, and possible constant-I models for flare energy release are outlined in section 4. The results are discussed in section 5.



(a) The current closes at each footpoint (b) The current closes between footpoints

Fig. 1. The current path (heavier line) (a) when a twisting or shearing motion generates the current near the photosphere, and (b) when the photospheric plasma is assumed sufficiently resistive that the current closes from one footpoint to the other. It is argued that neither applies to the important currents in flares.

2. Current Closure

How are the currents associated with solar flares set up? There are two possibilities: the currents build up in a magnetic flux tube after it emerges from below the photosphere, or the currents are already flowing in flux tubes before they emerge.

Figure 1a illustrates current closure in models that invoke twisting or shearing of existing coronal fields by photospheric motions, with the **J** × **B** force due to the cross-field current balancing the applied plasma force. One argument against such closure is that the model implies direct and return currents at both footpoints (Melrose 1991), but vector magnetograms (e.g., Hagyard 1989) show currents flowing from one footpoint to the other, with no evidence for a nearby return current of comparable magnitude, cf. Wilkinson, Emslie and Gary (1992) for a possible exception. A second argument against such closure concerns energetics (McClymont and Fisher 1989): the effective power input into a flux tube, from the kinetic energy of the photospheric flow across it, is inadequate to allow sufficient magnetic energy to be stored in the corona over a day or so before a flare.

The current lines follow the field lines below the photosphere provided that the time scale for diffusion of the current lines relative to the magnetic field lines is long compared with the Alfvén propagation time. This condition is well satisfied. The closure in Figure 1b can then never be set up. Thus one concludes that the source of the energy released in a flare, and the site of the closure of the current involved in a flare, occur deep in the atmosphere.

3. Potential Differences

How does the large potential difference, $\Phi \sim 10^9$–$10^{10}\,\mathrm{V}$, form across the coronal energy release site during a flare? One possibility is that the potential is generated by photospheric motions. One may estimate the potential differences set up due to a shearing motion in the photosphere ($z = 0$). Assuming antisymmetry about the neutral line ($x = 0$) in both the vertical component of the magnetic field, $B_z(-x) = -B_z(x)$, and in the shear velocity, $v_y(-x) = -v_y(x)$, the electric field, $E_x(x) = -v_y(x)B_z(x)$, can be derived from a potential,

$$\Phi(x) = \int_0^x x'\, v_y(x')B_z(x') = -\Phi(-x), \tag{1}$$

which is of opposite sign at opposite footpoints in the photosphere. Plausible parameters, $B_z = 0.15\,\mathrm{T}$, $v_y = 10^3\,\mathrm{m\,s^{-1}}$ and a distance 10^7–$10^8\,\mathrm{m}$, give $\Phi \sim 10^9$–$10^{10}\,\mathrm{V}$ of the desired order of magnitude. However, one encounters a logical inconsistency on assuming that these

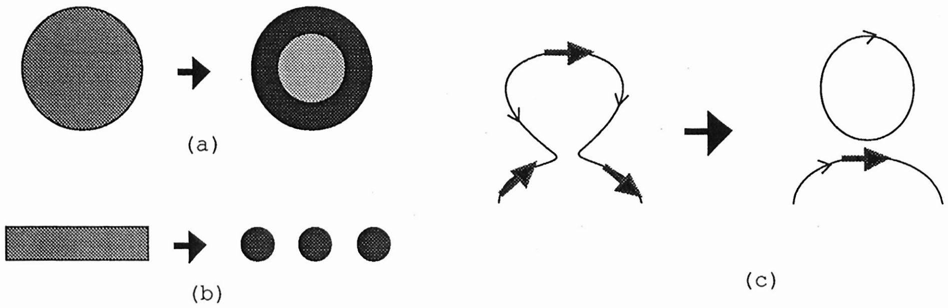


Fig. 2. Three ways in which magnetic energy may be released at constant I: (a) a uniform profile in a cylinder is redistributed toward the surface of the cylinder (shading denotes the strength of the current density), (b) a current sheet fragments into current lines, (c) the current (solid arrows) path shortens due to reconnection.

footpoints are connected by a field line through the corona: coronal field lines should be approximately equipotentials, except during a flare, and this is inconsistent with $\Phi \sim 10^9$–$10^{10}\,$V along the connecting line. One concludes that the large-scale shearing associated with flares is not due to the effect of photospheric motions on pre-existing structures, but rather to the emergence of a pre-sheared structure. Moreover, the Φ that is important in a flare must be across remote parts of the current circuit before and after a flare, and move to the corona when the dissipative process turns on at the onset of a flare.

4. Energy Release at Constant Current

Current closure deep in the solar atmosphere implies an inductive time scale $\gtrsim 1$ day, so that I must remain approximately constant during a flare (e.g., Spicer 1983; Holman 1985). The stored magnetic energy, $\frac{1}{2}LI^2$, can then change only due to L changing.

Three different ways of releasing magnetic energy at constant I are identified schematically in Figures 2. Figure 2a illustrates a change in a cylindrically symmetric current profile from a uniform current density to one concentrated near the surface of the cylinder (cf., Melrose 1992). Figure 2b corresponds to the break up of a current sheet into current filaments, as in a tearing instability. In both examples like currents move apart, decreasing the self-magnetic energy between them. From a circuit viewpoint, the decrease in magnetic energy may be attributed to a decrease in the mutual inductance as like current elements move apart (Khan 1990). Consider a current I breaking up into n filaments each with a current I/n, self-inductance L, equal to the original self-inductance, and mutual inductance, $M = L$. As the filaments separate, M decreases from L toward zero, and the magnetic energy decreases from $\frac{1}{2}LI^2$ toward $\frac{1}{2}LI^2/n$. Another way of releasing magnetic energy is illustrated in Figure 2c: the inductance, $L = \mu_0\ell/4\pi$, is reduced by shortening the current path, ℓ, (cf. Zuccarello et al. 1987). One other case not included in Figure 2 corresponds to unlike current filaments moving closer together, which may be relevant to a model with multiple, oppositely-directed current paths (cf. Holman and Benka 1992). In all three cases, the change in the stored magnetic energy is a substantial fraction of the initial energy: with $L \sim 10\,$H ($\ell \sim 10^{10}\,$cm) and $I \sim 10^{12}\,$A, the available energy $\sim 10^{25}\,$J is sufficient to account for a large flare.

There is no reliable vector magnetogram data on how the current evolves during a flare. However, some information on the current can be inferred from observations of erupting filaments (e.g., Moore 1988): as a filament erupts, the axial current in the filament decreases. The fact that the total current is conserved then implies that there must be at least two coupled, parallel circuits, that is, two alternative current paths. Then, as the current decreases in the circuit associated with the filament, the current along the other path increases correspondingly. This is consistent with the now favored picture in which a current sheet develops below the erupting filament (e.g., Hirayama 1974; Forbes 1992). The current in the filament can be redirected through this current sheet onto flux tubes that do not take part in the eruption.

5. Discussion and Conclusions

The main points made in this paper may be summarized as follows: 1). The large currents, $\sim 10^{12}$ A, involved in solar flares flow from one footpoint to another when the flux tube emerges from below the photosphere, and close deep in the solar atmosphere. 2). The energy released in a flare cannot be stored in the corona due to the effects of photospheric motions twisting or shearing magnetic structures that have already emerged. 3). The potential $\Phi \sim 10^9$ V required in a flare cannot be due to photospheric motions, and must move from deep in the solar atmosphere across the energy release site during the flare. 4). The long inductive time scale of the current circuit implies that the total coronal current cannot change significantly during a flare; magnetic energy may be released due to: (a) a change in the current profile, (b) filamentation of a current that involves like current elements moving away from each other, (c) unlike currents moving closer together, or (d) a shortening of the current path. 5). The current in an erupting filament decreases, implying that there are at least two parallel circuits such that the current is redirected from the circuit through the filament into a circuit in the non-erupting part of the magnetic structure.

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