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# Alfvénic Fronts and the turning-off of the Energy Release in Solar Flares

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**Abstract:** The effect of impulsively turning off the dissipation in an existing model for energy propagation through Alfvénic fronts into the coronal site of energy release in a solar flare is examined. In the optimum case of impedance matching, the flux tube re-stresses on a much longer timescale than it relaxes, suggesting an explanation for the timescales observed in homologous flares.

## 1. Introduction

Energy release in a solar flare must involve the entire coronal portion of a flaring magnetic loop, with energy propagating into the energy release site near the top of the loop. In an existing model for this process (Melrose 1992), the energy release site is represented by a dissipative region in a cylindrical flux tube carrying a current $I$. The power release in the flare (typically $\sim 10^{21}$–$10^{22}$ W for a large flare) may be equated to $I^2R_c$, to define a characteristic resistance $R_c$ for the dissipation. We refer to this as the *resistive region*. It is assumed to turn on at a time $t = 0$, launching Alfvénic fronts in response to the cross field potential implied by $R_c$. Goertz and Boswell (1979) provided a kinetic theory description

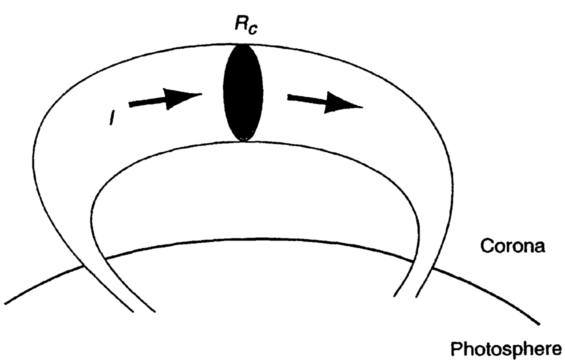


**Figure 1**—The resistive region at the top of the flux tube.

of this process in a magnetospheric context. In the present model, the Alfvénic fronts carry behind them a new current density but the same current still flows in the loop. This satisfies the requirement that the current itself can only change over the longer, inductive timescale of the current loop circuit (Melrose 1993). Effectively, part of the current is pushed to the surface of the flux tube and thereby avoids flowing through $R_c$. It is implicit in this model that the closure of the circuit must occur well below the photosphere. Figure 1 shows the resistive region $R_c$ at the top of the flux tube as it turns on.

At the propagating fronts, energy stored in the azimuthal component of the magnetic field of the loop is partially converted into a Poynting flux (to supply the resistive region) and partially into a bulk rotation of the plasma within the tube. The flux tube relaxes or unwinds at the fronts and reaches a steady state after multiple reflections of the fronts at the photosphere and the resistive region.

This paper addresses the question of what happens after the resistive region impulsively turns off. The turning-off of $R_c$ represents the end of the solar flare energy release. It is shown that energy continues to flow into the corona from the sub-photospheric portion of the flux tube to resupply the coronal flux tube with magnetic energy. The coronal flux tube returns to its initial state, allowing the possibility of repeated flaring activity, as is observed in homologous flares (Sturrock 1980).

## 2. Impulsive Turning-off of Energy Release

In the model under discussion, a solar flux tube is modelled as a cylinder, with ends representing the photospheric boundary and with the resistive region a cylindrical disk at the midpoint of the flux tube. The system is described in terms of cylindrical coordinates $r, \phi, z$ with origin in the resistive region. The radius of the flux tube is $r_0$ and its length is $l$. When the dissipative region is turned on at time $t = 0$, the Alfvénic fronts generated propagate to the photosphere ($z = \pm l/2$) where they are partially reflected. The propagation time to the photosphere is

$$\tau_A = \frac{l}{2v_{A1}}, \qquad (1)$$

where $v_{A1}$ is the coronal Alfvén speed. A uniform Alfvén speed is assumed above the photosphere. This represents a simplified picture of wave propagation in the solar atmosphere; a more sophisticated model would require an accurate description of the decrease in Alfvén speed through the chromosphere, where reflection of the front may occur. This detail is not crucial to the results presented here. Behind the fronts, a radial electric field is established by the change of $B_\phi$ implied by a new current density. This electric field causes a bulk rotation $v_\phi$ of the plasma behind the front according to $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$. In the case of outward propagating fronts from the resistive region, the established electric field is odd in $z$ and so the plasma in the flux tube counter-rotates either side of $z = 0$. Slippage of field lines continuously occurs at the resistive region; elsewhere the field lines are frozen-in to the plasma.

The nature of the dissipation in the resistive region is not addressed directly in the model. The dissipation mechanism in solar flares is not well understood and here $R_c$ is introduced only as a simple way of relating the dissipation to the current $I$. There is good observational evidence that flare regions correlate with regions of high current ($I \simeq 10^{12}$ A) flowing into the corona (e.g. Moreton and Severny 1968; Canfield *et al.* 1993; Leka *et al.* 1993; de La Beaujardière *et al.* 1993).

To model an impulsive end to energy release, the resistive region $R_c$ is assumed to turn off after the $2m$th reflection of an Alfvénic front from the photospheric boundary and the resistive region. That is, at a time $t_{2m} = 2m\tau_A$ when a front carrying a current density $J_{2m}$ behind it returns to the origin. As in the original model, the current densities behind fronts are assumed uniform for simplicity. The boundary condition at the photosphere is modelled as a discontinuous jump in Alfvén speed from $v_{A1}$ down to $v_{A2}$, due to increasing density. This is the second idealised boundary condition considered by Melrose (1992).

In the following, we also assume that the turning-off occurs before the initial Alfvénic fronts have time to propagate around the complete current circuit. This is consistent with the argument that current closure occurs deep below the photosphere, perhaps at the base of the convection zone.

The turning-on and -off of $R_c$, like the dissipation itself, is not explicitly addressed in terms of microphysics. A simple picture is that the new current density $J_{2m}$ has reached a critical value below which the central resistance can no longer be sustained. This would be appropriate if for instance $R_c$ were due to some form of anomalous resistivity.

The sudden turning-off of $R_c$ launches a new Alfvénic front to communicate the change at the origin. Behind this front a current density $\bar{J}_1$ is established. ($J_{2m}$ is denoted $\bar{J}_0$.) The simple geometry of the original model implies that the radial electric field $E_r$ within the flux tube is odd in $z$ and so continuity of $E_r$ in the plane $z = 0$ implies zero electric field behind the new front. This is consistent with the reasoning that there can no longer be counter-rotation of the two halves of the flux tube behind outward propagating fronts; ideal magnetohydrodynamics is restored when $R_c = 0$.

Considering the system after $k$ more reflections have occurred, the current density behind the propagating front inside $0 \le z \le l/2$ is $\bar{J}_{k+1}$. As in the original model, matching the power in the Poynting flux at the advancing front to the dissipation at $z = 0$ establishes the difference equations describing the evolution of $\bar{J}_i$:

$$\bar{J}_{2k+1} - \bar{J}_{2k} = (-\alpha_{12})^k(\bar{J}_1 - \bar{J}_0) \qquad (2)$$

and

$$\bar{J}_{2k+2} - \bar{J}_{2k+1} = (-\alpha_{12})^{k+1}(\bar{J}_1 - \bar{J}_0)\,, \qquad (3)$$

where

$$\alpha_{12} = \frac{R_{A2} - R_{A1}}{R_{A2} + R_{A1}} \qquad (4)$$

is the reflection coefficient at the photosphere and

$$\bar{J}_1 - \bar{J}_0 = \frac{R_{A2}}{R_{A1}}(J_0 - J_{2m})\,. \qquad (5)$$

Here, $J_0$ is the original current density at time $t = 0$ and the impedances $R_{A1,2} = \mu_0 v_{A1,2}/4\pi$ describe the coronal (subscript 1) and subphotospheric (subscript 2) plasma. So $v_{A2}$ is the (assumed uniform) sub-photospheric Alfvén speed, $v_{A2} \ll v_{A_1}$.

Equations (2)–(5) may be solved to give

$$\bar{J}_{2k} = J_{2m} + [1 - (-\alpha_{12})^k](J_0 - J_{2m})\,. \qquad (6)$$

The asymptotic value of current implied by equation (6) is

$$\bar{J}_\infty = J_0\,, \qquad (7)$$

that is, the current returns to its initial state after an infinite number of reflections. The flux tube as a whole returns to its initial state, allowing the possibility of later flaring activity as is observed in homologous flares. Equation (7) also follows from the requirement that the steady state of the system is that of the standard circuit model (Melrose 1992).

The energy stored in the magnetic field of the flux tube above the corona increases after the flare energy release turns off. This occurs because energy is being supplied by the continued unwinding of the sub-photospheric magnetic field of the flux tube as fronts propagate downwards.

The timescales for energy release and resupply to the corona in this model may be estimated from the series describing the current density, as follows. If the resistance $R_c$ turns off after many Alfvén transit times, then a time of interest is that for the current density to fall a fraction $f$ of the way to its asymptotic value. Using Melrose's (1992) equation (32), this is

$$t_{f_{down}} = \frac{\ln(1-f)}{\ln \alpha_{12}\alpha_c}\tau_A\,, \qquad (8)$$

where both logarithmic terms involve fractional arguments and so are negative. Similarly, the time for the current to return to a fraction $f$ of its asymptotic value after $R_c$ has impulsively switched off follows from equation (6);

$$t_{f_{up}} = \frac{\ln(1-f)}{\ln(-\alpha_{12})}\tau_A\,. \qquad (9)$$

For secular change, the magnitude of the $\ln(1-f)$ factors might be expected to be about unity. The important ratios in these times are

$$x \equiv \frac{R_{A2}}{R_{A1}}, \qquad y \equiv \frac{R_c}{R_{A1}}. \tag{10}$$

Clearly $x \ll 1$ but the value of $y$ is not determined independently in the model. However, maximum power release corresponds to $y = 1$, the case of *impedance matching*, and for a large flare it is expected that the system is driven hard and so impedance matching may be approached (Melrose 1992).

Two limiting cases are of relevance here. In the first, $R_c$ does not turn off until the current density has almost reached its asymptotic value, i.e. after many reflections. This corresponds to $y \ll 1$. Then the characteristic times for winding up and down are given by equations (8) and (9) in the limit of small $x$ and $y$;

$$t_{down} \simeq \frac{\tau_A}{x+y}, \qquad t_{up} \simeq \frac{\tau_A}{x}. \tag{11}$$

In this limit the times for relaxation and re-stressing are comparable.

The second limit applies when the system is driven hard, so that there is impedance matching and $R_c$ turns off in about one Alfvén transit time, i.e. $t_{down} \simeq \tau_A$. The characteristic time for the current density to rise again is unchanged, $t_{up} \simeq \tau_A/x$. So when the system is driven hard, it returns to its original state in a characteristic time $1/x = R_{A1}/R_{A2}$ longer than the energy release time. With $R_{A1}/R_{A2} = v_{A1}/v_{A2} \simeq 10^2$, a release time of a few minutes implies resupply occurs over several hours, consistent with the timescales observed in homologous flares (Sturrock 1980).

## 3. Conclusions

An existing model (Melrose 1992) for energy propagation into a solar flare energy release site in the corona is generalised to describe the evolution of the system after the flare energy release turns off. It is shown that energy is resupplied to the corona after the impulsive turn-off of the flare. The system ultimately returns to its original (pre-flare) state. This process may provide a simple explanation of the phenomenon of homologous flares, where repeated flaring activity is observed in the same site in an active region. For a flare to re-occur in a given region, the magnetic and current topology of the region must be re-established. This implies energy resupply to the coronal magnetic fields, as demonstrated in the present model. The timescale for energy resupply in this model is much greater than that for release if the system is driven hard in the release phase, consistent with the observed delay between homologous flares.

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