ENERGY RELEASE IN A PROMINENCE-LOADED FLARING LOOP

M. S. WHEATLAND* and D. B. MELROSE
Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006, Australia

(Received 13 January, 1995; in revised form 15 March, 1995)

Abstract. Zaitsev and Stepanov (1991, 1992) proposed a mechanism for energy release in solar flares that involves the intrusion of dense prominence material into a coronal loop. The resulting non-steady state conditions are claimed to increase the resistance of the loop by 8–10 orders of magnitude. It is shown here that the dramatic increase in resistance calculated by Zaitsev and Stepanov depends on a gross overestimate of the of the magnitude of the magnetic force in the loop prior to the flare trigger. A more realistic estimate of the increase due to the mechanism suggests that it is by no more than about four orders of magnitude. As a consequence, the 'prominence-loading' mechanism does not provide a tenable flare model.

1. Introduction

In the circuit picture of a solar flare, energy release is attributed to the local appearance of a resistivity, η associated with a field-aligned current density $\mathbf{J}$ in a coronal magnetic loop (Melrose, 1993). Integrating ηJ^2 over the energy release site gives the power, RI^2 associated with the flare, where R is a resistance assigned to the flaring loop. Classical (Spitzer) estimates of the resistance of a coronal loop, however, yield a value of order 10^{12}–10^{-11} Ω, whereas the power release of a large flare (10^{22} W) and the currents inferred from vector magnetogram data ($\approx 10^{12}$ A) imply $R \approx 10^{-2}$ Ω (Melrose and McClymont, 1987).

Zaitsev and Stepanov (1991, 1992; hereafter referred as ZS) presented a mechanism by which the resistance of the flaring loop is increased by up to 10 orders of magnitude over the classical value. ZS argued that the increase in coronal resistance of a flaring loop is due to the non-steady state, partially ionised conditions set up when a filament overlying the loop intrudes into the loop via the flute instability, introducing neutral plasma. Figure 1 illustrates this process. The intrusion of the filament is the trigger for the flare. ZS's argument is reproduced briefly here, followed by a specific criticism of the mechanism.

2. A Non-Steady-State Ohm's Law

ZS derived a generalized Ohm's law relevant to non-steady, partially ionized conditions, from the three-fluid equations of motion. The form found (in which terms of order $(m_e/m_i)^{1/2}$ are ignored) is

* Present address: Center for Space Science and Astrophysics, Stanford University, Stanford, CA 94305, U.S.A.

Solar Physics **159:** 137–141, 1995.

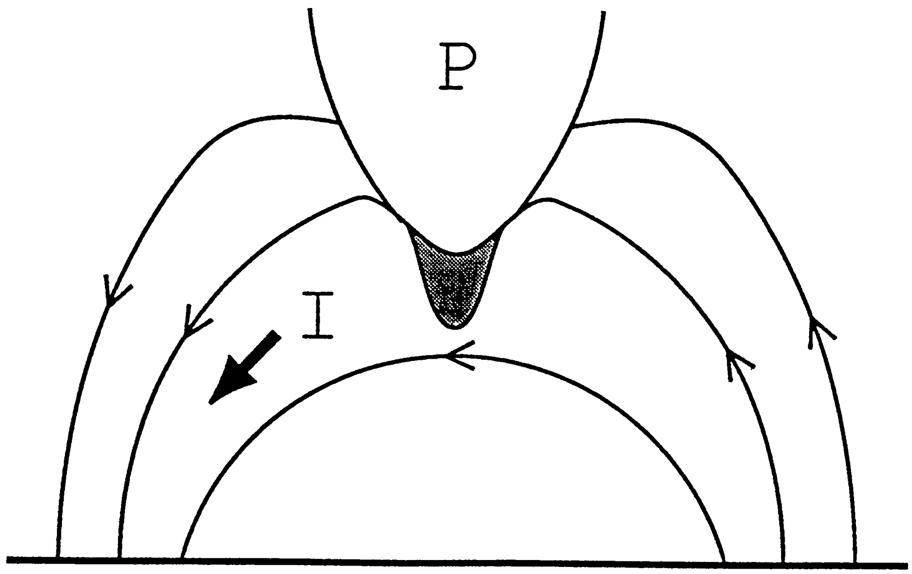

Fig. 1. A schematic diagram of Zaitsev and Stepanov's (1991, 1992) 'prominence-loading' flare model. A prominence, P, overlying a current-carrying loop, intrudes into the loop and introduces dense material (the shaded region) as well as non-steady state conditions. The arrowed curves represent field lines; their twist is not represented.

$$\mathbf{E}' = \frac{m_e(\nu_{ei} + \nu_{en})}{e^2 n}\mathbf{J} + \frac{1}{en}\mathbf{J} \times \mathbf{B} - \frac{F}{nm_i\nu_{in}}\nabla p_n \times \mathbf{B} - \frac{1}{en}\nabla p_e - \frac{\rho F^2}{nm_i\nu_{in}}\frac{\mathrm{d}\mathbf{V}}{\mathrm{d}t} \times \mathbf{B}\,, \tag{1}$$

where $\mathbf{V}$ is the mean plasma velocity, $\mathbf{E}' = \mathbf{E} + \mathbf{V} \times \mathbf{B}$ is the electric field in the moving frame, $F = n_n m_n/\rho$ is the relative density of neutrals and the other symbols have their usual meaning. Gravity terms are neglected. Note also that SI units are adopted here, whereas ZS used Gaussian units.

ZS applied Equation (1) as follows. They considered a cylindrical portion of the loop near its apex, of cross section S and length d. The filament material is assumed to intrude into this cylinder, which carries a field-aligned current density $\mathbf{J}$ corresponding to the field-aligned current I in the loop (see Figure 1). In this region prior to the intrusion of the filament material, the $\mathbf{J} \times \mathbf{B}$ force density must be balanced by the gradient of the gas pressure. When the flute instability develops, the neutral material introduced into the loop is assumed to smooth out the original pressure distribution, leaving a non-equilibrium state described by $\rho\mathrm{d}\mathbf{V}/\mathrm{d}t = \mathbf{J} \times \mathbf{B}$. Using this expression in the final term of Equation (1), the density of power dissipated in the volume of interest is

$$q = \mathbf{E}' \cdot \mathbf{J} = \frac{m_e(\nu_{ei} + \nu_{en})}{e^2 n} J^2 - \frac{F}{n m_i \nu_{in}} \nabla p_n \times \mathbf{B} \cdot \mathbf{J} -$$

$$- \frac{1}{en} \nabla p_e \cdot \mathbf{J} + \frac{F^2}{n m_i \nu_{in}} (\mathbf{J} \times \mathbf{B})^2 . \tag{2}$$

By integrating q over the cylindrical volume described above, ZS arrived at the total power dissipated, $\dot{W}$. ZS argued that the first and last terms on the right-hand side of Equation (2) make the dominant contribution to the power. ZS additionally assumed a purely axial current I in the cylinder of interest, with a uniform current density $\mathbf{J} = J_z \hat{\mathbf{z}}$. The magnetic field which contributes to the final term on the right-hand side of Equation (2) is assumed to be the azimuthal field B_ϕ produced by this $\mathbf{J}$. Then a straightforward calculation gives $\dot{W} = RI^2$, where

$$R = R_l + R_{nl} , \tag{3}$$

with

$$R_l = \frac{m_e(\nu_{ei} + \nu_{en}) d}{2\pi e^2 n S} \tag{4}$$

and

$$R_{nl} = \frac{\mu_0^2 F^2 I^2 d}{8\pi n m_i \nu_{in} S^2} . \tag{5}$$

Equation (4) is the usual Ohmic dissipation; Equation (5) is an additional resistance due to collisions between ions and neutrals under non-steady state conditions. The subscripts 'l' and 'nl' refer to the linear and nonlinear dependences, respectively, on the appropriate collision frequencies.

The evaluation of R given in ZS may be reproduced as follows. The solar parameters used by ZS are $n_\Sigma = n_n + n = 10^{18}$ m^{-3}, $T = 10^7$ K, $d = 5 \times 10^6$ m, $S = 10^{12}$ m^2, $F = 0.1$, and $I = 3 \times 10^{11}$ A. Only the collision frequencies are then needed to estimate R_l and R_{nl}. Using the standard form $\nu_{\alpha n} = n_n \sigma (k_B T / m_\alpha)^{1/2}$, where σ is the effective collision cross section (e.g., Krall and Trivelpiece, 1973), allows the estimates $R_l = 4 \times 10^{-13} (\sigma / 10^{-20}\ \mathrm{m}^2)\ \Omega$ and $R_{nl} = 7 \times 10^{-4} (10^{-20}\ \mathrm{m}^2 / \sigma) \Omega$. These values are comparable with ZS and reproduce the eight to ten order of magnitude increase in R that they claimed. Following ZS, we then find $R_{nl} I^2 \approx 10^{20}$ W, which is of order the power released in small flares.

3. A Specific Criticism

ZS's calculation produces a serious overestimate of the resistance of the loop for the following reason. ZS stated that before the filament intrudes into the loop, the loop is in equilibrium, with the Ampère force density, $\mathbf{J} \times \mathbf{B}$, balanced by the gradient of gas pressure. However, for the current density and magnetic field geometry they assumed in the derivation of Equations (3)–(5), this could not be the case. For their geometry, $|\mathbf{J} \times \mathbf{B}| = J_z B_\phi \leq (I/S)\mu_0 I/[2\pi(S/\pi)^{1/2}] \approx 3 \times 10^{-2}$ N m^{-3} is very much greater than any relevant pressure force. For example, a plausible estimate of the pressure force density is $|\nabla p| \approx nk_BT/(S/\pi)^{1/2} \approx 2 \times 10^{-4}$ N m^{-3}, implying $|\nabla p| \ll |\mathbf{J} \times \mathbf{B}|$ for most of the cylinder of interest. Even this estimate of the magnitude of the $\mathbf{J} \times \mathbf{B}$ force is probably an overestimate because it uses ZS's (flare) temperature, $T = 10^7$ K, rather than a lower, preflare temperature. The geometry of $\mathbf{J}$ and $\mathbf{B}$ assumed by ZS is the underlying problem: the current density and magnetic field in a coronal loop must be close to parallel (i.e., force-free), with the departure from parallel defined by a residual pressure gradient, $|\mathbf{J} \times \mathbf{B}| = |\nabla p| \approx nk_BT/(S/\pi)^{1/2}$. Following ZS's own argument, after the filament material intrudes into the loop, the pressure gradient is smoothed out and the $\mathbf{J} \times \mathbf{B}$ force density is unbalanced. Its magnitude must still be of order $nk_BT/(S/\pi)^{1/2}$, however, which provides a more self-consistent estimate of the contribution of the final term in Equation (2) to the resistance of the flaring loop:

$$R'_{nl} = \frac{F^2}{nm_i\nu_{in}I^2} \int |\mathbf{J} \times \mathbf{B}|^2 \, \mathrm{d}V \approx \frac{F^2 Sd}{nm_i\nu_{in}I^2} \left[\frac{nk_BT}{(S/\pi)^{1/2}}\right]^2 \approx$$

$$\approx 6 \times 10^{-8} (10^{-20}\ \mathrm{m}^2/\sigma)\,\Omega\,. \tag{6}$$

This (revised) estimate is about four orders of magnitude smaller than ZS's value. Whilst R'_{nl} provides a considerable increase over R_l, the increase is not enough to account for the energy release in even the most modest flares, and is dependent (as mentioned above) on the use of the flare temperature, $T = 10^7$ K. Adopting a plausible preflare temperature, say $T = 10^6$ K, gives $R'_{nl} \approx 2 \times 10^{-9} (10^{-20}\ \mathrm{m}^2/\sigma)\Omega$.

4. Conclusions

Zaitsev and Stepanov's (1991, 1992) 'prominence-loading' model for solar flares seriously overestimates the increase in resistance produced by the loading mechanism in a coronal magnetic loop. In Zaitsev and Stepanov's model, a filament overlying a current-carrying loop is assumed to intrude into the loop via an instability, introducing dense neutral material and non-steady state conditions near the loop apex. The Ohm's law relevant to these conditions implies an increase in resistance over the classical, Spitzer resistivity. It is shown here that the eight to ten orders of magnitude increase estimated by Zaitsev and Stepanov is based on a gross overestimate of the magnitude of the magnetic force in the loop before the introduction of the filament plasma. When this overestimate is corrected, a large increase in resistance is still implied, but the magnitude of the increase is much smaller. The corrected value of the enhanced dissipation is far too small to be relevant to solar flares. Consequently, Zaitsev and Stepanov's model does not provide a satisfactory flare mechanism.

Acknowledgements

One of the authors (M.S.W.) acknowledges the receipt of an Australian Postgraduate Research Award.

References

Krall, N. A. and Trivelpiece, A. W.: 1973, *Principles of Plasma Physics*, McGraw-Hill, New York.
Melrose, D. B.: 1993, *Australian J. Phys.* **46**, 167.
Melrose, D. B. and McClymont, A. N.: 1987, *Solar Phys.* **113**, 241.
Zaitsev, V. V. and Stepanov, A. V.: 1991, *Soviet Astron.* **35** (2), 189.
Zaitsev, V. V. and Stepanov, A. V.: 1992, *Solar Phys.* **139**, 343.