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LARGE-SCALE ELECTRIC FIELDS RESULTING FROM MAGNETIC RECONNECTION IN THE CORONA

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INTRODUCTION

Magnetic reconnection is an inevitable consequence of non-ideal MHD processes in the highly conducting coronal plasma. It occurs whenever the solar magnetic field has been stressed or topologically rearranged to the point where one or more imbedded sheet currents appear. Reconnection can take place on a wide variety of scales - ranging from small unresolved magnetic elements possibly related to the quasi-steady process of coronal heating (van Ballegooijen, 1985), to active region complexes that spawn major transient events, such as eruptive prominences, surges, and flares. Regardless of scale, however, or of the particular details of the reconnection process considered, the magnitude E_1 of the electric field in the vicinity of the neutral point (or "X"-line) is directly proportional to the merging rate, i.e. the rate at which plasma motions transport magnetic flux into the diffusion region where merging occurs:

$$E_1 = -\frac{1}{c} v_i B_i \tag{1}$$

(Petschek, 1963; Vasyliunas, 1975), where subscript i refers to quantities in the plasma inflow region near the neutral line.

At the present time the observational detection of strong d.c. E-fields at coronal heights has yet to be made but nevertheless holds promise (Foukal et al., 1983, 1984). This may ultimately provide the most direct means for probing the details of reconnection processes occurring there. In the following we have chosen to concentrate on a theoretical determination of the expected magnitude of E_1, during the decay phase of two-ribbon flares. The major characteristics of these largest and most energetic of solar events are commonly interpreted in terms of reconnection occurring over an extended time interval above the chromospheric flare site, and we regard it as quite likely that coronal electric fields will first be detected here (e.g., in the associated post-flare loop system).

ELECTRIC FIELD CALCULATED BY THE METHOD OF FORBES AND PRIEST

According to the reconnection picture of two-ribbon flares (Hirayama, 1974, Kopp and Pneuman, 1976), the leading edges of the bright Hα ribbons define at any instant the location in the chromosphere of the magnetic separatrices that meet at the coronal neutral line. Forbes and Priest (1984) used this fact to derive the interesting result that, in a cartesian system with one ignorable coordinate (i.e., 2-D reconnection), the electric field at the neutral point can be expressed entirely in terms of chromospheric quantities, namely,

$$E_1 = \frac{1}{c} V_R B_n \quad , \tag{2}$$

where V_R is the measured ribbon velocity and B_n is the normal component of the photospheric magnetic field at the ribbon leading edge. Note that the value of E_1 calculated from this expression is independent of the detailed shape of the merging coronal field lines; in particular, E_1 does not depend on the actual height of the neutral point itself.

We have applied the method of Forbes and Priest to the large two-ribbon flare of 29 July, 1973, for which both detailed Hα observations and magnetic data are available. For this flare the ribbons were long, nearly straight, and parallel to each other, and a 2-D model for the coronal field geometry may be adequate. The lower curve in Figure 1 shows the temporal profile $E_1(t)$ calculated from Equation (2), using the ribbon leading-edge velocity as determined by Moore et al. (1980) and the photospheric magnetic data published by Michalitsanos and Kupferman (1974). One sees from this calculation that, as reconnection sets in at the beginning of the decay phase, the electric field grows rapidly to reach a maximum value of about 2 V/cm within just a few minutes. Thereafter E_1 declines monotonically with time, as one would expect for any relaxation process: as more and more of the magnetic flux disrupted by the flare reconnects, the merging rate itself decreases.

MAXIMUM RECONNECTION RATE

The upper curve in Figure 1 illustrates crudely the behavior which the electric field would have, were reconnection occurring at every instant at the <u>maximum possible rate</u> allowed by compressible reconnection theory (Soward and Priest, 1982), i.e., were the merging being highly forced by the inflow boundary conditions. This maximum merging rate corresponds to

$$E_1(\max) = \frac{1}{c} B_i a_i M_A(\max) \quad , \tag{3}$$

where $a_i \equiv B_i/(4\pi\rho)^{1/2}$ is the Alfvèn speed in the inflow region and $M_A(\max)$ is an upper limit to the Alfvènic Mach number of the inflow provided by the theory. The reader is referred to Poletto and Kopp (1986) for specific details of this calculation. The important point to note is that, in addition to the general shape of the monotonic decline being similar for both curves, the maximum reconnection rate is more than an order of magnitude larger than the empirically determined rate. Thus, whereas in many physical situations (e.g. during the impulsive phase of geomagnetic storms or solar flares) reconnection is generally regarded as being strongly driven (Vasyliunas, 1975), such does not seem to be the case throughout the flare decay phase; here the merging proceeds at a much more leisurely pace dictated by dynamical relaxation of the external flow field.

RECONNECTION IN ACTUAL FLARE GEOMETRIES

Strictly speaking, the method of Forbes and Priest (1984) for calculating the electric field at the neutral line can be used only in certain 3-D geometries for which

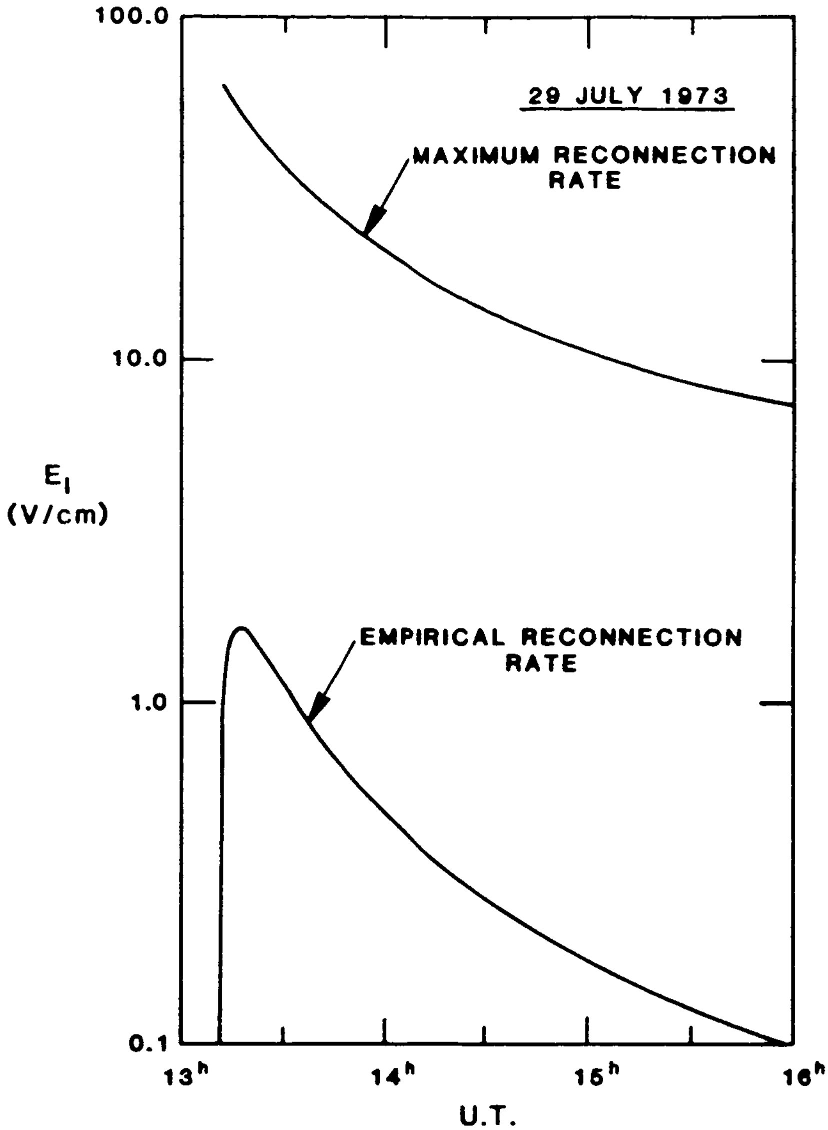

Figure 1. Time history of the electric field at the neutral line for the 29 July, 1973 flare, calculated by the method of Forbes and Priest (lower curve) and by the assumption of strongly driven reconnection (upper curve).

one coordinate is ignorable. Whereas the soft X-ray images from Skylab (Moore et al., 1980) suggest that this condition might have been approximately satisfied for the 29 July, 1973 flare, the vast majority of flares occur in regions of complex magnetic structure. We should inquire, then, as to what practical use can be made of the method in general.

Perhaps the most striking observational feature of the loop prominence systems associated with large flares, not taken into account in 2-D reconnection scenarios, is the tendency for individual loops to "lean away" from each other. Especially apparent when on occasion we view a loop system edgewise at the solar limb, this is generally attributed to an "edge effect" of the coronal magnetic field caused by the finite size of the active region (Forbes, 1985; Rust and Roy, 1971). A direct result of this "fanning out" of the loops is that the magnetic field strength B_i in the inflow region will be smaller than it would be, were the loops situated in parallel planes.

A rough estimate of this effect on the reconnection rates presented above can be made as follows. Let L denote the length in the chromosphere threaded by field lines undergoing reconnection at higher levels (i.e. the length of the Hα flare ribbons) and let L_x be the corresponding length of the X-line in the corona (i.e., the distance spanned by the tops of newly formed loops). Then, relative to the 2-D scenario described earlier, B_i will be smaller by the factor L/L_x. For a given inflow velocity v_i , E_1 (and thus the local rate of flux merging) will be smaller by the same amount. However, the maximum reconnection rate, as measured by E_1(max) in Equation (3), is proportional to B_i^2 and so decreases more rapidly than does E_1 as determined by the Forbes-Priest method. Given the uncertainties in the amount of spreading of the loops seen in the disk flare of 29 July, 1973, it is not possible to say precisely how much of the vertical displacement between the two curves of Figure 1 can be explained thusly. However, we do not consider it likely to bring them into perfect agreement in this way, as one would require $L/L_x < 0.1$ - a really large spreading factor for which there is no observational support.

In view of the paucity of empirical data on the 3-D loop geometry above any particular flare site, it is tempting to use the topological property on which the Forbes and Priest method was formulated in idealized 2-D geometries, to investigate the magnetic structure of more complex active regions. This may provide useful applications on at least two fronts. First, on the active region scale itself, we can replace Equation (2) by an integral relation for the total rate of flux merging, which gives the net potential difference Φ_1 along the coronal neutral line as a function of the instantaneous motion of either flare ribbon:

$$\Phi_1 = \int_0^{L_x} E_1(\ell_x)\, d\ell_x = \frac{1}{c}\int_0^{L} V_R(\ell)\, B_n(\ell)\, d\ell \quad , \tag{4}$$

where the first path integral is taken along the coronal X-line and the second is along the ribbon. Φ_1 may be of practical importance for explaining the continuous acceleration of particles during the flare decay phase.

Second, even lacking detailed knowledge of the coronal field structure, on a fine spatial scale it should be possible to map fieldline connections between the two flare ribbons. This is because at any point ℓ of a ribbon the quantity $1/c\ V_R(\ell)\ B_n(\ell)$ represents the local rate at which the magnetic separatrix is sweeping open flux into the growing arcade of closed loops. A newly formed closed field line should have the same value for this quantity at each of its footpoints. The fieldline connections thereby established might under ideal circumstances be compared with observed post-flare loop orientations, providing an additional test of the reconnection hypothesis. We are presently attempting to apply this method to the two-ribbon flare of 20 June, 1980.

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