QUASI-STATIC EVOLUTION OF FORCE-FREE MAGNETIC FIELDS AND A MODEL FOR TWO-RIBBON SOLAR FLARES

J. J. Aly
Service d'Astrophysique - CEN Saclay
91191 Gif-sur-Yvette Cedex, FRANCE

Abstract. We show that a sheared 2-D force-free field can evolve in a quasi-static way towards an open configuration, and apply this result to a qualitative theory of two-ribbon solar flares.

I. INTRODUCTION

A popular model for the main phase of a two-ribbon solar flare involves the reconnection of a magnetic field which has been previously blown open by some unspecified mechanism (Kopp and Pneuman, 1976). In this communication, I would like to show that such an open field can be produced (or at least closely approached) by slowly shearing, during a long enough period of time, the feet of the coronal field lines on the photosphere.

II. QUASI-STATIC EVOLUTION OF 2-D FORCE-FREE FIELDS

To show this result, let us consider a quite simple model in which the corona is taken to be the half-space $\{z > 0\}$ and the coronal field $\vec{B}$, which is force-free, is assumed to be invariant by the translations parallel to the $\hat{x}$-axis. Then we can write (Birn and Schindler, 1981) $\vec{B} = \vec{B}_p + B_x \hat{x} = \nabla A \wedge \hat{x} + B_x(A)\hat{x}$, where the potential $A(y,z)$, which can be used to label the field lines $\mathcal{C}$, as well as their projection $\mathcal{C}_p$ onto the plane $\{x=0\}$, obeys the equation

$$-\Delta A = \frac{d}{dA} \frac{B_x^2(A)}{2} . \tag{1}$$

On the other hand, we have the following relation between $\vec{B}$ and the difference $\xi(A)$ between the x-positions on $\{z=0\}$ of the left and right feet of $\mathcal{C}(A)$ (Fig. 1)

$$\xi(A) = B_x(A) \int_{\mathcal{C}_p(A)} \frac{ds_p}{B_p} = - B_x \frac{d\Sigma}{dA} \tag{2}$$

M. R. Kundu and G. D. Holman (eds.), Unstable Current Systems and Plasma Instabilities in Astrophysics, 221–224.

https://doi.org/10.1017/S0074180900075653 Published online by Cambridge University Press

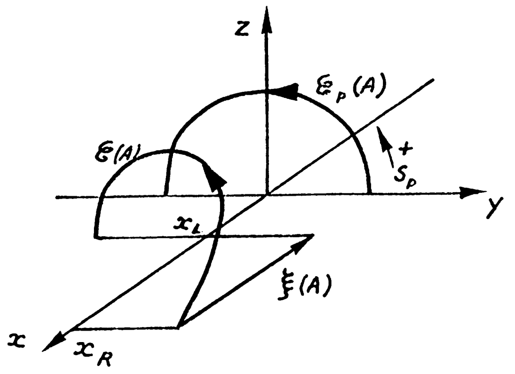

Fig. 1 Geometry of the model

where $d\Sigma$ is the area between $\mathcal{E}_p(A)$ and $\mathcal{E}_p(A+dA)$.

Let us now start from a potential configuration $A_0(y,z)$ without critical points ($\nabla A_0 \neq 0$), and apply to the feet of its lines on $\{z=0\}$ a given velocity field, parallel to the $\hat{x}$-axis. Then the coronal field is brought by electromagnetic coupling into an evolution that we suppose to be sufficiently slow for a quasi-static approximation to apply. If the embedding plasma is perfectly conducting, $\xi(A,t)$ can be assumed to be known and we will take it hereafter to be of the form $\xi(A) = \mu\zeta(A)$, where ζ is a given function and μ ($0 \leq \mu < \infty$) will be considered as a mere parameter.

If we assume that there is a continuous sequence of solutions $A_\mu(y,z)$ of (1)-(2) corresponding to these conditions, with the topology of the lines of A_μ being independent of μ, then, <u>when $\mu \to \infty$, A_μ approaches asymptotically an open field, in which all the current is concentrated in an infinitesimally thin sheet</u>.

The proof of this statement rests on the following fundamental inequality

$$\int_{\{z>0\}} B_x^2 dydz = -\mu\int\zeta(A)B_x(A)dA \leq \left[\int_{-\infty}^{+\infty} B_z^2(y,0)dy \int_{-\infty}^{+\infty} y^2 B_z^2(y,0)dy\right]^{1/2} \quad (3)$$

from which it can be deduced, with the help of (2), that $\lim_{\mu\to\infty} B_x(A) = 0$ for almost all values of A, and $\lim_{\mu\to\infty} |d\Sigma/dA| = \infty$ for almost all values of A for which $\zeta(A) \neq 0$. Then the field expands indefinitely and it approaches a configuration with open lines in which the current must necessarily be concentrated in singularities. Those can be shown to form

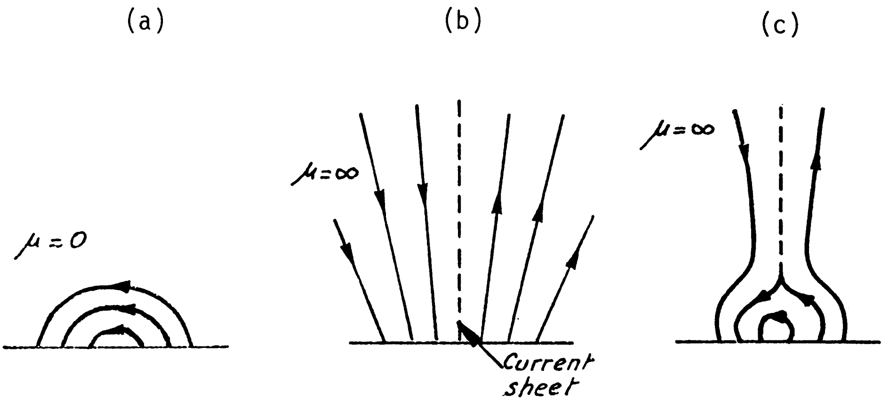

Fig. 2 Totally (b) and partially (c) open configurations which can be approached by large shearing of a potential field (a). See text for details.

a current sheet going to infinity and starting either from (0,0) at which $B_z(0,0) = 0$ (if $\exists a > 0$, $\zeta[A(y,0)] \neq 0$ for $y \in]0, a[$ (Fig. 2b), or (if $\exists\, b > 0$, $\zeta[A(y,0)] = 0$ for $y \in [0,b]$), from the line separating the region where $\zeta(A) \neq 0$ from the region around (0,0) where $\zeta = 0$ (Fig. 2c).

It is worth to note, to support our assumption on the existence of the sequence A_μ, that an explicit example having $\xi[A(y,0)] = \mu|y|$, has already been computed (Birn and Schindler, 1981).

III. APPLICATION TO THE THEORY OF TWO-RIBBON SOLAR FLARES

Let us now return to the problem of the origin of the two-ribbon flares, for which we suggest the following simplified scenario, in which the previous asymptotic result is included along with ingredients already proposed by other authors. At first, there is a préflare phase, which can be divided into two stages: in the first one, the magnetic structure, which is supposed to be sheared by photospheric motions parallel to the inversion line, does not change very much, but a large amount of energy is stored in it; in the second one, the field expands and is brought into a quasi-open configuration. This configuration however is resistively unstable and a tearing mode develops. That the sheared magnetic structure is not destroyed by such an instability before reaching the quasi-open configuration may be due either to the fact that the shearing process is fast enough for the tearing mode to not fully develop in the mildly sheared field, or to the existence of a stabilizing effect (line tying?...) whose effectiveness decreases when the field is stretched out. The tearing mode initiates a large scale reconnection process, which proceeds at a rising neutral point and releases the free magnetic energy stored in the configuration. This process is responsible for the appearance of the hot coronal flare loops and of the two receding bright H_α ribbons on the photosphere, as in Kopp and Pneuman's model. However, as our field is not really open, reconnection ceases after some period of time, and one is left with a configuration with almost zero shear but with a suspended weakly twisted flux tube (magnetic island). In accord with Svestka's interpretation (1983), the gigantic stationary arche, recently observed above two active regions where two ribbon flares occurred, may be identified with such a tube, assumed to be in equilibrium.

The results reported in this paper have been obtained during a stay of the author at the University of Illinois at Urbana, and the University of California at Berkeley, supported in part by a CNRS-NSF exchange grant, and by NASA grant NSG 7653 and NSF Grant PHY80-25605 at Illinois.

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