Magnetic Reconnection in the Solar Atmosphere
ASP Conference Series, Vol. 111, 1996
R.D. Bentley and J.T. Mariska, (eds.)

3D Magnetic Reconnection: Example of an X-Ray Bright Point

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Abstract. In the classical view magnetic reconnection occurs at neutral points and implies transport of magnetic field-lines across separatrices. Here we show that reconnection may also occur in the absence of neutral points at so-called "quasi-separatrix layers" (QSLs), where there is a steep gradient in field-line linkage at the boundaries. Reconnection occurs in QSLs where the field-line velocity becomes larger than the allowed maximal plasma velocity or where the electric-current density becomes too great. We describe both a theoretical and an observed configuration. In the case of a simple sheared X-field we show that even a smooth continuous shear flow, imposed at the boundary, gives strong plasma jetting inside and parallel to the QSLs. Applying the QSL method to an X-ray bright point observed by *Yohkoh*, we find field lines in the extrapolated field which are on both sides of QSLs and which are in good agreement with loops observed in Hα and X-rays related to emerging flux. The evolution of the QSL width may explain the brightness evolution of the XBP.

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1. Introduction

In previous papers we have analyzed the magnetic topology of flaring active-regions (Mandrini et al., 1995; Démoulin et al., 1994b; van Driel-Gesztelyi et al., 1994; Bagalá et al., 1995 and references therein). Our results show that solar flares represent a conversion of magnetic energy by magnetic reconnection. We found that Hα brightenings are invariably located along sections of regions where the computed separatrices intersect the photosphere and which are linked in pairs by magnetic field-lines. The 3D coronal magnetic field was computed by extrapolating the field of a set of subphotospheric magnetic sources, instead of using a more conventional extrapolation technique. The sources were chosen to match the observed photospheric field as closely as possible. The topology was defined by the linkage between these sources. It is now clear that the magnetic structure plays an important role in flares and that we need to characterize the connectivity of the coronal fields, in a general way, without any reference to null points or field lines tangent to the photosphere because generally these features are not present in flaring configurations (Démoulin, Hénoux and Mandrini, 1994a); however, they should be included as particular cases.

With the new concept of quasi-separatrix layers (QSLs), summarized in Section 2, we can go further in the understanding of the observations. First, the model of the coronal field is only limited by our ability to derive it directly from the observed photospheric magnetic field. Second, the locations of QSLs are spatially more restrictive than those of the separatrices, since QSLs are located only along a fraction of the separatrices defined by sources (see Démoulin et al., 1996b). Finally, QSLs have generally a finite thickness that is associated with the rate of reconnection, while the topology computed using sources contains separatrices that are infinitely thin (by definition).

2. Quasi-Separatrix Layers

In the solar context, Berger (1988), Priest (1988) and then Priest and Forbes (1992) have proposed that 3D magnetic reconnection may occur, in the absence of null points, at separatrix layers. Independently, the study of several flares convinced us that the magnetic structure plays a key role in determining the location of the energy release. Consequently, we developed a general method to determine the topology of extrapolated coronal fields (Démoulin et al., 1996b). The method is applicable to any kind of field configuration and is summarized below. We are interested in locating the region where a rapid change in field-line linkage occurs, i.e. where field lines initially close to one another separate widely over a short distance. Let us integrate, in both directions over a distance s, the field line passing through a point $\mathrm{P}(x, y, z)$ of the corona. The points (x', y', z') and (x'', y'', z''), which are the coordinates of the two end points, define a vector $\vec{D}(x, y, z) = \{X_1, X_2, X_3\} = \{x''-x', y''-y', z''-z'\}$. A rapid change in field-line linkage means that for a slight shift of point $\mathrm{P}(x, y, z)$, $\vec{D}(x, y, z)$ varies greatly.

The norm $\tilde{N}$, defined by

$$\tilde{N}(x,y,z,s) = \sqrt{\sum_{i=1,3}\left[\left(\frac{\partial X_i}{\partial x}\right)^2 + \left(\frac{\partial X_i}{\partial y}\right)^2 + \left(\frac{\partial X_i}{\partial z}\right)^2\right]}, \tag{1}$$

allows us to locate the region of rapid change in connectivity for a given value of s. The value of s can be limited either by a physical boundary or by the distance reached by waves during the reconnection process, say s_w. This definition looks well suited both for magnetic regions with field lines not reaching a boundary (as in tokamaks), and also for a reconnection process taking place in a time shorter than needed for information to travel from the reconnecting region to the boundary. In cases with line-tying to the boundary, the relevant s should be the minimum of s_w and the distance to this boundary. In many solar events, the whole process takes place in a fraction of hour, which is much longer than the Alfvén crossing time for the structures and so the distance to the photosphere should be used (so $z' = z'' = 0$).

In the approximation of an abrupt transition from a low- to a high-β plasma, line-tying is imposed at the photospheric level ($z = 0$): the location in the photosphere of the magnetic field-line footpoints is imposed as a function of x and y (and not z). Then

$$N(x,y) = \sqrt{\sum_{i=1,2}\left[\left(\frac{\partial X_i}{\partial x}\right)^2 + \left(\frac{\partial X_i}{\partial y}\right)^2\right]} \tag{2}$$

is the norm of the displacement gradient tensor, defined when mapping the field lines to the boundary; it is evaluated only on the boundary, stressing the particular role of line-tying. The locations of high values of $N(x,y)$ define the field lines involved in the QSLs, and so following these field lines we can locate the coronal part of the QSLs.

The simplest magnetic field with QSLs is a sheared X-field in a finite volume of size L: $B_x = x/L$, $B_y = -y/L$, $B_z = l$. We find that QSLs exist when the field component in the z-direction is weak compared to its maximum value in the x- and y-directions ($l << 1$). The norm N is of the order of $1/\epsilon$ in QSLs of width ϵL about the xz- and yz-planes, where $\epsilon = \exp(-1/l) \ll 1$.

Reconnection may occur at QSLs with a breakdown of ideal MHD and a change of connectivity of plasma elements even when a smooth boundary motion is imposed. This occurs because the imposed boundary velocities are typically amplified by a factor $\exp(1/l)$, so that the field-line velocity greatly exceeds the possible plasma velocity, typically the Alfvén speed (Figure 1). The consequence of this is that an electric field component is produced in the layer along the magnetic field and the field lines slip rapidly through the plasma.

However, if the evolution of the magnetic field is sufficiently slow, or if the QSLs are thick enough, the above breakdown of ideal MHD does not occur. Rather, Démoulin et al. (1996b) have shown that concentrated currents are naturally formed at QSLs. This is so because the effect of photospheric displacements is augmented in these thin regions. Along the QSLs two neighbouring field lines are subjected to different photospheric motions since their opposite footpoints are separated by a great distance; therefore, electric currents are mainly created

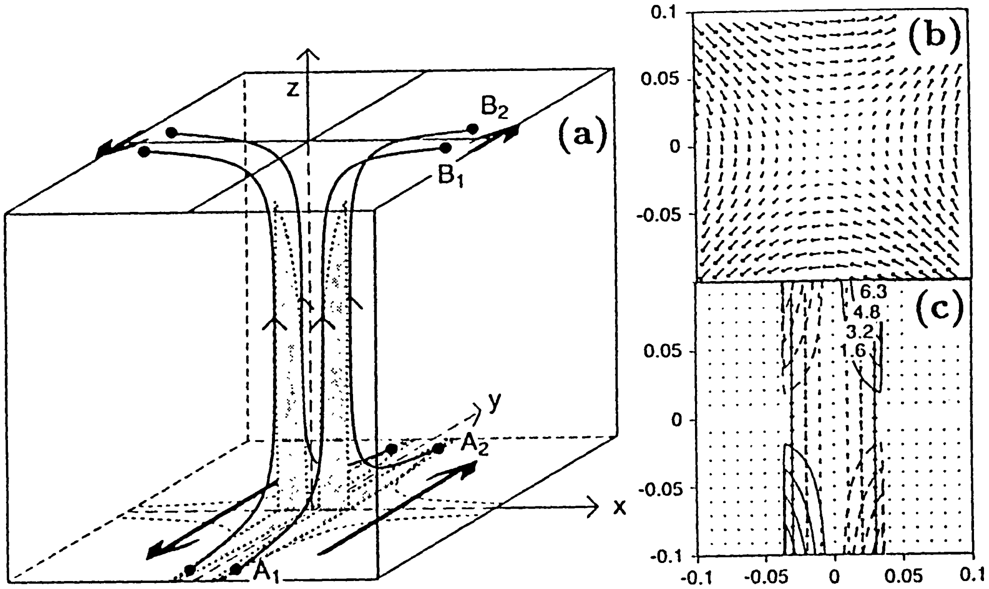

Figure 1. (a) Reconnection by magnetic flipping, driven by a slow continuous footpoint motion from B_1 to B_2 and producing a rapid slip of field lines from A_1 to A_2 in diffusive layers (shaded) near a quasi-separatrix layer. (b) Example of a regular flow applied on the top of the boundary cube (normalized to $v_{max} = 1$). (c) Ideal MHD produces at the bottom boundary concentrated and strong flows ($v_{max} = 190$ with $l = 0.3$).

at the QSLs. For a smooth photospheric flow pattern the current density is expected to be larger where the QSL is thinner. However, at the places where QSLs are too thin, say lower than a certain δ_{crit}, reconnection is initiated and the free magnetic energy is released. At the places where $\delta > \delta_{crit}$, mainly electric current build-up is achieved until a threshold is reached (e.g., a current-driven instability); then, there is a brusque release of magnetic energy. In conclusion, QSLs seem to possess all the prerequisites for flaring since energy can be stored and released there!

3. Evidence of Magnetic Reconnection at an X-Ray Bright Point

Ground-based optical observations, coordinated with those of *Yohkoh*/SXT of an old, disintegrating bipolar active region (NOAA 7493), provided a multiwavelength (magnetic fields, Hα and X-rays) data base for the study of a flaring X-ray bright point (XBP) of about 16 hours lifetime (van Driel-Gesztelyi et al., 1996). The XBP is related to the emergence of a minor bipole of about 10^{20} Mx. Rather than having a round shape, it was a loop-like feature linking the new negative polarity to an old positive polarity facular region. Other X-ray loops (FXL), much longer and fainter, are linked to the XBP. Extrapolating the photospheric magnetic field, we find field lines in good agreement with the observations both of the emerging flux (seen in Hα as an arch filament system) and the soft X-ray loops (XBP and FXL) as reported by Mandrini et al. (1996). The photospheric

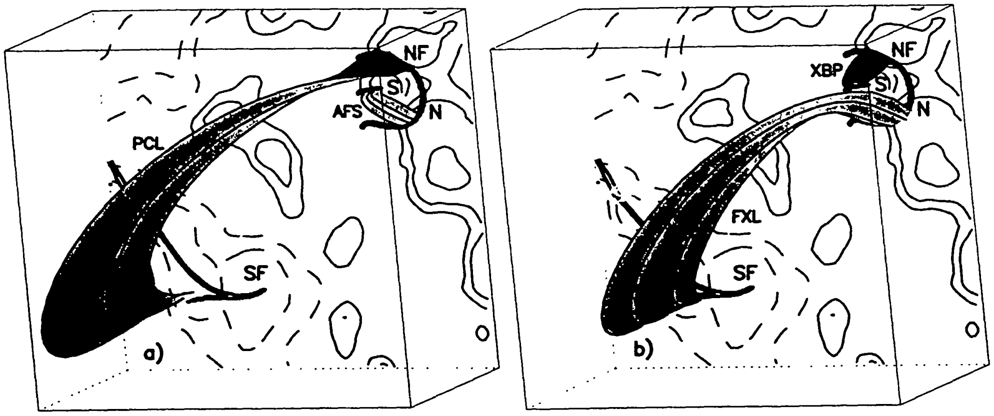

Figure 2. Extrapolated coronal field-lines related to an XBP. The QSLs are indicated by the thick isocontour of $N = 20$ at the photospheric level. The four sets of computed field lines (drawn with surfaces) have their footpoints along the borders of the QSLs. In (a) the emerging flux (AFS) impacts against the pre-existing coronal loops (PCL). In (b) the reconnected field-lines appear as the X-ray bright point (XBP) and the faint X-ray loops (FXL). The related photospheric flux concentrations are denoted by letters N, NF, S and SF, indicating their polarities ($B_l = \pm$ 40, 100 and 400 G).

footpoints of these field lines are at both sides of the computed quasi-separatrix layers (QSLs), as expected from a 3D reconnection model (Figure 2). We show that the X-ray loops, XBP and FXL, were due to reconnection between the field lines corresponding to the new bipole and the pre-existing plage fields, and that this process was induced by the motion of one of the new pores towards the old plage with a velocity of 0.2 km s^{-1}.

Our results agree with those of Parnell et al. (1994) showing that the studied X-ray bright points can be interpreted, using magnetic field-line computations, as being reconnected magnetic loops. In the present work we put forward the evidence. First, we use a direct extrapolation of the observed photospheric magnetic field rather than discrete magnetic sources. Second, we use a more sophisticated technique to compute the "topology" of the magnetic field using the knowledge gained from flare modelling. Third, we have had the opportunity to analyse the observed motion of the emerging flux during half a day. This motion is shown to be consistent with the evolution of the locations of X-ray loops. The evolution of the thickness of the QSL allows us to explain the global evolution of the X-ray intensity: initially the thickness decreases and the brightness increases, while later on the thickness becomes too large to allow significant magnetic energy release. Steady magnetic reconnection is probably induced in QSLs that are thin enough ($\delta < \delta_{crit}$). Superimposed on this global evolution of soft X-ray brightness, the XBP displays flaring episodes lasting for 1–10 minutes. This may be related to the successive build-up and release of electric currents at the places where QSLs are thick enough ($\delta > \delta_{crit}$). Finally, we show how the energy propagates along the long reconnected loops (FXL). The energy is released where the emerging bipole (AFS) impacts against the pre-existing coronal loops (PCL). Then, we conclude that the energy transport along the FXL is due to both fast particles and conduction fronts; the presence of the latter is mostly evident in soft X-rays.

4. Conclusions

In 3D magnetic configurations, both from theoretical and observational investigations, we find the need to generalize the concept of separatrices to quasi-separatrix layers (QSLs). QSLs are regions where the magnetic field-line linkage changes drastically (discontinuously in the limit of separatrices) and where ideal MHD may break down. Applying the QSL method to an X-ray bright point, we find field lines whose photospheric footpoints lie at both sides of QSLs, in good agreement with the loops observed in Hα and X-rays. In other studies (see references in the Introduction), we have found that the location of Hα flare brightenings is related to the properties of the field-line linkage of the underlying magnetic region. Furthermore, analysing twisted configurations (see Démoulin et al., 1996a), earlier we have found that the J-shape of the QSLs is typical of the shape of the ribbons observed in Hα and that reconnected field lines (twisted ones above arcade-like ones) are found in some eruptive flares observed by Yohkoh (see for example Manoharan et al., 1996 and this volume). Altogether these results strongly support the hypothesis that magnetic reconnection is going on in various coronal phenomena, ranging from XBPs to large-scale eruptions.

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1997ASPC..111...49D

Coronal Heating