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A NEW CONCEPT FOR MAGNETIC RECONNECTION : SLIP-RUNNING RECONNECTION

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Abstract. In magnetohydrodynamics (MHD), most models of magnetic reconnection suppose that this mechanism takes places when the magnetic field configuration contains separatrices. Separatrices are surfaces through which the magnetic field connectivity is discontinuous. But such topological structures are not always present when solar flares takes place. Quasi-separatrix layers (QSLs), which are regions of strong variations of magnetic connectivity, are a generalisation of separatrices. Using a 3D MHD simulation of several solar-like magnetic configurations containing QSLs, we investigated the link between the build-up of current layers and the location of QSLs. Thin current sheets are naturally formed along QSLs whatever the line-tied boundary driven motions are. When the line-tied driving is suppressed, magnetic reconnection is solely due to the self-pinching and dissipation of narrow current layers. In this reconnection process, field line continuously slip along each other while they pass through the current layers. This *slip-running reconnection* may naturally account for the fast motion of hard X-ray sources along chromospheric ribbons, as observed during solar flares.

1 Introduction

Due to its low plasma β, the solar corona is a medium which is governed by magnetic fields. The energy which is needed to power intense flares and to sustain quasi-steady coronal heating is there stored in non-potential magnetic fields. In plasmas with a high Reynolds number, MHD theory states that magnetic energy can only be released in localized regions where magnetic fields have small-scale gradients, i.e. in narrow current layers. The diffusion of magnetic fields in such current layers naturally leads to magnetic reconnection (Sweet 1958). During confined and eruptive solar flares, this process is believed to occur in magnetic configurations that have a complex topology (Démoulin 2006).

Complex topologies can be separated into two classes, first the ones defined by separatrix surfaces and second the ones defined by quasi-separatrix layers. Separatrices are formed by the ensemble of magnetic field lines which pass either through a null point or through a bald patch (BP, Titov et al. 2002). The connectivity of magnetic field lines is discontinuous across separatrices. But all flaring events cannot be related to such kind of topologies (see for example one of the 28 october 2003 X-class events studied in Mandrini et al. 2006).

Quasi-separatrix layers (QSLs) are narrow volumes across which the magnetic field connectivity remains continuous, though it has strong variations (Priest & Démoulin 1995; Démoulin et al. 1996). A QSL is a purely three-dimensional object (see Fig.1, left panel). In a given QSL, the connectivity gradients are the largest in the sub-region where the squashing degree Q (defined by Titov et al. 2002) peaks to its maximum value, which is known as the hyperbolic flux tube (HFT).

In the case of separatrices, the spontaneous formation of current sheets for any line-tied motion has been shown analytically and numerically. In the case of QSLs (and HFTs), this has not been demonstrated as clearly, mostly because of mathematical and conceptual difficulties. In Aulanier et al. (2005b), we performed new numerical experiments to address the question : can intense current layer naturally form along QSLs ?

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2 Current layer formation along Quasi-Separatrix Layers

Using a 3 dimentional zero-β MHD simulation (see code description in Aulanier et al. 2005a), we modeled realistic solar magnetic configurations (i.e. with one single line-tied plane, closed magnetic field lines and magnetic field decreasing away from well-defined flux concentrations). The initial “quadripolar” configuration formed by a main dipole and and less intense central one, which axis forms a non-null angle [π] with the axis of the main dipole (see Fig. 1, right panel). Such configurations contain no separatrix but QSLs (and a HFT).

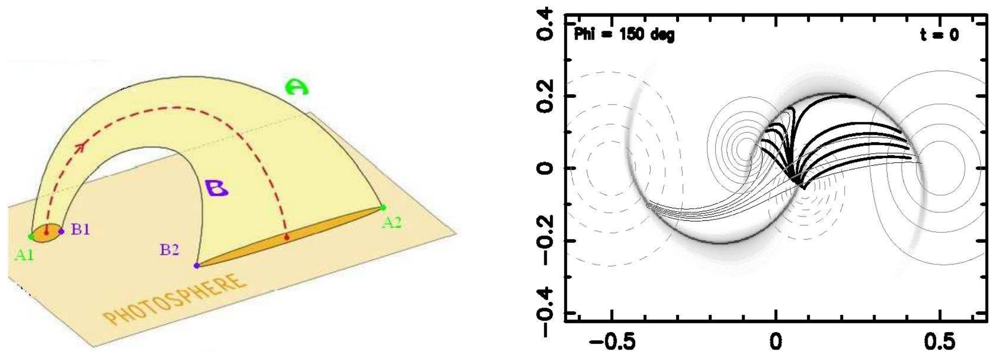

Fig. 1. Left : cartoon of a QSL (adapted from Titov et al. 2002). The central field line presents strong gradients of connectivity : the ratio of the length A2B2 to A1B1 is much larger than 1. **Right** : example of the initial configuration of our numerical simulation seen from the top. The isocontours are those of the magnetic field. The background image plots the squashing degree Q and localise the QSLs on the bottom boundary. The extrapolated field lines reveal the strong gradients of connectivity in the QSLs

In order to generate electric currents, we applied different kinds of motions (translation and twisting motions) along the bottom boundary, within the positive central polarity. We found that, as conjectured by Démoulin et al. (1996), narrow current layers spontaneously develop all along the QSLs, for any smooth and large-scale footpoint motion. We also found that the strongest currents always develop in the vicinity of the HFT (see Fig.2). Though, the detailed shape and magnitude of these current layers still depend on the boundary driving.

We also found that in magnetic configurations which initially contained broader QSLs, the electric currents in the HFT increased to higher magnitudes when the magnetic field gradients reached the dissipative scale. Then if the fast energy release is not the result of a global instability, as in our simulations, the narrower the initial QSLs are, the shorter time it takes to reach the dissipative scale and the less energy is accumulated before (and released during) a flare-like event. This implies that the most energetic solar flares must occur in magnetic configurations which corresponding potential field have broad QSLs. This is rather counter-intuitive if one considers the long history of the separatrix-related flare models which involve the formation of long current sheets, that are spontaneously infinitely thin, during the energy build-up phase.

Considering that current sheets do naturally form along QSLs in a similar way as they do in separatrices, a question which then arises is, what is the nature of magnetic reconnection in QSLs (and HFTs) ?

3 Reconnection in Quasi-Separatrix Layers

The question of separatrix-less reconnection was first addressed by Hesse & Schindler (1988). They demonstrated that the existence of parallel electric and magnetic fields was the condition for general 3D reconnection. When reconnection occurs without true 3D separatrices, Priest & Forbes (1992) suggested that magnetic field lines must slip along each other, along so-called magnetic flipping layers. Under the assumption that field lines simply exchange their connectivity with that of their neighbors, as one of their footpoints is displaced in time across a QSL, Priest & Démoulin (1995) proposed that magnetic flipping occurs in a QSL when the sub-Alfvénic displacement of one field line footpoint across the QSL results in a super-Alfvénic displacement of the other footpoint. Though, such mechanism is hardly justified in the frame of MHD.

As initial conditions we use the outputs of the previous simulations, starting from a time where the current layers were sufficiently developed in the QSLs, while they still remained resolved over several mesh points. All velocities are reset to zero and we used the same numerical code to perform zero-β resistive MHD relaxations

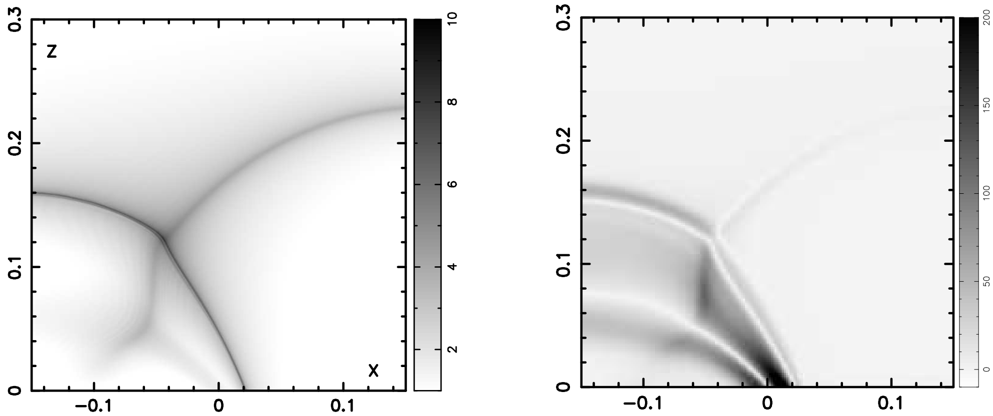

Fig. 2. Images of 2D vertical slabs (in x, z) at $y = -0.12$ of the QSLs and HFT for the configuration evolved with twisting motions. (**Left panel**): logarithm of the squashing degree. (**Right panel**): magnitude of the electric currents. Intense thin current layers naturally form where the gradients of connectivity are the strongest.

of the initial stressed magnetic field configurations. Three relaxations were performed for each configuration, using three different values for the uniform resistivities.

Whatever the values of the resistivity, during the relaxation, one observes a collapse of the intense currents layers that were formed during the previous simulations. Their collapse is due to the action of residual Lorentz forces. Even if QSLs are not so far from being force-free, the related Lorentz forces are there the strongest in the whole domain. These forces do not decrease very quickly in time. The force vectors are all directed more or less perpendicular to the QSLs and they have converging patterns toward the QSLs.

The collapse of the narrow current layers results in magnetic reconnection. The reconnecting current layers are at the location of the strongest currents along the QSLs (see j map in Fig. 2). These currents are nearly aligned with the magnetic field. So the strongest field-aligned resistive electric fields are co-spatial with the 3D reconnecting layers in our QSL configurations. Our calculations thus nicely follow the conditions for general magnetic reconnection in 3D (Hesse & Schindler 1988).

The magnetic reconnection is associated with the formation of sub-Alfvénic plasma jets. These jets diverge from the diffusive layers, and their velocity component along y has about the same amplitude as those in the $(x; z)$ plane. The outflow velocities in the reconnection jets are much lower than the perpendicular Alfvén velocity. This shows that the 2.5D Sweet-Parker reconnection regime is not reached in our 3D relaxations.

In spite of the fact that the MHD relaxations are performed using $\vec{u}(z = 0) = \vec{0}$ and $\eta(z = 0) = 0$, some magnetic field lines do not remain anchored at the same position in the line-tied bottom plane. Fig. 3 shows how such field lines gradually slip along one another. Each of them is integrated from a fixed footpoint position in the negative polarity, in the vicinity of a QSL. Their conjugate footpoints all move along the same arc-shaped trajectories at $z = 0$, from the positive polarity of the outer bipole to that of the inner bipole, or in the opposite direction, depending on the field line. The same process occurs more-or-less (but not exactly) symmetrically for field lines with fixed footpoints in the positive polarity.

While field line slippage has already been reported in MHD simulations of magnetic reconnection in a straight and stressed HFT (Pontin et al. 2005), the present calculations reveal that the arc-shape trajectories on both sides of inversion line correspond to the intersection of the QSLs with the line-tied plane. The tracking of field line footpoints suggests that some of them slip at velocities of the order of the Alfvén speed along the arc-shaped QSL. The speed of this process lead us to call it *slip-running reconnection*, in opposition to mild and slow diffusive slippage. More details about this reconnection process can be found in Aulanier et al. (2006).

These displacements do not correspond to real bulk motions, but to the rearrangements of the global field lines as a result of reconnection. Indeed, the magnetic field is locally and gradually diffused within the current layers. Field lines must naturally exchange their connectivities with that of their neighbors, in a continuous way. This is the physical origin of field line slippage in QSL reconnection, as already reported in past MHD experiments.

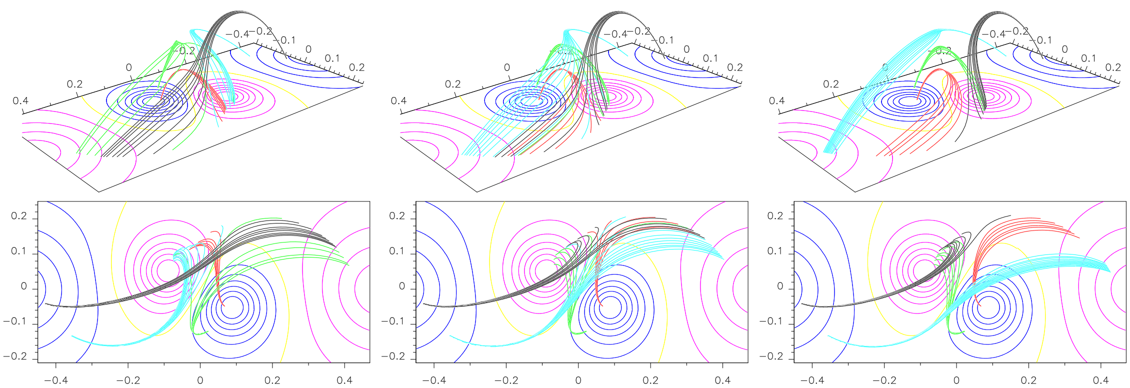

Fig. 3. Slip-running field lines at different times (left to the right). The contours of $b_z(z=0)$ are the same as in Fig. 1. At each time, each field line is integrated from the same footpoint position, in the negative magnetic polarity, near the intersection of the QSL with the bottom plane. For a given field line, the fixed footpoints are placed along a very short line-segment orthogonal to QSL. The (**upper ; bottom**) rows show (projection ; top - along z) views respectively.

4 Discussion

In terms of current formation, we showed that QSLs behave as separatrices. QSLs/HFTs can therefore play an equal role as separatrices/separators do, at least in the triggering of solar flares but also in the heating of the solar corona. We also reached the interesting conclusion that, when QSLs are thin enough, the slippage velocities of the field lines can be so fast that Alfvén waves traveling along them do not have the time to propagate from one footpoint to another. It follows that on MHD time-scales, such slipping field lines can physically behave nearly as if they were reconnecting at separatrices, i.e. as if they instantaneously changed their connectivities. We call this new phenomenon *slip-running reconnection*. It fills the continuous gap between two extreme regimes: abrupt field line reconnection in separatrices (i.e. infinite slippage velocity) and very slow field line diffusion in braided flux tubes.

The absence of artificial symmetries in our models also permits us to reveal reconnections in opposite senses at the same time in different locations in the QSLs, and they allow us to derive observational consequences for the evolution of EUV and hard X-ray emission along flare ribbons. Slip-running reconnection offers a simple explanation for the puzzling motions of hard X-ray (HXR) sources, which move along chromospheric ribbons, as observed in many solar flares (Bogachev et al. 2005). Particles accelerated by electric fields from a single coronal diffusion region within the QSLs, should quickly travel along field lines which footpoint positions gradually move along the intersection of the QSL with the chromosphere, as slip-running reconnection proceeds.

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