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Elementary heating events – Magnetic interactions between two flux sources

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Abstract. Observations taken by the SoHO MDI instrument have revealed that the quiet photospheric magnetic flux is, on average, recycled within a few days. As new flux emerges from the convection zone into the photosphere it is moved around by horizontal motions resulting from overshoots of convection cells. These motions cause the magnetic fields extending from flux fragments to tangle, forcing different magnetic flux systems to interact. Only the process of magnetic reconnection limits the complexity of magnetic field line connectivity. The energy liberated by these detangling or destressing processes act as a natural energy source which may heat the solar coronal plasma.

In this paper, we use a numerical approach to solve the MHD equations in a three-dimensional domain to examine the dynamical behaviour of one simple magnetic flux interaction. The model consists of a uniform magnetic field overlying two flux sources of opposite polarity that are initially unconnected and are forced to interact as they are driven passed each other. We find that the development from initially unconnected sources to connected sources proceeds quite quickly and simply. This change takes place through driven separator reconnection in a systematically twisted current sheet. The out flow velocity from the reconnection is highly asymmetric with much higher velocities in the region defined by the field lines connected to both sources. However, the change back to two independent sources after the nearest approach has past takes place on a much longer time scale even though the distance between the sources increases significantly. This is because the opening of the field has to take place through separatrix reconnection and at this phase of the development there are no forcing of the fluxes to drive a fast opening of the magnetic field.

Key words: Magnetohydrodynamics (MHD) – Sun: general – Sun: magnetic fields – Sun: photosphere

1. Introduction

The upper solar atmosphere, the corona, is a highly dynamical environment dominated by the presence of the Sun's magnetic field. It is well known from observations that the corona contains hot, tenuous plasma with temperatures of over a million degrees. However, it is not known how these temperatures are maintained. It is generally accepted today that the magnetic field plays a vital role in the process of energy transport from the convection zone into the corona where the energy is stored as free magnetic energy for a period of time before being released as thermal or kinetic energy. Different mechanisms have been suggested for these processes. They are traditionally divided into two groups depending on the ratio of the driving time of the perturbation to the Alfvén crossing time of the magnetic loops. In a dynamical environment, such as the solar corona, the distinction between the two may not be as clear cut because many interactions may occur on different length and time scales simultaneously.

To understand the evolution of the magnetic field we need to know how the flux sources in the photosphere change with time. It is well known that the magnetic field distribution in the Sun's atmosphere is highly irregular with most of the magnetic flux being concentrated into flux tubes connecting down to the photosphere at the locations of sunspots or active region plage areas. However, outside these regions, in what is known as the quiet Sun, the majority of flux is anchored in multiple small magnetic fragments each with a flux of about 10^{18} Mx. These fragments move along the edges of supergranule cells at about 0.1 to $0.5\,\mathrm{km\,s^{-1}}$ (Priest et al. 1994a and references therein). Cancellation or coalescence can occur between fragments if they interact with each other. Flux lost through cancellation is replaced through the emergence of bipolar regions at such a rate that the total absolute flux in the quiet Sun remains constant at about 2×10^{23} Mx. It is known that the emerged bipoles do not cancel with themselves, but always interact and cancel with other surrounding fragments. This can only occur through magnetic reconnection. Furthermore, the rate of flux emergence is such that over a period of about 2 days sufficient new flux is injected into the quiet photosphere as to completely replace all the existing flux there (Schrijver et al. 1998). Clearly this implies that many small magnetic reconnection events must be continuously occurring throughout the quiet corona.

Simultaneous observations taken of both the corona and the photosphere reveal evidence for heating in the corona above sites of cancellation and, therefore, one presumes sites of reconnection (Priest et al. 1994a). This evidence comes in the form

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of X-ray bright points, small multiple-loop-brightening events that occur throughout the quiet corona (Golub et al. 1979; Harvey 1985; Harvey 1984). Such events typically last for between a few minutes up to a day and release between 10^{25} and 10^{27} ergs. Harvey 1985; Webb et al. 1993 showed that more than 75% of bright points occur above sites of cancellation whereas at most 25% occur are associated with emerging flux regions.

In 1994, Priest et al. 1994a developed the Converging Flux Model for an X-ray bright point that naturally explained the observations. In this two-dimensional model two opposite polarity flux sources were situated in an overlying field such that initially the sources were unconnected. By calculating equipotential states for the flux sources located at ever decreasing separations they showed that the flux in the fragments starts to connect. As more and more flux links the two sources a neutral point rises up above the surface then back down again. Comparing the energies in these fields with that in a field where no connection changes have been allowed, i.e., one in which a current sheet has grown, they demonstrated that energy should be released through such a process. This process has been investigated numerically by Rickard & Priest 1994 and the potential picture of the reconnection location and structure was confirmed.

Although cancellation appears to be very important for the heating of X-ray bright points it is not the most important magnetic interaction event with respect to the heating of the quiet corona. This is because there simply are insufficient numbers of cancellations to explain the estimated heat losses of about $3 \times 10^5\,\mathrm{ergs\,cm^{-2}\,s^{-1}}$ from the quiet solar corona (Withbroe & Noyes 1977). If we estimate that each cancellation of 10^{18} Mx releases 10^{27} ergs (i.e., that a volume 10^{16} cm^2 by 10^8 cm containing a 30 G magnetic is reconnected) then over a 2 day period in which all the flux in the quiet sun is replaced, there will be approximately 2×10^5 such cancellations. However, this only produces a total of $1.7 \times 10^4\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, just 6% of the energy required to heat the quiet solar corona. Clearly, if the quiet corona is heated by magnetic reconnection, other magnetic interactions must occur. These include emergence of flux, which will produce a similar energy deposition rate as the cancellations, and so called “fly-bys” of magnetic fragments. Fly-bys result from the movement of fragments past one another with out cancellation. The numbers of such interactions are difficult to estimate, however, since they do not result in the actual loss of flux, just the transfer of flux. The numbers of such interactions are only limited by the freedom and speed of movement of the magnetic footpoints. Hence, it is possible that this is where the missing energy to heat the quiet corona arises.

The simple model by Priest et al. 1994b discussed above has been extended into three dimensions where more complicated situations can arise. The direct interaction between two sources becomes richer in the sense that now sources can interact without directly colliding, but just by passing each other within a given distance. Such interactions have been investigated by Longcope 1998. His three-dimensional model consists of two flux sources and a constant overlying magnetic field, as in the Converging Flux Model. However, now by varying the direction and strength of the constant magnetic field, the flux from the sources interact at different locations as they move around on the surface plane. In the simplest approach, this is found to drive separator reconnection as the two flux volumes are moved past each other.

More complicated scenarios have also been investigated, in an attempt to represents observations of bright points (Parnell et al. 1994; van Driel Gesztelyi et al. 1996). In these situations four or more sources were used. The location and strength of the sources were determined from magnetogram data and the topology of the extrapolated potential or constant-alpha force-free field investigated. These extrapolations appeared to successfully match up with the observations and, therefore, these models have been assumed to be valid models of the dynamical evolution of the magnetic field for the particular bright points studied. Clearly, though to understand properly how bright points or other small reconnection events are created and maintained the detailed behaviour of the plasma as well as the magnetic field must be investigated.

Until now just one numerical experiment had been conducted in three-dimensions in an attempt to model a bright point. In this model just the simple configuration of two opposite polarity sources converging head on in an overlying field were investigated (Dreher et al. 1997). Although this model revealed that energy could be released though both compression and reconnection due to its high degree of symmetry it does not represent a typical fundamental interaction between two initially unconnected flux sources.

In this paper, we investigate for the first time the dynamical evolution of a three-dimensional field configuration that resembles a typical interaction of two flux sources in an overlying field. That is, we analyse in detail the dynamics of what is likely to be a fundamental coronal heating event. The model setup is very similar to Longcope 1998, in that we investigate the dynamical changes in the magnetic field configuration as two opposite polarity magnetic sources lying in a uniform field move past each other. However, unlike Longcope 1998, we have solved the full set of non-ideal MHD equations numerically.

The emphasis in this paper is on the dynamical changes in the field line connectivity, with a discussion on the different types of magnetic reconnection that are found to be important for the dynamical evolution of the magnetic field. Analysis of the energy release provides us with information about the locations where hot dense plasma would be seen. A simple attempt to model the observational signature of the event has therefore been made.

In this paper, we only look at one particular set of initial conditions. In a second paper (Galsgaard et al. 2000a) we discuss the implications of changing the orientation of overlying magnetic field and try to relate the energy release found in these experiments to a characteristic event on the Sun.

The layout of the paper is as follows. The first section discusses the basic model and the numerical approach in more detail. The second section gives a general description of the dynamical evolution, followed by a more detailed discussion

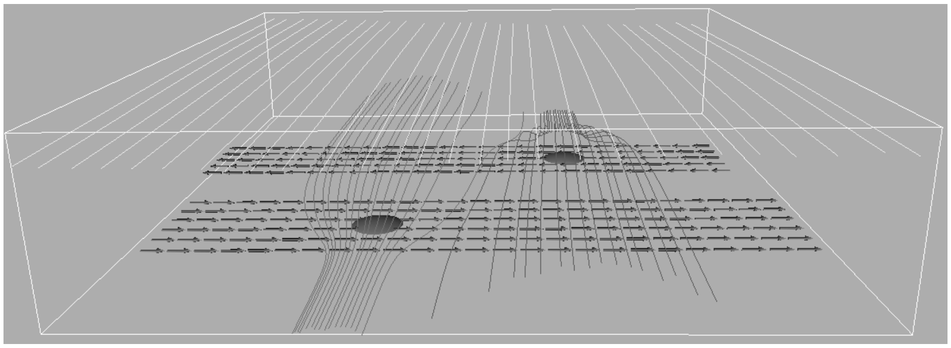

Fig. 1. The initial layout of the magnetic field topology. The isosurfaces indicates the locations of the two sources. The field lines indicate the locations of the magnetic separator surfaces that divides space into three independent flux regions and the overlaying open field. The vectors represent the topology of the imposed boundary driving.

on the two types of reconnection that occur and their relative importance for the changing connectivity and energy release. Then there is a section on the observational consequences of the model. This is followed by a comparison of the results with Longcope 1998. The fourth section gives a discussion of the limitations of the model in relation to the solar atmosphere. Finally, we present the conclusions of the paper in section five.

2. Model

In this sections, we first discuss the basic model that is used to investigate the dynamical evolution of a fundamental heating event, a simple flux interaction. Then there is a discussion of the numerical approach that has been used to follow the non-linear, non-ideal time-dependent evolution of the magnetic field topology as it is stressed by imposed boundary motions.

2.1. Basic model

The basic scenario that we model here is possibly the simplest model for the interaction between different flux systems and is, therefore, considered a fundamental event. It is likely that many phenomena, such as X-ray bright points and X-ray jets are built up of one or more of these fundamental events. The model uses a Cartesian domain where one boundary is taken to represent the photosphere. Two equal flux sources of opposite polarity are located at a given distance apart on this boundary. In the absence of any other sources in the system or an overlying field these two sources would form a dipole field where all the flux in one source connects to the other. In our model, this simply connected topology is broken by imposing an overlying magnetic field with a given direction and strength. As the strength and direction of the overlying uniform field is varied the topology of the magnetic field evolves as the fraction of connected flux between the sources changes. The effective interaction between the two sources, therefore, depends critically on both the direction and strength of the overlying magnetic field relative to (i) the angle of the line through the source centres, (ii) their magnetic flux and (iii) the relative direction of their transport. In this paper, the analysis is restricted to the case where the overlying field is directed at a 45 degree angle relative to the line of the sources and has a strength roughly 10% of that of the peak value of the sources, such that initially no connections exist between the two sources. A simple driving profile is then imposed in the source plane such that the sources are forced to move perpendicular to the overlying field direction in a direction that initially brings them closer, before moving further apart again, i.e., the sources perform a “near miss” or “fly-by”. Fig. 1 shows the initial topology of the magnetic field (lines) and the imposed boundary driving (arrows).

The numerical values of the initial magnetic field configuration are found by prescribing the normal component of the field strength of the sources on the boundary. Then, by assuming that no flux penetrates the walls anywhere else in the cube, a potential magnetic field is determined. To destroy the connectivity between the two flux sources a constant field component is added to the field. This component is chosen to be sufficiently strong as to ensure the sources are no longer connected and that there are only open field lines in the box. Initially the plasma is assumed to have a constant density and temperature and to be at rest.

2.2. Numerical approach

The dynamical evolution of the magnetic field topology described in the previous section is investigated in a 3D domain using a numerical approach to solve the non-dimensionalised non-ideal MHD equations,

$$\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\nabla \cdot \rho \mathbf{u}, & (1)\\
\frac{\partial \rho \mathbf{u}}{\partial t} &= -\nabla \cdot (\rho \mathbf{u}\mathbf{u} + \underline{\underline{\tau}}) - \nabla P + \mathbf{J} \times \mathbf{B}, & (2)\\
\frac{\partial e}{\partial t} &= -\nabla \cdot (e\mathbf{u}) - P \nabla \cdot \mathbf{u} - \rho (T - T_0)/t_{\rm cool} & \\
&\quad + Q_{\rm Joule} + Q_{\rm visc}, & (3)\\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E}, & (4)\\
\mathbf{E} &= -(\mathbf{u} \times \mathbf{B}) + \eta \mathbf{J}, & (5)\\
\mathbf{J} &= \nabla \times \mathbf{B}, & (6)
\end{aligned}$$

with density ρ, velocity $\mathbf{u}$, thermal energy e, temperature T, equilibrium temperature T_0, exponential cooling time $t_{\rm cool}$, magnetic field $\mathbf{B}$, electric field $\mathbf{E}$, magnetic resistivity η, electric current $\mathbf{J}$, viscous stress tensor $\underline{\underline{\tau}}$, gas pressure $P = e(\gamma - 1)$, viscous dissipation $Q_{\rm visc}$, and Joule dissipation $Q_{\rm Joule}$, respectively. An ideal gas, with $\gamma = 5/3$ is assumed.

The equations are non-dimensionalised by setting the magnetic permeability $\mu_0 = 1$, and the gas constant $R_0 = \mu$ (the mean molecular weight). One time unit is equivalent to the Alfvén crossing time of a unit length when both $|\mathbf{B}|$ and ρ are set to 1.

The equations are solved in a Cartesian box using staggered grids. A sixth-order method is applied to derive the partial derivatives and a fifth-order method used for doing interpolation. Viscosity and magnetic resistivity are both handled using a fourth-order method combined with a discontinuous capture mechanism to provide the highest possible spatial resolution for the given numerical resolution. The solution is advanced in time using a third-order predictor-corrector method (A description of the code is available at http://www-solar.mcs.st-and.ac.uk/˜klaus).

The foot-points of the field lines are frozen into the plasma on the boundaries and the velocity field is applied only to the boundary to move the foot-points of the magnetic field. This imposes stress on the system that propagates into the interior of the domain. The driver that we have chosen provides a ramp up to a constant velocity in a region that, in width, is larger than the sources and zero outside. Because the magnetic field only penetrates the photospheric boundary at the locations of the sources only the flux concentrations are moved by the imposed driving.

For simplicity, it is assumed that the domain is 2D periodic on the sides of the box perpendicular to the source boundary and bounded in the third direction. This is in contradiction to the way that the initial dipole magnetic field was derived, and will, therefore, generate current concentrations at the boundaries. The changes in the boundary conditions of the field structure turn out not to influence the magnetic field structure of particular interest to us.

To increase the resolution in the region where the important dynamics are taking place, the height of the domain is lowered so that it is just one quarter of the initial data cube. The field above this boundary is found to be totally dominated by the imposed constant magnetic field and, therefore, does not participate in any active way to the dynamics that takes place lower down. The dimensions of the domain are thus (0.25,1,1). The basic experiment has (65,129,129) grid points in the three directions, where the first represents the height above the photosphere. An experiment with twice this resolution (129,257,257) is also analysed to control the reliability of the numerical results.

3. Dynamical behaviour

This section concentrates on the dynamical evolution of the magnetic field configuration as it is being stressed by the imposed boundary motions. The following subsections first discuss the global evolution of the field as it is stressed. Then, we focus in more detail on the different types of magnetic reconnection that are found to dominate the changes in field connectivity as time progresses. An attempt has been made to visualise the consequences of the energy release using both the energy release and the temperature profile of the plasma, assuming an optically thin plasma. Finally, the last subsection gives a comparison of the results discussed in the previous sections with the analytical work by Longcope 1998.

3.1. Global behaviour

When the boundary driving starts the foot-points of the sources are forced to move with the boundary flow. This initiates MHD waves that propagate into the domain and perturb the initial magnetic field line structure. As shown in Fig. 1, only a small part of the volume above the driving surface is connected with the surface. It is, therefore, only these field lines that directly feel the perturbations from the boundary motions. The non-connected (or open) field lines only experience the driver motions as indirect perturbations created by the changes in forces along the boundary connected field lines. The displacement of the boundary connected foot-points, therefore, forces the open field to flow over the surface, known as a separatrix surface, that divides the boundary between connected and open flux regions. In the regions of the separatrix surfaces that are closest to the sources, the open field experiences large shifts in position. These result in a change in the field line direction across parts of the separatrix surfaces. The current that arises from this seems only to drive reconnection at a very slow rate.

As the sources are continuously moved by the boundary flow they force their way in under the flux next to them. This causes the open flux between the two separatrix surfaces to slowly lift up so that eventually the two separatrix surfaces enclosing the two flux sources start to interact. Upon the interaction of these two flux systems a separator line is formed connecting the two nulls that lay in the driving plane and a current sheet is generated through which the field line connectivity is changed from open field lines to field lines that connect the two flux sources. This reconnection continues throughout the passing of the two sources. In deed, even when the two sources are well separated after their near miss there is still a small residual amount of flux from each source that remains open and continues to slowly reconnect. Snapshots of the development (Fig. 2) show isosurfaces of strong current and magnetic field lines at four different times through the evolution.

The direction of the main outflow velocity from this reconnecting current sheet is directed downwards. Thus, the newly formed magnetic field lines connecting the two magnetic sources are pushed down towards the driving boundary. Hence, the height of the connections between the two flux sources are very low lying in the domain, especially since the height of the current sheet decreases with time.

As time progresses the central current sheet shrinks to midway between the two sources and two new current sheets develop around the separatrix surfaces that divide the newly connected flux from the sources and the overlying uniform field. These current sheets form close to the foot-points of the sources where the change in the field line direction varies across the separatrix surface. They grow along the separatrix surface around the flux connecting the two sources as the last flux from the two sources finally becomes connected. Because there is no strong

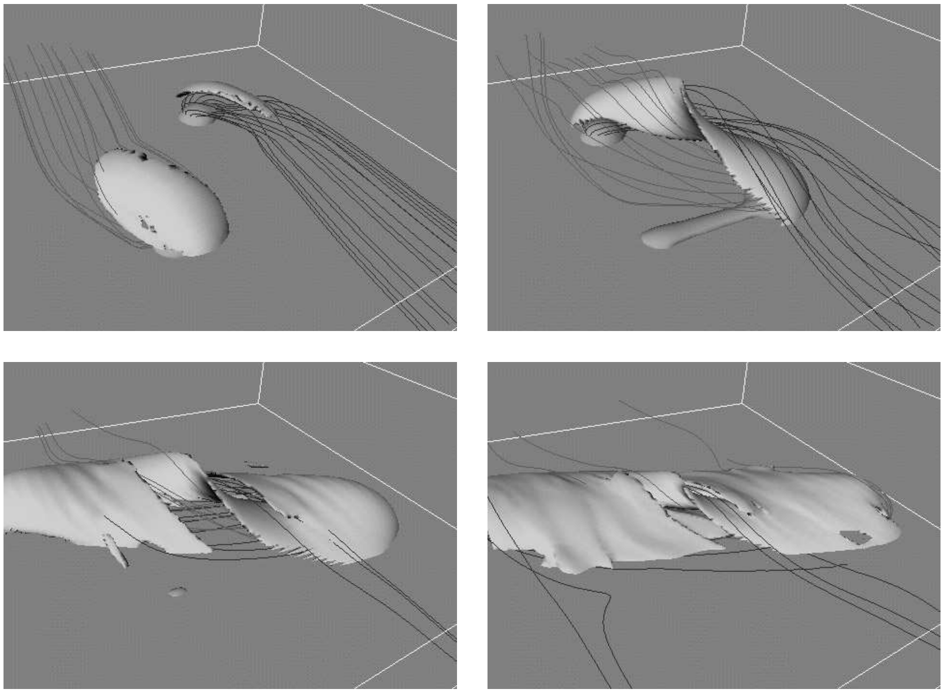

Fig. 2. The panels show the time development of the current isosurfaces and magnetic field lines as a function of time, t=(1.46, 5.43, 9.61, 12.58). The field lines are traced from the boundary sources, that are indicated by the roundish isosurfaces in the top panels

force pushing the two regions towards each other the time scale for reconnection in these current sheets is much longer. Hence the process of disconnecting the two magnetic flux sources is much slower than the time scale for connecting the two sources in the first place. This implies that the flux connecting the two sources slowly becomes stretched out over a long distance. In the experiments we find that no more than a small fraction of the flux becomes open again after the two sources have passed each other (within the time scale that we follow them). This is a natural artifact of the situation that we have created in this experiment. If a more complicated flux systems was modelled where new flux was allowed to appear from below, then these low lying stretched field lines would easily reconnect with the new flux injected beneath them.

3.2. Reconnection patterns

There are two main reconnection patterns that are important for the dynamical evolution of the magnetic field in this numerical experiment. The first is associated with separator reconnection and is responsible for generating connections between the two sources. The second generates a current over large parts of the separatrix surfaces dividing the connected and open flux so it can be classified as fan reconnection. The current is created by the tangential change in field line direction between the open and connected flux systems. This “fan” reconnection is first activated as the initial open flux from the sources is pushed under the overlying field, and is also responsible for the reconnection that opens up the connected field again after the two sources have past each other.

3.2.1. Separator reconnection

Reconnection at the separator is by far the most efficient of these two types of reconnection. It arises as a natural consequence of the initial topology of the magnetic field. The two sources are initially connected in opposite directions due to the effect of the overlying field (Fig. 1). The two independent separatrix surfaces, the fan surfaces (Priest & Titov 1996), are anchored in the two magnetic null points that are located on the source boundary. The fan planes define the boundary between the magnetic field that is connected to the sources and the overlying field that is not connected to either source. When the fan surfaces intersect, they define a single magnetic field line, known as a separator, that connects the two null points. From previous investigations, (Lau & Finn 1990; Priest & Titov 1996; Galsgaard & Nordlund 1997; Galsgaard et al. 1997; Galsgaard et al. 2000b), it is known that the separator is a preferred location for electric currents to be generated when the field configuration is perturbed. Furthermore numerical experiments (Galsgaard & Nordlund 1997; Galsgaard et al. 2000b) show that the separator always develops into a current sheet as the magnetic field of the systems is perturbed by boundary motions that stress the fan surfaces. In the case studied here the nulls are located on the driving base and it is, therefore, not possible with full confidence to follow their development in time. However, it is found that current slowly grows along the fan surfaces eventually focusing strongly at the location of the separator when the two separatrix surfaces finally intersect. This can not be directly proved as we can not follow the field lines topology precisely enough down to the locations of the nulls. These are at this time extremely difficult to identify.

Some aspects of the evolution of the system are on the other hand very reminiscent to that of flux braid-

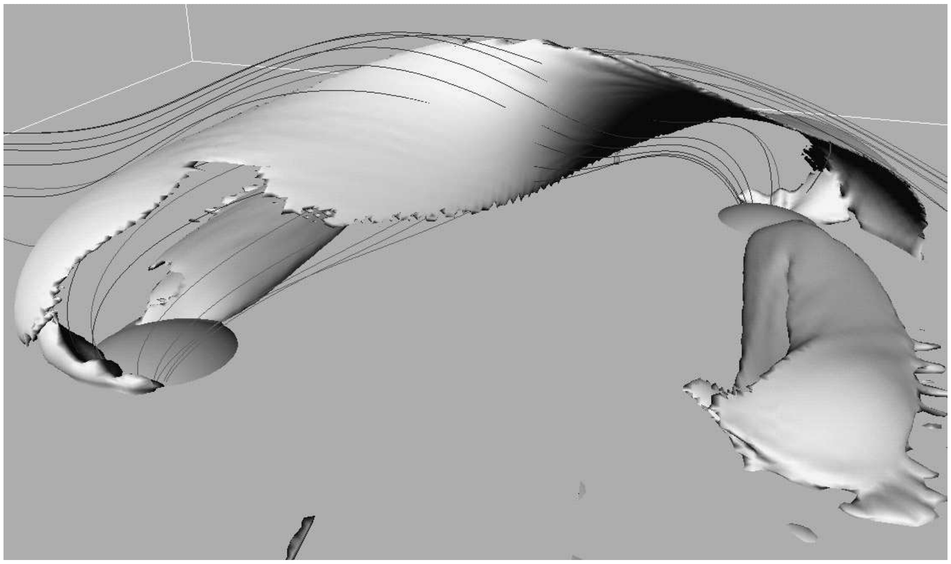

Fig. 3. The light isosurfaces show the location of the separator current system that reconnects the field lines from the two flux systems. The two round flat isosurfaces give the locations of the two magnetic sources. The field line traces show that three different types of connectivity involving the sources exist at the present time. Flux that is open at one end and connected to the first or second sources at the other end and also flux connected to both sources.

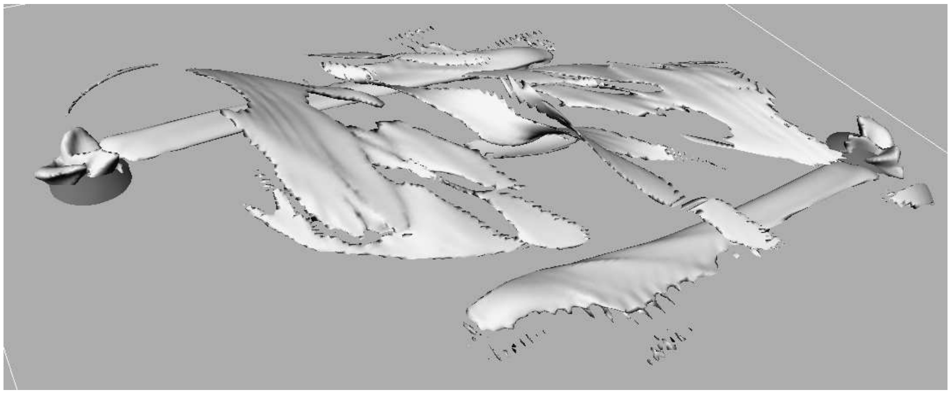

Fig. 4. The colors are the same as in Fig. 3. This is a snapshot showing the current isosurfaces at the end of the separator reconnection and the beginning of the following fan reconnection that opens the field again after the passage of the sources.

ing (Galsgaard & Nordlund 1996; Longbottom et al. 1998; Ng & Bhattachrjee 1998). For instance, the generation of a current sheet through the interlocking of the two flux systems due to foot-point motions is analogous to current sheet formation in those models. However, the separator current sheet is special in this case, in that it has a twist of π (Fig. 3). This twist arises because of the way the current sheet is created as the two flux sources are forced in under the neighbouring flux. This feature again resembles the type of current sheets observed in the flux braiding experiments more than those current sheets seen in previous separator reconnection simulations.

When the flux from the two sources have nearly finished reconnecting the length of the separator current region decreases until, eventually, it is only maintained at the midpoint between the two sources as the last unconnected flux is being reconnected (Fig. 4).

By investigating the velocity flow around the location of the separator it is found that the convergence of the two bounded flux systems initially generates an up flow that makes the open flux pass above the flux from the two sources. Then the separator and associated current sheet form causing the velocity flow to change into a characteristic stagnation-type flow often found near reconnection sites. In most reconnection experiments the outflow from reconnection sites is found to be more-or-less symmetric with respect to the centre of the current sheet. However, in this experiment this is not the case. There is a clear asymmetry, with the centre of the stagnation-point flow located in the upper 25% of the current sheet and the downwards directed outflow velocity much higher than the upwards flow velocity (Fig. 5). The reason for this asymmetry is that the downward tension force is much stronger then the upward tension force. This is because in the downwards outflow region there is a stronger tension force generated by the high curvature of the newly reconnected field lines that link the two sources. On the other hand, the field lines in the upwards outflow region are open field lines with little curvature and so experience a much weaker tension force for two reasons. First, the reconnection point generally lies close to the summit of these field lines and, second, since these field lines are not rooted at a fixed point on the source boundary they may relax much easier so that the height of the complete field lines can readily adjust to the height variations imposed by the changes in field line connectivity.

3.2.2. Fan reconnection

Both before and after the separator reconnection takes place there is another type of reconnection occurring. This reconnection is due to the compression and shearing of the magnetic field

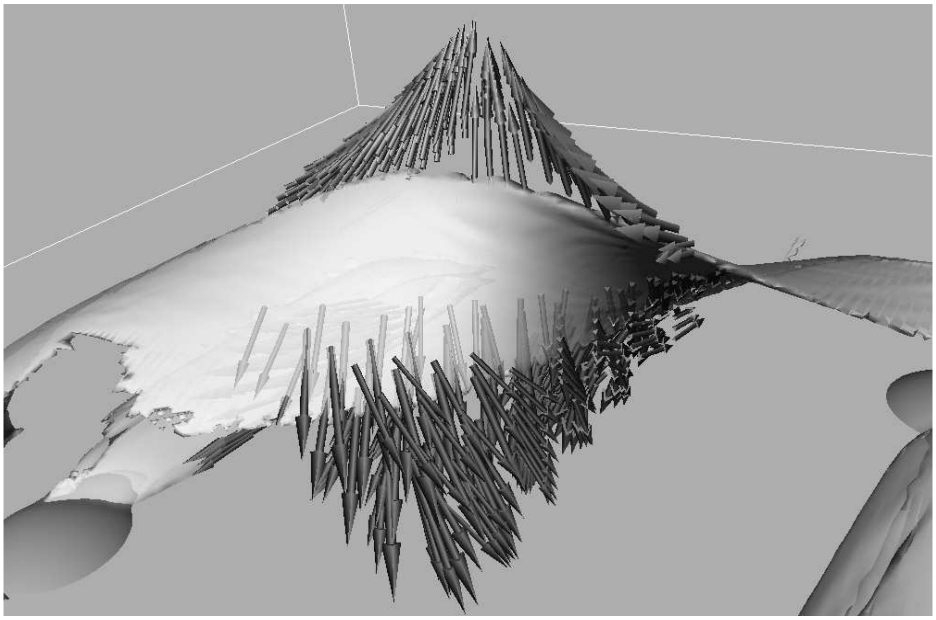

Fig. 5. Vectors indicate the outflow velocity from the separator current sheet. Highest velocities are found for the downwards velocity.

generated by the relative transport of the source flux systems and the overlying open flux. The different flux systems are separated by fan surfaces, and it is on the fan surfaces that several current concentrations are formed (Fig. 4). These current sheets are created by the tangential variations of the magnetic field between the two sides of the fan surfaces. Although the current sheets extend over a relatively large area, the reconnection that occurs in them is much less efficient than the separator reconnection. This is because the force that drives the separated flux systems together in these cases is much weaker than around the separator. The opening of the magnetic field is, therefore, a very slow process compared with the closing of the field due to separator reconnection. The fan reconnection that we have seen here is different from that typically discussed (Rickard & Titov 1996; Priest & Titov 1996; Craig et al. 1995). In the general case the current is found to be strongest at the null, but as the null in this experiment is located in the driving boundary it is not possible to realistically follow the development of the current structure here. The effect of the patchy fan reconnection in this experiment also has similarities to the flux braiding scenario in that the magnetic field has a strong tangential change over a very short length scale.

The process of opening the magnetic fields up again after the fly-by of the sources could potentially be speeded up if additional forces are introduced by allowing more complicated dynamics to take place across the photospheric boundary. However, under the conditions that have been imposed in this experiment this is not possible. In the solar atmosphere, however, there exists a much more dynamical environment in which emergence of new flux may lift the region up again and force reconnection to take place both between the emerging flux and accelerate the opening of the field at the fan surfaces towards the field above it. This, of course, would make the system more complex and is effectively the same as combining two or more fundamental reconnection events like that described above. The investigation of such coupled events is worth an independent investigation.

3.3. Patterns of the energy release

The energy equation in this numerical experiment does not include heat conduction and radiation. It is therefore not possible to make a direct comparison between the experiment and observations. The results from the code give a temperature distribution that is too concentrated around the location of the energy release. Despite these limitations an attempt is made to visualise the location and spacial distribution of the energy release. Because the coronal plasma is optically thin, a simple approximation to this is to integrate the energy release along the line of sight. In this case we assume that the event is taking place at the centre of the solar disk, the integration is therefore equivalent to summing up all the energy release in the numerical columns from the photosphere to the top boundary of the domain. This can easily be performed as a time dependent evolution for all the data sets in the experiment. Looking at these, it becomes obvious that there are three spacial locations that show a high degree of dissipation. Six different times during the time evolution are shown in Fig. 6.

The frames show the three locations that are seen if only the energy deposition is taken into account in the MHD equations. Two location are at the front of the moving sources as they are pushed into the surrounding magnetic field, the third location is right at the centre between the two sources. This is interesting, as we saw in Sect. 3.2.1 since the current sheet driving the reconnection between the two interacting flux bundles forms all along the line between the two sources. The reason that we only see the energy release half way between the sources is because the current sheet is twisted through an angle π between the two sources. This means that there is only one location along the sheet where the current sheet is sampled all the way across the

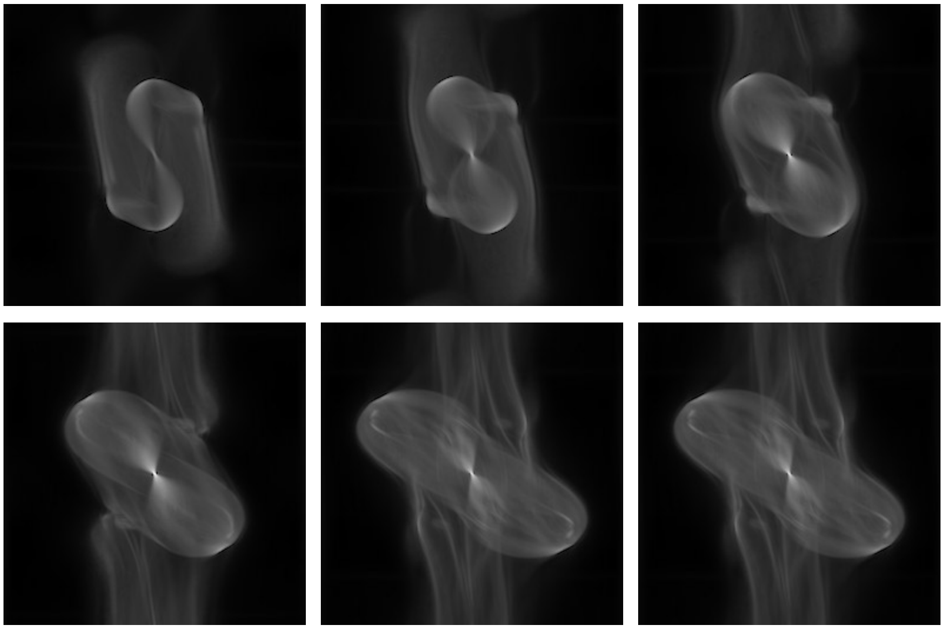

Fig. 6. The panels show the joule dissipation integrated with height at 6 different times during the interaction of the two flux systems.

column. Doing the same exercise, but with different viewing angles shows that the central energy location moves along the sheet towards one of the sources, while the locations at the front of the sources are much more stationary. For a comparison the same analysis was preformed with the plasma temperature, and this showed the same locations of hot plasma as found from the energy dissipation.

From the temperature plots another interesting feature appeared. It is seen that the high velocity (downflow) outflow regions from the separator reconnection have a temperature that is lower than both the hot region in the current sheet and the background average temperature. This can only be explained by an adiabatic cooling of the hot plasma as the volume expands while it is being dragged out of the sheet and down towards the lower boundary. This result is in contradiction to many other experiments of magnetic reconnection where the outflow regions are generally hotter than the background plasma. The inclusion of heat conduction will only effect this result if it can spread the hot region in the current sheet over a much larger volume faster than the new cold plasma is processed through the reconnection region. Further more the down flow jet velocity found here is lower than expected in a realistic coronal experiment as the physical parameters in the present experiment represents a high β plasma. A change in parameters to coronal values could increase the plasma temperature in the current sheet enough that the out flow region, despite the near adiabatic expansion, would decrease in temperature but still reach a temperature that is higher then the background plasma. This aspect of the experiment will be examined in more detail in a following paper (Galsgaard 2000).

3.4. Comparisons with Longcope 1998

An analytical investigation of the scenario modelled in this paper has been carried out in three dimensions by Longcope 1998. In his analysis two opposite polarity sources interact in a dominating background field. The free magnetic energy gained from moving the sources accumulates at the separator connecting the two nulls in the source plane. By extending the technique that Syrovatsky 1971 developed for the collapse of 2D null points into three dimensions, Longcope 1998 is able to follow the current build up in a current sheet along the separator assuming that the rest of the field is maintained in a potential state - *the minimum current corona*. In this dynamically simple approach the free energy is assumed to be released when the current in the separator current sheet exceeds a given arbitrary threshold. As the energy is released the field relaxes down to either a fully potential state or a state where the current in the sheet contains much less free energy. The continued stressing of the field will then subsequently buildup the free energy in the system once again giving rise to a bursty-type energy release.

Using this approach serves three purposes. First, it gives the general basic location and topology of the energy release in the separator current sheet. Second, it gives an estimate of the total energy release during the complete event. Third, the topology of the system is described at all times. Allowing the field to relax to a potential field outside the separator, means that the field line topology after the interaction is similar to the initial condition with only the sources having changed position. However, the numerical experiment discussed above shows that this simple potential picture is not followed when a more detailed analysis of the flux interaction is done. There are a number of reasons for this.

First, the numerical experiments are only close to being potential right at the beginning of the experiment since that is the chosen initial state. After this the magnetic energy in the system continues to grow until the boundary driving is turned off after the two sources have passed each other. Fig. 7 shows the energy development as a function of time for the numerical experiment (top) and the energy of the potential solution for the

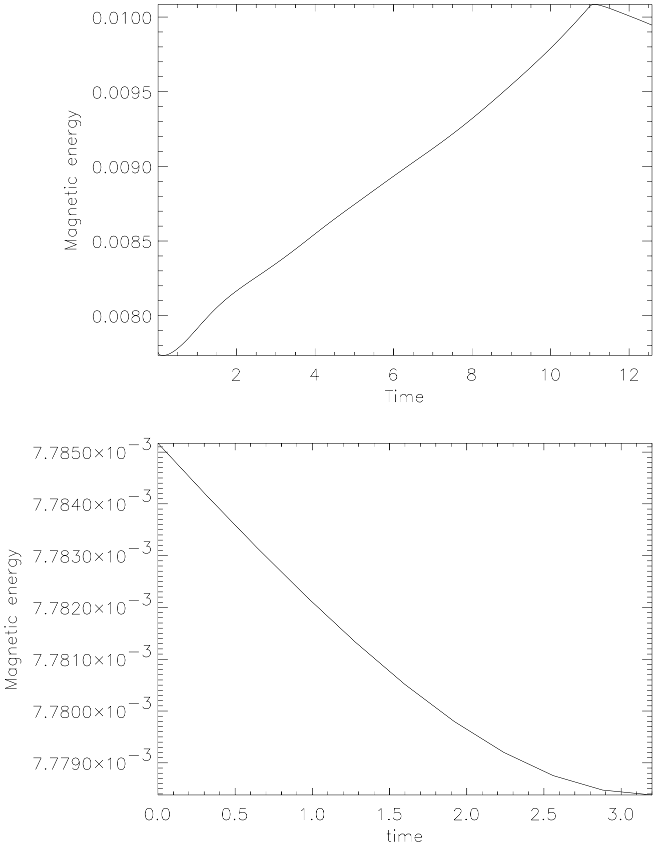

Fig. 7. Comparison between the magnetic energy in the numerical experiment (top) and the potential solution (bottom) with the same boundary conditions. The bottom panel shows how the energy decreases as the two sources are moved into closest contact. In the numerical experiment the closest contact is reached at t=3.2 and the driving is stopped at t=11.

same boundary conditions (bottom). Two things are to be noted: in the potential modelling the minimum energy of the system is reached when the two sources are fully connected as they reach their minimum separation; the numerical experiment has a systematically higher than potential magnetic energy throughout the run. The energy of the system grows not only because work is being done on the system, but also because the effect of plasma pressure is taken into account. In large parts of the domain the pressure gradient nearly balances the Lorenz force which allows for non-potential magnetic field configurations to exist in an almost steady state situation. This fact makes it more difficult to get situations where the free magnetic energy can be released on a short time scale. Also the investigation is conducted fully dynamically which allows for changes in the field line curvature without requiring that they are at all times in a static equilibrium. Here we naturally encounter a numerical problem, in that we cannot simulate the required parameter range for the corona. This influences the balance between the forces, in that the plasma β in the experiment is too high and the Alfvén velocity too low compared to the driving velocity. This directly implies that more energy will be stored in the magnetic field compared to the potential solution, because insufficient time is given to allow the field to relax towards a globally force-free state.

Second, the dynamics of the separator reconnection clearly generate deviations of the magnetic field line structure away from the expected potential solution for the same boundary conditions. It is found that the outflow velocity forces the newly reconnected field lines to obtain a very low height compared to the location of the separator. This imposes an obstacle to opening the magnetic field again after it has first become connected.

Third, it is very difficult to get the low lying field lines to reconnect with the overlying ambient magnetic field - a process which would enable them to gain height again and so obtain a connectivity more similar to the one before the sources near fly-by. This means that the field line topology after the near fly-by is very different from the potential solution expected for the same normal component of the boundary field. In this experiment there does not seem to be a significant force pushing the two magnetic domains together after the passage and so the time scale for opening the field becomes very long. While the boundary driving is on, the time scale is shorter than the diffusion time scale, but after the driving is stopped then the time scale approaches the diffusion time scale as the forces in the system relax.

From the topological point of view, there is one significant difference between the numerical experiment and Longcope 1998. In Longcope 1998 the continued relaxation to a near potential field and continued stressing means that the topology all the time has a magnetic separator line defined by the intersection of the fan planes of the two nulls. The process of connecting and opening the field between the two sources is therefore all the time taking place through the separator line and its associated current sheet. In the numerical experiment we find that the separator is only well defined in the phase where the to sources are connected. After this, the flux connecting the two sources is well confined under the separator surface dividing the flux systems into an open and a fully connected part. Though even towards the end of the numerical experiments there is still a small amount of flux that has not yet become connected and a very weak separator sheet is still present. Fig. 8 illustrates the difference in field line connectivity between a potential solution and the numerical result. The rows of panels show sketches of the null points intersection with the photosphere as the sources are moved passed each other. The important difference between the analytical (top) and numerical (bottom) result is that there is no reason for the magnetic field in the numerical experiment to evolve into a new configuration where a new separator line accumulating the current is formed. Instead the connected flux is being stretched out underneath the open field and very slow reconnection is taking place between the closed and open field at different locations all over the separatrix surface. This process is mainly driven by the perturbations of current strength that arises from the different waves propagating across the periodic domain. In the analytical approach the situation with the continued separator reconnection is obtained because the system at regular intervals is relaxed towards a fully potential field that contains a separator as long as the distance between the

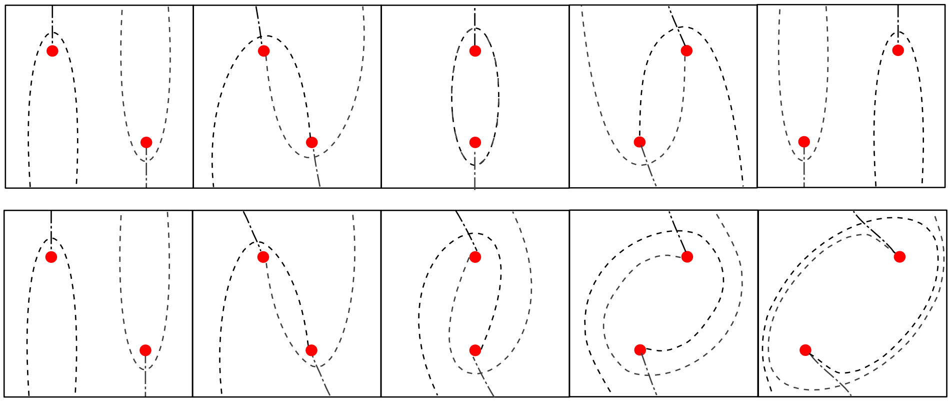

Fig. 8. The sketches in the top panels indicate the positions of the separatrix surfaces on the photosphere as the two sources pass each other in the potential case. The dashed lines represent the separatrix surfaces and the dot-dashed lines the spine axis. The sketches in the bottom panels represent the same situations for the numerical experiment.

source is below a given limit. In fact a state similar to the one found in the numerical experiments would be found if the minimum current corona model evolved exactly through the state where all the free energy is released at the closest approach of the sources. This would limit the topology of the system to having only two different regions, as seen in the top middle panel of Fig. 8. As this field is stressed current has to accumulate all over the separatrix surface. This then requires a much higher free magnetic energy before the threshold for relaxation can be reached and a new potential state containing a separator would again be possible.

4. Discussion

The experiment presented here is not following the order of velocities found in the Sun. This is because the experiment has a constant atmosphere model with the plasma β much larger than in the corona. Here the sound speed is larger than the Alfvén velocity. This, of course, influences the results. The simplest way to change this is to include a stratified atmosphere. With such an atmosphere a high plasma β at the foot points could be maintain, which is required to suppress numerically initiated waves generated as the footpoints move, while getting a lower plasma β at the reconnection locations. This would change the out flow velocities of the reconnection jets, but would not significantly change the topological evolution described above.

Let us estimate the diffusion time of the interaction of two flux concentrations that could provide a heating source on the Sun. If we assume that the typical diameter of a flux tube in the upper atmosphere is 2 Mm and that the relative velocity of such a tube is of the order of $1\,\mathrm{km\,s^{-1}}$, then the time taken for the two fluxes to pass, if we assume that the field behaves as a potential field, is $t_i = 4Mm/1\,km\,s^{-1} \approx 1hour$. This time can be compared with the time taken for the two flux tubes to diffuse through each other, $t_d = 4Mm/\eta \approx 45$ days for a 1 Million degree plasma. The connection phase - separator reconnection - observed in our experiment occurs at a much faster rate than the diffusion time because it is a driven process, but as the opening of the field - fan reconnection - is not driven in the same efficient way and the diffusion time scale gives an indication as to how long it would take for such a process to occur if other interaction forces were not present.

The problem we have found is that the flux after the reconnection connecting the two sources becomes very low lying in the atmosphere and thus it becomes a very slow process to open up this field again. To some extent this indicates one of the limits of the model, since plasma flows across the driving boundary are not permitted. In the solar environment this is not the case. The solar environment is much more complex than we can simulate today. The Sun contains multiple sources that interact on different length and time scales and it also allows for new flux to emerge up through the convection zone. All of these processes may be involved in changing the connectivity of the magnetic field, preventing all the low lying flux to change connectivity and become involved in the continued development of the solar coronal magnetic field. It is, therefore, vital in the future to make more advanced models that contain more complicated magnetic topologies of the solar atmosphere. The full understanding of the processes that will be involved in realistic systems have to be understood on a fundamental level before we can fully appreciate the physics involved in the solar coronal environment.

5. Conclusion

This paper has investigated the results of the interaction between two independent flux systems in a background magnetic field. The experiments have shown that the main driver of the energy release through magnetic reconnection is the formation of a separator current formed as the two flux regions interact. The driving of the two flux systems into each other drives magnetic reconnection that alters the field line connectivity. In this process the newly formed field lines connecting the two sources lie at a very low height. The height of the field lines connecting the two sources have strong influences on the rate at which the opening of the field lines takes place after the passing of the two sources. The main force that pushes the open and connected field lines towards each other are related to the continued transport and the small curvature in the open field as a result of the closed field passing underneath it. The opening of the field is therefore a very slow process that will not significantly contribute to the heating of the plasma.

This investigation, like other papers (Galsgaard & Nordlund 1997; Galsgaard et al. 1997;

Craig & Fabling 1996; Craig et al. 1999), suggests that separator reconnection is the most important type of reconnection involving magnetic null points. In this particular case the reason relates to the distribution of forces in the two types of interaction process.

The aspect of the slow opening of the field again after the flux interaction in the experiments is the most important difference from the analytical investigations by Longcope 1998. It clearly shows that to get a full picture of the evolution of complicated magnetic topologies, we have to take into account the extra complications that the inclusion of plasma provides and the dynamical state allowing for a non potential magnetic field topology.

More detailed investigations have still to be made to analyse the full implication of the models importance for heating the solar corona. Some of these will be investigated in following papers. These address the importance of the angle of the overlaying magnetic field relative to the dynamical evolution and the indications of a low temperature plasma region in the high velocity outflow region. This last surprising result could provide a possible explanation for the combination of hot and cold loops that are observed side by side in the corona (Harra-Murnion et al. 1999) or just be an artifact of the experiment being conducted in an inphysical parameter regime compared to the solar corona.

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