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A Numerical Investigation of a Simple 3D Magnetic Flux Interaction Event

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Abstract. The discovery of the magnetic carpet on the sun, the continuously changing of small scale magnetic flux elements in the solar atmosphere, indicates that the life time of individual flux elements is less than one day. During this time the elements interact with each other and eventually become impossible to identify individually. The complexity of the coronal magnetic field relating to this source distribution provides a complex pattern of overlying field line connectivity, with one flux element connecting possibly to several other flux elements. Stressing such a complex magnetic field by movements of the flux sources in the photosphere, must lead undoubtfully to the formation of many localised current concentrations that can provide local heating for the transition region and lower coronal plasma. In this paper we investigate a simple flux interaction event between two unbalanced magnetic sources. Using a numerical MHD approach we examine when and how the free magnetic energy may be released when the flux patches are rotated relative to one another. It is found that this topological simple magnetic configuration does not reach easily a state where a measure of the imposed stress is released on a short dynamical time scale.

1. Introduction

Investigations of MDI indexMDI!SoHo data from SoHO (Schrijver et al. 1997, 1998) have revealed that the magnetic field in the solar photosphere is made up of a magnetic carpet. The carpet persists of a continuously changing distribution of magnetic flux elements of positive and negative polarity. The life time of the individual flux elements is found to be down to the order of only 14 hours (Hagenaar 2001). During this short time they emerge through the photospheric surface, move around randomly, interact with the ambient flux and eventually become impossible to identify individually. The flux elements are advected around as nearly passive trace particles by the convective motions. Therefore they are forced to interact with neighbouring flux sources of the same or opposite polarity particularly as they are buffeted into the intergranular lanes. This allows individual flux elements to (i) merge with other elements of same polar-

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ity to form larger elements; (ii) annihilate flux from opposite polarity elements, thereby decreasing the total flux or (iii) break up into smaller flux fragments. This process of moving and interacting flux sources is the main reason for changing the magnetic flux connectivity in the lower solar atmosphere and is driven totally by the random convective motions. Potential coronal magnetic field extrapolated from such a photospheric flux distribution reveals a complex pattern of magnetic field line connectivity, with one flux element connecting to several neighbouring elements. Therefore when the elements are moved around by the convective motions, the complexity in the field line connectivity leads to differences in the imposed stress on neighbouring field lines. Such differential stresses will without doubt lead to the formation of strong current concentrations at the interfaces between field lines of different connectivity. These locations, known as Quasi Separatrix Layers (Priest and Demoulin 1995, Titov et al. 1999), will be the prime locations for releasing free magnetic energy in the form of Joule heating and bulk plasma and particle acceleration through driven magnetic reconnection.

Recent attempts to determine the heating profile along assumed magnetic loops in the solar atmosphere (Priest et al. 1998, Mackay et al. 2000, Aschwanden et al. 2000) using loop temperature profiles obtained from both Yohkoh and TRACE observations, suggest that the energy deposition has to take place within a scale height of 10-20 Mm above the photosphere. This is consistent with the above picture of the magnetic carpet where flux interactions take place low down in the solar atmosphere where the direct linkage to the overlying coronal magnetic field topology is changing continuously.

To increase our general understanding of this continuously changing magnetic connectivity as a consequence of the magnetic carpet, we must investigate different possible scenarios of flux interaction. In the following experiment we simplify the situation by analysing a simple flux interaction in an unbalanced two source flux system. In Section 2 the simple setup of the experiment is described while in Section 3, the highlights of the numerical results are discussed. Finally in Section 4 we draw several conclusions from the investigation.

2. Outline of Numerical Experiment

The dynamical evolution of the magnetic carpet provides the possibility for an extremely complex magnetic topology in the lower part of the solar atmosphere. How this affects the dynamical consequences for heating the transition region and corona plasma is virtually unknown. In principle it is possible to investigate numerically the dynamical response of such a complex magnetic field to the imposed photospheric motions. However achieving this with sufficient resolution, in space and time, would stretch present computational resources to their limits. Therefore we have adopted a more simplistic approach in an initial attempt to investigate a basic flux interaction between only two unbalanced sources, (Fig. 1). In doing this, we assume that the next nearest flux elements are far enough away not to have any important influences on the local dynamical evolution. For simplicity the initial condition is taken to be potential and is defined by two point sources of different magnitude located beneath the numerical domain.

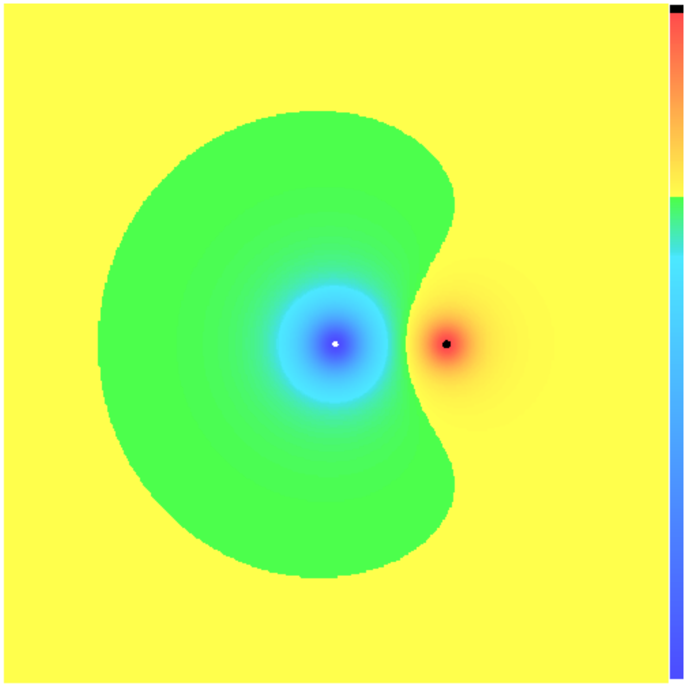

Figure 1. The flux distribution of the bottom boundary of the numerical experiment. The shading indicates the variation in the field strength with the colourbar displaying the relative scaling of the peak strength. Zero level is at the discontinues jump in colours (green/yellow).

The flux of the major source (the strongest of the two point sources, blue in Fig. 1) is divided into two independent regions; one connects all of the flux in the minor source (red in Fig. 1) to the major source while the other contains the excess flux from the major source that connects outside the numerical domain to an extended source surface at infinity. The division of the two flux systems is defined by the fan surface of the 3D magnetic null point that lies on the line connecting the two point sources, on the side opposite of the major source when seen from the minor flux source. The topology of the magnetic field is shown in Fig. 2. The contour lines represent the location of the two sources and the field lines (orange) define the dome over the minor source, indicating the location of the separator surface which divides the closed and open flux regions.

The model atmosphere is taken to be as simple as possible, namely having a constant plasma temperature. Due to the fast decrease in magnetic field strength away from the sources, gravity is included to provide a possibility for a decreasing plasma density with height. This way the decrease in Alfvèn velocity with height is less pronounced. This allows perturbations imposed on the lower boundary to propagate into the domain with a reasonable speed, decreasing the requirements for computing time to perform the numerical experiment.

On the Sun the flux sources are moved around by near random walks imposed by the convective motions. This can lead to two sources being advected

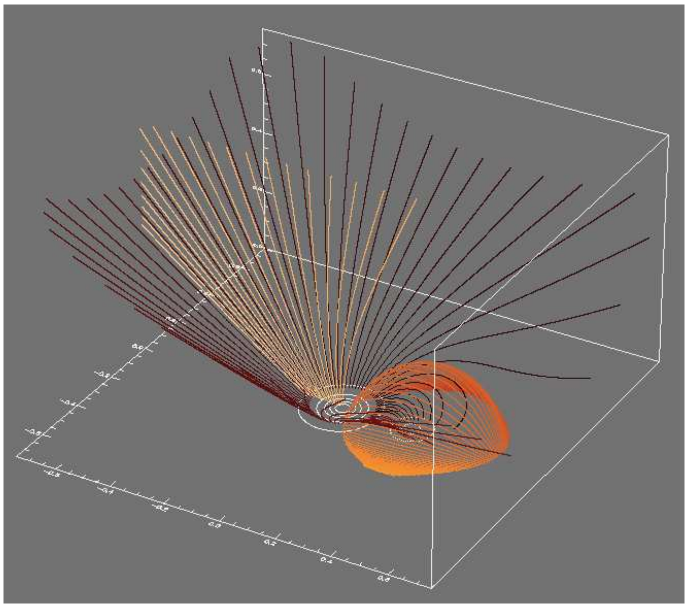

Figure 2. The initial magnetic topology is indicated by showing the location of the separatrix dome using orange coloured field lines, and the open field topology using dark and light brown coloured field lines. The white contour lines represent the location of the major and minor source on the bottom boundary of the numerical domain.

past one another in a close fly-by encounter. If we assume that the foot points of the sources are only advected by the flow and not rotated simultaneously, then a fly-by motion can be decomposed into two components; a translation and a rotation of the sources. From a numerical point of view, translation requires a large numerical domain to avoid severe interaction with the boundaries of the domain; rotation can be simulated in a much smaller numerical box. Therefore this experiment is limited to a situation where the two sources are rotated in the same direction around their central axis at a fixed distance apart. This mimics the rotation of one source around the other and is achieved by imposing two vortex flows on the bottom boundary of the numerical domain centred on the two flux sources, providing the same angular velocity to both.

The experiment involves solving numerically the full set of non-dimensionalised non-ideal 3D MHD equations in a Cartesian domain (a basic description of the code is available at http://www.astro.ku.dk/~kg).

3. Numerical Results

As the vortex flows are initiated on the source boundary, the twist slowly spreads along the magnetic field lines into the interior of the domain. Due to the difference in the field line connectivity on the major source, the field lines on either side of the separator surface experience different forces and hence react accordingly. As time progresses, the separator surface is squashed on its sides parallel

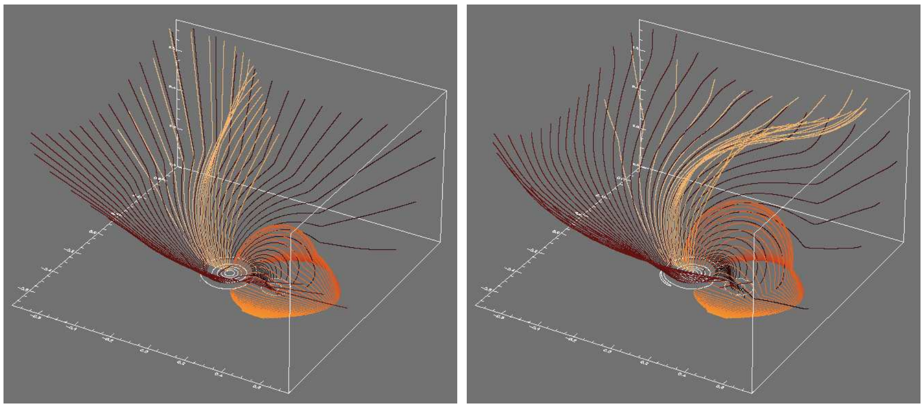

Figure 3. The two images show the field line topology of field lines having the same starting positions close to the bottom boundary as those displayed in Fig. 2 except this time traced at an instance half way through and at the end of the experiment.

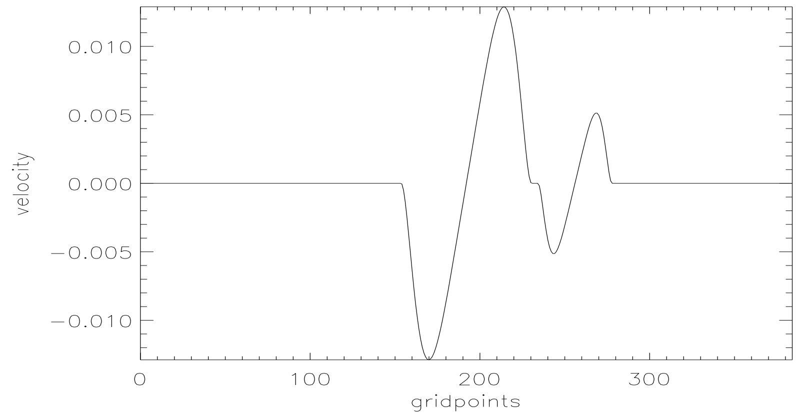

Figure 4. The velocity profiles of the vorticity flow imposed on the two sources. The graph is drawn through the the line connecting the center of the two sources.

to the source alignment while it also increases in height. This evolution is further enhanced by the twisting up of the magnetic field inside the separator surface, which is imposed mainly by the rotation of the minor source. This development is indicated by the two images in Fig. 3, that show the field line topology at two different times of the experiment. (The talk with animations is available at http://www-solar.mcs.st-and.ac.uk/˜klaus)

From the images in Fig. 3 it can be seen that the field lines emerging from different radii on the large source have different twist along them. This is a combined effect of the imposed driving profile and the divergence of the magnetic field lines with height as the radial distance of the foot points from the source centre increases. The inner half of the driving profile on each source has a

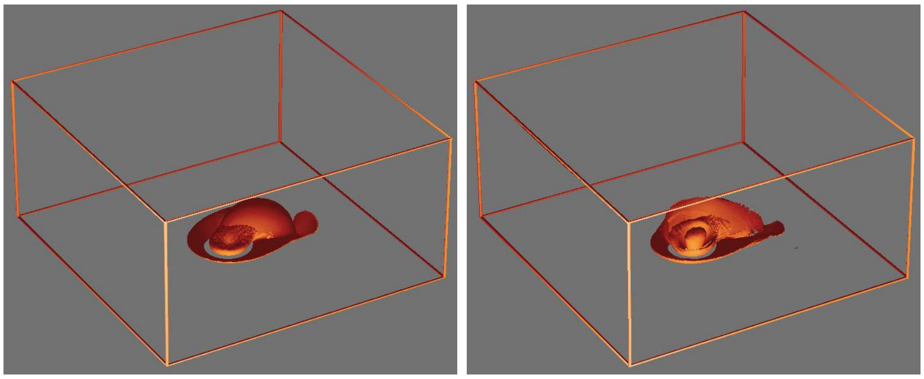

Figure 5. Isosurfaces of strong electric current at halfway through and at the end of the experiment. From these images it is easily seen that joule heating will be located close to the foot points of the magnetic field lines.

near constant rotation period while the outer part the rotation periods increases towards the outer radius of the rotation profile. These limited driving profiles are chosen because magnetic flux penetrates all of the bottom boundary. The vortex profiles are restricted to only twist up the strong central part of the flux regions. As there is a finite distance between the two sources, a maximum radius for the driving profiles exists, making sure that the two profiles do not overlap. The driving profiles imposed on the two sources along the line connecting the sources is displayed in Fig. 4.

Two effects are influencing the changes in the structure of the perturbed magnetic field lines. One is due to the divergence of the field in the near rigid rotating part of the source and the other is due to the rotational velocity going to zero again towards its outer boundary. In the rigid rotating part of the major source, the field lines spread out and fan away from the centre of the source. This makes the central field lines experience a slow twist around themselves as they are not diverging very far away from the symmetry line. Field lines with a larger radial distance to the source centre spreads out more in the horizontal direction. Therefore these field lines are dragged along and round the source by the imposed rotation. Thus, on one side of the separator dome, they are pulled away from it while, on the other side, they are pushed into it, making the external force on the dome asymmetric. The decrease in rotational velocity towards the outer edge of the profile gives rise to a shear velocity across this part of the rotation profile. It is therefore expected that strong currents close to the boundary may develop in this region around both sources, eventually leading to numerical slippage of the field lines through the plasma.

Fig. 5 shows the location of strong current at two different times of the experiment (for the same times as in Fig. 3). This shows that the strongest current is located close to the driving boundary and in the regions of the shear flow imposed by the rotational velocity near the edge of the flux source distributions and towards the strong magnetic field at the center of the major source. In other words these are the locations where one can expect a significant contribution towards heating the plasma.

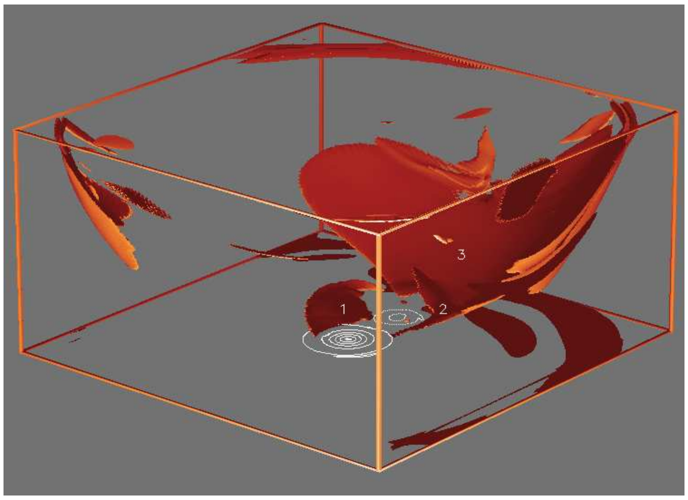

Figure 6. Isosurface of magnitude current divided by the magnitude of the magnetic field at the end of the experiment. This shows three prime locations of possible fast field line changing regions. The source locations are indicated by the white contour lines on the bottom boundary.

Despite showing the locations of significant Joule heating, these strong current images do not show the spatial locations of where the most significant changes in the field line topology can take place. Instead we must divide the current magnitude with the magnitude of the magnetic field. This is an ad-hoc way of calculating where the diffusion part of the magnetic induction equation is large relative the magnitude of the magnetic field, giving a better tracer of where magnetic reconnection or diffusion may be important. A image of $\frac{|\mathbf{j}|}{|\mathbf{B}|}$ towards the end of the experiment is shown in Fig. 6. From this figure it is seen that two regions on either side of the sources are likely locations for fast changes in the field line connectivity (marked 1 and 2 in Fig. 6). These coincides with the location of strong current seen in the right panel of Fig. 5.

Also, there is a large sheet propagating towards the boundary of the domain beyond the minor source (marked 3 in Fig. 6). This sheet marks the location of the Alfvèn pulse initiated by the driving of the sources. This front becomes increasingly stronger with time. This is due to the decrease in the Alfvèn velocity along the magnetic field lines as the pulse propagates away from the flux sources and towards weaker magnetic field. The decrease in Alfvèn velocity along the field lines makes the initial front steepen as the information from behind slowly catches up with the front of the wave. At the volume of space where both the scaled and non-scaled current sheets are found in the experiment both plasma heating and changes in the field line connectivity take place. However, the changes in field line connectivity are not large.

To demonstrate the actual twist of the major source and the small changes in connectivity, the evolution of the distribution of the field line connectivity on the major source as a function of time is shown in Fig. 7 for three snapshots

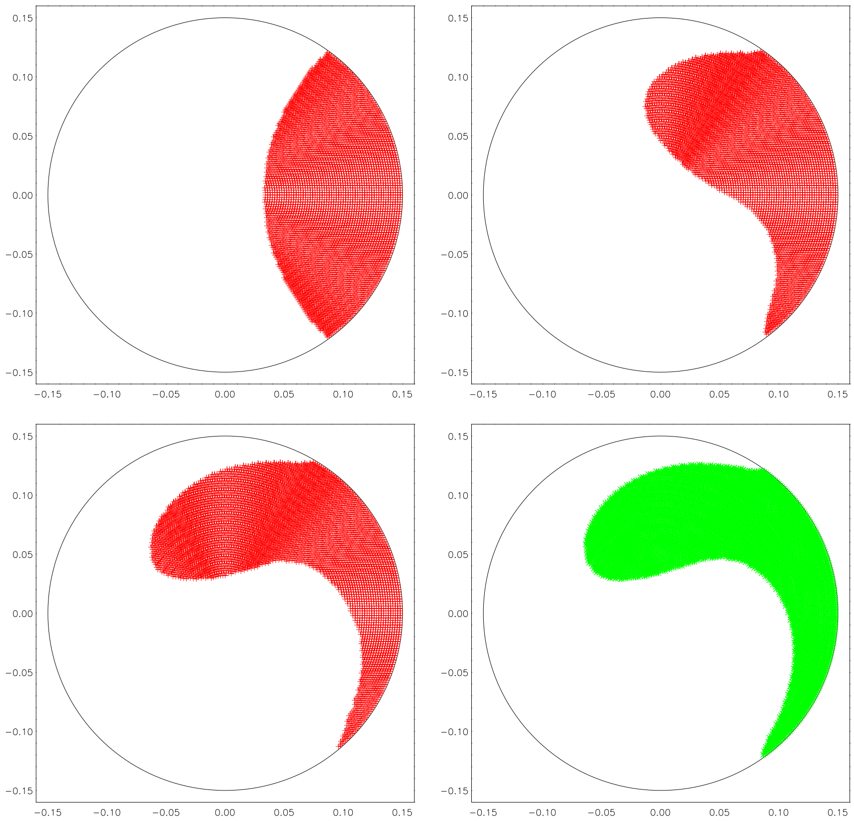

Figure 7. The field line connectivity of the major source at three different times through out the experiment: initial, halfway, final stage. The red area represents the open flux, while the non coloured indicates the fully connected flux. The last panel shows the ideal evolution of initial flux pattern to the final stage.

during the experiment. The red colour represents the open flux, while the white coloured area inside the circle indicates the fully connected flux. The circle represents the area of the imposed vortex flow on the major source. The first three images show how the vortex flow advects the connected area around the source as a function of time for the initial, halfway through and final distribution. The fourth image shows how the initial distribution of flux connectivity would have change at the final time if the evolution would have been ideal (the green area). By comparing image 3 and 4 it is found that there are small difference between the actual and ideal flux pattern. Thus only very small changes in the initial flux connectivity has taken place in the experiment so far. At present further advances in time of the experiment has been prohibited due to a numerical problem.

4. Discussion

From magnetic potential model predictions (Priest and Schrijver 1999), this unbalanced bipolar magnetic field should undergo magnetic reconnection quite easily with the magnetic field at all the times attempting to evolve towards its initial potential state. One clear simplification is to assume that the magnetic field is always nearly potential; this only is valid if the driving time scale is significantly longer than the diffusion time-scale. This is not the case in the above numerical experiment and as a result, the magnetic field evolution is far from being potential. The magnetic field easily absorbs a substantial amount of twist from the boundaries without showing any tendency to release the non-potential magnetic energy on a short time-scale. In fact the magnetic field seems unconcerned with the clearly non-potential and non-force free configuration reached towards the end of the current experiment.

This demonstrates that any attempt to describe the dynamical evolution of magnetic field configurations with a potential field model can only be taken as a "simple" first order approximation to a realistic dynamically evolving system. To investigate more realistic evolutions of magnetic field configurations one has to allow for non-potential and non-force-free dynamical evolutions of the magnetic field structures. Only this way will we have a chance to reproduce the behaviour of the different magnetic controlled phenomena found in solar and stellar atmosphere.

The magnetic configuration investigated here is not particularly active. This is not such a big surprise for two reasons. Firstly, the rotation of the sources creates a form of twisted flux rope and it is known that these are dynamically stable until a significant twist is reached - more than we have imposed in this experiment - before an ideal kink instability is initiated. Secondly, the twisting of the sources does not create a strong enough force to push the open and closed flux together in such a way that they cannot escape strong interaction rather than pushing simply the separator surface around in space. Thus changes in the field line connectivity will happen mainly on the much slower diffusion time scale of the system through the locations of strong current accumulation and not on a fast driven time scale.

The importance of this second point can be seen from the experiment by Galsgaard et al. (2000), where two independent flux systems are driven into each other by imposed foot point motions. Here the initial reconnection between the two initially unconnected sources occurs on a short time scale because the flux systems are forced into each other by the imposed boundary motion. On the other hand, when the flux systems are nearly fully connected, they are found to only open up again, after their near fly-by, on the diffusion time scale. Again, in this phase of the evolution, there are no strong forcing of the two flux systems that can drive fast magnetic reconnection.

Recent TRACE data (8-10 August 2000 in 171 Å, shown by Phil Judge at the conference) displays a rotating sunspot that appears to undergo significant changes in the field line connectivity with only small changes in the angular position. In this real situation the total field line connectivity is much more complicated. There are several minor sources scattered around the main source and the main source swallows up new flux continuously. The additional complexity of the magnetic field sources changes significantly the field line connectivity, providing the possibility for having several locations where the systematic stress of the field influences neighbouring field lines differently. This makes it much easier to drive dynamical activity than in the simple field configuration used in our investigation.

Therefore one can conclude that to drive any fast reconnection the magnetic field needs to have a sufficiently complicated topology, i.e. containing several QSLs. The QSLs are the prime locations for fast energy release. However it has to be noted that QSLs only becomes active if they are stressed in the correct way; such that the flux systems on either side of the separator surface are forced strongly into each other. The solar magnetic field may have many of QSLs in each active region though only a few of them will, at any given time, be involved in active magnetic reconnection.

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