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3D magnetic reconnection, flares and coronal heating

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Abstract. Magnetic reconnection is known to be an important energy release mechanism in many solar, stellar, magnetospheric and astrophysical phenomena. Also it is the only way in which magnetic fields can change their topological structure. Reconnection in three dimensions is not well understood. In particular, knowing where and how reconnection is going to occur and at what rate it occurs at is not generally obvious in time-dependent 3D resistive MHD systems. In order to find answers to the above questions the simple interaction of two opposite-polarity magnetic sources in an overlying field is considered. This simple interaction represents a typical building block of the Sun's magnetic atmosphere. By following the evolution of the skeleton of the magnetic field we are able to explain where, how and at what rate the reconnection occurs in this building block of the Sun's magnetic field. Remarkably there were found to be up to five energy release sites and the reconnection rate is significantly higher than one would expect.

Key words. Sun: flares – Sun: coronal heating – Sun: magnetic reconnection

1. Introduction

Magnetic reconnection is a fundamental plasma physics process that is central to many phenomena on the Sun, such as solar flares, CMEs, coronal heating, nano/microflares, X-ray bright points, explosive events and the solar dynamo. It is also an extremely important mechanism in the magnetosphere where is plays a key role in linking the magnetic fields from the Sun and Earth and in powering flux transfer events and substorms. It is also very important in many astrophysics applications such as accretion discs, stellar flares and coronae, astrophysical jets and stellar dynamos.

Magnetic reconnection is important for two key reasons. First, it is a mechanism by which energy stored in a magnetic field may be rapidly released and converted into thermal energy, bulk plasma motions and the acceleration of particles. Secondly, it is the mechanism by which global restructuring of the magnetic field may take place. Indeed it is this restructuring that facilitates the release of energy by allowing the magnetic field to access a lower energy state.

Clearly, reconnection operates on a wide range of scales from kinetic to MHD. The physics at the kinetic scales govern the portioning of the released energy into its various new forms and play a role in determining the rate of reconnection. MHD determines where the reconnection takes places and hence where the energy is deposited and also effects the reconnection rate.

Two-dimensional reconnection has been studied in detail and is relatively well understood, especially in the solar and magnetospheric contexts, however our knowledge of three-dimensional reconnection is no where near as advanced. In the following sections I shall consider, from an MHD perspective, both where and at what rate reconnection takes place in the solar corona. First though I shall determine an estimate of how much reconnection occurs in the quiet-Sun corona.

2. How much reconnection is there in the solar corona?

The entire surface of the Sun is threaded by magnetic fields that are directed both into and out of the Sun. The magnetic field is clumped into numerous photospheric flux features that range from large sunspots with fluxes of about 10^{20} Mx (Schrijver & Harvey, 1994) down to tiny intranetwork fields with just 10^{16} Mx or less (Wang et al., 1995). These photospheric features, both small and large, are the feet of magnetic loops that are intermingled and expand to fill the whole of the solar atmosphere (Figure 1).

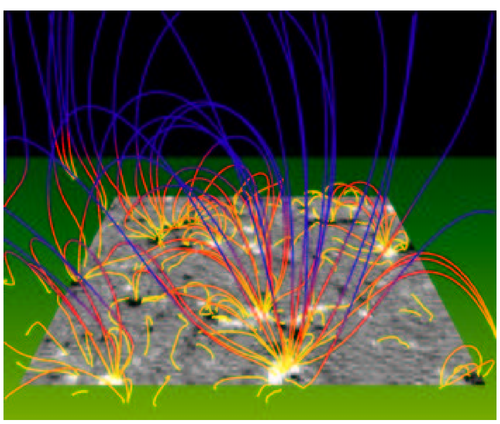

Fig. 1. Potential magnetic field extrapolation from a quiet-Sun magnetogram. The colours on the fieldlines indicate their height above the photosphere.

Supergranular and granular flows, overshoots of convection cells from below the Sun's surface, drive these photospheric flux features towards downflow regions at the convergence of three or more cells. These photosphere motions result in the following behaviours being displayed by the flux features: (i) emergence, in which pairs of features, with equal but opposite-polarity flux, appear; (ii) cancellation, the disappearance (generally through submergence) of equal amounts of flux from a pair of opposite-polarity features; (iii) coalescence, the merging of two like-polarity features creating a larger feature and (iv) fragmentation, the splitting of a large feature into two or more smaller features. Clearly, all these changes in photospheric flux cause changes to the intermingled magnetic loops in the atmosphere above leading to the redistribution of flux between features – that is these flows and flux changes drive magnetic reconnection.

To estimate the time it takes to completely redistribute all the flux between the features during solar minimum Close et al. (2004; 2005) considered a 12 hr series of high-resolution MDI magnetograms. All photospheric magnetic features were identified and then tracked in time. Their birth mechanism (emergence or fragmentation) was noted, as was their death mechanism (cancellation or coalescence). Potential field extrapolations were then used to determine the connectivity of the photospheric flux features. By assuming the evolution of the field through a series of equi-potential states the observed connectivity changes were coupled with the birth and death information of the features to determine the coronal flux recycling/reconnection time. Remarkably it was found that during solar minimum the total flux in the solar corona completely changes all its connections in just 1.4 hrs (Close et al. 2004; 2005). A factor of ten times faster than the time it takes for all the flux in the quiet-Sun photosphere to be completely replaced (Schrijver et al. 1998; Hagenaar, 2003).

3. Where is the energy released?

Clearly, the above result suggests that there is a massive amount of reconnection going on all the time throughout the solar atmosphere,

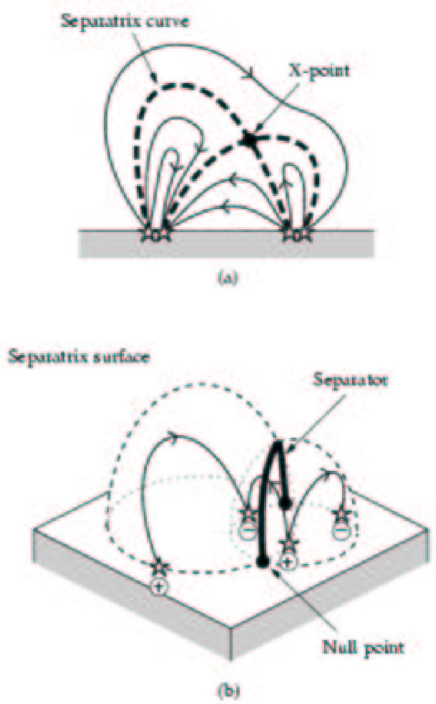

Fig. 2. Sketch showing the key features of a typical (a) 2D and (b) 3D magnetic skeleton.

but a key question is where is this energy released? The simple answer is where current sheets form. Current sheets arise due to gradients in the magnetic field which can be created by a variety of mechanisms such as MHD instabilities and MHD motions. In two dimensions, they often occur at magnetic null (X) points – points where the magnetic field $\mathbf{B} = \mathbf{0}$ – or along separatrix curves – curves that extend out from a null point and divide topologically distinct regions (Figure 2a). In three dimensions, current sheets also form at the weaknesses in the magnetic topology, i.e., at *3D null points*, *separatrix surfaces* – the 3D equivalent of the 2D separatrix curve – or *separators* – the intersection of two separatrix surfaces (Figure 2b). Separators are special field lines that link two magnetic null points and are the dividing line between four topologically distinct regions or flux domains. These three features, as well as the sources themselves, make up what is known as the magnetic skeleton of a three-dimensional magnetic field. For more information on the elements that make up a magnetic skeleton see Cowley (1973), Fukao, Ugai and Tsuda (1975), Greene (1988), Lau and Finn (1990), Parnell et al. (1996) and Priest and Bungey (1997).

Magnetic reconnection generally involves the transfer of flux between four flux domains. Hence, reconnection in three dimensions is likely to occur at separators since they form the boundary between four flux domains. The magnetic skeleton, which includes all the features that enable us to identify separators, as well as the separators themselves, is a very useful tool for identifying the locations of energy release within an evolving magnetic field. Below we give an example illustrating the usefulness of the magnetic skeleton to furthering our understand of events/phenomena involving reconnection.

4. Resistive MHD interaction of opposite-polarity flux features

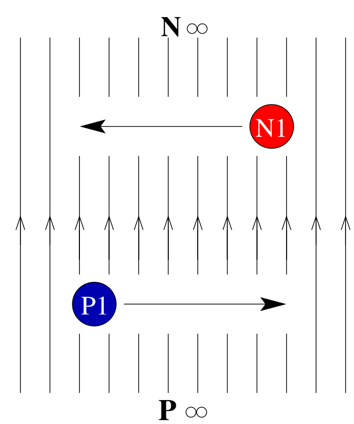

Fig. 3. Sketch of the experimental setup showing the two opposite-polarity sources, $P1$ & $N1$ and the overlying field due to $P\infty$ & $N\infty$. The arrows indicate the direction of advection of $P1$ and $N1$.

We consider a situation where two opposite-polarity magnetic features pass by one another in an overlying field (Galsgaard, et al. 2000; Parnell and Galsgaard 2004; Galsgaard and Parnell 2005; Haynes et al. 2007; Parnell et al. 2007). This very simple interaction may be considered as a building block of the Sun's complex coronal magnetic field. One would imagine that this interaction is trivial, after all there are only four sources, $P1$ & $N1$ – the two opposite-polarity sources prescribed on the base – and $P\infty$ & $N\infty$ that produce the overlying magnetic field (Figure 3). Initially, there are just three flux domains: one domain linking $P1$ to $N\infty$ and another linking $P\infty$ to $N1$, as well as the overlying field which links $P\infty$ to $N\infty$. The two opposite-polarity magnetic sources $P1$ and $N1$ are driven in an antiparallel manner such that their fluxes interact creating flux connecting $P1$ to $N2$. After the sources have been driven far enough passed each other one would expect that this connected flux should decrease leaving the two opposite-polarity sources just connected to the sources at infinity. Hence, we would imagine that the magnetic flux from a single source would reconnect twice as it evolved from

$$\text{open} \rightarrow \text{closed} \rightarrow \text{re-opened}.$$

By looking at the current structures created during the resistive MHD evolution of this simple interaction it was clear that things were not as straight forward as one would imagine. For instance, the closing and re-opening phases overlapped and there were at least 3 strong current sheets, and hence three sites of energy release, apparent for long periods during this interaction. What was happening at these current sheets? Why were there so many? Why they form where they formed?

To answer all the above questions we determined the evolution of the three-dimensional magnetic skeleton for our field. It was found to evolve through six different topological phases. In each phase there are always two null points, one positive and one negative. From each null point there is a separatrix surface. Figure 4 shows a frame from each of the six phases. In each frame the separatrix surfaces are mapped out by the field lines lying in them. The blue field lines show the separatrix surface originating from the positive null and the red field lines show the surface that originates from the negative null. The intersections of these separatrix surfaces, the separators, are shown as yellow curves which join the two null points. These three-dimensional images are difficult to interpret and so we also include cross-sections of the magnetic skeleton for each of these six frames in Figure 5. Here, it is clear that the separatrix surfaces, shown by a thick (positive separatrix surface) or thin (negative separatrix surface) line intersect each other multiple times giving rise to multiple separators. Filled contours of current in these cross-sections clearly demonstrate that the current sheets in the system are all threaded by a separator. Hence, the number of reconnection sites is governed by the number of separators in the system.

Each topological phase corresponds to a different number of reconnection sites, hence has a different number of separators, X:

$$Phase : D1 \rightarrow D2 \rightarrow D3 \rightarrow D4 \rightarrow D5 \rightarrow D6$$

$$X: \; 0 \rightarrow 2 \rightarrow 1 \rightarrow 5 \rightarrow 3 \rightarrow 1$$

and a different number of flux domains, D:

$$D: \; 3 \rightarrow 5 \rightarrow 4 \rightarrow 8 \rightarrow 6 \rightarrow 4$$

The reconnection process at each separator may be either closing or re-opening the magnetic flux from the sources $P1$ and $N1$.

The two phases that last the longest are $D3$ involving a single separator and the $D5$ which has 3 separators. Figure 6 shows a sketch of the direction of reconnection at separator $X1$ in phase $D3$ (green arrows). This phase occurs near the start of reconnection in the system and so naturally the flux is being closed at this separator. To determine the rate of reconnection, α_1, here one can simply calculate the rate of change of closed flux,

$$\alpha_1 = \frac{d\phi_c}{dt}.$$

In Figure 7, a sketch shows the direction of reconnection at each of the three separators. Here once again the flux is being closed at the central separator, $X1$ (green arrows). At the two outer separators $X2$ & $X3$, however, it is being

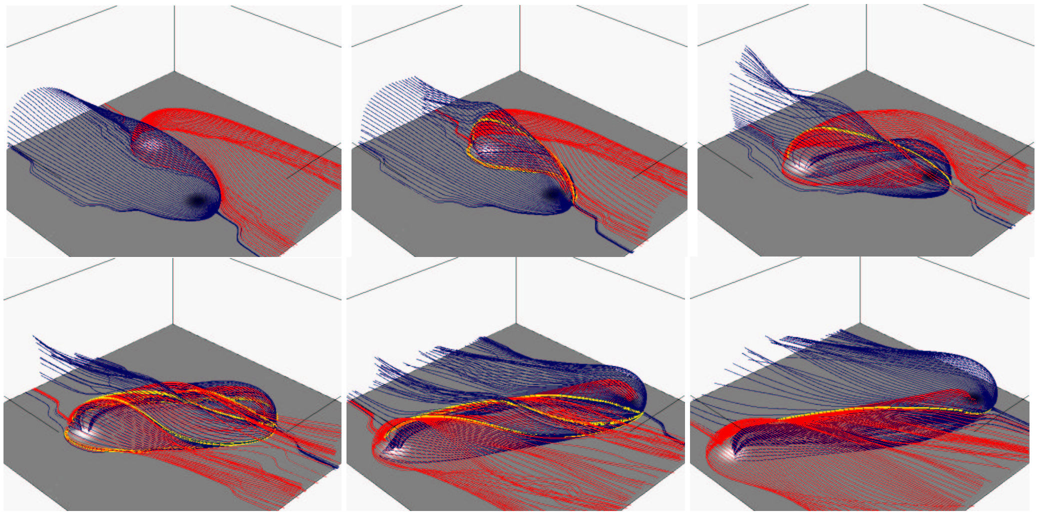

Fig. 4. A three-dimensional view of the magnetic topology evolution during the interaction of two opposite-polarity features in an overlying field. Field lines in the separatrix surfaces from the positive (blue) and negative (red) are shown. The yellow lines indicate the separators.

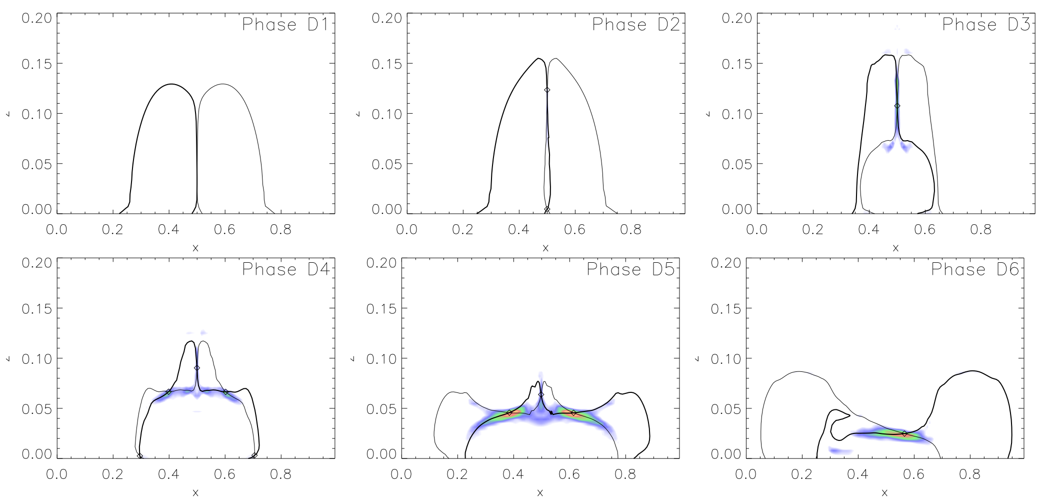

Fig. 5. A cross-sectional cut showing the magnetic topology evolution during the interaction of two opposite-polarity features in an overlying field. A cut thought the positive separatrix surface is shown by a thick line whilst the cut through the negative one is given by a thin line. Diamonds indicate where the separators intersect the plane. The coloured contours represent current.

re-opened (magenta arrows). This overlapping of the two reconnection processes allows flux to both close and then re-open multiple times, hence the interaction of these sources is not as simple as originally imagined:

$$\text{open} \rightarrow \text{closed} \rightleftharpoons \text{re-opened}.$$

This recycling reconnection behaviour is made possible because all the separators link the same two null points: the nulls are said to be *multiply connected*. Multiply-connected nulls go hand-in-hand with multiply-connected source pairs and have the following important consequences:

- *Greater spread of released energy*: the more separators there are the more sites for reconnection, and hence energy release, leading to a better/wider distribution of energy. This is important for the background coronal heating process which requires the injection of energy at as many locations as possible.
- *Faster release of energy*: energy is being released at multiple locations enabling the overall reconnection rate of the system to be higher than if it was simply being reconnected at one location. This, of course, is likely to be important for solar flares which require extremely rapid releases of energy.
- *Repeated heating of the plasma*: since flux is repeatedly reconnected over and over it is possible for certain parts of the plasma to have injections of energy in rapid succession over a short period of time enabling it to potentially get significantly hotter than other regions of plasma around it. Furthermore, this repeated reconnection of certain parts of flux may explain why, in some circumstances, you can observe solar flare loops before they reconnect when you would normally expect them to be cool and so invisible in X-rays.
- *Longer heating process*: since flux is not simply closing and then re-opening, but these processes repeat themselves many times, the entire heating process can last longer than if it simply closed and re-opened just once. This again is useful from a coronal heating perspective.

We can also see from Figure 7 that to determine the reconnection in the system at this time it is not enough to know the rate of change of closed and re-opened flux. The rates of reconnection at separators $X2$ and $X3$ may be estimated reasonably simply since they just depend on the rate of change of flux in domains $\phi 1$ and $\phi 4$,

$$\alpha_2 = \frac{\mathrm{d}\phi 1}{\mathrm{d}t} \quad \& \quad \alpha 3 = \frac{\mathrm{d}\phi 4}{\mathrm{d}t}.$$

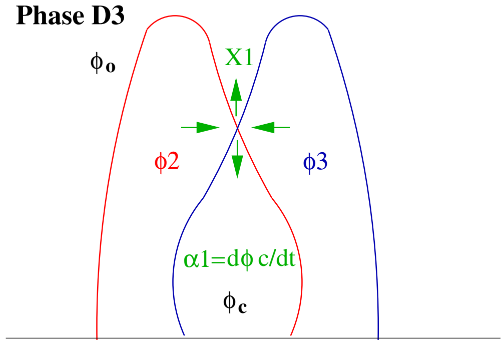

Fig. 6. Sketch showing the direction of reconnection at the separator, $X1$, in phase D3. The rate of reconnection at this separator is α_1, where ϕ_i equals the flux in domain i.

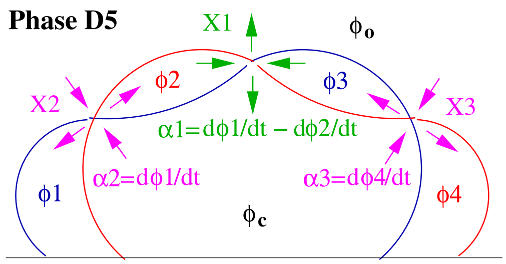

Fig. 7. Sketch showing the direction of reconnection at each of the separators, $X1$-$X3$, in phase D5. The rate of reconnection at separator Xi is given by α_i, where ϕ_j equals the flux in domain j.

However, to determine the rate of change of flux at $X1$ you must know either the reconnection rate α_2 or α_3 before the rate α_1 can be determined,

$$\alpha_1 = \frac{\mathrm{d}\phi 1}{\mathrm{d}t} - \frac{\mathrm{d}\phi 2}{\mathrm{d}t} = \frac{\mathrm{d}\phi 4}{\mathrm{d}t} - \frac{\mathrm{d}\phi 3}{\mathrm{d}t}.$$

So to go back to our original questions. What is happening at the current sheets? Reconnection of course, but this is either closing or re-opening the magnetic flux depending on which particular separator the current sheet surrounds. It is only by looking at the magnetic skeleton that the direction of the reconnection at each separator can be easily found. Why are there so many current sheets? There are so many because there are multiple separators. The multiple separators arise due to a global double-separator bifurcation (Haynes et al. 2007) which is the most nature way in which magnetic fields can initiate a change from one topological state to another. Finally, why have the current sheets formed where they formed? They have arisen through either magnetic pressure or magnetic tensions forces driving the magnetic field at certain locations creating gradients in the fields and, hence currents.

5. Conclusions

Through the detailed analysis of a simple three-dimensional magnetic interaction, forming a building block of the Sun's magnetic atmosphere, we have demonstrated that the reconnection of magnetic flux systems is not only non-trivial, but is highly complex. Determining the evolution of the magnetic skeleton of a three-dimensional system allows

- the reconnection/heating sites to be located,
- the process of reconnection occurring at each site to be determined,
- the rate of reconnection to be determined. (Note: to determine the rate of reconnection correctly the location and reconnection processes at each location need to be known first).

An unexpected discovery from the magnetic skeleton analysis was of multiply-connected source and null pairs. These two features go hand-in-hand and provide

- extra sites for reconnection/heating,
- a faster total reconnection rate,
- better distribution of heat.

Clearly, these all make it easier to heat the corona and generate solar flares.

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