UNDERSTANDING MAGNETIC STRUCTURE IN THE SOLAR CORONA THROUGH TOPOLOGICAL ANALYSIS

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ABSTRACT

The next generation of solar telescopes will quickly produce a huge quantity of high-quality vector magnetogram data requiring analysis. Realistic magnetic fieldline extrapolations (e.g. nonlinear force-free) are useful but can be overcrowded and difficult to interpret, as well as time consuming. Focussing on the magnetic topology is an elegant way to pick out the key features of the structure and connectivity of the magnetic fieldlines. This technique allows easy and clear visualisation of 3D magnetic structures in the solar atmosphere, highlighting the important regions where dynamical and energetic processes will be concentrated. A new topological code currently being developed at St Andrews will enable the construction of the magnetic field topology from observational or computational magnetic field measurements, providing a new way of understanding both observational data and results from numerical (MHD) simulations.

1. INTRODUCTION

Due for launch in the second half of 2006, Solar-B (Fig. 1) is a new satellite which will observe the Sun in visible light, extreme ultrviolet, and X-rays, at an unparalleled level of resolution. Its Solar Optical Telescope (SOT) will produce high-time-cadence (5 minutes) vector magnetograms of active regions, with $0.25''$ resolution in space and 1-5G (longitudinal) and 30-50G (transverse) resolution in the magnetic field $\mathbf{B}$. This is a significant improvement over current capabilities, which for the most part are still line-of sight magnetic field measurements, with poorer resolution. In summary, the excellent quality of the magnetic data provided by Solar-B presents us with an important new opportunity to improve our models and our understanding of the structure and evolution of the coronal magnetic field.

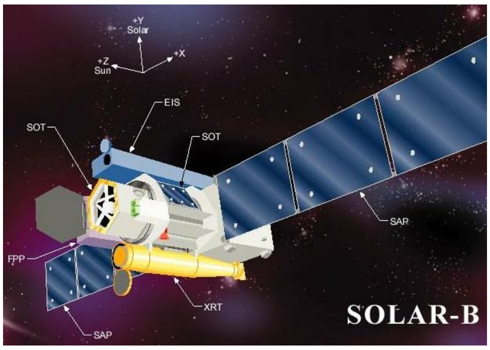

Figure 1. Schematic of the Solar-B satellite showing the locations of the instruments; SOT is the Solar Optical Telescope which will produce high-quality vector magnetograms of active regions.

However, the large quantity of interesting data that will soon be available poses a different kind of problem in itself. What is the best way to reduce the sheer volume of data to manageable levels and isolate the valuable information? We propose here that magnetic topology analysis (Longcope, 2005) is a useful technique to do just this, providing a simple and clear way of interpreting magnetogram data in terms of the structure and connectivity of the magnetic field.

2. BENEFITS OF TOPOLOGICAL APPROACH

Extrapolations of arbitrarily chosen magnetic fieldlines in a realistic nonlinear force-free field can be constructed relatively easily from magnetogram data such as those from Solar-B or MDI/SOHO. However, such extrapolations are often crowded and difficult to interpret. Extracting the topological *skeleton* from the data allows clear visualisation of the underlying magnetic field structure and how the different magnetic polarities are connected.

As an example, we have calculated the potential magnetic field above a small active regions observed by MDI. Fig. 2 shows one hundred randomly chosen fieldlines superimposed on the magnetogram. Fig. 3 then shows the equivalent photospheric footprint of the topological

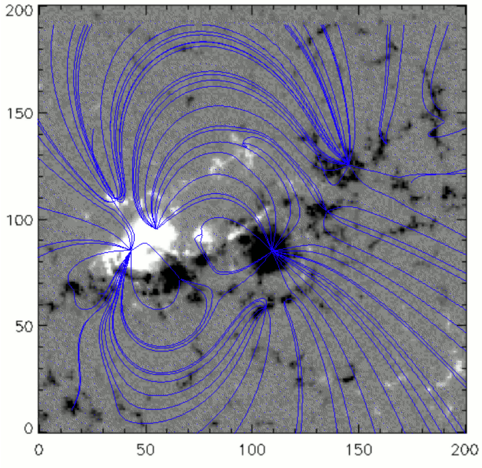

Figure 2. MDI magnetogram overlaid with extrapolated potential magnetic fieldlines.

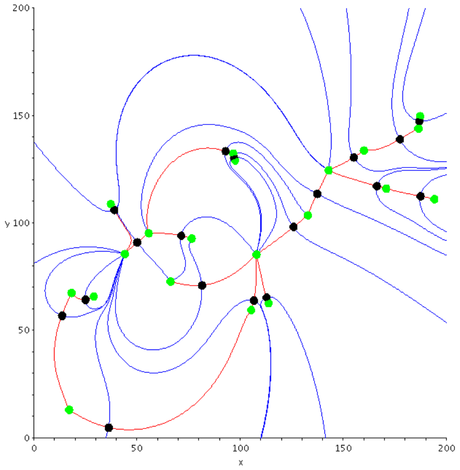

Figure 3. Photospheric footprint of the topological skeleton of the same region shown in Fig. 2.

skeleton of the magnetic field. Notice how only the fieldlines that outline regions of different connectivity are shown, highlighting only the structural information. Comparing Figs. 2 and 3 clearly shows that a smaller number of such carefully chosen fieldlines can convey all the essential information in a clear and concise way. In the next section we explain exactly what is meant by a topological skeleton and how it is constructed.

3. OVERVIEW OF MAGNETIC TOPOLOGY

The structure of a generic first-order potential magnetic null point (Parnell et al., 1996), where $\mathbf{B} = 0$, is shown in Fig. 4. It is found by linearising the expression for the magnetic field close to the null; for this specific case, the eigenvalues will be real, with one always having the opposite sign to the other two. This eigenvalue and its associated eigenvector define the starting point for the *spine* fieldline which passes through the null. The rest of the fieldline can then be extrapolated in the usual way. Similarly, the *separatrix surface* or *fan* of fieldlines passing through the null is defined by the eigenvectors associated with the tow remaining eigenvalues which have the same sign.

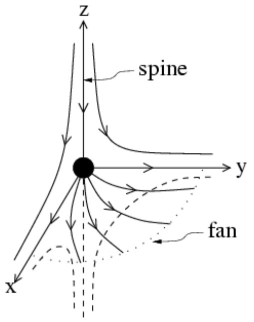

Figure 4. Structure of the magnetic fieldlines near a generic first-order potential magnetic null point.

Separatrix surfaces are especially important in magnetic topology as they lie on the division between two distinct, unconnected domains of magnetic flux. Visualising the separatrices is therefore a short cut to understanding which flux patches are magnetically connected and which are not.

When two separatrix surfaces intersect one another, they do so in a special fieldline called a *separator*, which runs between the two null points associated with the separatrices. The separator is thus the bounding line between, in general, four distinct magnetic flux domains. Both separatrices and separators are prime locations for magnetic reconnection and hence where heating is expected to take place (Priest et al., 2005).

Fig. 5 is an example with four magnetic sources on the surface of a sphere. Two null points are created, each with the spine and fan structure of fieldlines mentioned above, making two separatrix domes of fieldlines. Where the domes intersect there is a separator. This particular topology was studied by Maclean et al. (2006a) and is called the “intersecting” state due to the arrangement of the two separatrix surfaces.

4. THE NEW MAGNETIC TOPOLOGY CODE

At present, most magnetic topology analysis is accomplished by reducing line-of-sight magnetogram data to a finite set of point magnetic sources, analytically calculating the potential field they produce, and analysing it as explained in Section 3. However, similar techniques could be applied to a much wider range of magnetic field

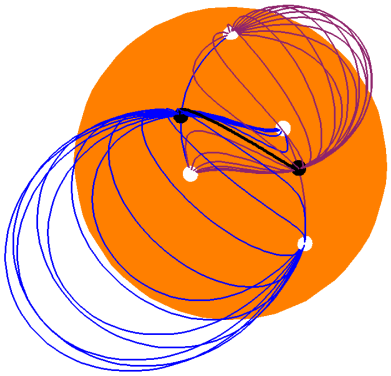

Figure 5. One possible magnetic topology resulting from four magnetic sources (white circles) on the sphere. Two magnetic null points (black circles) are created, each with its associated separatrix surface (blue and purple fieldlines). The two separatrices intersect in a separator (black fieldline).

data. For example, it would be beneficial to use magnetic topology to study data produced using finite instead of point sources, or with linear or nonlinear force-free magnetic field reconstructions replacing the more restrictive potential ones. The method could also be very helpful in analysing the results of 3D numerical MHD simulations.

A new magnetic topology code currently under development at St Andrews will make it possible to achieve these goals. The approach is the same in all cases. All that is required as an input is the three components of magnetic field on a 3D numerical grid, regardless of how these data were produced, and knowledge of the boundary conditions. The code will first identify null points on the photospheric boundary, then use these to calculate the photospheric footprint of the topology (the spine and separatrix fieldlines). Subsequently, it will search for nulls in the corona and calculate the coronal separatrix surfaces and spines. Finally the separators will be located to complete the magnetic topology.

Fig. 6 shows the topological skeleton of a magnetic field which itself was the result of a 3D numerical MHD simulation. It shows how complex magnetic configurations with multiple separators can be clearly visualised with the new code.

It is anticipated that this code will greatly enhance our understanding of the structure of magnetic fields in the corona for many kinds of feature, including solar flares, prominences, X-ray bright points, etc. Time sequences showing how the magnetic structures vary and evolve should prove especially interesting and useful.

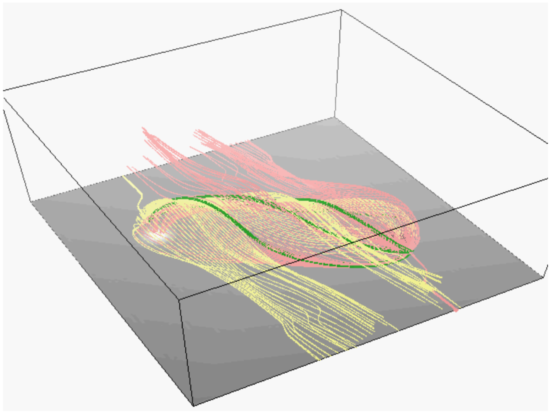

Figure 6. ***B*** *from 3D MHD simulation with two finite magnetic sources creating two separatrices (red and yellow fieldlines) which intersect to give three separators (green fieldlines).*

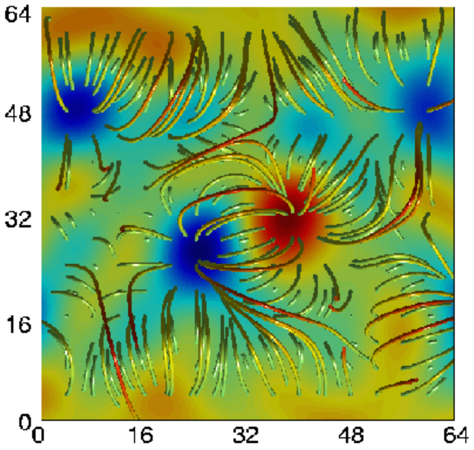

Figure 7. Magnetogram with extrapolated fieldlines. Positive flux is red, negative flux is blue.

5. CASE STUDY: X-RAY BRIGHT POINTS

In this section we give an example of how magnetic topology analysis can be applied to the results of a numerical experiment and how it provides a fresh interpretation of those results which adds to our understanding.

Fig. 7 is a magnetogram of a region where an X-ray bright point occurred. It gave the initial condition for a 3D numerical MHD simulation (Maclean et al., 2006b). We started from a potential field, and some of these fieldlines are shown in Fig. 7. The central negative polarity was then rotated to mimic the observations and find out where this caused reconnection to occur in the field. Fig. 8 is a contour plot showing where high values of parallel electric field built up, and hence where reconnection is likely to occur.

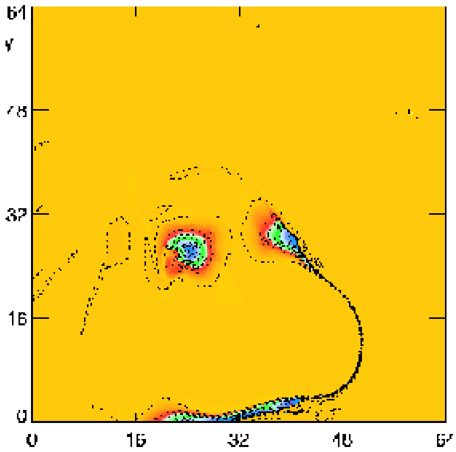

Figure 8. Contour plot of the parallel electric field in the same region as Fig. 7.

A topological model was then constructed by reducing the magnetogram to a set of fourteen point sources. We calculated the potential field of this configuration and constructed its topological skeleton, as described in section 3. Fig. 9 shows the topological footprint of the skeleton in the photosphere. The separatrix dome of a coronal null covers the rotating polarity and touches the photosphere along the circuit of spines from the central positive polarity down along the lower edge of the picture and back up the lower left-hand edge. This corresponds very well to the location of increased parallel electric field in Fig. 8. We conclude that the magnetic topology is indeed an excellent predictor for sites of magnetic reconnection and heating.

6. CONCLUSIONS

Vector magnetograms from Solar-B and other new high-resolution magnetic data will benefit from analysis with magnetic topological methods. This will help to select interesting areas for further study and is a good predictor of sites of dynamical processes, as we showed in our X-ray bright point example. A code is currently being developed at St Andrews which will allow the application of topological analysis to any 3D numerical magnetic data, whether observational or the result of simulation. This will be a valuable new tool for interpreting magnetic field data and improving our understanding of the structure and evolution of the magnetic field in the solar corona.

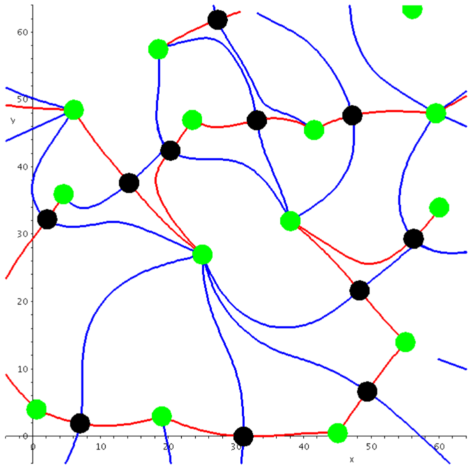

Figure 9. Photospheric footprint of the topological skeleton of the same region as Figs. 7 & 8. Magnetic sources are green circles, null points are black circles, spine fieldlines are red and separatrix fieldlines are blue.

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