THE MAGNETIC TOPOLOGY OF SOLAR ERUPTIONS

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ABSTRACT

We present an explanation for the well-known observation that complexity of the solar magnetic field is a necessary ingredient for strong activity such as large eruptive flares. Our model starts with the standard picture for the energy buildup—a highly sheared, newly emerged magnetic field near the photospheric neutral line held down by an overlying unsheared field. Previously, we proposed the key new idea that magnetic reconnection between the unsheared field and neighboring flux systems decreases the amount of the overlying field and, thereby, allows the low-lying sheared flux to "break out." In this Letter, we show that a bipolar active region does not have the necessary complexity for this process to occur, but a delta sunspot has the right topology for magnetic breakout. We discuss the implications of these results for observations from *SOHO* and *TRACE*.

Subject headings: MHD — Sun: flares — Sun: magnetic fields — Sun: prominences

1. INTRODUCTION

One of the outstanding questions in solar physics concerns the magnetic topology responsible for major eruptive activity such as coronal mass ejections (CME) and large two-ribbon flares accompanied by a filament/prominence eruption. This question is critical both for understanding the physics of solar eruptions and for predicting them. It has long been known empirically that two features are required for strong solar activity: magnetic shear and magnetic complexity (e.g., Patty & Hagyard 1986). By shear we mean that the field near the photospheric neutral line is observed to be almost parallel to the neutral line, rather than perpendicular to it, as would be the case for a potential field (Schmieder et al. 1996). By complexity we mean that the active region is not simply bipolar, consisting of a leading sunspot and a well-separated trailing polarity region, but contains instead an intermingling of polarities as in a delta sunspot in which two opposite polarity umbrae share a common penumbra (Bray & Loughhead 1964). Delta sunspots, in particular, are well known to be prolific flare producers (e.g., Patty & Hagyard 1986; Tanaka 1991; Zhang 1995).

The physical reason for the observed requirement of shear is straightforward to understand. The field must contain free energy in order to power the eruptive event; somewhere, there must be a large deviation of the field from its potential state. Furthermore, since the free energy is most easily generated in the deep photosphere, it should appear in the field that has most recently emerged and, therefore, is nearest the neutral line.

The second feature, magnetic complexity, is more difficult to understand. CMEs, filament eruptions, and two-ribbon flares usually appear to occur along only a single neutral line, i.e., in a bipolar region. The posteruption X-ray emission is observed to straddle only one neutral line. In fact, the standard picture for flare/filament eruptions, the so-called tether cutting model (e.g., Sturrock 1989; Moore & Roumeliotis 1992), involves only a single sheared magnetic arcade. Although magnetic complexity plays no role in this model, the observations show that it is essential for the event to occur in the first place. Also, recent observations indicate that multiple neutral lines may be a common feature of CMEs (Webb et al. 1997). In this Letter, we clarify why the magnetic complexity of a delta sunspot, or worse, is necessary for violent eruptions.

2. MAGNETIC TOPOLOGIES

Recently, we developed a new model for solar mass ejections (Antiochos, DeVore, & Klimchuk 1998) that shares with the standard picture the features that the eruption and the bulk of the energy release occur in a sheared arcade. As usual, the shear is concentrated near the neutral line, so that the stressed core field near the neutral line provides the free energy and the upward push, whereas the unsheared overlying field provides the downward pull that restrains expansion of the core field. The key new feature proposed in our model is that additional flux systems are present, which make it possible for reconnection to take place between the unsheared overlying flux and the flux in those neighboring systems. This reconnection transfers unsheared flux to the neighboring flux systems, thereby removing the overlying field and the restraining pull. Hence, reconnection allows the innermost core field to "break out" to infinity without opening the overlying field and violating the Aly-Sturrock open-field energy limit (Aly 1991; Sturrock 1991).

A two-dimensional model for this "breakout" process has been presented (Antiochos et al. 1998). The model postulated a global magnetic field topology for the Sun consisting of a four-flux system in which reconnection between the upper and lower systems transfers flux to the two side systems. The question we address in this paper is the following: *What is the minimum complexity needed in the magnetic field of an active region so that a similar process can occur in a fully three-dimensional geometry?*

In order to answer this question, let us first determine the topology of a bipolar active region. For this case, the relevant magnetic field corresponds to a large-scale background solar bipole in which an active region bipole has emerged. Since we are interested only in the basic topology, it is sufficient to consider a potential, unsheared field; a typical example is shown in Figure 1. The yellow surface in the figure corresponds to the photosphere chosen to be at $z = 0$, and the view is oriented so that the $+z$-direction is vertical, $+y$ is to the right, and $+x$ is out of the page. The background field is that due to a magnetic dipole pointing in the $-y$-direction, with relative magnitude 10^6, and located at position $(0, 50, -100)$. The active region is due to another dipole, in the $+y$-direction, with magnitude 2×10^4, and located at $(0, 12, -10)$. The active region "sunspots" are indicated in the figure by the black and white spots,
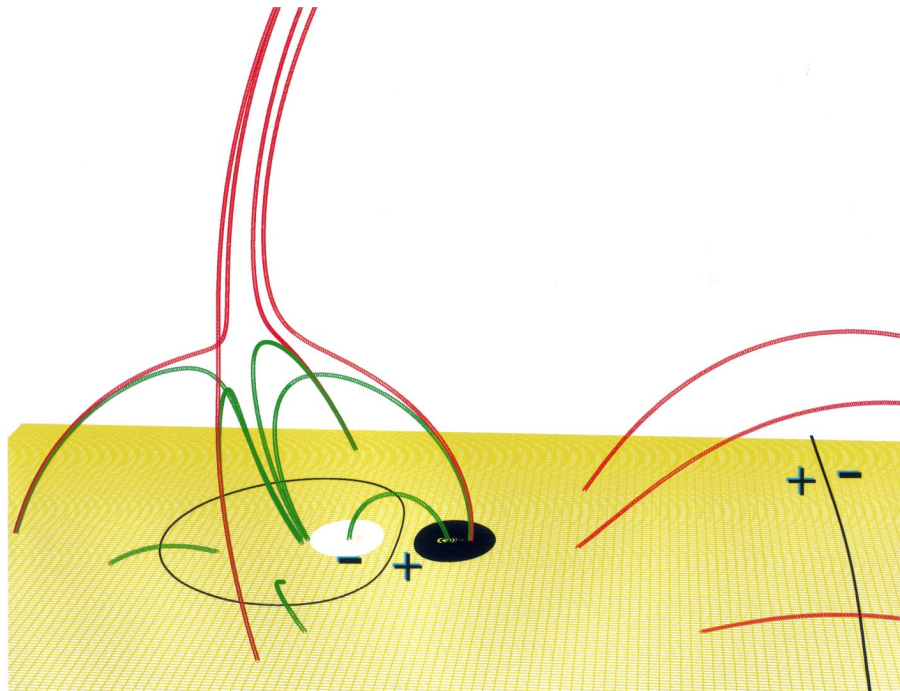
Fig. 1.—Magnetic topology of a dipolar active region

which contain all the contours of B_z on the photosphere that are greater than half-maximum. Note that B_z is smooth everywhere; the contours simply indicate where there is concentration of the field, and they can be thought of as indicating the umbra of the spots. A true sunspot would have much higher field concentration than our example here, but the topology would be the same.

There are three polarity regions on the photosphere: a semi-infinite negative region due to the background dipole; a semi-infinite positive region consisting of the positive background plus the positive, leading-polarity active region sunspot; and a finite negative region due to the trailing polarity sunspot. The two neutral lines defining the three polarity regions are indicated by the black lines on the yellow photospheric plane. The closed neutral line surrounding the finite negative polarity region would correspond to the edge of the trailing spot's penumbra.

It is evident from Figure 1 that the topology of a bipolar active region is simply that of an embedded dipole (Antiochos 1996). It consists of only two flux systems, the flux connecting the positive polarity region to the background field (*red field lines*) and the flux connecting the positive polarity region to the negative spot (*green lines*). The separatrix surface can be visualized by examining those field-line sections where the four pairs of red and green lines are indistinguishably close together in the figure. These red-green sections outline a hemispherical separatrix surface that encloses the green flux and across which the magnetic connectivity is discontinuous. The connectivity is also discontinuous at a singular line originating at a point inside the negative sunspot region (where the four green field lines appear to come together in the figure) and continuing into the background region (the four red field lines that are close together). A magnetic null occurs in the corona where this singular line passes through the separatrix surface (e.g., Lau & Finn 1990). The intersection of the separatrix surface with the plane of the photosphere forms a closed curve that encircles

the negative sunspot and defines the photospheric boundary between the green and red field lines. The photospheric connectivity is discontinuous at this curve and at the two points where the singular line intersects the photosphere.

We now imagine that the field near the photospheric neutral line of the negative spot is strongly sheared and ask what happens to the overlying green flux. The key point is that, in this case, the amount of overlying unsheared flux cannot decrease. The green flux inside the photospheric separatrix curve must always be exactly equal to the amount of flux in the trailing negative polarity sunspot. Note, however, that reconnection and energy release can still occur. For example, if the "sunspots" in Figure 1 move, then red and green flux can reconnect at the null (Antiochos 1996), exchanging positions and causing the separatrix curve to move to its most energetically favorable position. But the amount of green flux inside the separatrix never changes. Therefore, in order for the sheared core field to open, a fixed amount of unsheared overlying flux would have to open as well, which is energetically unfavorable (Aly 1991; Sturrock 1991). This is the fundamental reason why bipolar active regions do not exhibit violent eruptive activity even if strongly sheared—their topology is too restrictive to allow a decrease in the overlying unsheared flux.

Now, let us consider a delta sunspot. To the system of Figure 1, we add a dipole that is pointing in the $+z$-direction, with magnitude 7×10^4, and located inside the negative spot region at $(0, 0, -6.5)$. The resulting topology is shown in Figure 2, which focuses on the region around the negative spot for clarity. Because of the presence of the additional dipole, a positive polarity umbra and a neutral line have appeared inside the negative spot, giving it a delta appearance. In order to make the topology easier to visualize, we chose the dipole parameters so that the parasitic polarity is located centrally within the parent spot, but the results described below remain valid for the usual case where the parasitic spot is off to one side.

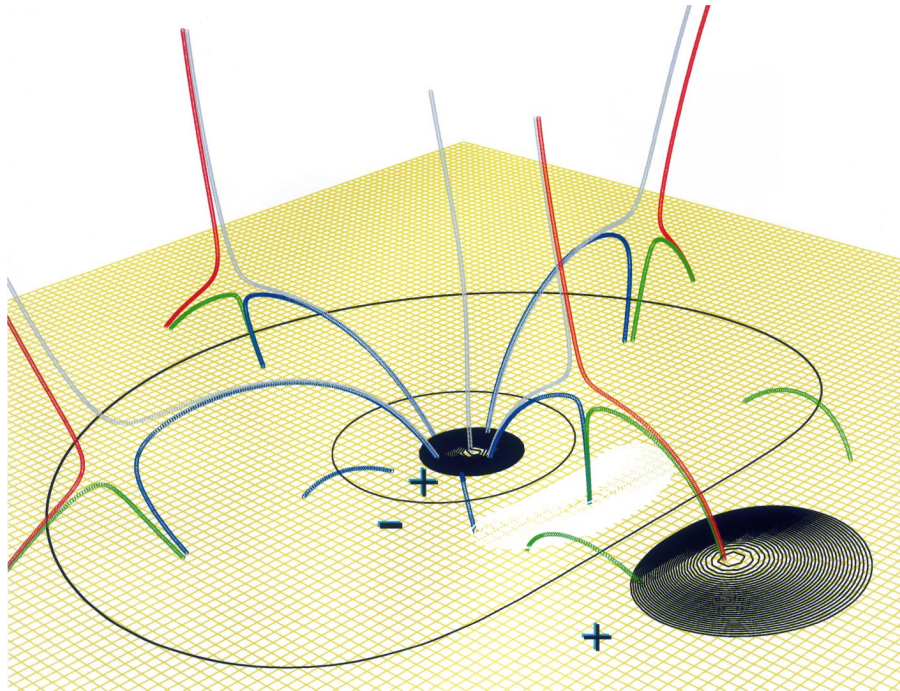Now four distinct flux systems are present. In addition to

Fig. 2.—Magnetic topology of a delta sunspot region

the original red and green systems, there is a blue flux system composed of field lines that connect the negative spot to the parasitic positive polarity. We expect this system to appear with the addition of the parasitic polarity, but surprisingly, another flux system (*gray field lines*) appears inside the parasitic spot and connects some of the innermost positive flux to the distant, negative polarity background region. The separatrix surfaces now consist of a horizontal and a vertical torus, both cut by the photosphere plane. The horizontal torus can be visualized by joining the field-line sections where the red and green lines are indistinguishably close to the sections where the blue and gray lines are close. Similarly, the vertical torus is formed by joining the blue-green sections to the red-gray sections (only a small base section of this torus can be seen in the figure). In the corona, the curve of intersection of the two tori defines a separator line along which all four flux systems come in contact. For the particular delta spot of Figure 2, which has a high degree of symmetry, there are four magnetic nulls located on this separator line, but there can be as few as two. The intersection of the two separatrix surfaces with the plane of the photosphere forms three concentric closed curves across which the photospheric connectivity is discontinuous. As before, an approximately circular curve outside the negative spot marks the photospheric boundary between red and green flux, a closed curve lying inside the negative spot but outside the positive spot denotes the boundary between green and blue, and a closed curve lying inside the positive parasitic spot bounds the blue from the gray.

This four-flux topology is precisely what is needed for eruption to occur and is the direct three-dimensional analog of our two-dimensional model (Antiochos et al. 1998). Assume, as before, that the neutral line around the negative spot is strongly sheared. The green flux overlying the core neutral line field can now be decreased by reconnection between the green and gray systems at the coronal separator line. This will convert green and blue flux into red and blue. Note that, unlike the

dipolar active region case above, the actual amount of green flux decreases, which allows the sheared core field to erupt outward. On the photosphere, the outer separatrix curve shrinks inward while the middle separatrix curve expands outward. An identical behavior can be obtained by shearing the inner neutral line. Reconnection between blue and red field lines at the separator line converts them into green and gray. Of course, a real active region on the Sun can have much more complexity than this very simplest of delta configurations; even so, we expect that the topology of four flux systems meeting along a coronal separator line is the basic topology underlying eruptive activity. It is unlikely that more than four systems would share a common boundary.

We conclude, therefore, that a delta sunspot has sufficient complexity for the breakout model to operate and propose that this is why delta spots are so active. Note that, if eruption does occur, it will take place on only one neutral line at a time, because a decrease in the field overlying one neutral line requires an increase in the field overlying the adjacent neutral line. This explains why solar eruptions typically appear to involve only one sheared arcade.

The eruption itself is exactly the same in our model as in the standard picture, except that now even the lowest lying sheared field can open (Antiochos et al. 1998). The sheared field at one neutral line blows open, ejecting a filament if present, and then reconnects with itself to close back down and form the observed hot X-ray loops. It should be emphasized that this posteruption reconnection, which can release a great deal of energy, is completely different from than the reconnection proposed in our model, which acts only as a trigger for the eruption.

Our model has interesting implications for observations. A crucial feature of the topology in Figure 2 is the presence of the gray flux connecting the parasitic spot to the distant background region. This feature is the main difference between the delta and the bipolar field of Figure 1, in which all the flux of

the negative sunspot connects locally. Even though the parasitic polarity flux in our example is significantly smaller than the flux of the parent spot, this nonlocal connection is the minimum-energy, current-free state of the magnetic field. Of course, if the parasitic spot is sufficiently small, then all its flux will close locally into the parent spot, so that the topology becomes that of an embedded dipole within an embedded dipole. These considerations imply that, as flux emerges through the photosphere, one should see an abrupt jump in the structure of coronal loops after it becomes energetically favorable for the parasitic spot to form distant connections. Such dramatic jumps in coronal connections, correlated with magnetic emergence, should be directly observable with the magnetograph on *SOHO* and the high-cadence XUV telescopes on *TRACE*.

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