FLUX EMERGENCE AND PROMINENCES: A NEW SCENARIO FOR 3-DIMENSIONAL FIELD GEOMETRY BASED ON OBSERVATIONS WITH THE ADVANCED STOKES POLARIMETER

B. W. LITES and B. C. LOW
High Altitude Observatory, NCAR, P.O. Box 3000, Boulder, CO 80307–3000, U.S.A.*

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Abstract. This paper presents an interpretation of the evolution of the vector magnetic field at the photosphere based on measurements of the advanced Stokes polarimeter, along with chromospheric Hα from the Lockheed instrument operating on La Palma and X-ray images of the corona from *Yohkoh*. These measurements are consistent with the emergence of a nearly closed magnetic structure from the solar interior into the corona. The highly non-potential field topology inferred from the data suggests that strong field-aligned currents exist in the emergent magnetic structure as it buoyantly rises through the photosphere. Material trapped in this closed structure is pulled upward to later condense into a prominence. By analogy of this small active region evolution with the observed properties of large quiescent prominences, we speculate that this process might also be operative on a much larger scale. A 3-dimensional magnetostatic model is presented which has many topological features in common with the observations.

1. Introduction

In the past, our conceptual models of magnetic fields emerging from the solar interior into the solar atmosphere have been prejudiced by the simple connectivity of potential, or nearly-potential magnetic field topologies. We often think of simple loops arching smoothly from one footpoint of, e.g., positive magnetic polarity observed at the photosphere to a negative polarity footpoint observed at some horizontal distance away. Non-potential aspects of the field are then presumed to come about by relative motions (often fairly large in scale) of the magnetic footpoints as a result of systematic flows of the plasma at and just below the solar surface, thus 'shearing' the field in the observable region of the solar atmosphere. However, in these pictures one rarely envisions the field geometry to depart radically from the rather simple potential-like configurations.

The justification for such simple field topologies is a strong one: they suffice to show how a build-up of energy may take place starting from an initial state which is a minimum-energy state. Furthermore, one might invoke 'Occam's razor': why should there be a complex field geometry when a simpler one will adequately describe a given physical situation? The danger with the approach of simple topologies is that it may embrace some fundamentally wrong assumptions regarding certain solar magnetic field structures: the simple topology may not take into account features of the observed behavior which are crucial to the form and

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stability of the magnetic structures residing in the solar envelope and atmosphere. An alternate scenario is that the magnetic field upon entering the photosphere and above is already far from being potential, with strong shears and twists which had developed during its extensive journey through the convection zone. Such a field does not begin as a potential field in the atmosphere. We believe this scenario of a complex magnetic field rising through the photosphere merits exploration and investigation, especially in the context of the support of solar prominences. There is need to develop a theoretical intuition for the possible topology of complex field structures, and for the physics of such structures during their emergence and post-emergence evolution.

The possibility that twisted, non-potential fields could be generated within the interior and then emerge in a non-potential state was, to our knowledge, first discussed by Piddington (1974) and then by McClymont and Fisher (1989), both in the context of energetics of solar flares. Subsequently, Tanaka (1991) demonstrated that the evolution of a complex flaring active region is consistent with the emergence of highly twisted (perhaps even knotted) magnetic flux from below. Recently, Leka (1994) used both vector magnetogram data and the movement of sunspots and pores to observe the evolution of the twist in active regions directly at the photosphere. She also concluded that most of the twist resides in the field before emergence.

Here we propose a concept for the buoyant rise of twisted fields, and the plasma that accompanies them, into the solar atmosphere as a possible explanation for the prominence phenomenon. This concept was motivated by one rather well-observed event (Lites *et al.*, 1995, hereafter Paper I) in which most of the data are compellingly consistent with a rope of magnetic flux passing vertically through the atmosphere into the corona, pulling material upward with it to form a prominence during its later stages. We regard this event as perhaps a relatively uncomplicated glimpse into a process which *may* be acting commonly on much larger scales, where the fields are much more diffuse, to produce quiet region filament channels, filaments, and locations of coronal mass ejections. This concept is supported by an analytic model of a toroidal flux rope. Although the field geometry of such a rope is complex in comparison to more potential-like models, it at once explains the observed evolution of the vector magnetic field at the photosphere, the appearance and subsequent disappearance of the filament, the evolution of the corona as observed in X-rays, and observed structure of prominences in general. In this paper we present a visualization of the observed magnetic field structure, and also a visualization of the magnetic topology of the theoretical model which demonstrates how such a field topology might produce and support solar prominences.

2. Observed Vector Magnetic Field Structure

Figure 1 shows a perspective image of the observed magnetic field structure of the δ-sunspot described in Paper I. At the time represented by this figure, the δ-sunspot

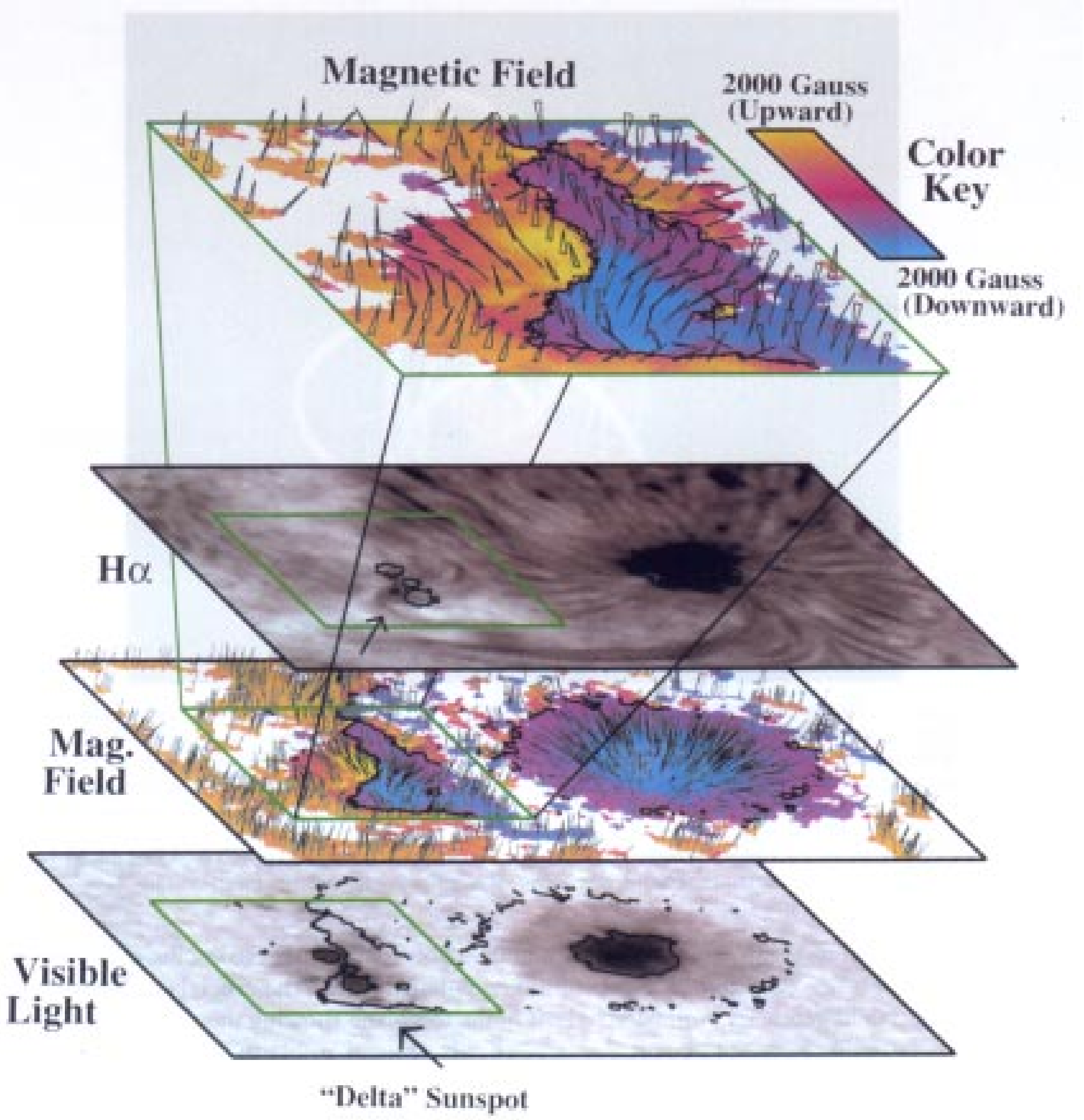

Figure 1. This stack of images illustrates in perspective the observed structure of the photospheric vector magnetic field within a sunspot group observed on 19 June, 1992 using the advanced Stokes polarimeter, and the corresponding structure of the chromosphere in Hα obtained 5 hours earlier using a Lockheed instrument at the Swedish Solar Observatory on La Palma. The lower image is the continuum spectroheliogram at 630 nm, with sunspot umbrae outlined in yellow and polarity inversion lines shown in red. The 'hair' in the next panel above illustrates the orientation of the vector magnetic field at the solar surface, with the field strength indicated by colors on the plane (see color key). The third image from the bottom, an Hα filtergram, shows a developing filament (arrow) which appears along much of the inversion line passing through the δ-sunspot. The magnetic field structure of the δ-sunspot is seen in expanded detail in the top image. Arrowheads presented in perspective indicate the field orientation.

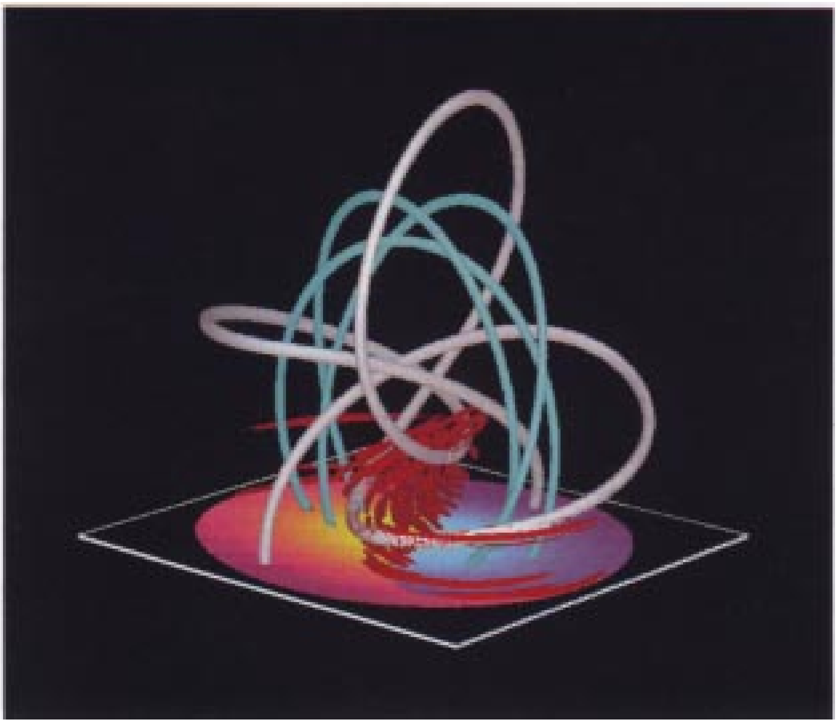

Figure 2. This perspective view illustrates a few magnetic lines of force of the 3-dimensional magnetostatic model. Field lines describe toroidal surfaces. The solar surface, represented by the bottom colored plane (see color key, Figure 1), is a slice through this model in which most of the torus resides above the surface. The three aqua-colored field lines indicate a rather conventional field geometry proceeding via straightforward arching paths from positive to negative polarity on an inner toroidal surface. The single, white field line on an outer toroidal surface takes a much more circuitous path: there are two places along its length which are local minima in height. The red segments make visible the global collection of such minima which all occur above the polarity inversion line.

had reached its maximum development in the photosphere after coalescing over a period of a few days from a group of mixed-polarity pores. The crucial concave-upward field geometry is illustrated best in the top plane showing the vector field orientation as elongated triangles, or ‘arrowheads’. Negative polarity, to the right of the polarity inversion line, shows the field pointing *down and toward the inversion line*. The field rotates and decreases its inclination toward the inversion line so that its component in the horizontal plane is *parallel to the inversion line along its length*. The positive polarity region to the left of the inversion line shows the field pointing *up and away* from the inversion line.

At this time, an Hα filament was just beginning to form along the inversion line, as indicated by the arrow on the Hα image. One day later, the δ-sunspot at the photosphere had become somewhat smaller, but the filament was much better developed. A transient event viewed in both X-rays and Hα strongly suggests a substantial vertical shear in the orientation of the magnetic field above the filament, such that the field in the low-lying filament is dominantly along the inversion line, but it is nearly perpendicular to it at greater heights. By the second day after the observations of Figure 1, the δ-sunspot had disappeared at the photospheric level, as had much of the magnetic flux in its vicinity. Much of the filament was gone as well, but the region remained bright in X-rays, showing a significantly twisted topology.

The evolution of this region strongly suggests to us that a twisted, and probably nearly closed magnetic field structure had emerged through the photosphere into the corona. We surmise that buoyancy is the driving force that lifts this structure upward, and that much of the observed evolution of the field is due simply to our view of different ‘slices’ of this structure as it passes upward into the visible atmosphere.

3. An Analytic, Three-Dimensional Toroidal Force-Free Flux Rope Model

The observations described in the previous section are consistent with a magnetic structure in the form of a ball-like magnetic flux rope in the form of a torus with a main portion of it sticking out above the photosphere. In this interpretation, an increasingly greater part of the magnetic ball rises above the photosphere as the observed flux emergence proceeds. In the realistic atmosphere, we imagine this ball of magnetic field is confined to its volume by the plasma and magnetic field in its exterior. The construction of a static model of such a structure is a first step to theoretically investigate how such a three-dimensional magnetic field might be configured. The reader is referred to Paper I for a particular static model describing such a magnetic field in static equilibrium with a gravitationally stratified atmosphere. In this paper, we present a physically simpler model based on the classical constant-α force-free magnetic field.

The basic idea behind the theoretical construction is the following. How a ball of toroidal magnetic flux rope is confined within its volume is not especially relevant to the point that such a magnetic ball can explain topologically the observed vector field distributions on the photosphere. To demonstrate such a point requires generating an explicit equilibrium solution which locally describes a magnetic ball. The simplest example is the classical dipole solution for a force-free magnetic field with a constant α (Chandrasekhar and Kendall, 1957).

To generate this solution, one writes the magnetic field $\mathbf{B}$ in spherical coordinates of the magnetic stream function A and the function Q which specifies the ϕ component:

$$\mathbf{B} = \frac{1}{r\sin\theta}\left(\frac{1}{r}\frac{\partial A}{\partial\theta}\hat{r} - \frac{\partial A}{\partial r}\hat{\theta} + Q\hat{\phi}\right) , \tag{1}$$

assuming axisymmetry. The force-free field equation

$$\nabla \times \mathbf{B} = \alpha\mathbf{B} \tag{2}$$

for a constant α implies

$$Q = \alpha A \; , \tag{3}$$

leading to the equation

$$\frac{\partial^2 A}{\partial r^2} + \frac{\sin\theta}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\frac{\partial A}{\partial\theta}\right) + \alpha^2 A = 0 \; . \tag{4}$$

By the method of separation of variables, the dipole solution representing the solution with the lowest order of field complexity is given by

$$A = a_0 \left(\frac{\sin\alpha r}{\alpha r} - \cos\alpha r\right)\sin^2\theta \; , \tag{5}$$

where a_0 is a constant amplitude. This solution describes a force-free magnetic field in the form of a single toroidal rope of twisted flux running around the axis of symmetry. It is regular everywhere in the spherical region $r < r_0$ where

$$\frac{\sin\alpha r_0}{\alpha r_0} - \cos\alpha r_0 = 0 \; , \tag{6}$$

for some value of α which determines the twist of the field. We could prescribe a fixed spherical volume of the field by giving r_0. Then the field has a twist characterized by a value of α such that Equation (6) is satisfied.

As an aside, the above dipole force-free magnetic field can be confined by an exterior uniform magnetic field suitably deformed such that the deformed exterior field is tangential at the spherical boundary of the force-free field. This external potential field is generated by $A = A_{\text{pot}}$, where

$$A_{\text{pot}} = a_1 \left(r^2 - \frac{r_0^3}{r}\right)\sin^2\theta \; , \tag{7}$$

where the constant amplitude a_1 is given in terms of amplitude a_0 to ensure that $\mathbf{B}$ is continuous across $r = r_0$. As we have pointed out, we are not concerned with the confinement issue.

Given the ball of force-free magnetic field, we can take the photosphere to be a plane and allow it to intersect the magnetic ball to study what distribution of $\mathbf{B}$ obtains on the photospheric plane. The observations presented in this paper are topologically consistent with the $\mathbf{B}$-distributions constructed in this manner, taking the photosphere parallel to the axis of symmetry of the mathematical solution of $\mathbf{B}$ and progressively positioning the photospheric plane relative to the symmetry axis to locate an increasing larger portion of the magnetic ball above the photosphere.

4. Visualization of Lines of Force in the Toroidal Flux Rope Model

Figure 2 shows a perspective view of an analytic 3-dimensional toroidal magnetostatic model. This force-free model illustrates how some of the characteristics of the observations presented above can be realized in an actual three-dimensional magnetic geometry. A more comprehensive model having cross-field currents (i.e., not force-free), accounting for gravitational stratification, was presented in Paper I. However, the magnetic topology of that model and the one presented here are quite similar and the present model serves to illustrate this topology very well. The illustration of Figures 2 gives only a limited view of this topology. A much better view is available on the web (http://www.hao.ucar.edu/public/research/spmf/bcbl.html), where one may see in color these flux tubes as they 'emerge' into the atmosphere, then one 'flies' around the structure to understand its 3-dimensional character.

The lower plane of this simulation indicates the field polarity at the 'photosphere', with a curved inversion line separating the two opposite polarities. The field lines on the outer flux surface, indicated here by one such line shown in white, emerge first showing a potential-like geometry with lines arching from positive to negative, and magnetic footpoints on the plane spreading away from the inversion line. As the emergence proceeds, the inversion line rotates counter-clockwise, so that the tops of lines of the inner flux surface (shown in aqua color) also first emerge in a potential-like manner, but they are somewhat more sheared in orientation relative to the inversion line. By the time that the lower reaches of the white field line are emerging, the field is no longer arching simply from one polarity to the other: it now has the characteristic concave upward geometry mentioned above, with field lines pointing away from the inversion line, and oriented nearly parallel to it at their lower reaches above the inversion line.

We have selected a uniform grid of over 300 footpoints covering the entire lower plane. From these footpoints we have traced the field lines upward into the volume above that plane, and located the positions within that upper volume where such field lines have a local minimum in height. These local minima, shown in red, indicate where cool, dense prominence material would collect in such a field geometry. The 'prominence' formed in this theoretical model shows many features in common with real prominences; notably, the structures forming rather shallow angles with the inversion line, the appearance of 'barbs' extending to either side of the prominence axis, and the overall 'handedness' of the prominence structure. *It is important to note that all of these features are produced by a field geometry whose lines of force do not connect to the 'photosphere' via simple, nearby paths.* All of these field lines return to the upper part of the volume before intersecting the lower plane. This characteristic provides (Low and Hundhausen, 1995): (1) a means of support of the prominence material by strong currents in the upper part of the atmosphere, (2) physical isolation of the prominence from the hot coronal material, and (3) a field around the prominence having the 'inverse' polarity relative to the potential field extrapolated from the photosphere.

5. Implications for Existing and Future Observations, Theory

So far, only one case of flux emergence of this type has been documented with simultaneous vector magnetic field, chromospheric, and coronal coverage. It is very important to determine if such events are common or relatively rare. A more difficult observational task will be to determine if flux rope geometries are responsible for the large-scale polar crown filaments and associated coronal features. In this case, it is possible that no signature of the vector field topology in the chromosphere and corona will be observable at the photospheric level because of the coalescence of the relevant magnetic flux into intense, small-scale flux tubes which always become nearly vertical at photospheric levels due to strong buoyancy forces. For the polar crown filaments, measurements of the Hanle depolarization observed at the limb has already provided us with crucial information, and further observational progress in this area may be quite revealing of the topology of fields within prominences.

From a theoretical standpoint, the analytic magnetostatic model presented in Paper I is already quite sophisticated, having full 3-dimensionality, and compensating the forces of gravity by cross-field currents. On the other hand, it does not yet represent the lateral expansion of the field as it enters the atmosphere, nor is it dynamic in nature. A difficult but potentially quite revealing next step would be to carry out numerical simulations of the buoyant emergence of such closed flux systems.

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