MAGNETIC FLUX ROPES: WOULD WE KNOW ONE IF WE SAW ONE?

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ABSTRACT

There has been much debate lately about whether twisted magnetic flux ropes exist in the corona. When asked for observational evidence of them, the temptation is to show images of apparently twisted structures (e.g. see Figure 1). However, we must be very careful of projection effects in interpreting these observations. Two critical aspects of understanding how we might observe flux ropes are 1) the 3D nature of the flux rope, and 2) physically, which bits are visible and for what reasons? In this paper we will use a simple but physically reasonable 3D analytic model to address these two issues, and develop techniques that can in future be used on more general models, both analytic and numerical.

Key words: solar corona, magnetic flux ropes, CMEs.

1. INTRODUCTION

Solar explosive events such as coronal mass ejections (CMEs) and flares are commonly considered to be driven by the free magnetic energy stored in current carrying (twisted or sheared) coronal magnetic fields. One possible and appealing picture is that the twisted coronal magnetic structures form as a result of the emergence of twisted magnetic flux tubes from the solar interior. This is supported by numerical models of the solar interior which find that a minimum amount of twist is needed for flux tubes to be able to rise cohesively through the convection zone (Emonet and Moreno-Insertis, 1998; Fan et al., 1998; Abbett et al., 2000, 2001). It is also supported by photospheric observations (Tsuneta, 1991; Leka et al., 1996) which suggest the emergence of twisted flux tubes. We therefore might imagine a scenario where a flux rope forms subphotospherically, emerges through the photosphere, exists in the corona until it loses its stability and erupts in a CME which moves out through interplanetary space until ultimately impacting on the Earth's magnetosphere. Attractively simple as this picture

is, reality is likely to be much more complicated since the various regimes traversed are physically very different and pre-existing structures would get in the way of our traveling flux rope.

Figure 1. Coronal structures with apparent twist: (left) criss-cross structure of CME core (SOHO LASCO/C2 white light); (center)Slinky-like “Granddaddy” prominence (HAO H-α); (right) criss-cross structure in NON-erupting filament (TRACE 195 Ångstroms absorption).

Our ultimate goal is to join two of these regimes, by considering how a flux rope could rise from beneath the photosphere and emerge into the corona, interacting with pre-existing coronal structures. In this paper, we will consider the more specific question of how such a flux rope might manifest itself observationally.

2. CORONAL EVIDENCE FOR FLUX ROPES

Magnetic flux rope models have been used to explain observations of the so-called three-part structure of CMEs and their precursors, that is white light structures having a front, cavity, and core (Low and Hundhausen, 1995; Chen, 1996; Gibson and Low, 1998; Guo and Wu, 1998). Figure 2 shows examples of such structures, both for a quiescent (non-erupting) structure and for a CME. Since a well defined cavity and core is visible prior to the eruption, the flux–rope interpretation implies that ropes also exist in the corona prior to the eruption. In the flux–rope interpretation, the core of the CME is identified with the coronal prominence (or filament: we use

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the terms interchangeably in this paper). The bottoms of the windings of flux ropes provide natural dipped magnetic field configurations capable of supporting prominences. Observed properties including magnetic inverse configuration (where the field across the filament is opposite to that predicted by a potential field), apparently vertical filament "feet", and S-shaped filaments can be reproduced by flux rope models (Figure 3) (Priest et al., 1989; Rust and Kumar, 1994; Lites and Low, 1997; Gibson and Low, 1998; Aulanier and Demoulin, 1998).

Figure 3. Two views (left, side-view; right, top-view) of a spheromak-type magnetic flux rope capable of supporting a filament. Blue field lines are simple bipoles, the white field line winds around the rope axis and (along with similar winding lines) provides dips where the filament material has been sketched in brown (from Lites and Low (1997)).

Magnetic flux rope models can also be applied to X-ray sigmoidal (Figure 4). S-shaped magnetic field lines are natural products of any twisted or sheared field: in fact, field lines oriented both as forward and backwards S's tend to arise (see e.g. Figure 5). It is not enough to point to a subset of the magnetic field lines having S shapes: a convincing comparison to observations should address the question, why is that particular part of the magnetic field heated? Reconnection or dissipative heating could occur in current sheets, which, according to Parker (1994) can form at tangential discontinuities during the dynamical evolution of a magnetized fluid. Such discontinuities can occur along separatrices between flux regions kept topologically distinct by field lines tied to the photosphere (For discussion of a 2D example, see Low and Wolfson (1988)). In a 3D system, a separatrix could arise between winding vs. non-winding field lines (Figure 5) (Titov and Demoulin, 1999; Low and Berger, 2002; Gibson et al., 2002).

3. ANALYTIC 3D MODEL

Our model is described mathematically in terms of magnetic field \( \mathbf{B} \) and gas pressure \( p \), by:

\[
\frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p = 0, \quad \nabla \cdot \mathbf{B} = 0.
\]

\[
\mathbf{B} = \frac{1}{r \sin \theta} \left[ \frac{1}{r} \frac{\partial A}{\partial \theta} + \frac{\partial A}{\partial r} \theta + Q_\phi \right]
\]

\[
A_{\text{int}} = \frac{1}{2} \gamma (r - r_o)^2 - \frac{2\pi}{5} \rho_o r^2 (r^2 - r_o^2) \sin^2(\theta)
\]

\[
Q_{\text{int}}^2 = Q_o^2 - 2\gamma A; \quad p_{\text{int}} = p_o A
\]

\[
A_{\text{ext}} = \gamma \rho_o \left( r^2 - \frac{r_o^3}{r} \right) \sin^2(\theta)
\]

\[
Q_{\text{ext}} = Q_o; \quad p_{\text{ext}} = 0.0
\]
Figure 6. Model magnetic field lines (bottom panels) and dippi ed portions of magnetic field capable of supporting a filament (top panels). The left-most panels in each image show the view at the limb parallel to the rope axis, the middle panels the view at the limb perpendicular to the rope axis, and the right-most panels the view projected onto the solar disk (the upper right hand panel also shows the vertical magnetic field - red is positive, green negative). The black line shows the curved flux rope axis. Field lines are colored yellow if they wind more than once about the axis, blue if they wind less than a full rotation, but nonetheless contain dips (none in this figure, but see Figure 7 for examples), and red if they contain no dips. Parameters chosen were $\gamma_1 = 0.01, r_s = 4.0, p_o = 1.0, Q_o = 21.1,$ and $x_o = 1.45$.

This 3-D (axisymmetric) model describes a spheroidal flux rope, having a boundary between internal and external field at a sphere of radius $r_s$. We consider the portion of one hemisphere that lies above a plane lying at some prescribed height $x_o$ from the axis of symmetry: we take this plane to represent the rigid or heavy boundary of the solar photosphere. Figure 6 shows magnetic field lines of the resulting structure. The upper three panels represent only the portion of the magnetic field that contains dipped field lines, where we have plotted material lying at heights up to an arbitrary “scaleheight” of the dip bottoms (set here to be 0.2 in the unspecified units of the figure.) We identify the separatrix surface as that surrounding the volume of yellow field lines in a manner similar to that of Titov and Demoulin (1999) and Low and Berger (2002). The maximum number of winds about the rope axis of any of the plotted field lines is 1.99. By using the same parameters except with $Q_o = 16.1$, we find a maximum number of winds of 2.85, but no great change in the form and shape of the dipped field regime or separatrix surface. Figure 7 shows how the separatrix and locus of dipped field changes as the structure emerges. (Note we do not claim a magnetic structure such as our rope would smoothly emerge, and we present this “time-sequence” to demonstrate how and where structures would appear depending on how much of the flux rope lies above the photosphere.)

4. SUMMARY AND FUTURE WORK

Despite its simplicity, the analytic model presented here is able to reproduce the basic features of the X-ray sigmoid and its related filament, and most importantly provides reasons why these features are visible when and where they are. In particular, by assuming that the modeled filament lies in the bottoms of the winds of the flux rope, and that the separatrix surface between winding and non-winding magnetic field lines is the site of current sheets and heating, we predict qualitatively the form and shape of the (H-α) filament and its relationship to the X-ray sigmoid. Because it is a 3D model, it allows us to directly consider how projection, as well as the amount and orientation of emerged filament affects what we observe. When viewed on the disk the modeled filament appears as an inverse-S shape having the same direction and similar orientation to its associated separatrix sigmoid, similar to the observed relationship of filament and X-ray sigmoid (Figure 4). When viewed on the limb the modeled filament has a criss-crossed structure akin to those in the (quiescent) filaments of Figure 1, and when viewed at the limb perpendicular to the axis, it has a braided appearance in a manner very similar to the white light CME core in Figure 1. When viewed on the limb the filament/prominence can appear as an arch, with distinct legs extending down to the photosphere: despite their vertical appearance, these legs are a superposition of predominantly horizontal density enhancements (e.g. the last two panels in columns four and five of Figure 7). Although we do not expect the flux rope to emerge smoothly through the photosphere, this model shows how the degree to which it lies above the photosphere could affect the size, location, and relative orientation of sigmoidal separatrix and filament (Figure 7). We also find that by increasing the maximum number of winds in the rope, we affect the girth of the separatrix and filament, but do not change the fact that both appear as a single inverse S. Another interesting result is that because the axis of the flux rope is itself curved, dipped field lines (relative to the plane of the photosphere) can exist even if they do not wind a full rotation about the axis (Figure 7).

The techniques described here, which determine the dipped regions of magnetic field as an indicator of filament position, and the separatrix surface as an indicator of X-ray sigmoid location, will be applied in future to more complex analytic models (Gibson and Low, 1998; Low and Berger, 2002) as well as numerical simulations of magnetic flux rope emergence (Fan, 2001). Moreover, we will consider how such quantities as current helicity, magnetic helicity, and free energy relate to each other and how they vary with the emergence of structures and variation of model parameters. Finally, we will compare model predictions of photospheric magnetic field to vector field observations. Analytic models such as the one presented here can be used as a test of the assumptions that go into vector magnetogram interpretation. In this manner, we hope to gain essential insight into how twisted magnetic fields are formed.
and how they could be ultimately removed from the solar corona.

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Figure 7. Same as figure 6, with the photosphere positioned at progressively lower heights within the structure. Figure 6 is the case fifth from the bottom. The first three columns correspond to the bottom panels of Figure 6 (rotated 90 degrees), and the last three columns correspond to the top panels (also rotated 90 degrees).