THE EMERGENCE AND EVOLUTION OF TWISTED MAGNETIC FLUX ROPES IN THE SOLAR CORONA

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ABSTRACT

We examine twisted magnetic flux ropes as the basic underlying magnetic field structure of CME precursors, and their loss of equilibrium as a mechanism for triggering CME onset. We present numerical simulations in spherical geometries of the evolution of the coronal magnetic field as a twisted magnetic flux rope is transported kinematically through the lower boundary into a pre-existing coronal potential arcade field. We find an initial quasistatic evolution during which a sequence of confined flux rope equilibria form with stored free magnetic energy, followed by a dynamic stage where the flux rope erupts. Finally, we also review simulation results on the dynamic process of how twisted magnetic flux ropes emerge from the high-β plasma of the interior through the photosphere into the solar corona.

Key words: MHD — Sun: corona — Sun: magnetic fields.

1. INTRODUCTION

To understand the nature of coronal mass ejections (CMEs) and ultimately to predict their onset, we must first address the following fundamental questions: (1) what are the underlying magnetic field structures for CME precursors in which free magnetic energy can be built up and stored over long periods? and (2) what is the triggering mechanism for the sudden explosive release of the stored magnetic energy? An appealing candidate for the basic magnetic field structure for CME precursors is a twisted magnetic flux rope with field lines twisting about each other by more than one wind between the two ends anchored to the dense photosphere (e.g. Low, 2001). Twisted magnetic flux ropes in the corona may form as a result of flux emergence from the interior (e.g. Fan, 2001; Magara & Longcope, 2001; Magara, 2004; Manchester et al., 2004), or as a result of turbulent diffusion of magnetic fields on the photosphere (e.g. van Ballegooijen, Cartledge, & MacKay, 1998; van Ballegooijen, Priest, & MacKay, 2000; MacKay & van Ballegooijen, 2001, 2005; Amari et al., 2003).

Besides containing free magnetic energy, which is believed to be the main energy source for driving flares and CMEs, models of twisted magnetic flux ropes can explain several observed features of CME precursors. The dipped field lines contained in the twisted flux ropes naturally provide support for the dense cool prominence mass against gravity. Furthermore, the so-called “bald-patch” separatrix surface (BPSS) of a partially emerged line-tied flux rope, comprising field lines that graze the photosphere at the polarity inversion line, is argued to be a site for current sheet formation under dynamic perturbations (e.g. Titov & Demoulin, 1999; Low & Berger, 2003; Fan & Gibson, 2004; Gibson et al., 2004). The current sheet tends to form along the BPSS because it represents a discontinuous transition in the dynamic behavior between the twisted field lines that graze the photosphere and the neighboring anchored field lines. The heating resulting from the current sheet forming along the BPSS may explain the observed X-ray sigmoidal structures that are found to be often associated with the CME source regions.

Direct MHD simulations by Fan & Gibson (2004) found that, at the onset of the kink instability of a line-tied twisted flux ropes, a sigmoidal shaped current sheet indeed forms along the BPSS. The current sheet is of an inverse-S (forward-S) shape for a left-hand-twisted (right-hand-twisted) flux rope, consistent with the observed hemispheric preference for active region twist and X-ray sigmoid morphology. The onset of the kink instability is just one of the possible mechanisms that drives the formation of sigmoid shaped current sheets, which may explain the transient bright X-ray sigmoidal seen during eruptive flares (e.g. Sterling & Hudson, 1997; Moore et al., 2001). Since the BPSS represents a “fault line” in
the coronal magnetic field across which field lines behave very differently when driven dynamically, other dynamic perturbations, e.g. photospheric motions at the footpoints of the field lines or continued magnetic flux emergence, may be constantly causing the development of magnetic tangential discontinuities (or current sheets) along it and thus producing long-lived X-ray sigmoid.

Twisted magnetic flux ropes may exist in stable equilibria over long periods of time in the corona, and a sudden catastrophic loss of equilibrium due to, e.g. the build-up of too much twisted flux with respect to the confining overlying field, may lead to an explosive release of the stored free magnetic energy, resulting in a CME (e.g. Priest & Forbes, 2002; Sturrock et al., 2001). Catastrophic loss of equilibrium of 2D flux rope configurations has been demonstrated analytically (e.g. Forbes & Priest, 1995; Lin et al., 1998). Loss of equilibrium and eruptive behavior of both 2D and 3D twisted flux rope configurations have also been observed in numerical simulations (e.g. Amari et al., 2003, 2004; Roussev et al., 2003; Fan, 2005; Fan & Gibson, 2005). In this paper, we examine twisted magnetic flux ropes as CME precursors and their loss of equilibrium as a mechanism for triggering CME onset. We describe MHD simulations of the evolution of the coronal magnetic field as a twisted magnetic flux rope is driven kinematically through the lower boundary into a pre-existing corona potential arcade field (Fan, 2005; Fan & Gibson, 2005). We have consider both an idealized 2D axisymmetric toroidal flux rope and also a 3D line-tied flux rope in spherical geometries. In both cases, we find two distinct stages of the evolution of the coronal magnetic field. The initial evolution is quasi-static, during which the magnetic energy transported into the corona is being stored in a sequence of confined flux rope equilibria, followed by a dynamic stage in which the flux rope loses confinement and erupts. Finally, we review simulation results on the dynamic process of how twisted magnetic flux ropes emerge from the high-\(\beta\) plasma of the interior through the photosphere into the solar corona.

2. TWISTED MAGNETIC FLUX ROPES AS CME PRECURSORS

2.1. Model description

We aim to model the evolution of the coronal magnetic field under the conditions of high electrical conductivity and low plasma \(\beta\). Thus, we have greatly simplify the treatment of the thermodynamics of the coronal plasma by using an isothermal equation of state. We have developed a numerical code that solves the following isothermal MHD equations in 3D spherical geometry:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}
\]

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right) = -\nabla p - \rho \frac{GM}{r^2} \hat{r} + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{\rho \nu \nabla^2 \mathbf{v}}, \tag{2}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \tag{3}
\]

\[
\nabla \cdot \mathbf{B} = 0, \tag{4}
\]

\[
p = \rho \varepsilon. \tag{5}
\]

The initial corona is assumed to be an isothermal atmosphere in hydrostatic equilibrium, containing a pre-existing potential arcade field whose normal field \(B_n(0, \theta, \phi)\) at the lower boundary is concentrated into two isolated bands. The isothermal sound speed \(c_s\) is much smaller than the characteristic Alfvén speed \(v_A(\theta)\) measured at the footpoints of the coronal arcade field. So the Lorentz force is the dominant force in the momentum equation, representing the low-\(\beta\) condition of the lower solar corona. For the induction equation, no explicit resistivity is included. Thus in evolving the magnetic field, only numerical diffusion is present, which is small in smooth regions and becomes significant only in regions of large gradient, e.g. at sites of intense current layers. A small viscous term is included in the momentum equation which provides some necessary smoothing of the velocity field in the thin layer near the line-tying lower boundary, where the magnetic field is significantly non-force-free.

We have carried out numerical simulations in spherical geometries of the evolution of the coronal magnetic field as a twisted magnetic flux rope emerges slowly into the low-\(\beta\) corona. (Fan 2005, Fan & Gibson 2005). In these simulations, the flux emergence is driven kinematically by imposing at the lower boundary (\(r = R_{\odot}\)) a time dependent transverse electric field that corresponds to bodily lifting a prescribed twisted flux tube at a velocity that is less than 1% the Alfvén speed. We have considered both an idealized 2D axisymmetric configuration of a twisted toroidal flux rope circling around the sun, and also a 3D flux rope with its ends line-tied to the lower boundary. The simulation domain is given by \(r = [R_{\odot} 14.4 R_{\odot}],\) \(\theta = [\pi/3, 2\pi/3]\) in the 2D axisymmetric case, and \(r = [R_{\odot} 6 R_{\odot}],\) \(\theta = [\pi/3, 2\pi/3],\) \(\phi = [-\pi/4, \pi/4.8]\) in the 3D case. The direction of the pre-existing potential arcade field is very close to the direction of the outer field lines of the emerging flux tube.
Figure 1. From Fan & Gibson (2005). Evolution of the coronal magnetic field from a 2D axisymmetric simulation of a twisted toroidal flux rope emerging into a pre-existing poloidal potential arcade (corresponding to Case A shown in Fig. 2). The images show the magnetic field in a meridional plane with the contours showing the poloidal magnetic field lines and the gray scale intensity showing the toroidal magnetic field strength ($B_\phi$). The times are given in units of $R_\odot/v_\infty$. 
2.2. Results

Fig. 1 shows the evolution of an idealized 2D axisymmetric coronal magnetic field resulting from the emergence of a twisted toroidal flux tube into a pre-existing poloidal potential arcade. The evolution of the rise velocity and the height of the flux rope axis after emergence, and also the evolution of the magnetic energy are shown in Fig. 2 for three different cases in which the flux emergence is stopped at respectively $t = 118R_\odot/v_{\odot}$ for Case A, $t = 114R_\odot/v_{\odot}$ for Case B, and $t = 112R_\odot/v_{\odot}$ for Case C. The magnetic field evolution shown in Fig. 1 corresponds to Case A in Fig. 2. It is found that the evolution from $t = 0$ to about $t = 114R_\odot/v_{\odot}$ is nearly quasistatic during which if the flux emergence is stopped, the system settles to a neighboring equilibrium. This is demonstrated in Case C (the dashed-dotted curves in Fig. 2), for which the flux emergence is stopped at $t = 112R_\odot/v_{\odot}$, and subsequently the rise velocity settles to zero and the magnetic energy remains constant. In other words, the free magnetic energy transported into the corona through flux emergence is being stored in the equilibrium flux rope. If the flux emergence is continued beyond about $t = 114R_\odot/v_{\odot}$, it is found that the flux rope can no longer find a stable equilibrium and erupts, as can be seen in Cases A and B (the solid and the dashed curves in Fig. 2). In these cases, the flux rope accelerates to a peak velocity of about $0.4v_{\odot}$, and the magnetic energy drops sharply. Because of the imposed azimuthal invariance, the entire flux rope erupts and all of the overlying arcade field is stretched out with the flux rope. A current sheet forms behind the flux rope and magnetic reconnection takes place which enables the flux rope to escape. Eventually, the reconnecting post-flare loops reform a configuration that is similar to the initial arcade field, although some of the toroidal flux of the original flux rope is trapped in the reconnected field.

Fig. 3 shows the 3D evolution of a line-tied twisted flux rope emerging into the corona previously occupied by a potential arcade field. In Fig. 4, the solid curves show the evolution of the rise velocity and the height of the apex of the emerged flux rope axis, and the evolution of the total magnetic energy, for two different runs where the flux emergence is driven until $t = 83R_\odot/v_{\odot}$ (Run A) and $t = 96.5R_\odot/v_{\odot}$ (Run B), when the field-line twist in the emerged tube reaches 1.88 and 1.6 winds, respectively. The magnetic field evolution shown in Fig. 3 corresponds to Run A. As is in the previous 2D case, there is an initial stage of quasi-static evolution (from $t = 0$ to roughly $t = 85R_\odot/v_{\odot}$) during which if the flux emergence is stopped, the flux rope settles into a neighboring equilibrium state. This is illustrated in Run B in Fig. 4: after the flux emergence is stopped, the flux rope settles to a mildly kinked equilibrium (see the structure shown the $t = 83$ panel of Fig. 3), with

Figure 2. From Fan & Gibson (2005) The evolution of the rise velocity (top panel) and the height (middle panel) of the flux rope axis, and also the evolution of the magnetic energy (bottom panel), from 3 different 2D axisymmetric simulations for which the flux emergence is stopped at $t = 118$ (Case A, see Fig. 1), $t = 114$ (Case B), and $t = 112$ (Case C) respectively.
Figure 3. The 3D evolution of the coronal magnetic field resulting from the emergence of a twisted flux rope line-tied to the lower boundary, corresponding to Run A shown in Fig. 5. (from Fan, 2005)
Figure 4. Panel (a) shows the rise velocity as measured at the apex of the flux rope axis for both Run A and Run B (solid curves) and the rise velocity at the central point of a prominence field line bundle for Run A (triangle points). Panel (b) shows the height evolution of the apex of the flux rope axis for both Run A and Run B (solid curves) and the height evolution of the central point of the prominence field line bundle for Run A (triangle points). Panel (c) shows the evolution of the magnetic energy in the domain (solid curves) and the time integration of the Poynting flux through the lower boundary (dash-dotted curves) for both Run A and Run B. The vertical dotted line marks the time when the emergence is stopped in Run A. (from Fan, 2005)

Figure 5. On-disk intensity image produced by column integration of $j^2$, where $j$ is the electric current density, along the line of sight that directly looks down on the erupting flux rope at $t = 102R_\odot/v_{\text{eq}}$. Assuming simply that local heating rate and X-ray emission is proportional to $j^2$ and that the X-ray emission optically thin, then the image gives a proxy of the appearance of the X-ray brightening. (from Fan, 2005)

the rise velocity settling to zero and the magnetic energy remaining constant. However, if the flux emergence is continued, as in Run A, it is found that after about $t = 85R_\odot/v_{\text{eq}}$, when the field line twist in the emerged tube reaches about 1.7 winds, the flux rope shows a significant acceleration (see Run A in Fig. 4), and erupts through the arcade field at a localized area (Fig. 3) with most of the arcade field remaining closed. The flux rope continues to accelerate after the flux emergence is stopped at $t = 96.5R_\odot/v_{\text{eq}}$, and it eventually moves out of the outer boundary ($r = 6R_\odot$) with a speed of about $0.3v_{\text{eq}}$. The nonlinear evolution of the kink instability produces a significant rotation of the tube orientation at the apex, with the length-wise direction of the upward moving tube changing from being perpendicular to the arcade field to being parallel. As a result the upward intrusion of the flux rope becomes more localized and it becomes easier for the flux rope to push through the arcade field. This is a 3-dimensional effect that is described in Sturrock et al. (2001).

It is also found that an inverse-S-shaped current sheet develops as a result of the eruption of the line-tied left-hand-twisted flux rope. Fig. 5 shows an image produced by column integration of $j^2$, where $j$ is the current density, along the line of sight looking down on the erupting flux rope (corresponding to the $t = 103R_\odot/v_{\text{eq}}$ panel in Fig. 3). The im-
age suggests that the heating resulting from the current sheet may produce transient soft X-ray sigmoid brightening during the onset of the eruption, which has been seen in some events (e.g. Sterling & Hudson, 1997; Moore et al., 2001).

Furthermore, to understand the nature of the long-lived sigmoids and also the limb observations of a hot soft X-ray source within the cavity of a stable filament (the so called “chewy nougat”, see e.g. Hudson et al. 1999), we have examined the current density associated with the stable confined flux ropes during the initial quasi-static stage of the evolution, for both the 2D and 3D cases. Fig. 6 shows the magnetic field, the current density, and the plasma density in a meridional cross-section of a 2D axisymmetric flux rope in stable equilibrium, resulting from a simulation where the flux emergence is stopped during the quasi-static stage. The current density distribution within this stable flux rope (middle panel) show three major concentrations. In reference to the magnetic structure shown in the left panel of Fig. 6, the outer most layer of current concentration corresponds to the boundary surface between the emerging flux rope and the pre-existing potential arcade field. In reality this boundary is likely a current sheet or magnetic tangential discontinuity due to the discontinuous jump in field direction between the emerging flux rope and the pre-existing potential field. This boundary surface of the flux rope is identified with the boundary of the coronal cavity (see right panel of Fig. 6) or filament channel which in our model is created by the expansion of the emerging flux rope due to its strong toroidal magnetic field. Within the flux rope (or the cavity) there is a second layer of current concentration, which coincides with the field line (or the flux surface) that just grazes the lower boundary surface. This is in fact the 2D version of the so called bald-patch separatrix surface (BPSS), separating the completely detached field lines from those that are anchored. The layer of current concentration at the BPSS is likely a current sheet (limited by numerical resolution), because the detached twisting field lines within the surface have very different dynamics compared to the short anchored field lines outside and, as a result, the two types of field lines relax differently in the corona to form magnetic tangential discontinuities (Titov & Demoulin, 1999; Low & Berger, 2003; Gibson et al., 2004). The central diffuse current distribution is simply the current that flows along the twisted flux rope. The two current sheets along the flux rope boundary and the BPSS respectively are likely to be dissipative and may produce significant heating. Specifically, the inner current sheet that forms along the BPSS may appear as a bright X-ray source within the filament channel or cavity, enclosing the cool prominence material that is located at the dips of the twisted field lines. This explains the “chewy nougat”, i.e., the presence of a hot soft X-ray source at the prominence location within a stable cavity that has been seen in several SXT observations against the limb (see http://solar.physics.montana.edu/YPOP/Nuggets/1998/981009/981009.html).

In our interpretation, “chewy nougats” and X-ray sigmoids are of the same physical origin, namely current sheets forming along the BPSS of a twisted, partially emerged flux rope. For a quasi-2D flux rope that may be associated with a crown filament, the BPSS forms a long “tunnel” enclosing the filament, and when projected against the limb, appears as the hot X-ray source in the filament cavity. On the other hand, in the case of a more compact 3D line-tied flux rope with field-lines twisting about the axis by less than 2 winds between the anchored ends (see left panel of Fig. 7), the BPSS, comprising field lines that graze the photosphere at the polarity inversion line, forms a sigmoid-shaped ribbon (see middle panel of Fig. 7). The 3D simulation shows that as the flux rope emerges quasistatically through the lower boundary, a current concentration develops along the BPSS, as can be seen in the right panel of Fig. 7, which shows a horizontal cross section of current density J near the lower boundary. This current concentration along the BPSS is likely a current sheet which may give rise to a quiescent X-ray sigmoid when viewed against the disk.

3. DYNAMICS OF FLUX EMERGENCE THROUGH THE PHOTOSPHERE

The simulations described in the previous section model the evolution of the coronal magnetic field as it is driven at the lower boundary by a prescribed kinematic emergence of twisted flux rope into the corona. The actual dynamic process of magnetic flux emergence from the high β plasma of the interior through the photosphere into the solar atmosphere is very complex. Recently, several 3D MHD simulations have been performed to study the emergence of a twisted magnetic flux tube from the top layer of the solar convection zone (with the initial buoyant tube starting out from a depth of ~ 10 times the photospheric pressure scale height), through the photosphere, into the solar atmosphere and the corona (e.g. Fan, 2001; Magara & Longcope, 2001; Magara, 2004; Manchester et al., 2004). These simulations show that it is difficult for a significantly twisted flux tube to rise smoothly into the corona as a whole due to the heavy plasma that is trapped at the bottom concave portions of the field line winds. Magnetic reconnection near the photosphere is necessary to remove the mass-laden lower part of the winding field lines and “release” the flux rope into the corona.

Manchester et al. (2004) simulated the emergence of a twisted magnetic flux tube where the central emerging segment contains about 1.5 field-line winds. The resulting evolution is shown in Fig. 8. It is found
Figure 6. The magnetic field (left panel), the current density distribution (middle panel), and the density (right panel), in a meridional cross-section of a 2D axisymmetric flux rope in stable equilibrium. In the left panel, the contours show the poloidal magnetic field lines and the gray scale intensity shows the toroidal magnetic field strength ($B_\phi$).

Figure 7. The left panel shows the 3D magnetic field of a partially emerged line-tied flux rope confined by an external arcade. The middle panel shows the field lines comprising the BPSS viewed in projection against the lower boundary surface on which the contours show the normal component of the magnetic field. The right panel shows a horizontal cross-section of the current density $J$ near the lower boundary.
Figure 8. From Manchester et al. (2004). Three series of images illustrating the expansion of the flux rope from the photosphere into the corona. Panels a-f show the middle cross-section ($x = 0$) of the emerging flux rope where the white stream traces indicate the direction of the magnetic field in the cross-section, and the color indicates respectively the shear velocity $U_x$ along the flux rope axial direction (for the top three panels) and the angle between the magnetic field and the axial ($x$) direction (for the middle 3 panels). Panels g-i show 3D magnetic field lines at the 3 different times. In panel h the isosurfaces of shear velocity is also shown.
that the upper half of the flux tube first expands into the stably stratified atmosphere as a result of the magnetic buoyancy instability caused by the steep magnetic pressure gradient built up at the photosphere (Shibata et al., 1989). The bottom parts of the winding field lines are stuck at the photosphere due to the heavy plasma trapped there. However, as the upper part of the flux rope expands, a shearing motion develops in the z-direction, as indicated in the color images of panels a-c of Fig. 8. This shearing motion is driven by the x component of the magnetic tension force: \( F_x = (\mathbf{B} \cdot \nabla) B_z \), which transports axial flux \( B_z \) upward into the expanded portion of the flux rope (see panels d-f), trying to establish constant \( B_z \) along each field line. The transport of \( B_z \) upward causes further rise of the flux rope and eventually drives the formation of a current sheet just above the photosphere. The reconnection in the current sheet then allows the flux rope to “pinch off” from the photosphere, leading to the emergence of a twisted flux rope into the corona (see panels e, f, g). So the flux rope that is transported into the corona is the pinched off part of the original flux tube from the interior. Furthermore, viewed in 3D (see Fig. 9), the current sheet that is formed in the lower atmosphere has a sigmoid shape, following along the dipped field lines that are just about to pinch off from the photosphere, i.e. along the BPSS. Thus continued reconnection at the lower part of the emerging flux rope can explain the long-lived X-ray sigmoids.

4. SUMMARY AND CONCLUSIONS

In summary, we draw the following conclusions based on the simulation results described above. (1) The emergence and formation of twisted magnetic flux ropes in the solar corona most likely requires magnetic reconnection near the photosphere. Shearing motion along the polarity inversion line naturally develops for an emerging flux rope due to the effect of the magnetic tension force that drives the axial flux upward into the expanded flux rope. (2) A current sheet forms along the BPSS of the partially emerged flux rope due to continued flux emergence or other photospheric dynamic perturbations, explaining both the quiescent X-ray sigmoides, and also the observed presence of a hot X-ray source at the prominence location within the cavity of a stable long filament. (3) Loss of equilibrium and eruption are found for both the 2D axisymmetric flux rope and the 3D line-tied flux rope when too much twisted magnetic flux is transported into the corona. In the 2D case, the imposed azimuthal invariance prohibits the kink motion. The entire flux rope erupts with all of the arcade field being stretched out with the flux rope. Reconnection takes place in a vertical current sheet that forms behind the erupting flux rope, allowing the flux rope to escape. In the 3D case, with the build-up of a moderate amount of twist (< 2 full winds of field line twist about the axis), the line-tied flux rope kinks and erupts through the arcade field at a localized area, with most of the arcade field remaining closed. A sigmoid-shaped current sheet forms below the flux rope during the eruption, which may explain the transient soft X-ray sigmoid brightening that has been observed during the onset of some of the eruptive flares and CMEs (e.g. Sterling & Hudson, 1997; Moore et al., 2001).

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