

SIGMOID STRUCTURE OF AN EMERGING FLUX TUBE

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ABSTRACT

We present the results from three-dimensional magnetohydrodynamic (MHD) simulations of a magnetic flux tube emerging through the solar photosphere. The simulation is initialized with a straight tube of twisted magnetic field located in the upper convection zone. Buoyancy effects drive an arched segment of the tube upward through the photospheric layer and into the corona. Matter drains from the coronal field which thereafter undergoes a rapid expansion. The coronal magnetic field formed in this manner exhibits outer poloidal field lines resembling a potential arcade, and inner toroidal field lines, which emerge after the tube axis, forming sigmoid structure. The simulations suggest that neutral-line shear and sigmoidal field arise as a natural by-product of flux emergence.

Subject headings: MHD—Sun: magnetic fields—Sun: corona—methods: numerical

1. Introduction

It is now widely believed that a magnetic field plays an important role in various activity in the solar corona. During last decades, a lot of work has been devoted to modeling coronal magnetic structures in order to study their equilibrium states, stability, and dynamical evolution. On the whole, this work has successfully revealed the basic property of coronal magnetic field and made a great deal of contribution to the understanding of the physical mechanism of coronal activities, such as solar flares, prominence eruptions, coronal mass ejections. Some recent studies in this line of work presented an interesting results on the formation process of sigmoid structures observed in the corona (Matsumoto et al. 1998; Titov & Démoulin 1999; Amari et al. 2000). These sigmoid structures are suggested to have a close relation to explosive events on the sun (Canfield, Hudson, & McKenzie 1999).

So far the study of the dynamics of coronal field has mainly focused on the behavior of magnetic field above the photosphere. In such a study, a bottom boundary is located at a

photospheric level to investigate how the magnetic field evolves above the photosphere, while the emergence of subphotospheric magnetic field into the outer atmosphere is simulated by changing a photospheric boundary condition in a particular way. The most self-consistent way to simulate the emergence of magnetic field is to attach the convection zone below the photosphere and reproduce the emergence process directly. In order to do this, we need to know the state of magnetic field in the convection zone. According to several studies of the dynamics of magnetic field in the convection zone, the magnetic field rising through the convection zone has a shape of isolated tube with twisted magnetic field (Schüssler 1979; Choudhuri & Gilman 1987; Howard 1991; Caligari, Moreno-Insertis, & Schüssler 1995; Fisher, Fan, & Howard 1995; Longcope, Fisher, & Arendt 1996; Dorch & Nordlund 1998; Emonet & Moreno-Insertis 1998; Fan et al. 1999). Based on this result, Magara (2001) studied the evolution of a magnetic flux tube initially placed in the convection zone by means of 2.5-dimensional MHD simulation. Magara (2001) made a detailed investigation of the emergence and following expansion processes of the flux tube. This uncovered a problem in lifting the tube axis to the corona through a purely 2.5-dimensional process because the matter remaining inside a flux tube reduces the buoyancy effect on the tube. In this respect, Magara (2001) mentions several possibilities to solve this problem, one of which is to introduce a 3-dimensionality to flux tube system.

The present paper is the first report on our work that extends Magara (2001) by including 3-dimensional effects in the evolution of an emerging flux tube. We start with a straight flux tube with a uniform twist (Gold-Hoyle flux tube) placed horizontally in the upper convection zone and follow the evolution of this tube by performing a 3-dimensional MHD simulation. We find that the coronal magnetic field formed after emergence exhibits outer poloidal field lines resembling a potential arcade, and inner toroidal field lines, which emerge after the tube axis, forming sigmoid structure. We show results in §3 and discuss the formation process of sigmoid structure in §4, after describing our simulation model in §2.

2. SIMULATION MODEL

Our simulation code solves the 3-dimensional, compressible, ideal MHD equations including a uniform gravity. The primitive variables \mathbf{v} , \mathbf{B} , ρ and p , represented on a non-uniform, cartesian grid are time-advanced using the modified Lax-Wendroff method (Magara 1998). Each physical quantity is rescaled by its photospheric value. In particular, velocity, length, and time are scaled to $C_{Sp} = 8.6 \text{ km s}^{-1}$, $2\Lambda_p = 300 \text{ km}$ and $2\Lambda_p/C_{Sp} = 35 \text{ sec}$ respectively. The gas density and pressure are scaled to $\rho_p = 2.7 \times 10^{-7} \text{ g cm}^{-3}$ and $\gamma P_p = 2 \times 10^5 \text{ dyne/cm}^{-2}$. The adiabatic index takes its ideal monatomic value $\gamma = 5/3$.

Temperature and magnetic field are scaled to $T_p = 5100\text{K}$ and $(\rho_p C_{Sp}^2)^{1/2} = 450\text{G}$. The gravitational acceleration is constant throughout the domain except near the top and bottom boundaries where gravity is zero.

We use a Cartesian coordinate system in which z increases upward, and $z = 0$ is the nominal photosphere. The domain box spans the dimensionless coordinates $(-100, -100, -10) \leq (x, y, z) \leq (100, 100, 100)$; it is 60×60 Mm horizontally, and extends from 3 Mm below the photosphere to 30 Mm above. The grid consists of a cartesian product in which each coordinate-grid is refined toward the center. The area of finest mesh ($\Delta x = \Delta y = 0.4, \Delta z = 0.2$) is located within the region $(-8, -12, -10) \leq (x, y, z) \leq (8, 12, 10)$. The grid spacing gradually increases to $\Delta x = \Delta y = \Delta z = 4.0$ in a $N_x \times N_y \times N_z = 149 \times 167 \times 168$ grid. Periodic boundary conditions are imposed at the four sides, a fixed boundary condition at the bottom, and a free boundary condition at the top. A wave-damping zone is placed along all the boundaries to minimize their effects.

The initial condition is an isolated, twisted flux tube confined within an unmagnetized, stratified, static atmosphere. The initial atmosphere, identical to that used in Magara (2001), can be characterized as a convection zone $-10 \leq z \leq 0$, a photosphere at $z = 0$, a transition region around $z = 7.5$ and a corona above $z = 10$ (see figure 1). The initial flux tube is a uniformly twisted Gold-Hoyle equilibrium whose axis runs in the y direction at $(x_0, z_0) = (0, -4)$ (i.e. an initial depth of 1.2 Mm) in the convection zone. The tube has a radius of $r_0 = 2$ (600 km) inside of which the gas pressure is lower than the atmosphere's in order to maintain pressure balance at the tube's surface. The magnetic field is

$$\mathbf{B} = \frac{B_0 [-b(z - z_0) \hat{\mathbf{x}} + \hat{\mathbf{y}} + bx\hat{\mathbf{z}}]}{1 + b^2 [x^2 + (z - z_0)^2]}, \quad \sqrt{x^2 + (z - z_0)^2} \leq r_0. \quad (1)$$

Our choice of $b = 1$, implies that field lines wrap in a left-handed helix pitched over the axial length $\Delta y = 2\pi/b = 6.3$. The magnetic field on axis, $B_0 = 17.4 = 7.8\text{kG}$ corresponds to a local value of $\beta = 3.3$ at the center. The total axial flux of the tube, $\Phi = 3.5 \times 10^{19}$ Mx, is somewhat smaller than a full bipolar active region.

Initially the whole system is in mechanical equilibrium. The atmosphere outside the tube is in hydrostatic balance and the magnetic field within the tube is force-free. The total pressure is continuous across the tube's surface due to a discontinuity in gas pressure there: the temperature inside the tube is lower than outside the tube. Since the Gold-Hoyle magnetic field is weakly unstable to current-driven kink instabilities (Linton, Longcope, & Fisher 1996), the dominant source of instability is the Parker instability (Parker 1966). The purpose of the present study is not, however, to study the instability of the tube, but rather to observe its emergence into the corona. Toward this end we initiate the Parker instability

by firmly driving the middle portion of the tube upward and the ends downward for an interval $0 \leq t \leq t_0$. The fluid velocity

$$v_z(x, y, z, t) = \begin{cases} \frac{\pi}{2t_0} \cos\left(2\pi\frac{y}{\lambda}\right) \sin\left(\frac{\pi}{2}\frac{t}{t_0}\right) & -\frac{\lambda}{2} \leq y \leq \frac{\lambda}{2}; \\ -\frac{\pi}{2t_0} \sin\left(\frac{\pi}{2}\frac{t}{t_0}\right) & \text{otherwise,} \end{cases} \quad (2)$$

is prescribed ($t_0 = 5$ and $\lambda = 30$) within the fixed volume $x^2 + (z - z_0)^2 \leq r_0^2$, and the usual momentum equation is used outside. We observe a steep gradient in velocity at the edge of the driven region during the period of driving. After the driving period, $t > t_0$, the region is advanced according to the momentum equation, and we find that the steep gradient has almost disappeared by $t = 10$, in a couple of sound relaxation times.

3. RESULTS

After the initial driving phase the flux tube continues upward and emerges into the unmagnetized corona. The flux emergence is depicted in figure 2 using the horizontal velocity and vertical magnetic field at the photospheric plane $z = 0$. Once the edge of the tube crosses the photosphere, at $t \simeq 10$, the total unsigned flux grows steadily, reaching its maximum value 350 seconds (10 time units) later, after the tube's axis crosses the photosphere. The vertical magnetic field forms a classic magnetic bipole. The bipole is initially oriented perpendicular to the tube's axis ($\hat{\mathbf{x}}$) due to the strongly azimuthal nature of the field at its edge. During emergence the opposing polarity regions separate and rotate toward a more axial ($\hat{\mathbf{y}}$) orientation (Fan 2001). The separation, specifically the distance between points of maximum positive and negative B_z , increases throughout the simulation, but slows toward the end.

Figure 3 shows coronal magnetic field lines at two times during the tube's emergence. The first snapshot ($t = 20$, left panels) is just after the emergence of the tube's axis, the second snapshot ($t = 40$, right panels) is well past the axis emergence. Selected field lines, traced in colored lines, are shown from a top view (upper panels), a perspective view (middle panels) and a side view (bottom panels). At $t = 40$ most, but not all, of the magnetic field lines cross into the corona. The vertical and horizontal components of velocity at the $z = 0$ plane, are shown with colors and white arrows respectively. Strong draining-downflow ($v_z \simeq -2$ km/sec) is evident near the footpoints, $(x, y) = (\pm 2, \mp 8)$, in the early snapshot, but has largely subsided by the later one.

In the early snapshot, the outermost field is almost perpendicular to the neutral line (y -axis), while the inner field is more parallel to the neutral line. This probably reflects

the fact that the inner field lines, closer to the tube’s axis, are more axial, while the outer field lines are more azimuthal. After the axis emerges (right panels), the inner field lines show a distinct inverse-S shape, reminiscent of sigmoid structures observed by the soft X-ray telescope on board *Yohkoh* (Figure 4a). In contrast to the inner field lines, the outer field lines form a potential-like arcade with a *forward-S shape*. These contrasting field-line configurations can be attributed to the fact that a potential-like arcade structure is formed by the outermost azimuthal field lines of the flux tube while a sigmoid structure is made of the axial field lines near the tube’s axis.

The contrasting field lines in the post-emergence field are shown more clearly in figures 4b-4d. Figure 4b shows the magnetic field (black arrows) and mass density (color scale) within the $y = 0$ vertical mid-plane at $t = 40$. The twisted flux tube structure is clearly visible as arrows circulating clockwise about a central point at $z = 14$, about 4.2 Mm above the photosphere. Above the central point the density has been greatly depleted by expansion and draining. Three magnetic field lines were selected according to their location within the mid-plane (Fig. 4c). The white field line is the tube’s center where the magnetic field is normal to the plane. The red and orange field lines cross the mid-plane directly above ($z = 24.5$) and below ($z = 12$) the center point. A top view of each field line (Fig. 4d) shows that the lower-lying orange field line forms an inverse-S while the higher red field line forms a tightly curved forward-S. Both field lines wrap leftward around the much straightway central field line (white).

4. DISCUSSION

Observational studies have shown that active regions with negative helicity ($\alpha < 0$) have soft X-ray loops with inverse-S shapes (Canfield *et al.* 1999). Our simulation begins with a flux tube twisted in the left-handed sense, and its emergence produces photospheric fields characterized by negative ”observed” values of α . Notably, the coronal field contains both forward and inverse S shapes. To reconcile these simulations with observation it is necessary to explain why the inverse-S field would be most visible in soft X-ray images.

Several recent studies have shown the formation of sigmoids in the magnetic field. Matsumoto *et al.* (1998) show by simulation that a sigmoid is produced by a twisted flux tube emerging after undergoing the kink instability. Amari, Luciani, Mikic, & Linker (2000) construct a force-free coronal field with sigmoid structure and discuss the stability of this solution. In each of these studies only the shape of field line is discussed so the soft X-ray emission is not an issue. Titov & Démoulin (1999) investigate the 3-dimensional shape of the separatrix surface formed inside a magnetic structure. They show that the separatrix has

an inverse-S shape, and appeal to the notion that reconnection would occur in its vicinity. This explains both the formation and illumination of the sigmoid.

If the process of energization is considered, the active region formed in our simulation would appear as an inverse-S in soft X-ray images. Those field lines exhibiting an inverse-S configuration are also the field lines on which energy deposition would occur. Figure 4d shows a top view of the three field lines over a color map of current density $|\mathbf{J}|$ at the lower chromosphere ($z = 3$, i.e. 900 km above the photosphere). From this color map, it is evident that high current-densities are concentrated at the footpoint of an inverse-S shaped field line (orange line). Although the precise mechanism by which coronal loops brighten remains uncertain, one study finds a direct link between coronal heating and the current measured at the lower atmosphere (Lee *et al.* 1998). Accepting this result, then we can assume that the strong concentration of current density at the footpoint of inverse-S shaped field lines could provide a significant heat source for these lines. Furthermore, this result also presents an idea to solve the problem of why only inverse S-shaped field lines are strongly brightened to be observed as a sigmoid

In summary, we have simulated the emergence of a twisted flux tube into the corona using a three-dimensional, time-dependent code. After emergence, the outer, azimuthal field of the tube expand to naturally form potential-like arcade structure, while the inner, axial field that emerges after the tube axis produces a twisted sigmoidal structure. The low-lying, inner field lines originate from regions of the highest current concentration and therefore will be the most visible in coronal emission such as soft X-rays.

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Fig. 1.— Initial distribution of physical quantities along the vertical axis. ‘ Pm ’, ‘ Pg ’, and ‘ ρ ’, the magnetic pressure, gas pressure and mass density, are plotted logarithmically against the left axis. Temperature ‘ T ’ is plotted linearly against the right axis.

Fig. 2.— Time sequence of flux emergence, characterized using the magnetic field at the photospheric plane ($z = 0$). Total unsigned flux vs. distance (dotted line, right axis) shows flux crossing the plane at $t = 10$, and the axis crossing the plane by $t \simeq 20$. A second horizontal axis gives time in seconds beginning at the moment of emergence. Separation distance (solid line, left axis) is found from a B_z -weighted position average in the immediate neighborhood of the extreme pixel. Insets show B_z (contours and grey-scale) and v_{\perp} (arrows) are times $t = 12, 16, 20, 28$ and 40 .

Fig. 3.— *Top left* : Top-view snapshot of magnetic field lines (colored lines), horizontal velocity field (white arrows), vertical velocity (color map), and vertical magnetic field (contour lines, contour interval is 0.6.), taken at $t = 20$. The 2-dimensional plane is located at $z = 0$. *Top right* : Top-view snapshot taken at $t = 40$. *Middle left* : Perspective-view snapshot taken at $t = 20$. *Middle right* : Perspective-view snapshot taken at $t = 40$. *Bottom left* : Side-view snapshot taken at $t = 20$. *Bottom right* : Side-view snapshot taken at $t = 40$. Each colored field line is drawn by Lagrangian tracing method and a black line shows the tube axis.

Fig. 4.— (a) An example of a sigmoid structure taken by the SXT telescope on board *Yohkoh*. Courtesy of *Yohkoh* team members. (b) 2-dimensional view of the magnetic field projected onto the $y = 0$ plane (black arrows) and density (color map) at $t = 40$. (c) Perspective-view snapshot of three magnetic field lines (red, white, and orange lines), horizontal velocity field (white arrows), vertical velocity (color map), and vertical magnetic field (contour lines, contour interval is 0.6), taken at $t = 40$. The 2-dimensional plane is located at $z = 0$. The position where each field line penetrates the $y = 0$ plane is marked in (b) with a dot of the same color as the field line. (d) Top view version of (c), but a color map shows the absolute value of the current density measured at $z = 3$.