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SIGMOID STRUCTURE OF AN EMERGING FLUX TUBE

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ABSTRACT

We present the results from three-dimensional 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 that resemble a potential arcade and inner toroidal field lines that emerge after the tube axis, forming sigmoid structure. The simulations suggest that the neutral-line shear and sigmoidal field arise as a natural by-product of flux emergence.

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

1. INTRODUCTION

It is now widely believed that a magnetic field plays an important role in various activities in the solar corona. Some recent studies of coronal magnetic fields presented 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 a coronal field has mainly focused on the behavior of a magnetic field above the photosphere. In such a study, a bottom boundary is located at a photospheric level in order 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 the photospheric boundary condition in a particular way. The most self-consistent way to simulate the emergence of the 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 the magnetic field in the convection zone. According to several studies of the dynamics of the magnetic field in the convection zone, the magnetic field rising through the convection zone has the shape of an isolated tube with a 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 that was initially placed in the convection zone by means of 2.5-dimensional MHD simulation. Magara (2001) made a detailed investigation of the emergence and of the 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 for solving this problem, one of which is to introduce a three dimensionality to the flux-tube system.

The present Letter is the first report on our work that extends Magara (2001) by including three-dimensional effects in the evolution of an emerging flux tube. We start with a straight flux tube with a uniform twist (the Gold-Hoyle flux tube) placed horizontally in the upper convection zone and follow the evolution of this tube by performing a three-dimensional MHD simulation. We find that the coronal magnetic field formed after emergence exhibits outer poloidal field lines that resemble a potential arcade and inner toroidal field lines that 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 three-dimensional, compressible, ideal MHD equations, including a uniform gravity. The primitive variables $\boldsymbol{v}$, $\boldsymbol{B}$, ρ, and p that are represented on a nonuniform Cartesian grid are time-advanced using the modified Lax-Wendroff method (Magara 1998). Each physical quantity is rescaled by its photospheric value. In particular, the velocity, length, and time are scaled to $C_{\rm Sp} = 8.6$ km s^{-1}, $2\Lambda_p = 300$ km, and $2\Lambda_p/C_{\rm Sp} = 35$ s (where Λ_p and $C_{\rm Sp}$ are the pressure scale height and adiabatic sound speed), respectively. The gas density and pressure are scaled to $\rho_p = 2.7 \times 10^{-7}$ g cm^{-3} and $\gamma P_p = 2 \times 10^5$ dyn cm^2. The adiabatic index takes its ideal monatomic value of $\gamma = 5/3$. The temperature and magnetic field are scaled to $T_p = 5100$ K and $(\rho_p C_{\rm Sp}^2)^{1/2} = 450$ G, respectively. 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, which is identical to that used in Magara