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DYNAMIC AND TOPOLOGICAL FEATURES OF PHOTOSPHERIC AND CORONAL ACTIVITIES PRODUCED BY FLUX EMERGENCE IN THE SUN

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ABSTRACT

We study the emergence of magnetic fields in the solar atmosphere with a focus on photospheric and coronal activities produced by flux emergence. These activities are examined using a three-dimensional MHD simulation of an emerging flux tube. The simulation has been performed for a highly twisted flux tube (highly twisted case) and a weakly twisted one (weakly twisted case). The emerging flux tube globally forms a bipolar region associated with a flow in the photosphere. We decompose the flow into several fundamental flow components, such as rotation, expansion/contraction, and distortion. The analysis shows that as the emerging field becomes vertical, a torsional flow appears in a polarity region with intense flux, and the polarity region apparently rotates opposite to the torsional flow. We also find that the evolution of the photospheric neutral line in the highly twisted case is different from that in the weakly twisted case. We then study the coronal structure of an emerging field by focusing on the distribution of current density at the chromospheric footpoint of emerging field lines. Field lines with high current density at their footpoints display a distinct shape in both highly twisted and weakly twisted cases: the highly twisted flux tube produces the confined, sigmoidal structure of coronal loops, while the expanded loop structure appears in the weakly twisted case. Based on these results we discuss the mechanism for producing several solar phenomena, such as filament channels, flux ropes, and sigmoids.

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

1. INTRODUCTION

Magnetic fields are believed to play a fundamental role in producing various activities in the solar atmosphere. These magnetic fields originally come from the subphotosphere by magnetic buoyancy (Parker 1955), and they form magnetic structures in the corona that are associated with plasma motions in the photosphere. Photospheric motions have been of great importance in the study of coronal activities, because these motions perturb the photospheric footpoint of coronal field lines, thereby driving coronal evolution. Clarifying how photospheric motions affect a coronal structure is therefore a key to understanding the mechanism for coronal activities such as flares, filament eruptions, and coronal mass ejections. Observations have so far provided us with useful information about photospheric motions in magnetic polarity regions (Ishii et al. 1998; Kusano et al. 2002; Welsch et al. 2004; Longcope 2004; Li et al. 2004), while the measurements of the coronal field are developing to the point that they can reproduce the coronal structure (Kramar & Inhester 2005). The extrapolation of the coronal field from the photospheric field has also made a significant contribution to the understanding of coronal field topology (Longcope 2005 and references therein).

Theoretical models of the dynamic formation of coronal structures associated with photospheric motions have also been made in which subphotospheric dynamics is incorporated into a model for photospheric and coronal evolution. Since pioneering work done by Shibata et al. (1989), works using a flux emergence simulation have so far presented fruitful results on photospheric and coronal activities (Nozawa et al. 1992; Yokoyama & Shibata 1996; Matsumoto et al. 1998; Fan 2001; Magara & Longcope 2003; Abbett & Fisher 2003; Miyagoshi & Yokoyama 2004; Archontis et al. 2004; Manchester et al. 2004; Galsgaard et al. 2005, Isobe et al. 2005; Leake & Arber 2006). A good review of these works is given by Fan (2004). A recent work by Nozawa (2005) presents an extended survey of the parameters characterizing flux emergence.

In this paper we make a detailed investigation into the features of photospheric motions and coronal structure dynamically produced by flux emergence. The purpose of this work is to understand how these features are related to the twisting of the subphotospheric field. Toward this end we examine the emergence of a twisted flux tube by performing a couple of MHD simulations in which we use different twists of the flux tube as the initial state. We analyze the photospheric flow driven by flux emergence by decomposing it into several fundamental flow components such as rotation, expansion/contraction, and distortion. Particular attention is paid to the evolution of the photospheric neutral line, which is recognized as a key observational signature of filament formation. We also investigate how the twisting of the subphotospheric field affects coronal structure. In this respect, Abbett & Fisher (2003) present an interesting result that an emerging flux tube composed of weakly twisted field lines forms a potential-like structure in the corona. In the present study we discuss the topological feature of coronal structure in terms of the current density distributed at the chromospheric footpoint of emerging field lines.

The organization of this paper is as follows. In § 2 we present a basic explanation of our model, including the method of numerical simulation used for this study. Section 3 presents the results for the evolution of the photospheric neutral line, photospheric motion, and coronal structure. In § 4 we discuss the mechanism for photospheric and coronal activities found in the simulation, presenting some suggestions for future studies.

2. MODEL DESCRIPTION

2.1. *Basic Equations*

We use a set of ideal MHD equations in Cartesian coordinates with the *z*-axis directed upward against uniform gravity;

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \tag{1}$$