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LETTER

A Possible Structure of the Magnetic Field in Solar Filaments Obtained by Flux Emergence

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Abstract

We report a result, that the emergence of a subsurface magnetic field naturally reproduces the feature of the global magnetic configuration observed in solar filaments. This was obtained by performing a three-dimensional simulation of a twisted flux tube that emerges in the shape of a multi-Ω-loop in a highly stratified solar atmosphere, extending from the subsurface layer to the corona. One of the key findings is that a kinking of the twisted flux tube occurs at the site of a linkage between adjacent Ω-loops. This develops a magnetic structure that has remarkable similarities to the structure of a filament, in that the inner part of the twisted flux tube can be applied to the main body of a filament, while the outer part is reminiscent of observations of filament feet and a coronal arcade overlying the main body of a filament. Based on the result, we concluded that the orientation of filaments observed on the Sun may have its origin in the handedness of a twisted magnetic field below the solar surface.

Key words: magnetohydrodynamics: MHD — methods: numerical — Sun: filaments — Sun: magnetic fields

1. Introduction

Solar filaments, or prominences observed at the solar limb, are one of the prominent objects showing a floated structure on the Sun (Zirin 1988). The gas density in a filament is significantly higher than its surroundings, and now it is widely believed that the mass of a filament is magnetically supported against gravity (Kippenhahn & Schlüter 1957; Kuperus & Raadu 1974; Tandberg-Hanssen 1995). The magnetic field has a significant effect on the dynamic and thermodynamic states of filaments via the Lorentz force and thermal conduction along the magnetic field lines; thus, the structure of the magnetic field in filaments has been an important issue for studying the nature of filaments.

Filaments tend to form in the region around the neutral line of the photospheric magnetic flux, which is called a filament channel surrounded by positive and negative polarity regions. Above these major polarity regions is observed the main body of a filament. There are also small weak-flux regions distributed around a filament channel (Martin 1998; Chae et al. 2001); these small regions, which are called parasitic polarity regions, compared to the major polarity regions, contribute to producing a secondary structure, such as filament feet. A notable result of the parasitic polarity regions is that these regions have the opposite polarity to a nearby major polarity region (Martin et al. 1994), and field lines with their footpoints in the parasitic polarity regions are suggested to have a dipped structure (Aulanier & Démoulin 1998; López Ariste et al. 2006).

A question then arises: how does the magnetic structure having those characteristics mentioned above form on the Sun? The magnetic field initially comes below the solar surface via magnetic buoyancy (Parker 1955), which is called flux emergence. Recent studies of flux emergence have revealed various aspects of this highly dynamic process (Fan 2004; Archontis et al. 2004; Moreno-Insertis 2007). One of these studies has shown that a filament channel could be formed by the emergence of a flux tube composed of highly twisted field lines (Magara 2006). It is, though, still unclear how the secondary structure associated with the parasitic polarity regions appears as a result of flux emergence. In this respect, Magara (2004) has suggested that a twisted flux tube emerging in the shape of a multi-Ω-loop produces a possible structure of the magnetic field in filaments. Although the complete modeling of filaments is far beyond the subject of this paper, we here place our focus on multi-Ω-loop emergence to investigate how this process reproduces the feature of the global magnetic configuration observed in filaments.

2. Description of a Numerical Model

Figure 1 shows the distribution of magnetic field lines obtained from a three-dimensional magneto-hydrodynamic simulation using Cartesian coordinates with the z-axis directed upward. The snapshots show early and late phases of the simulation. The basic setup of the simulation follows a previous study presented in Magara (2006). As the initial state of the simulation, we assume a hydrostatic atmosphere with an isolated magnetic flux tube inside it. Based on the temperature profile in figure 1, the atmosphere stratified under uniform gravity is divided into several layers: the subsurface layer, the photosphere or the solar surface placed at $z = 0$, the chromosphere, a transition region, and corona. A straight flux tube with a radius of 1 Mm is placed 1.6 Mm below the surface along the y-axis, which is in mechanical equilibrium with the background atmosphere. The flux tube is composed of twisted field lines having a uniform-twist profile (Priest 1982), in which the magnetic field has a left-handed twist with a maximum strength of 6500 G at the central portion of the flux tube. These field lines make one helical turn when they run a