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Emergence of a Partially Split Flux Tube into the Solar Atmosphere

Tetsuya MAGARA
Hinode Science Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588
t.magara@nao.ac.jp

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Abstract

We performed a three-dimensional MHD simulation for the emergence of a partially split flux tube into the solar atmosphere, which was focused on the mechanism of activity observed on the Sun, such as the merging of magnetic polarity regions in the photosphere and the formation of multi-flux domains in the corona. The simulation reproduced that a small polarity region associated with a rotational flow merges into a main polarity region, and the main polarity region later develops a rotational flow in the same direction as the small polarity region. In accordance with the photospheric merging process, multi-flux domains form in the corona and a current layer separating these flux domains travels outward as the flux domains expand. We also investigated the time variations of the magnetic flux, energy, and helicity injected into the atmosphere by the partially split flux tube to see the nature of helicity injection in a multi-pole system.

Key words: methods: numerical — MHD — Sun: corona — Sun: magnetic fields — Sun: photosphere

1. Introduction

The Sun shows various active phenomena on its surface, and the magnetic field has been believed to be a key player in producing these phenomena. The magnetic field travels through the solar interior toward the surface, and after emerging into the surface it expands widely in the solar atmosphere, providing the seeds of activity observed on the Sun. This indicates that active phenomena observed on the Sun are, more or less, related to invisible subsurface processes of the magnetic field, so taking these subsurface processes into account is a key to a good understanding of the physical mechanism of observed phenomena. For example, the so-called flux cancellation is a typical phenomenon observed at the surface, in which the opposite-polarity regions approach each other and disappear at the neutral line between them (Martin et al. 1985; Livi et al. 1985; Li et al. 2004). Observationally, it has been inferred that various kinds of activity are related to flux cancellation: solar flares (Livi et al. 1989; Wang & Shi 1993), microflares / surges / jets (Chae et al. 1999, 2002; Liu & Kurokawa 2004), X-ray bright points (Webb et al. 1993), Ellerman bombs (Pariat et al. 2004), filament formation (Martin 1986), and its activation (Wang et al. 1996; Kim et al. 2001). Flux cancellation even relates to one of the most large-scale events on the Sun, such as coronal mass ejections (CMEs) (Zhang et al. 2001); a model of CMEs based on flux cancellation has been studied (Forbes & Isenberg 1991; Linker et al. 2003).

Flux cancellation might be a direct manifestation of annihilating the magnetic field right on the surface; however if we consider the subsurface process related to this surface phenomenon, the other two mechanisms emerge as possible candidates causing flux cancellation. One of them is the emergence of U-loops (van Driel-Gesztelyi et al. 2000; Bernasconi et al. 2002; Lites 2005), and the other is the submergence of Ω-loops. A magneto-hydrodynamic (MHD) simulation based on the scenario of U-loop emergence has successfully reproduced flux cancellation (Magara 2007).

The present paper deals with a similar phenomenon observed at the surface, in which the same-polarity regions merge together to form a large polarity region (Vrabec 1974; McIntosh 1981; Zwaan 1985). Zhang (1994) reported that the merging of the same-polarity regions is related to the occurrence of major X-class flares, and MHD calculations support this result (Gerrard et al. 2003). Observations have also shown the rotation of a sunspot, into which nearby pores are merging (Brown et al. 2003). When we consider subsurface processes, the apparent merging of polarity regions observed at the surface might be explained by the so-called oak tree model of flux convergence (illustrated by Zwaan 1985, in figure 1). In this model a partially split flux tube continuously emerges into the surface, and when the coalescent part of the tube rises up to the surface, we then observe the merging of individual poles with the same polarity. Beyond cartoon-based considerations, we here aim to clarify the dynamic nature of this merging process. Toward this end, we use a relatively simple geometry of the magnetic field to perform an MHD simulation for the emergence of a partially split flux tube into the solar atmosphere. This study is focused on the flux emergence that connects invisible subsurface processes and observed surface phenomena.

So far, MHD simulations that have focused on flux emergence have successfully explained the physical mechanism of various phenomena observed on the Sun: the dynamic expansion of arch filament systems (Shibata et al. 1989), the formation of sigmoids (Matsumoto et al. 1998; Magara 2004), photospheric shear flows (Manchester 2001; Fan 2001), and their effect on the eruption of a magnetic flux rope into the corona (Manchester et al. 2004; Manchester 2007), and the interaction between the coronal field and the emerging field (Yokoyama & Shibata 1996; Isobe et al. 2005; Archontis et al. 2004, 2007; Galsgaard et al. 2007; Moreno-Insertis et al. 2008). The preemerged condition of the magnetic field