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DYNAMICS OF EMERGING FLUX TUBES IN THE SUN

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ABSTRACT

This paper is intended to study the evolution of a magnetic flux tube that rises from the upper convection zone to the solar atmosphere by means of a 2.5-dimensional MHD simulation with the focus on the cross section of the flux tube. A cylindrical flux tube placed horizontally in the convection zone starts rising by magnetic buoyancy. When the top of the tube reaches the photosphere, the cross section of the tube changes from the circular shape to horizontally extended shape, forming a magnetic layer under the contact surface between the tube and the photosphere. As the plasma inside that magnetic layer is squeezed out to both sides of the layer, the contact surface is locally subject to the Rayleigh-Taylor instability because the lighter magnetic layer is overlain by the heavier photospheric layer. The wavelength of the undulating magnetic layer at the contact surface increases as the flattening of the tube proceeds, and after it becomes longer than the critical wavelength for the Rayleigh-Taylor instability, the tube can emerge through the photosphere. The emergence part of the tube starts expanding into the atmosphere if it has a sufficiently strong magnetic pressure compared to the surrounding gas pressure. We find that this expansion process is characterized by a self-similar behavior, that is, both the plasma and the magnetic field have a steady distribution in the expanding area. On the basis of those results, we try to clarify several important features of emerging flux tubes expected from observations. We focus on two solar phenomena, the birth of emerging flux tubes and the formation of filaments, and discuss the physical processes related to these phenomena.
Subject headings: MHD — Sun: atmosphere — Sun: filaments — Sun: magnetic fields

1. INTRODUCTION

Recently, magnetic flux tubes have been among the most attractive objects that draw the attention of many solar physicists. They are now believed to be connected with a variety of phenomena observed in the Sun, such as tiny bipoles, arch filament systems, sunspots, filaments, X-ray brightenings, coronal mass ejections, the sigmoid structure of coronal arcades, and so on (Tanaka 1991; Thomas & Weiss 1992; Ishii, Kurokawa, & Takeuchi 1998; Yoshimura & Kurokawa 1999; Kankelborg & Longcope 1999; Canfield, Hudson, & McKenzie 1999). It is therefore important to clarify the dynamics of flux tubes in various situations in order to understand the physical mechanisms of these kinds of phenomena. The behavior of flux tubes in the convection zone has been studied extensively by means of the thin flux tube model (Spruit 1981). Choudhuri & Gilman (1987) investigated the latitude where flux tubes emerge through the convection zone, and they concluded that the magnetic field of flux tubes at the bottom of the convection zone is more than 10^4 G, the equipartition value to the convective motion at that layer. Howard (1991) determined the dependence of the tilt angle of emerging bipolar systems on the latitude, and the calculation by D'Silva & Choudhuri (1993) successfully reproduced this dependence assuming that the initial strength of the magnetic field is 10^5 G at the bottom of the convection zone. Caligari, Moreno-Insertis, & Schüssler (1995) performed three-dimensional simulations of a flux tube rising from the bottom to the top of the convection zone and illustrated the asymmetric proper motion of sunspots. Fisher, Fan, & Howard (1995) investigated the relation between tilt angle and net flux of bipoles.

While the thin flux tube model provides little information on the deformation process of the cross section of rising flux tubes, several two- or 2.5-dimensional MHD simulations have clarified this process for a cylindrical flux tube placed horizontally in the convection zone. Schüssler (1979) studied a flux tube without any twisting magnetic field (untwisted flux tube) and found that the initial circular cross section was changed into an umbrella shape with an arc-shaped edge. Longcope, Fisher, & Arendt (1996) also discovered that a rising flux tube was subject to both the deformation and decomposition effects so that it finally stopped rising. Emonet & Moreno-Insertis (1998) studied the effect of field line twist on the tube dynamics, suggesting that the strong twist can suppress the deformation of the cross section, making the tube rise continuously.

Detailed studies have also been carried out on the behavior of the magnetic field rising from the upper convection zone to the solar atmosphere (Shibata et al. 1989; Kaisig et al. 1990; Nozawa et al. 1992; Yokoyama & Shibata 1996). This series of works assumes a horizontal flux sheet initially placed under the photosphere, which later emerges to the atmosphere by magnetic buoyancy instability (Parker instability). Shibata et al. (1989) discovered a self-similar expansion process of the magnetic field in the nonlinear stage of the Parker instability by performing two-dimensional MHD simulations. This process was later considered in more detail by an analytical method in Shibata, Tajima, & Matsumoto (1990). Nozawa et al. (1992) discussed the effect of convective collapse at the footpoints of an expanding loop, while Yokoyama & Shibata (1996) studied the magnetic reconnection between the expanding magnetic field and the overlying field.

The works introduced above have explored the expansion process of flux sheets in the atmosphere, while here we focus our attention on discrete flux tubes and investigate their emergence and expansion processes in the atmosphere. The study lying in this line of works is found in Krall et al. (1998), in which they studied the rise process of a flux tube in the chromosphere and