The Astrophysical Journal, 586:630–649, 2003 March 20

INJECTION OF MAGNETIC ENERGY AND MAGNETIC HELICITY INTO THE SOLAR ATMOSPHERE BY AN EMERGING MAGNETIC FLUX TUBE

T. Magara and D. W. Longcope
Department of Physics, Montana State University, Bozeman, MT 59717-3840; magara@solar.physics.montana.edu
Received 2002 August 26; accepted 2002 November 26

ABSTRACT

We present a detailed investigation of the dynamical behavior of emerging magnetic flux using three-dimensional MHD numerical simulation. A magnetic flux tube with a left-handed twist, initially placed below the photosphere, emerges into the solar atmosphere. This leads to a dynamical expansion of emerging field lines as well as an injection of magnetic energy and magnetic helicity into the atmosphere. The field-aligned distributions of forces and plasma flows show that emerging field lines can be classified as either expanding field lines or undulating field lines. A key parameter determining the type of emerging field line is the aspect ratio of its shape (the ratio of height to footpoint distance). The emergence generates not only vertical but also horizontal flows in the photosphere, both of which contribute to injecting magnetic energy and magnetic helicity. The contributions of vertical flows are dominant at the early phase of flux emergence, while horizontal flows become a dominant contributor later. The emergence starts with a simple dipole structure formed in the photosphere, which is subsequently deformed and fragmented, leading to a quadrupolar magnetic structure.

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

1. INTRODUCTION

Magnetic flux emergence has been one of the most important subjects in solar physics because it provides seeds of energetic activity on the Sun. According to prevailing ideas, the magnetic field is initially amplified near the bottom of the convection zone and then starts to rise toward the surface by magnetic buoyancy, finally emerging into the atmosphere. During its residence in the convection zone the magnetic field is believed to form a thin flux tube whose motions are strongly controlled by surrounding convective plasma. A particularly fruitful version of the confined state is the thin flux tube model, which assumes that the magnetic field behaves like a " one-dimensional string " (Spruit 1981; Stix 1991, p. 270). The validity of this model is suggested from observational results for sunspots, whose behavior is related to the evolution of subsurface magnetic fields. Recent work based on this model has successfully explained many observed properties of sunspots, such as latitude, tilt angle, and east-west asymmetry (Choudhuri & Gilman 1987; Howard 1991; D'Silva & Choudhuri 1993; Fan, Fisher, & McClymont 1994; Fisher, Fan, & Howard 1995).

The success of thin flux tube modeling enables us to infer that the invisible subsurface magnetic field is probably composed of slender tubes of twisted flux. The necessity of twist was demonstrated by separate studies in which untwisted tubes could not maintain their integrity in the face of the forces of interaction with the surrounding medium (Schüssler 1979; Longcope, Fisher, & Arendt 1996; Emonet & Moreno-Insertis 1998; Abbett, Fisher, & Fan 2000; Dorch & Nordlund 2001; Dorch et al. 2001).

Although the thin flux tube model has contributed significantly to our understanding of the dynamics of interior magnetic field, it provides less information about the details of flux emergence, where the magnetic field cannot be approximated as a one-dimensional string. The emergence process is essentially dynamical and difficult to study owing to the dramatically changing plasma environment in the vicinity of the photosphere. The gas pressure drops by 10^{-6} in a few megameters, since the pressure scale height in the photosphere is about 150 km. As this pressure drops abruptly, the magnetic field becomes free to expand into the atmosphere.

A feasible approach to the study of flux emergence is to reproduce the temporal development of emerging magnetic fields by directly solving time-dependent, nonlinear MHD equations. Toward this end, a lot of effort has been devoted to performing MHD numerical simulations in which the confined magnetic field rises from the dense subphotosphere into the tenuous atmosphere. Those numerical simulations were first available for two-dimensional studies, which clarified several important physical processes related to flux emergence, such as the nonlinear Parker instability (Shibata et al. 1989; Shibata, Tajima, & Matsumoto 1990; Tajima & Shibata 1997, p. 189) and the development of the Rayleigh-Taylor instability at the flattening part of an emerging flux tube (Magara 2001).

Recently, three-dimensional flux emergence simulations have been performed that naturally display more realistic and complicated behavior. Most importantly, only three-dimensional simulations permit a flux tube to drain material, thereby reducing the mass carried into the atmosphere. The emerged magnetic field lines form a sigmoidal structure (Matsumoto et al. 1998; Magara & Longcope 2001) and an arch filament system (Fan 2001).

The present work provides further insights into the three-dimensional evolution of flux emergence by studying the field-aligned distributions of forces and flows in individual field lines. This approach clarifies the underlying physics of flux emergence and explains an apparent contradiction in the results reported from the small number of simulations performed to date. In the simulation of Fan (2001) the axis of the tube remains near the photosphere after emergence. In a similar simulation, but using a slightly different profile of flux, Magara & Longcope (2001) observed the axis reaching substantial heights. Our analysis will focus on the