The Astrophysical Journal, 731:122 (8pp), 2011 April 20 doi:10.1088/0004-637X/731/2/122

ENERGY INJECTION VIA FLUX EMERGENCE ON THE SUN DEPENDING ON THE GEOMETRIC SHAPE OF MAGNETIC FIELD

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Received 2010 July 28; accepted 2011 February 20; published 2011 April 1

ABSTRACT

Flux emergence is a complicated process involving flow and magnetic field, which provides a way of injecting magnetic energy into the solar atmosphere. We show that energy injection via this complicated process is characterized by a physical quantity called the emergence velocity, which is determined by the spatial relationship between the flow velocity and magnetic field vectors. By using this quantity, we demonstrate that the geometric shape of magnetic field might play an important role in the energy injection via flux emergence.

Key words: magnetohydrodynamics (MHD) – Sun: activity – Sun: surface magnetism

Online-only material: color figures

1. INTRODUCTION

Magnetic fields are commonly observed on the Sun, spreading over the solar surface on various spatial scales (Stix 2004). A region called a pore or sunspot is formed by the magnetic field clustering on a large spatial scale, while the small-scale concentration of the magnetic field is also found in the intermediate region among convective cells such as granules and supergranules. Those magnetic fields distributed on the Sun are believed to play a fundamental role in producing various kinds of activity in the solar atmosphere, such as solar flares, coronal mass ejections, solar winds, and other small-scale brightenings and jets (Nishizuka et al. 2008). The magnetic energy producing these phenomena is originally provided below the surface by means of flux emergence.

Flux emergence is a process transporting magnetic field from the solar interior into the solar atmosphere, which is driven by magnetic buoyancy (Parker 1955). The interior of the Sun is occupied by dense plasma which interacts with the magnetic field. When the plasma is contained in an intense magnetic flux tube where the typical flow velocity is smaller than the local Alfvén velocity, plasma flow is controlled by the magnetic field so that the plasma tends to move along the magnetic field. If the flux tube locally has a convex shape in the direction opposite to gravity, a diverging downflow may arise around the convex portion by gravitational force, reducing the gas density there. The convex portion therefore starts to rise via buoyancy, which locally strengthens the convex shape of the flux tube to enhance the diverging downflow. This positive feedback facilitates the rising motion of convex field lines, which eventually makes them emerge into the surface (Fan 2009).

As mentioned above, the geometric shape of the magnetic field is one of the key factors of flux emergence. In a region governed by gravitational field, such as the solar surface, one of the geometric features characterizing the configuration of the magnetic field is the inclination of a field line against the gravity direction. Another geometric feature may be the curvature of a field line, which describes how much a field line is curved in either a convex or a concave shape against the gravity direction. We first focus on the field line inclination to derive a physical quantity characterizing the energy injection via flux emergence. We then use this quantity to demonstrate that the curvature of a field line might make a significant contribution to the energy injection via flux emergence.

2. EMERGENCE VELOCITY

In Cartesian coordinates (x, y, z), where the z-axis is directed upward against gravity, the flux of magnetic energy through the surface $(z = 0)$, i.e., the vertical component of the Poynting flux, may be written in the following way:

$$F_{Mz} = \iint_{z=0} -\frac{1}{4\pi}(B_x B_z v_x + B_y B_z v_y)dxdy + \iint_{z=0} \frac{1}{4\pi}\left(B_x^2 + B_y^2\right)v_z dxdy, \tag{1}$$

where $\mathbf{v}$ and $\mathbf{B}$ represent the flow velocity and magnetic field, respectively (Magara & Longcope 2003). The first term called shear part on the right-hand side of this equation indicates the flux produced by horizontal motions on the surface (shear flow), while the second term called emergence part represents how a vertical flow, or emergence flow, contributes to the injection of magnetic energy into the atmosphere with $z > 0$. Equation (1) may be transformed in the following way:

$$\begin{aligned} F_{Mz} &= \iint_{z=0} -\frac{1}{4\pi}(B_x B_z v_x + B_y B_z v_y)dxdy + \iint_{z=0} \frac{1}{4\pi}\left(B_x^2 + B_y^2\right)v_z dxdy \\ &= \iint_{z=0} \frac{-(B_x B_z v_x + B_y B_z v_y) - B_z^2 v_z + B_z^2 v_z + \left(B_x^2 + B_y^2\right)v_z}{4\pi} dxdy \\ &= \iint_{z=0} \frac{-(\mathbf{B}\cdot\mathbf{v})B_z + B^2 v_z}{4\pi} dxdy \\ &= \iint_{z=0} \frac{B^2}{4\pi}\, v_{\rm emg}\, dxdy, \end{aligned} \tag{2}$$

where

$$v_{\rm emg} \equiv v_z - \frac{\mathbf{B}\cdot\mathbf{v}}{B^2}B_z \tag{3}$$

is called the emergence velocity. A geometric description of this quantity is given in Figure 6 of Magara (2006). We here define the net emergence of the magnetic field, or the net injection of