Thesis for the Degree of Doctor of Philosophy

An MHD Simulation Study of Solar Coronal Dynamics with Solar Winds and Solar Eruptions

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Abstract

In this thesis, we use three-dimensional magnetohydrodynamic (MHD) simulations to study the physical properties of the dynamic solar corona filled with the magnetic field, where continuously existing solar winds and intermittently occurring solar eruptions play key roles in determining the dynamic state of the corona.

Firstly, we investigated the magnetic configuration responsible for the generation of solar wind and the heating of the corona. We performed a set of three-dimensional MHD simulations to reproduce emerging flux regions with different magnetic configurations, where we focus on two key quantities characterizing the magnetic configuration of an emerging flux region: the force-free parameter α and the flux expansion rate f_{ex}, the former of which represents how much the magnetic field is twisted to produce a field-aligned electric current, while the latter represents how sharply the magnetic field expands from the gas pressure-dominant photosphere to the magnetic pressure-dominant corona. We derived the distributions of these quantities in simulated emerging flux regions. The main result is that an emerging flux region is composed of the outer part where magnetic loops take a large flux expansion rate but a small value of α at the photospheric footpoints, and the inner part occupied by those loops having a strong field-aligned electric current. We also found that a magnetic loop has the exponential expansion profile near the photosphere, while it has the quadratic expansion profile in the corona. The detailed information on the magnetic configuration of an emerging flux region obtained by this study will make a significant contribution to developing a realistic model for the magnetic heating of the corona and the generation of solar wind.

Secondly, we constructed an MHD model of solar eruption based on the dynamic state transition from the quasi-static state to the eruptive state of an active region magnetic field. For the quasi-static state before an eruption, we consider the existence of a slow solar wind originating from an active region, which may continuously make the active region magnetic field deviate from mechanical equilibrium. In this model, we performed a three-dimensional MHD simulation of Active Region 12158 producing a coronal mass ejection, where the initial magnetic structure of the simulation is given by a nonlinear force-free field derived from an observed photospheric vector magnetic field. We applied a pressure-driven outflow to the upper part of the magnetic structure to achieve a quasi-static pre-eruptive state. The simulation shows that the eruptive process observed in this active region may be caused by the dynamic state transition of an active region magnetic field, which is essentially different from the destabilization of a static magnetic field. The dynamic state transition is determined from the shape evolution of the magnetic field line according to the κH-mechanism. This work demonstrates how the mechanism works to produce a solar eruption in the dynamic solar corona governed by the gravitational field and the continuous outflows of solar wind.

In appendix, we explain the simulation methods and several physical processes related to this study.

Keywords:

magnetohydrodynamics (MHD) — Sun: corona — Sun: magnetic fields — Sun: solar wind — Sun: coronal mass ejections (CMEs)

Table of Contents

Appendix B. Key Physical Processes

B.1. κH-Mechanism for Solar Eruptions

We briefly explain the κH-mechanism characterized by the curvature (κ) of magnetic field lines and the scale height of magnetic field strength (H). Details are reported in Magara (2013)[2] and An & Magara (2013)[3].

κ and H are related to the downward magnetic tension force (F_T) and the upward magnetic pressure gradient force (F_M) exerted on the top of an Ω-loop, respectively.

$$F_T = \frac{1}{4\pi} B \cdot \nabla B_z = -\frac{B^2}{4\pi}\kappa \tag{B.1}$$

$$F_M = -\frac{\partial}{\partial z}\left(\frac{B^2}{8\pi}\right) = \frac{1}{H}\frac{B^2}{4\pi} \tag{B.2}$$

where

$$H^{-1} = -\frac{1}{B}\frac{\partial B}{\partial z}. \tag{B.3}$$

The spatial distributions of these two quantities along the symmetric axis of an Ω-loop are shown in Figure B.1. They increase and take the maximum at a critical height ($z = z_c$), which gives the quasi-static range where the magnetic field expands mainly vertically. Above the critical height, the curvature decreases with height, while $1/H$ tends to weakly vary. It gives the expansion range corresponding to an eruptive state, where the loop expands both vertically and laterally.

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[2] Magara, T. 2013, PASJ, 65, L5

[3] An, J. M., & Magara, T. 2013, ApJ, 773, 21

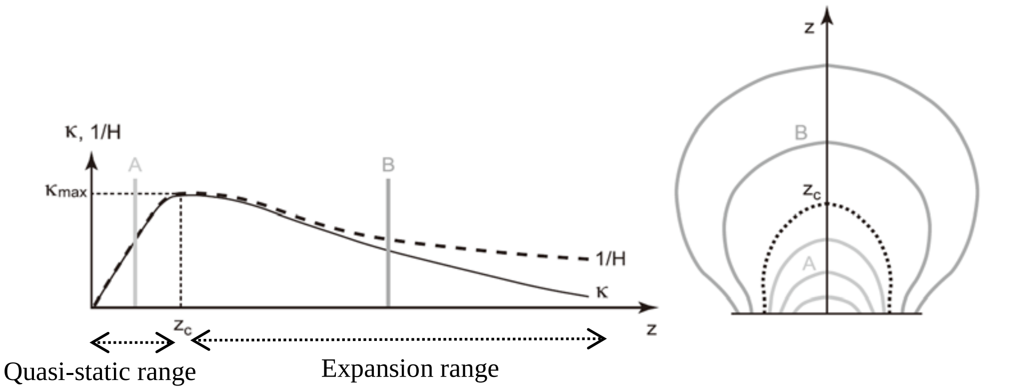

Figure B.1 The profiles of κ and $1/H$. z_c is the critical height (From Figure 5 in Magara 2013)

B.2. Flow Velocity Field of an Active Region

It is hard to observe the flow velocity field of an active region. Instead, we can infer it from the result of flux-emergence simulation. Figure B.2 shows the flow velocity field along an outer and inner magnetic field lines. The outer field line expands vertically and laterally to form a fanlike structure with low density. On the other hand, the inner field line is surrounded by adjacent twist field lines, which prevents lateral expansion compared to the outer field line. From the viewpoint of κH-mechanism, the inner field line is in a quasi-static state where vertical expansion is dominant.

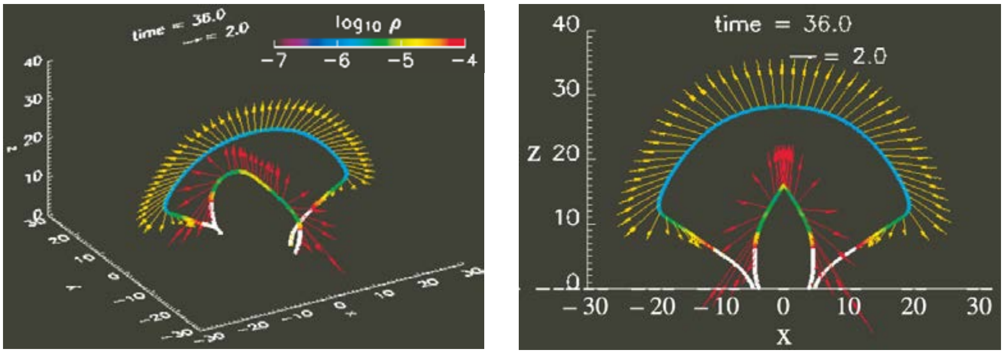

Figure B.2 The flow velocity field along an outer and inner field line obtained from a flux-emergence simulation is presented in a perspective (left) and side (right) view (From Figure 3 in Magara 2004[4]). Arrows and color lines indicate the velocity and gas density. White part of the field lines means high density in excess of the color-bar range.

[4] Magara, T. 2004, ApJ, 605, 480

B.3. Pre-Eruptive Oscillation

Figure B.3a presents the time variation in the rising velocity of an eruptive loop evolving from the quasi-static state to the eruptive state. It shows an oscillatory behavior before experiencing the dynamic state transition. This behavior can be explained by cyclic variations of the upward magnetic force and downward gravitational force (Magara 2004[5], 2015[6]). The oscillation has acceleration and deceleration phases. At the acceleration phase, the upward magnetic force is dominant because the mass drain along the loop reduces the downward gravitational force. As the loop height increases, the upward magnetic force is reduced due to the decrease of magnetic field strength. Then, the gravitational force becomes dominant. It causes the deceleration of the loop until the mass drain makes the gravitational force weaker than the magnetic force. The oscillation period is given by $\pi\sqrt{2H/\mathrm{g}_0}$ (Magara 2004), where H is the scale height of magnetic field strength and g_0 is the gravitational acceleration.

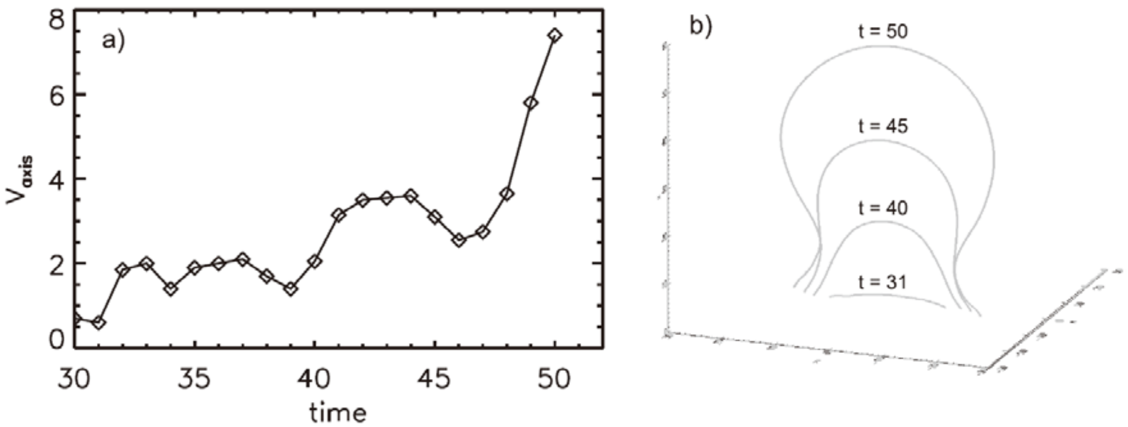

Figure B.3 (a) Time variation in rising velocity along the z-axis. (b) Field-line shapes at selected times (From Figure 2 in Magara, 2013[7])

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[5] Magara, T. 2004, ApJ, 605, 480

[6] Magara, T. 2015, PASJ, 67, L6

[7] Magara, T. 2013, PASJ, 65, L5