Thesis for the Degree of Doctor of Philosophy

MHD Simulation Studies of Solar Flux Ropes with Dynamic State Transition and Their Propagation in the Interplanetary Space

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Abstract

A solar active region (AR) is the region where various kinds of active phenomena tend to occur, such as solar flares and coronal mass ejections (CMEs). It has been known that an AR is formed via flux emergence from the convection zone. Although it has been observationally shown that an AR slowly evolve for weeks or even months before flares and CMEs suddenly occur, the triggering mechanism of such eruptive events is still not clear. A CME entered the interplanetary space, called interplanetary CME (ICME), sometimes travels toward the Earth, causing space weather disturbances as it interacts with the Earth's magnetosphere. These disturbances potentially damage spaceborne and ground-based systems and services. Regarding these topics, we focus on two questions: 1) how does the solar flux rope that eventually develops to an ICME evolve from the quasi-static state to the dynamic state (dynamic state transition); 2) how do ICME properties in the interplanetary space affect the space weather disturbances in the vicinity of the Earth.

Firstly, we performed a three-dimensional magnetohydrodynamic (MHD) simulation to investigate the dynamic state transition of a solar flux rope. In this simulation, we obtained a flux rope by reproducing flux emergence from the solar convection zone into the solar corona. In order to investigate the dynamic evolution of emerging magnetic field in the corona, we used two key parameters κ and H, the former of which represents the curvature of an emerging magnetic field line and while the latter the scale height of emerging magnetic field strength along the symmetry axis of an emerged magnetic loop. Here κ is related to downward magnetic tension force, while $1/H$ is related to upward magnetic pressure force. The plot of κ and H along the symmetry axis shows that they tend to increase with height until they reach their common peak. Below the location of the common peak, $1/H$ tend to be almost balanced by κ, whereas above that location, $1/H$ tends to exceeds κ, suggesting that upward magnetic pressure force is dominant over the downward magnetic tension force. When the flux rope axis exceeds the peak, it experiences the dynamic transition from a quasi-static state in which the upward and downward forces are balanced to an eruptive state. We also investigated the torus instability and compared to the

dynamic state transition that we proposed.

Secondly, we performed an MHD simulation to investigate the relation between ICME properties and space weather disturbances in the vicinity of the Earth. Toward this end, we used a spheromak-shaped ICME model parametrized by the injection speed, mass, location, magnetic field strength, and magnetic field orientation. The parameter values were determined based on a halo CME event observed on 10 September 2014 by Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO). We simulated the ICME travelling through a background solar wind reconstructed via an MHD-interplanetary scintillation (MHD-IPS) tomography method with the photospheric magnetogram data and IPS data. We compared simulation results to in situ observations in the vicinity of the Earth and discussed how the arrival time and solar wind profiles associated with the ICME vary with the properties of the ICME.

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Chapter 1   Introduction

1.1 Emergence of Solar Magnetic Fields

Solar magnetic fields are a key ingredient of various kinds of active phenomena on the Sun, such as solar flares, jets, and coronal mass ejections (CMEs). It is therefore important to understand how these magnetic fields are formed in the solar interior (Figure 1.1), emerge to the solar surface and produce solar active regions (ARs). Results from the helioseismology show that the magnetic fields are probably amplified at the base of the convection zone, called tachocline (Spiegel and Zahn, 1992), due to strong shear flows there. The magnetic fields in the convection zone then emerge to the solar surface by the magnetic buoyancy (Parker, 1955) and produce ARs.

The buoyancy of the magnetic fields could be understood as follows. Suppose that a magnetic flux tube has formed in the convection zone with gas pressure p_i and magnetic field strength B_i (Figure 1.2). The total pressure (gas pressure + magnetic pressure) balance in the lateral direction of the tube requires

$$p_i + \frac{B_i^2}{8\pi} = p_e, \tag{1.1}$$

where, p_e is the external gas pressure outside the tube. If the temperature of the structures are uniform ($T_i = T_e = T$), and using the perfect gas law, the internal density ρ_i should be smaller than the external density ρ_e. This produces a buoyancy force of $(\rho_e - \rho_i)g$ and make the tube rises, where g is the solar gravity. Once the tube starts to rise and its shape is curved, the tube also feels downward magnetic tension force ($B_i^2/4\pi L$, where L is the length of the tube), making short flux tubes difficult to rise.
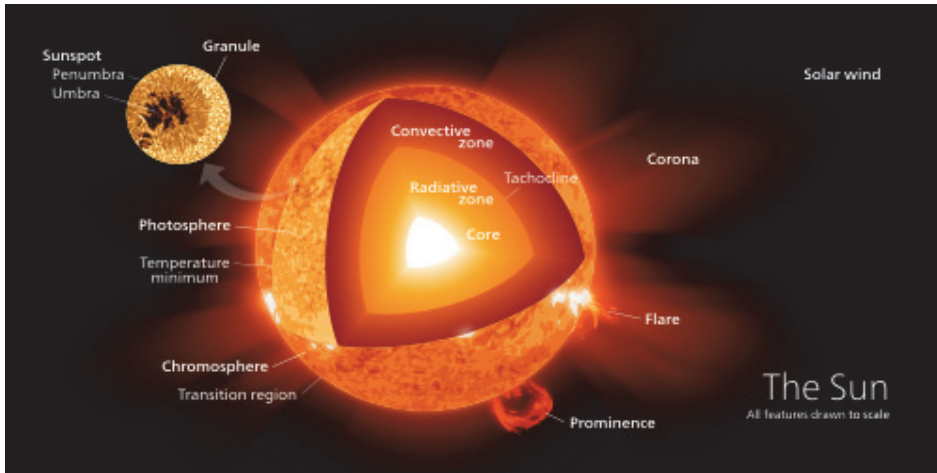
Figure 1.1 Structure of the Sun (adapted from https://en.wikipedia.org/wiki/Sun).
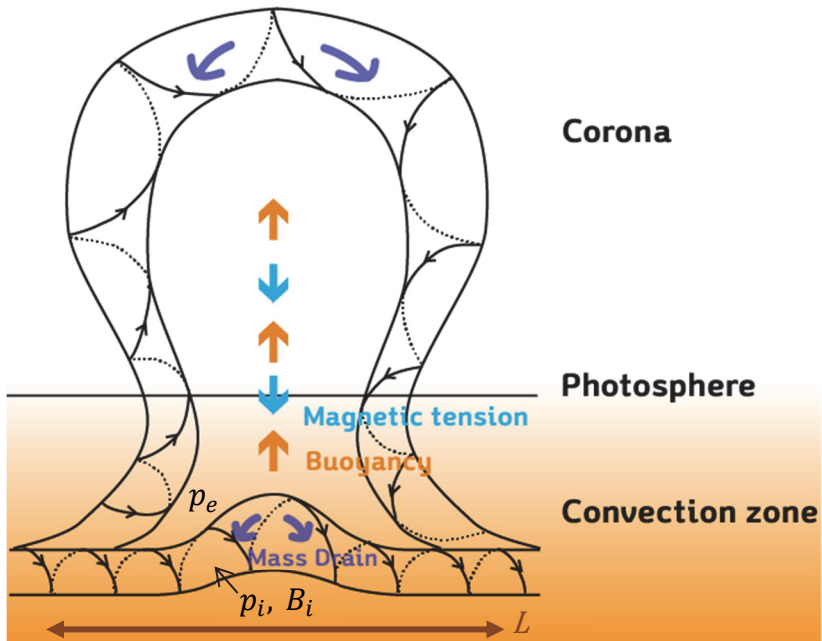

Figure 1.2 An illustration of the emergence of a flux rope from the solar convection zone.