論文の内容の要旨

論文題目

Numerical and Observational Studies of Flux Emergence in the Sun
(太陽の浮上磁場に関する数値的・観測的研究)

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The birth of active regions (ARs) in the Sun, or, the flux emergence, is one of the most important scientific targets in solar physics. It is widely believed that the ARs are created by rising magnetic fields from the deeper interior below the visible surface, i.e., the convection zone, although we cannot investigate such subsurface magnetic flux from direct optical observations. In this thesis, motivated by a scientific curiosity to understand the dynamics of the magnetic flux, particularly when the flux rises through the top convection zone and approaches the surface layer, we carried out numerical and observational studies of flux emergence.

First, we performed three-dimensional magnetohydrodynamic simulations of magnetic flux tubes rising from a depth of -20 Mm in the convection zone (Figure 1). As a result of the simulation, we found that the rising flux expands and slows down as it approaches the solar surface. Here, the expansion is due to the decrease in the pressure and density of the surrounding material. The deceleration of the rising flux tube occurs because unmagnetized plasma is trapped between the flux tube and the solar surface, which is an isothermally-stratified (i.e., convectively-stable) layer. Then, the trapped plasma escapes around the surface as a horizontal divergent flow (HDF). When the field strength of the flux tube increases enough, the flux restarts its ascent from the surface to the upper atmosphere. Based on the numerical results, we suggested a theoretical “two-step emergence” model of the rising magnetic flux.

We also conducted a parametric study of the numerical simulation by varying the field strength, the twist, and the perturbation wavelength of the initial tubes, aiming to investigate the relation between these parameters and the properties of the flux emergence. Consequently, we succeeded in obtaining the parameter dependencies of the flux evolution and of the HDF. It is also found that the HDF is driven by the lateral pressure gradient. Furthermore, the numerical results were explained by taking an analytical approach.

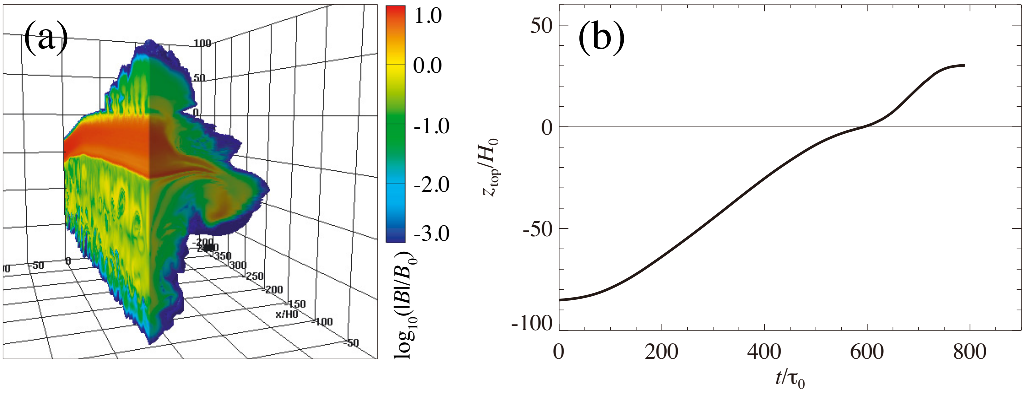

Figure 1: Evolution of the magnetic flux tube. (a) Logarithmic total field strength $\log_{10}(|B|/B_0)$ in a limited region ($x/H_0 < 0, y/H_0 > 0$) at the time $t/\tau_0 = 800$. The solar surface ($z/H_0 = 0$) is shown by a horizontal line. (b) Height-time evolution of the flux tube. The photospheric height $z/H_0 = 0$ is indicated with a horizontal line. Here, $H_0 = 200$ km, $\tau_0 = 25$ s, and $B_0 = 300$ G.

Second, in order to examine the theoretical "two-step emergence" model, we carried out two observational studies by developing our original methods. In this study, we exploited observational data obtained by *SOHO* and *SDO*. Thanks to their continuous full-disk observations, now we are able to analyze the very moment of, or even before the start of flux emergence.

The first observation target is the HDF of the unmagnetized plasma, which is expected to appear at the visible surface just before the flux itself emerges. We investigated the temporal evolution of the Dopplergram and the line-of-sight (LoS) magnetogram of NOAA AR 11081 taken by *SDO*/HMI, and detected the HDF about 100 minutes earlier than the start of the LoS magnetic flux emergence (Figure 2). The HDF duration and its speed were found to be comparable to the numerical results. By analyzing Hα images, we also investigated the chromospheric response to the flux emergence at the surface.

For a statistical analysis of the HDF, we repeated our detection in another 23 flux emergence events. As a result, we found HDFs in more than half of the entire data set. If we exclude the emergence events in the central region of the solar disk, which are supposed to have less LoS velocity components, the detection rate increases up to more than 80%. Therefore, we can conclude that the HDF is rather a common feature in the earliest phase of the AR appearance. The HDF duration and the maximum HDF speed were, on average, consistent with the event study and our numerical results.

The second target of the observational study is the rising magnetic flux in the uppermost convection zone. For detecting the subsurface flux, we used helioseismology, the unique way to probe the solar interior. We newly developed a helioseismic technique that measures acoustic oscillation signals, and applied this method to the *SOHO*/MDI Dopplergram of NOAA AR 10488. The obtained oscillation powers showed reductions, indicating that a magnetic flux rises through the top convection zone with a gradual deceleration (Figure 3). The estimated rise velocity of the flux and its decelerating nature were well accorded with the numerical

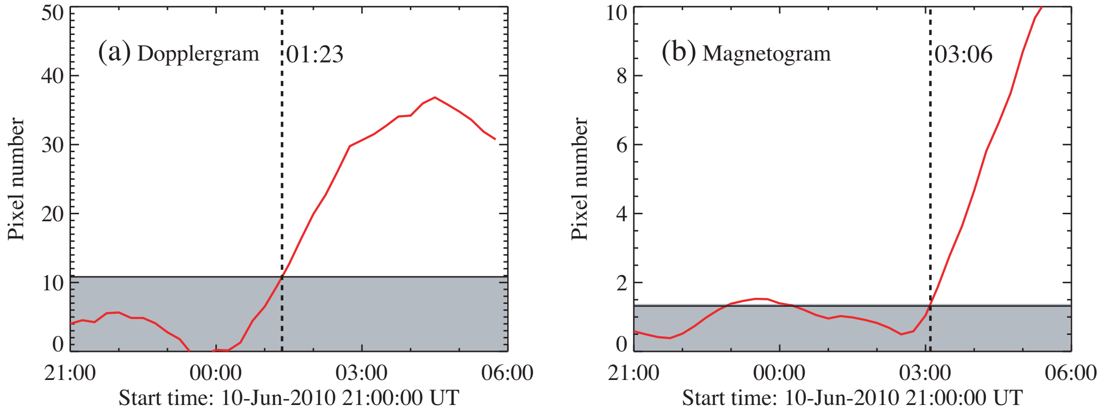

Figure 2: (a) Temporal evolution of the signal obtained from the Dopplergram. The shaded area indicates the one standard deviation level. The signal exceeds the standard deviation level at 01:23 UT, June 11. (b) The same for the magnetogram. The signal exceeds at 03:06 UT.

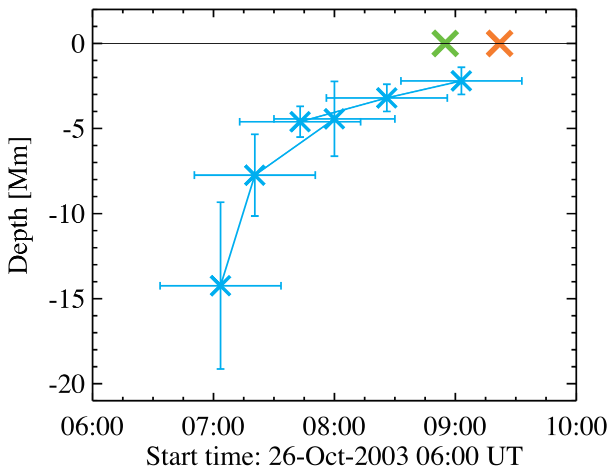

Figure 3: Depth-time evolution of the reduction start times for 6 different filters (blue). The vertical and horizontal error bars indicate the uncertainty in the effective target depth of each filter and 60-min smoothing average, respectively. Green and orange X's are the occurrence time of horizontal divergence flow (HDF) and the flux appearance.

results.

The clear consistencies between the numerical and the observational studies strongly support the "two-step emergence" model (Figure 4) that the rising magnetic flux slows down in the top convection zone before the flux evolves further into the upper atmosphere. Our results demonstrate that the surface layer plays an important role in the large-scale transportation of magnetic flux from the deeper convection zone to the higher atmosphere, changing the structure, velocity, and plasma-β of the emerging flux. Moreover, our study provides the means to investigate the physical state of subsurface magnetic flux, even before the flux appears at the visible surface. We believe that, by developing our numerical and observational methods, the transportation mechanism of the magnetic flux in the Sun will be revealed further in the future.

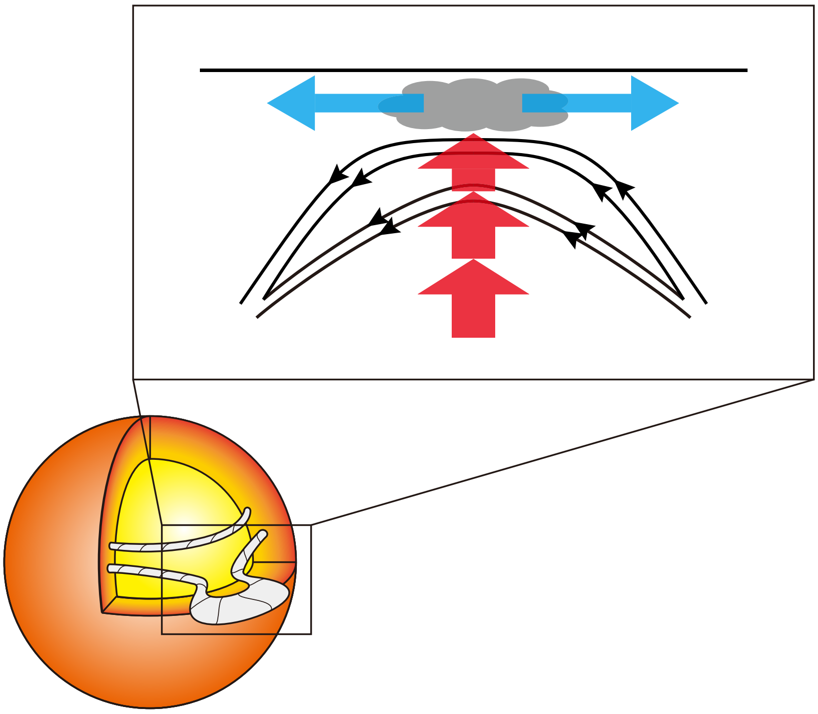

Figure 4: "Two-step emergence" model of the rising magnetic flux. The toroidal flux at the bottom of the convection zone partly starts its ascent and approaches the visible surface. The flux decelerates (red arrows) because the unmagnetized plasma becomes trapped between the flux and the surface layer. The plasma escapes horizontally around the surface as an HDF (blue arrows).