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Numerical experiments on the two-step emergence of solar magnetic fields from the convective layer

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Abstract. Emerging magnetic fluxes in the solar convection zone are thought to be responsible for the formation of active regions. In the past two decades, many numerical experiments have carried out to investigate the emergence of magnetic fluxes in the solar interior and in the atmosphere. Shibata et al. (1989) assumed the initial flux sheet located in the uppermost convection zone and perturbed it to trigger the Parker instability. They reproduced some characteristics of the emerging flux, e.g., arch filament systems and the downflows along them. Since then, many 2D/3D MHD simulations have revealed the physics of flux emergence. In every experiment, however, the initial flux was placed in the uppermost convection zone, i.e., no experiment included the formation of the initial flux.

A direct MHD calculation inside the convection zone is difficult because of the significant scale difference between the top and the bottom of the convective region. Thus, some simplifications such as thin-flux-tube (TFT) approximation have developed and various fruitful results have obtained by using them. One of the most important conclusions of the TFT model is that small magnetic flux (below 10^{21} Mx for 10^{4} G at the base of the convection zone) cannot reach the solar surface because the apices of the flux tube loose the magnetic field and finally 'explode' (Moreno-Insertis et al. 1995). However, the TFT approximation fails in the upper convection zone (at a few tens of Mm depth) so that fully compressible MHD calculations are needed to investigate the emergence from the deep convective layer to the solar corona through the surface.

In this study, we perform 2D MHD simulations of the flux emergence from the solar interior to the corona. The flux sheet is initially located moderately deep (-20,000 km) in the adiabatically stratified convection zone and is perturbed to trigger the Parker instability. The flux rises through the convection zone, but decelerates just beneath the strongly sub-adiabatic photosphere/chromosphere. As the magnetic pressure gradient increases, the flux becomes unstable to the Parker instability again so that the further evolution into the corona occurs. This 'two-step emergence' was recently observed by Otsuji et al. (2007 and ASJ autumn meeting 2009) through Hinode/SOT. We show the results of our numerical experiments based on the 'two-step emergence' model and discuss the dependence of the flux tube's behavior ('two-step emergence', 'direct emergence' or 'failed emergence') on its magnetic strength and amount of fluxes.