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Three Dimensional MHD Simulation of Convection and Emerging Flux

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Abstract. We present results of three dimensional magnetohydrodynamic simulation of convection and emerging flux. Although simulations of emerging flux tube have been presented in the literature, effect of convection on the dynamics of emerging flux has not been studied in detail. We carried out simulation of emergence of twisted flux tube from vigorously convecting convection zone. It is found that the flux tube emerges to the upper atmosphere and forms loop like structures, but finally it is broken by the convecting flows and loses its coherence in several turn over time of convection.

1. Introduction

Emergence of magnetic flux from the convection zone into the atmosphere is the origin of sunspots and active regions. It also plays an essential role in energy accumulation and triggering of flares and jets (Kurokawa, Wang, & Ishii 2002; Yokoyama & Shibata 1995). Three dimensional structure of emerging flux and its dynamics is one of the important targets of Solar-B/Solar Optical Telescope. In this paper we present the result of a three dimensional MHD simulation of twisted magnetic flux tube emerging from vigorously convecting convection zone into the choromosphere and the corona. Three dimensional MHD simulations of the emergence of twisted flux tube have been presented in the literature (e.g., Matsumoto et al. 1998, Fan 2001, Magara & Longcope 2001). However, previous models assumed hydrostatic initial condision, so the influence of convective flows on the dynamics of emerging flux is yet to be examined.

Numerical simulations of a flux tube in the three dimensional convective flow are carried out by Dorch et al. (2001) and Fan, Abbett, & Fisher (2003). Those models are relevant to investigate the dynamics of flux tube in the convection zone. Fan et al. (2003) found that magnetic buoyancy force dominates the hydrodynamic force due to the convective flows if the field strength B is greater than about $3B_{eq}$, where B_{eq} is the field strength in equipartition with the kinetic energy density of the convective flow.

Our simulation model includes the upper convection zone, phorosphere, chromosphere, and corona. In order to develope statitically steady state convection, artificial cooling at the photosphere and internal heating near the bottom of the model convection zone is assumed. The cooling at the photosphere is a very simple approximation of radiative cooling. All the diffusions, i.e., resistivity, viscousity, and thermal diffusivity, are numerical. Therefore we can not discuss the effect of radiative transfer and diffusions. However we believe that our simulation provides the first insight into the effect of turbulent convection on the emerging flux.

2. Model setup

We use Cartesian coordinates (x, y, z) with z in the vertical direction. The gravitational acceleration g is constant. The gas is assumed to be a perfect gas, and the specific heat γ is set to be 5/3. For normalization constants we adopt the pressure scale height H_{ph}, density ρ_{ph}, temperature T_{ph}, and sound velocity $C_{s,ph}$ at the photosphere ($z = 0$). The computational domain is $0 < x < 40$, $0 < y < 40$, and $-6 < z < 30$, which is resolved by $256 \times 256 \times 250$ grids. In order to drive the continuous convection, the energy is extracted in a layer near the photosphere ($-0.5 < z < 0.5$) at a spatially and temporarily fixed rate. Also, artificial heating is assumed in a finite layer near the bottom of the convection zone ($-6 < z < 5$) at the same rate, i.e., the net energy is conserved in the computational domain.

We start the calculation with a hydrostatic field-free initial condition and give a random perturbation in the convection zone. The initial atmosphere consists of convection zone ($-6 < z < 0$) with superadiabatic temperature gradient, isothermal photoshpere-chromosphere ($0 \leq z < 15$), and hot corona ($15 \leq z$), which is similar to the background atmosphere of the previous simulations in the literature (Matsumoto et al. 1998, Fan 2001, Magara & Longcope 2001). The initial temperature gradient in the convection zone is taken to be two times the adiabatic temperature gradient. Therefore the initial small perturbation in the convection zone grows rapidly, and finally a statistically steady and turbulent convection is obtained. At this point the upper atmosphere has been highly disturbed by the acoustic (shock) waves generated by the convective flows below. This causes unnecessary complexity and severe Courant condition. Therefore the temperature, density and velocity field are reset to smoothly approach the initial (hydrostatic) condition in $15 < z$. Since the diffusions are numerical, we cannot tell the exact values of the Rayleigh number nor the Prandl number in the convection zone. To give an idea how strong the convection is, the average horizontal velocity at $z = 0$ is ~ 0.2, and the vertical velocity in the strong downflow region is ~ 1.

After the background convecting atmosphere is set up, a magnetic flux tube is injected in the convection zone. The flux tube is Gold-Hoyle type which is similar to that used in Magara & Longcope (2001). The axis of the tube is along the y-axis and its center is located at $z = -3$. The radius of the tube is 2. The twist parameter $b = 1$, that means the field lime wraps in a left handed helix pitched over the axial length $2\pi/b$. The plasma beta in the tube is 4.

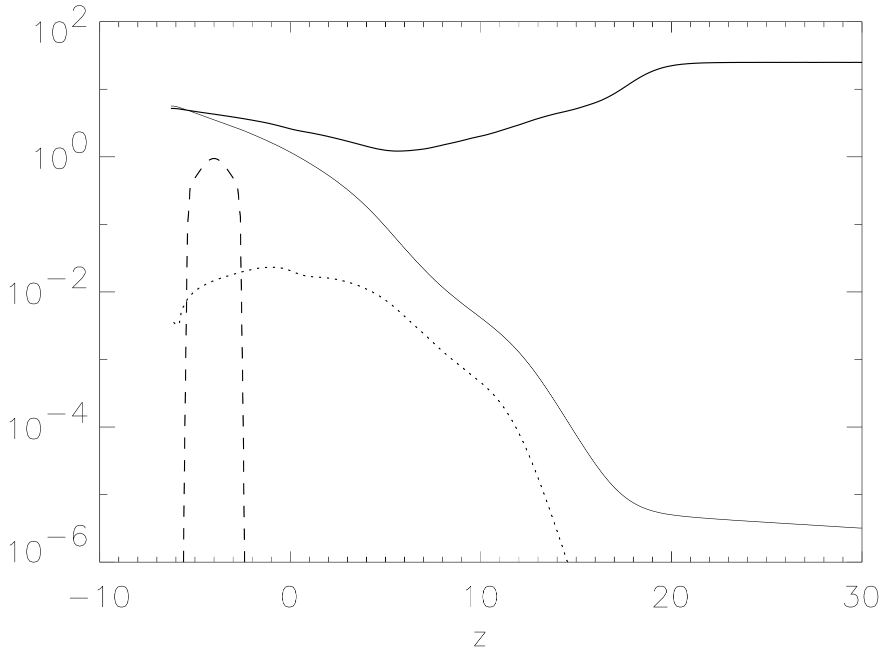

Figure 1. Initial condition.

The vertical distributions of the temperature, density, magnetic pressure and kinetic energy density are shown in figure 1 by thick solid, thin solid, dashed and dotted lines, respectively. Here the magnetic pressure is that along a vertical line that intersects the tube axis, while the other quantities are horizontal averages. The magnetic field strength is nearly two order of magnitude larger than the equipartition value with the average kinetic energy density. It is also about three times larger than the equipartition value with the kinetic energy density of the strongest downflow. So it satisfies the condition of Fan et al. (2003) in which the magnetic buoyancy force dominates the hydrodynamic force of the convective flow.

3. Result

The initial flux tube suffers the hydrodynamic force from convective flows. However, since initial magnetic field is strong enough, the convective flows give only small perturbation and excite Parker instability without breaking the coherence of the flux tube.

The left panels of figure 2 show the three dimensional view of isosurface of $|B|$ at $t = 20$, 50, and 100. Also shown by grey scale on the horizontal planes is the vertical velocity distribution at the photosphere ($z = 0$). The bright/dark parts correspond to the upflow/downflow regions. The pattern of convection is similar to the solar granulation, i.e., hotter upflow region is surrounded by

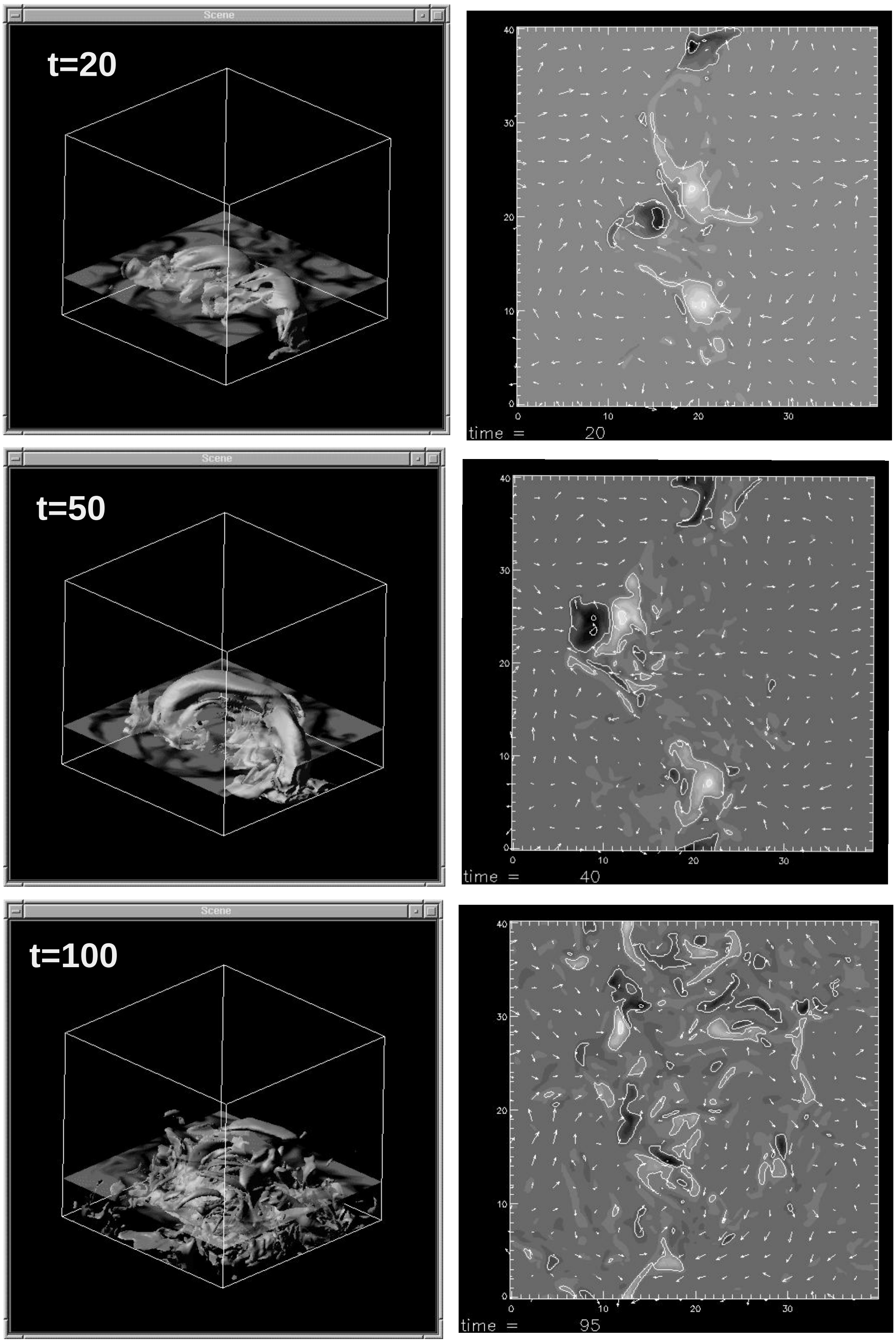

Figure 2. Left panels: isosurface of magnetic field strength and $z = 0$ plane showing the vertical component of velocity. Right panels: vertical component of magnetic field (gray) and horizontal velocity field (arrows) at $z = 0$.

narrow downflows. The right panels show the vertical component B_z (gray) and horizontal velocity field (arrows) at $z = 0$.

It is seen that two loop systems emerge above the photosphere (t=20, 50). The footpoints of the loops are seen as pores in the B_z distribution. However, at t=100 the pores are broken by the convective flows and hence the B_z distribution at $z = 0$ becomes small scale. As a result, the loop systems above the photosphere also lose their coherence and become small scale. The life time of the loop systems is found to be several turnover time of convection. It is much small than the observed life time of emerging flux if we consider surface granulation.

We note that in the present calculation the size and magnetic flux of the flux tube is smaller than those of observed emerging flux that reaches to the corona. Therefore the present calculation is probably more relevant to the ephemeral regions. We plan to carry out larger simulation and parameter survey to find conditions for an emerging flux tube to keep coherence for long time.

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