Abstract.

It is suggested that emerging flux build up magnetic energy in the solar corona that could become the source of flares or jets. Emerging flux also plays an important role in active region formation and disappearance. To investigate these phenomena, it is necessary to study the evolution of an emerging flux from the convection zone to the corona. The solar atmosphere is highly stratified by gravity. For example, the density ratio between photosphere and corona is about $\sim 10^8$. However, to study emerging flux process by numerical simulations, it is needed to treat this process with that highly stratified calculation domain. In this paper, we introduce our numerical simulation results for (1) X-ray jets associated with emerging flux and magnetic reconnection in the solar corona, (2) twisted magnetic flux tube emergence into the solar corona, and (3) surge caused by emerging flux tube.

1. Introduction

It is suggested that emerging flux tubes build up magnetic energy in the corona that could become the source of flares or CMEs. Emerging flux also plays an important role in active region formation and disappearance. To investigate these phenomena, it is necessary to study the evolution of emerging flux from the convection zone to the corona by magnetohydrodynamic numerical simulations. In this paper, we introduce our numerical simulation results for, (1) X-ray jets associated with emerging flux and magnetic reconnection in the solar corona, (2) twisted magnetic flux tube emergence into the solar corona, and (3) surge caused by emerging flux tube.

2. X-ray jets in the solar corona associated with emerging flux and magnetic reconnection

Recently solar observations have revealed a dynamic behavior of the solar corona. One of the most interesting phenomena is solar coronal X-ray jets, which are observed as transitory X-ray enhancements with an apparent collimated motion. We studied solar coronal X-ray jets by MHD numerical simulations with
heat conduction effect based on the magnetic reconnection model. Key physical processes are included, such as emergence of magnetic flux from the convection zone, magnetic reconnection with the coronal magnetic fields, heat conduction to the chromosphere, and the chromospheric evaporation. The difficult point of this simulation is that the time scale of MHD and that of heat conduction is very different each other in the solar corona (heat conduction time scale is about ten times faster than MHD one). So we developed new code to solve this problem. In our code, MHD part is solved by explicitly and heat conduction part is solved implicitly. For this treatment, very fast conduction process can be solved coupled with MHD time scale process.

The numerical simulation result is shown in Figure 1. From numerical simulations, we found that high-density evaporation jets were successfully reproduced as shown in figure 1. These high-density jets are observed as X-ray jets in the solar corona. We derived parameter dependence of the evaporation jet mass. Mass of the evaporation jets $M$ is described as

$$M = 6.8 \times 10^{12} \text{g} \left( \frac{B}{10 \text{ G}} \right)^{15/7} \left( \frac{T_{\text{cor}}}{10^6 \text{ K}} \right)^{5/14} \left( \frac{L}{5000 \text{ km}} \right)^{12/7} \left( \frac{t}{400 \text{ s}} \right),$$  

(1)

where $B$ is the strength of magnetic fields, $T_{\text{cor}}$ is the coronal temperature, $L$ is the loop height, and $t$ is the duration of ejection, respectively (Miyagoshi et al. 2003).
This result is explained as follows. The balance between the conductive flux and the enthalpy flux is written as,

$$\frac{\kappa_0 T^{7/2}}{L} \sim \frac{\gamma}{\gamma - 1} p_{eva} V_{eva},$$

where $T$ is the temperature of the flare, $p_{eva}$ is the gas pressure of the evaporating plasma, and $V_{eva}$ is the average velocity of the evaporation flow, respectively. The temperature of the flare loop is given as follows (e.g., Fisher & Hawley 1990, Shimojo et al. 2001);

$$T \sim (F_h L / \kappa_0)^{2/7},$$

by the balance between the heating rate and the conduction cooling rate. Here $F_h$ is the heating flux of magnetic reconnection and $\kappa_0$ is conduction coefficient, respectively. The heating flux $F_h$ can be regarded as an energy flux into the reconnection region and can be approximated to

$$F_h \sim M_a \cdot B^2 \frac{V_A}{8\pi} \sim M_{A} \cdot B^3 \frac{k_b \ T_{cor}}{4\pi m p_{cor}},$$

where $V_A$ is the Alfvén speed of the reconnection inflow region, $B$ is the magnetic strength of the corona, $M_a$ is the Alfvén Mach number of the reconnection inflow, and $p_{cor}$ is the coronal gas pressure, respectively. If the average velocity of the evaporating plasma and the cross section of the jet are nearly constant in time, the total mass becomes

$$M = \rho_{eva} V_{eva} S t,$$

where $S$ is the cross section of the jet and $t$ is the time from the start of the energy deposition, respectively. Using equation (2), (3), (4), and (5), the equation (1) is derived (for the details, see Miyagoshi & Yokoyama 2004).

We compared this result with Yohkoh observations (e.g. Shimojo et al. 1996, 2000), and we found that our scaling low, equation 1, can explain Yohkoh observation results well (Miyagoshi & Yokoyama, 2003, 2004). We also derived a theoretical model about a Mach number of the reconnection jets as a function of the ambient coronal variables. Numerical simulations also show that two different type jets (evaporation jets and low-density jets) exist simultaneously around emerging flux region (EFR), and the energy of evaporation jets is somewhat larger than that of the low-density jets (for detail analysis, see Miyagoshi & Yokoyama, 2003, 2004)

3. Twisted emerging flux tube into the corona

To study emerging process of twisted emerging flux tube, three dimensional simulation is necessary. Matsumoto et al. (1998) performed three-dimensional MHD simulations near the photosphere and found that sigmoid structure is formed by emergence of very strongly twisted tube. Abbett et al. (2000) performed numerical simulations of emerging flux tube through convection zone with anelastic approximation. Magara & Longcope (2001, 2003) performed numerical simulations of emerging flux tube below the photosphere to the upper
corona, and showed that outer fields of an emerging flux form the structure like a potential arcade and inner fields form sigmoid structure (see also Fan 2001). Magara (2004) suggests the analytic formation of time development of emerging flux tube and compare with numerical simulation results. Archontis et al. (2004, 2005) and Galsgaard et al. (2005) treat magnetic reconnection between emerging flux tube and overlying parallel fields. Manchester et al. (2004) showed filament is formed as flux tube emerges.

However, in almost all past numerical simulations for studying emerging process of twisted flux tube from convection zone to the upper corona (the density ratio is more than $\sim 10^8$), very strong twist (more than one times round in perturbed region at initial state) is approximated. On the other hand, from observation, more weak twist (less than $\sim$ one round in emerging region) is often seen (e.g. Pevtsov et al. 2003). Studies for twist intensity, especially for weak twists, have hardly done. So, to applicable the numerical simulation results to the observed emerging flux tubes, this study is needed.

In this section, we show the results of our three-dimensional MHD simulation of emergence of a twisted flux tube in various twist intensity, especially for weak twists. From past studies, the weak twist tube hardly emerges into high corona because it easily fragments. We performed long time integration calculation, and found that those weak twist tube can emerges to high corona finally. For these results, we can shorten gap between simulations and observations.
Figure 3. Time development of magnetic fields intensity on $x = 0$ plane. (a) $q = 0.005$ (weak twist case) and (b) $q = 0.1$ (strong twist case).

Figure 2 shows numerical simulation results. Magnetic lines of force are shown. Three dimensional view (left column) and top view (right column) of magnetic field lines are shown. Panels of (a) and (b) are the results of $q = 0.05$ case, (c) and (d) are $q = 0.005$ case, respectively. Here, the parameter $q$ is twist intensity. The initial magnetic field structure is given as Gold-Hoyle type force-free field with $q$ as follows,

$$B_\phi = B_0 qr/[1 + (qr)^2], \quad B_x = B_0/[1 + (qr)^2].$$

The parameter $q$ means twist intensity of magnetic field. Magnetic field rounds once within an interval $2\pi/q$.

The time of displayed image is $t = 140$ in $q = 0.05$ case, and $210$ in $q = 0.005$ case, respectively. This time delay is caused by suppress of the emerging motion around the solar surface which is seen remarkably in weak twist case.

Figure 3 shows the comparison with $q = 0.1$ case to $q = 0.005$ one. In $q = 0.005$ case, tube once fragments at $z \approx 0$ as it emerges ($t = 140$). Then emerging motion is rapidly suppressed. After this, it starts emergence again into the corona ($t = 155$). On the other hand, in the strong twist cases, this behavior does not occur. The panels (b) of Figure 3 is the same as panel (a) but the case of $q = 0.1$. From the panels (b) of Figure 3 flux tube hardly fragments around $z \approx 0$. Its emerging motion is hardly suppressed here and continuously emerges upward, with the tube structure kept almost coherently.

The reason why weak twist tube remarkably fragments near the photosphere is that the forces to keep flux coherent is weaker than that of strong twist case. From the analysis of the force which works to the tube, we found (1) the
dominant force as buoyancy in this stage is magnetic pressure gradient. That intensity of $q = 0.1$ case is about twice as large as that of $q = 0.005$ case. (2) The magnetic tension force, which works as keeping tube coherently, of strong twist case is much larger than that of weak twist case. The detail will be given in Miyagoshi et al. (2006).

4. Surge caused by magnetic flux tube emergence

We investigated interaction between emerging magnetic flux tube and overlying magnetic fields as active region corona. The numerical simulation results are shown in figure 4. In this simulation, interaction between flux tube and overlying magnetic fields occur in the photosphere. Then, wave (both compressional and Alfvén) is produced. The mode conversion from Alfvén wave to compression wave occurs as it travels along the magnetic field lines from photosphere to the corona (e.g. Kudoh & Shibata 1999). The produced compression wave causes magnetic and/or gas pressure enhancement in the chromosphere. It pushes the chromospheric cool matter into the corona. These cool jets are observed in the corona as surges. It is often observed by Hα observations.

5. Discussion

The fundamental physical process of emergence of magnetic flux in the solar atmosphere is gradually revealed recently. However, mainly for limit of computation resources, several problem still exists. For example, typical active region size is more than $10^4$ km. On the other hand, in numerical simulation possible spatial scale of radius of emerging flux tube is about $\sim 2000$ km. The typical time scale of active region formation is about one or several day. On the other hand, possible integration time in numerical simulations is about one hour. These are mainly caused by limit of computation resources nowadays. Also, our
numerical simulations does not take account of convection motion below the photosphere. These problems are homework in the future.

References

Miyagoshi, T., Isobe, H., Yokoyama, T., & Shibata, K. 2006, in preparation