SIMULATION STUDY ON THE SELF-ORGANIZATION OF SIGMOIDAL STRUCTURE AND THE ONSET OF SOLAR FLARES

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ABSTRACT

Although the recent observations strongly support the reconnection scenario, in which magnetic reconnection plays a key role for the energy liberate in flare processes, the onset mechanism of flares is not yet well understood. In order to clarify that, we have to explain not only the dynamics in the main phase of flares, but also the transition mechanism from pre-flare to main flare phase. It is an important test bench for this purpose to examine the causal relationship between the formation of sigmoids and the trigger of flares, because sigmoids are widely believed to be typical precursor phenomena for the several eruptive events. Aiming to understand the flare onset process from sigmoidal activity, the high-resolution simulation is developed to investigate the nonlinear evolution of a thin current sheet formed above the magnetic neutral line. The results indicate that the tearing mode instability growing on the thin current sheet, where the magnetic shear is steeply reversed, can drive both the self-organization of sigmoidal structure, and the impulsive onset of arcade eruption. The structure of sigmoid is shown to be consistent with the Taylor’s minimum energy state, in which the torsional parameter $\alpha$ is limited by the eigenvalue decided geometrically. The simulation results strongly suggest that the nonlinearity of the tearing instability growing on the reversed-shear layer can play a role for the transition from pre-flare to flare phase. The consistency with the observation is also examined by comparing the vector magnetogram and the ultra-violet image of flares observed by the TRACE satellite. Based on the results, we predict that solar flares tend to occur from the reversed-shear region.

Key words: MHD — Sun: flares — Sun: activity — Sun: magnetic fields.

1. INTRODUCTION

Solar flares are the biggest explosion in our solar system, and the understanding of the onset mechanism of them is a key subject in the astrophysical plasma physics. Although the recent observations strongly support the theoretical scenario, in which magnetic reconnection plays a key role for the energy liberation in flare processes, it still remains as a fundamental open question why and how magnetic reconnection can be triggered impulsively in flare events. In order to find the answer of that, it is especially important to understand the causal relationship between the electromagnetic condition on the solar surface and the dynamics in the solar corona. The high-precision numerical simulation based on the three-dimensional magnetohydrodynamic (MHD) model is a powerful tool for this purpose, because three dimensional structure of the coronal magnetic field is hardly observable.

Recently, we found that solar flares tend to arise in the region where the magnetic shear is steeply changed (Kusano et al., 2003a; Yokoyama et al., 2003). In the basis of this finding, a new model of the flare onset mechanism called “reversed-shear flare model” was proposed [Kusano et al. (2003b, 2004a)]. In the reversed-shear flare model, the onset of solar flares is explained as a consequence of double reconnection process, in which the out-flow jet from one reconnection drives another reconnection. The mutual excitation of double reconnection can be commenced after the moderate evolution of the resistive tearing mode instability growing on the shear inversion layer.

The main objective of this paper is to review our recent study of the pre-flare physics based on the numerical simulation and the observation. The nu-
2. SIMULATION MODEL

The simulation box is a rectangle region corresponding to the solar corona including magnetic neutral line, where magnetic polarity on the solar surface is reversed. The force-free equilibrium of magnetic arcade is used as the initial reference state, in which the axial magnetic component along the magnetic neutral line is steeply reversed on some flux surface and a thin current sheet is formed on the reversed-shear layer. The simulations are commenced by adding the small perturbation, which is the linear eigen-function of the tearing mode instability growing mainly on the thin current sheet.

The force-free equilibrium with the reversed-shear layer is dynamically set up by the two-dimensional (2D) simulation, in which the variation along the magnetic neutral line is inhibited. The 2D simulation starts from the 2D linear force-free field, in which the torsional parameter $\alpha$ is constant in space, and the feet of field lines is gradually untwisted near the magnetic neutral line by imposing the shear motion on the photosphere. Different snapshots from the 2D simulation, in which the flux amount of the reversed-shear field is changed, are used for the reference states for the 3D simulations of cases A and B. Figure 1 represents the field line structure and the distribution of the axial magnetic field along the magnetic neutral line on a cross-section of the two different reference states (cases A and B), in which the reversed field is weak and strong, respectively.

The basic equations in non-dimensional form are described by

$$\frac{\partial V}{\partial t} = -V \cdot \nabla V + J \times B + \nu \nabla^2 V, \quad (1)$$

$$\frac{\partial B}{\partial t} = \nabla \times (V \times B - \eta J), \quad (2)$$

and $J = \nabla \times B$, in which the pressure gradient force and the density variation are neglected based on the approximation that the plasma $\beta$ is generally very small in the solar corona. The simulation box spans a rectangular region $(0,0,0) < (x,y,z) < (L,L,10L)$, where $z$ denotes the height from the photosphere. The unit for length, velocity and time are given by $L$, $V_A$ (Alfven speed defined by $B_0$), and $\tau_A = L/V_A$, respectively, where $B_0$ is the typical magnetic field strength on the arcade feet.

The numerical algorithm consists of the finite difference of the second order accuracy for the spatial
derivative and the Runge-Kutta-Gill method of the fourth order accuracy for the time integration. The numbers of grid points collocated on the horizontal plane and on the vertical axis are 512 × 512 and 1024, respectively. The grid points are highly packed in the region near the reversed-shear layer to improve the resolution on the reconnection sites. The calculations were carried out with 64 nodes of The Earth Simulator (Sato, 2004), using the domain decomposition algorithm with Message Passing Interface (MPI) library.

3. SIMULATION RESULTS

The time evolution of the magnetic and kinetic energies are plotted respectively in Figs.2a and 2b for the two different cases. In the early phase (t < 20), the both cases exhibit the typical behavior for the MHD relaxation, in which the fast decay of magnetic energy and the small enhancement of kinetic energy proceed simultaneously. The more reversed the magnetic shear (case B), the more delayed the initiation of the MHD relaxation phase is. The result can be explained by the difference in the linear growth rate of the resistive tearing mode instability, because the MHD relaxation is driven by magnetic reconnection caused by the instability.

Figure 3 shows the typical structure of the magnetic field lines before and after the reconnection on the reversed-shear layer. It is clearly seen that the oppositely seared field lines are reconnected and the axial flux is canceled. The linear stability analysis indicates that the several Fourier modes along the magnetic neutral line are unstable. Thus, after the growth phase of the instability, the nonlinear coupling between the different modes drives the turbulent dynamics, in which the excess magnetic energy is liberated and the the quasi-stable configuration is self-organized.

Fig.4 shows the structure of field lines in the quasi-stable state, which is spontaneously generated through the relaxation phase in cases A and B. They indicate that the S-shaped field lines are self-organized in the both cases. The structure is much similar to so-called sigmoids, which is often observed in the lower corona by the soft X-ray telescope (SXT) on-board Yohkoh satellite [Rust & Kumar (1996)]. This result suggests that sigmoid is able to be formed through magnetic reconnection driven by the resistive tearing mode, in contrast to the widely believed model based on the ideal kink mode instability.

The previous simulations by Magara & Longcope (2001), Kliem, Titov, & Török (2004) and Fan & Gibson (2004) demonstrated that the electric current channel of S-shape can be formed when a highly twisted flux tube is deformed by the kink mode instability. Although it may account for the S-shape structure as a transient process, the formation of long-lived sigmoids, which appeared associated with the eruptive events [Canfield et al. (1999)], was still puzzled so far.

On the other hand, S-shape structure in our simulation can be maintained for longer period than the MHD time-scale. It indicates the possibility that the simulation result may account for the long-lived sigmoid. The quasi-steady feature of the sigmoidal structure might be related to the fact that the torsional parameter $\alpha (= |\nabla \times B|/B)$ is almost flattened inside the sigmoid. The result means that the formation of the sigmoidal field can be understood as a consequence of the energy relaxation toward the Taylor’s minimum energy state, which is described by the linear force-free field (LFFF). According to the Taylor’s minimum energy theory, the magnitude
of \( \alpha \) can not exceed the lowest eigenvalue \( \alpha_1 \) for the curl operator, even though magnetic helicity is sufficiently large. It is due to the fact that the LFFF bifurcates into the coupled state and the mixed state, which are determined by the boundary condition of the domain subject to the energy relaxation (Taylor, 1986; Kusano et al., 1995; Kusano & Nishihawa, 1996). Actually, the value of \( \alpha \) in the sigmoidal region reproduced by the simulation well matches to the Taylor’s prediction, if the reversed-shear layer is regarded to bound the relaxed region. Also the difference of the sigmoid size between cases A and B (see Fig.4) can be explained by this fact [Kusano (2005)].

Although the sigmoidal structure is fairly stable, since the reconnection gradually proceeds on the reversed-shear layer, which bounds the sigmoidal region, the sigmoid can survive only for the Sweet-Parker time-scale \( \tau_r = (\tau_\rho \tau_A)^{1/2} \), where \( \tau_\rho \) and \( \tau_A \) are the resistive and Alfvén times, respectively. After the substantial axial fluxes of opposite shear are annihilated by the reconnection, magnetic arcade collapses into the reconnection point, so that the cusp structure is spontaneously formed, as shown in Fig.5, and the second reconnection starts, driving the upward eruption of magnetic arcade. This process causes the sudden onset of the explosive increase of kinetic energy and the quick reduction of magnetic energy, as shown in Fig.2. However, the eruption arises only in case B, not in case A. It implies that the linear growth rate is not a crucial parameter to control the onset process of eruption.

The notable feature in this onset phase of eruption is that the two reconnections, which are on the reversed-shear layer and on the top of cusp field seen in Fig.5, mutually drive each other. The downward jet from the second reconnection of the cusp field collides with the reversed-shear layer, and greatly excites the first reconnection. On the other hand, the first reconnection on the reversed-shear layer cancels the axial flux, and thus accelerates the collapsing of magnetic arcade. As a result, reconnection rate on the reversed-shear layer quickly increases, and the aspect ratio between length and width of the current sheet decreases, as shown in Fig.6. It indicates that the reconnection on the reversed-shear layer is switched from “spontaneous reconnection” with the Sweet-Parker current sheet to “driven-type reconnection” with a compact diffusion region through the feedback activity in the double-reconnection process.

Here, we should point out that the cusp structure, which may correspond to post flare loop, exists above the sigmoidal field and the sigmoid-remnant. It means that sigmoid itself could not be erupted, but it stays underneath the cusp structure. However, the field twist in sigmoid is unraveled by magnetic reconnection. Sterling et al. (2000) examined the morphological evolution from sigmoid into cusps and arcades by the SXT observations, and they concluded that the cusp-producing fields may be overlying sigmoidal field in the pre-flare phase. Our simulation is well consistent with their observation, and can naturally explain the erupting process of the cusp structure.

4. DISCUSSION: COMPARISON WITH OBSERVATION

The simulation clearly demonstrates that the nonlinear growth of the resistive tearing mode instability on the reversed-shear layer leads to the onset of arcade eruption through the double reconnection process. It implies that the energy liberation in very early phase of flares should be commenced from point located on the reversed-shear layer. We have examined this prediction by comparing the vector-magnetograms and the 1600 Å image observed by the TRACE satellite.

Figure 7 represents the map of active region 9026 for the onset phase of the flare at 14:58 UT on 2000 June 6. The color scale (blue to red) indicates the axial
component of the transverse magnetic field, which is defined by \(a \cdot (B - B_P)\), where \(B_P\) is the potential field derived from the normal component of magnetic field on the photosphere, and \(a\) is the unit vector directed to the vector potential of \(B_P\). The green contours represent the magnetic neutral line where the normal magnetic field is reversed, and the yellow contours are for the intensity of 1600 Å image.

We can find that, in the pre-flare phase, several bright points denoted by arrows (1, 2, and 3 in a) appeared in the region where the axial field changes the sign. The sequential tracking of the 1600 Å image indicates that the bright point 1 extended to the main flare, which formed the two ribbon structure. Since it is likely that the reversal of the axial field corresponds to current sheet, the results are well consistent with the prediction from the simulations.

Recently, several studies showed that there were spatial correlation between the reversal of magnetic shear and the site of eruptive events. Wang, Zhou, & Zhang (2004) found that the shear reversal caused by the flux emerging was associated with the coronal mass ejections. Hahn (2005) pointed out that flare initiation tends to occur close to chirality inversion line, where the torsional parameter \(\alpha\) changes the sign. These observations are consistent with the simulation results, and strongly support the reversed-shear flare model.

5. CONCLUSION

We have performed the simulation, which is able to reproduce both the formation of sigmoidal and the onset of arcade eruption [Kusano (2005)]. The results are well consistent with the observation as well as with the prediction of the reversed-shear flare model [Kusano et al. (2004a)], and strongly suggests that magnetic reconnection on the shear inversion layer plays a crucial role for the onset of flaring activity in the solar corona.

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