J. Plasma Physics (2006), *vol.* 72, *part* 6, *pp.* 979–982. © 2006 Cambridge University Press
doi:10.1017/S0022377806005423 Printed in the United Kingdom

Simulation study of the Solar flare onset mechanism and the self-organization in the Solar coronal plasma

K. KUSANO,[1] N. NISHIKAWA,[1]
S. INOUE,[2] T. MAESHIRO[2]'† and T. SAKURAI[3]

[1]The Earth Simulator Center, Japan Agency for Marine–Earth Science and Technology,
3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan

[2]Graduate School of Advanced Sciences of Matter, Hiroshima University,
1-3-1 Kagamiyama, Higashi-Hiroshima 739-8530, Japan

[3]National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

(Received 15 August 2005 and accepted 14 February 2006)

Abstract. Three-dimensional magnetohydrodynamics of the Solar coronal plasma is investigated by numerical simulation, aiming to understand the mechanisms of the Solar flare onset. It is demonstrated by the simulations that the resistive tearing mode instability growing on the magnetic shear inversion layer can drive the large-scale eruption through the mutual excitation of double reconnections. It is also revealed that the instability is able to cause the magnetohydrodynamic energy relaxation, in which the typical sigmoidal structure is self-organized prior to the onset of eruption. The simulation results predict that both the formation of sigmoids and the onset of flares should occur around the electric current sheet where the magnetic shear is steeply reversed. It is consistent with the reversed-shear flare model and the vector magnetograph observations.

1. Introduction

Solar flares are the largest explosions in our Solar system, and the onset mechanism of those is a crucial subject in 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 a fundamental open question why and how magnetic reconnection can be triggered abruptly in flare events. In order to find the answer to this, 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 in terms of the three-dimensional magnetohydrodynamic (MHD) model is a powerful tool for this purpose, because the three-dimensional structure of the coronal magnetic field is hardly observable.

Recently, we found that Solar flares tend to arise from a point on the magnetic shear inversion layer [1, 2]. On the basis of this finding, a new model of the flare onset mechanism called the 'reversed-shear flare model' was proposed [1, 3]. In the

---

† Present address: Information and Mathematical Science Laboratory, Inc., 1-5-21 Ohtsuka, Bunkyo-ku, Tokyo 112-0012, Japan.

https://doi.org/10.1017/S0022377806005423 Published online by Cambridge University Press

reversed-shear flare model, the onset of Solar flares is explained as a consequence of the double reconnection process, in which one reconnection drives another reconnection through the strong plasma jet. The mutual excitation of reconnections 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 examine the reality of the reversed-shear flare model by comparing the numerical simulation and the observations. For this purpose, a new numerical model was developed, in which the stability of thin current sheet, plasma pressure, and the observed structure of the Solar magnetic field can be taken into account.

2. Simulation model

The simulation box corresponds to a rectangle region in the Solar corona including the magnetic neutral line, where magnetic polarity on the Solar surface is reversed. The force-free equilibrium forming magnetic arcade is used as the initial reference state, in which the axial magnetic component along the neutral line is steeply reversed on some flux surface to simulate the recent vector magnetograph observation [2]. The simulations are commenced by adding the small perturbation, which is given by the linear eigen-function of the tearing mode instability mainly growing on the reversed-shear surface.

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 surface to enhance the resolution on the reconnection sites. The calculations were carried out with 64 nodes of The Earth Simulator [4], using the Message Passing Interface (MPI) library.

3. Results and discussion

Figure 1 shows the typical structure of magnetic field lines calculated by the simulation. We can see here that the resistive tearing mode instability causes magnetic reconnection between the field lines of opposite shear, AA′ and BB′ in Fig. 1(a), and generates the shear-less fields, AB′ and BA′ in Fig. 1(b). This process annihilates the axial magnetic flux on the reconnection point.

The growth of the instability liberates the excess magnetic energy, and the magnetic field inside the shear inversion layer is relaxed to the quasi-stable configuration, as shown in Fig. 1(c). As a result of the relaxation, the S-shaped field lines denoted by ‘S’ are self-organized. The top view of field line evolution is represented in Fig. 2 (bottom), where the thickness of field lines indicates the intensity of electric current averaged along each line. The shape of the thick field lines on $t = 27.0$ is very similar to the so-called sigmoidal structure, which was often observed in the lower corona by the soft X-ray telescope (SXT) on board the Yohkoh satellite [5]. It suggests that sigmoids can be formed through magnetic reconnection driven by the resistive tearing mode, in contrast to the widely believed model that the ideal kink mode instability is responsible to the formation of sigmoids. The top rows in Fig. 2 illustrate how reconnection between oppositely sheared fields can form the sigmoid-like structure.

https://doi.org/10.1017/S0022377806005423 Published online by Cambridge University Press

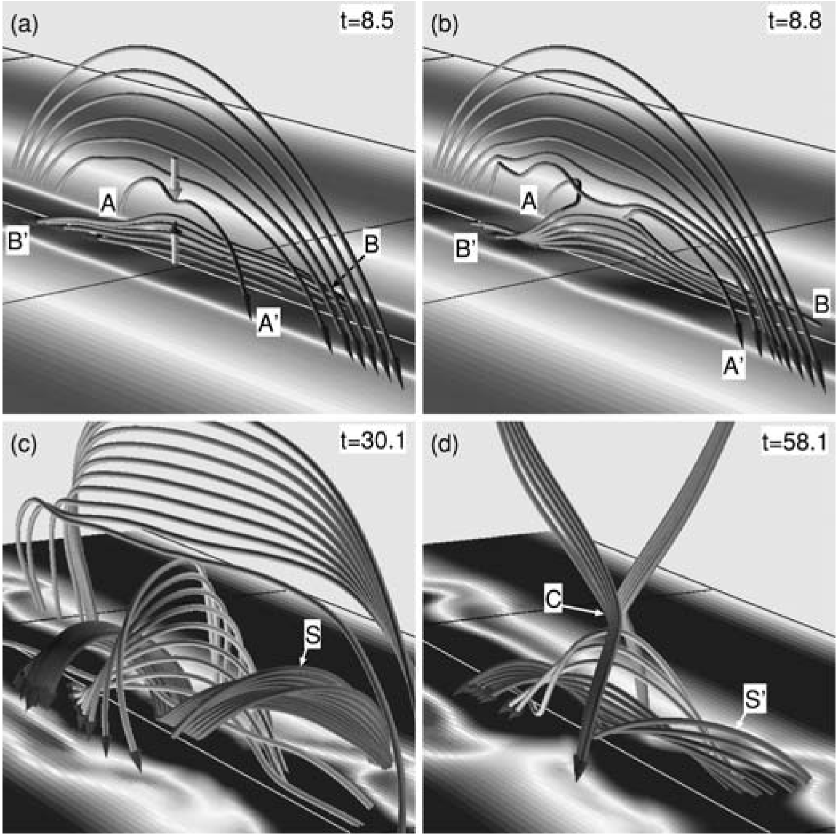

Figure 1. Three-dimensional structure of magnetic field lines (a) before and (b) after reconnection by the tearing mode instability, (c) in the pre-flare phase, and (d) in the onset phase.

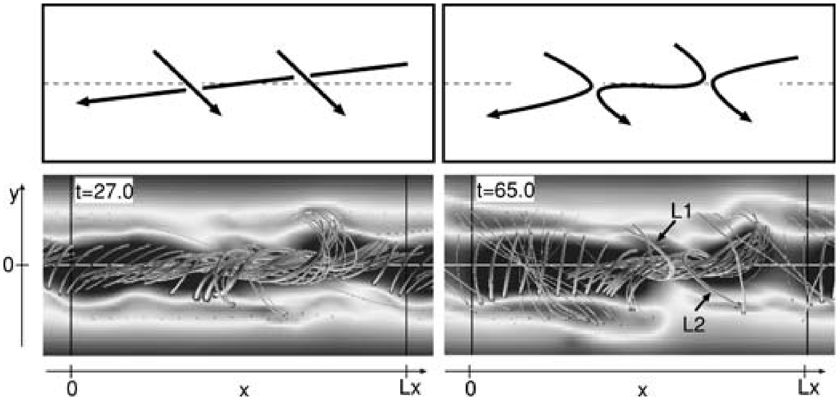

Figure 2. Magnetic field lines on the top view. Top: Schematic diagram of the sigmoidal formation due to magnetic reconnection between the oppositely sheared field lines. The left and right correspond to field structure before and after reconnection, respectively. Bottom: The simulation results at $t = 27$ and 65, respectively.

https://doi.org/10.1017/S0022377806005423 Published online by Cambridge University Press

In our simulation, the sigmoidal field sits below the current sheet between the oppositely sheared field, and reconnection on the current sheet slowly proceeds even after the sigmoid is formed. After the substantial axial fluxes of the opposite shears are annihilated by the reconnection, the magnetic arcade collapses into the reconnection point, so that the cusp structure (C in Fig. 1(d)) is spontaneously formed. Finally, since the downward jet from the new reconnection of the cusp field greatly drives the reconnection on the shear inversion layer, energy liberation quickly proceeds and the eruption occurs.

Here, we should point out that the cusp structure, which corresponds to the post-flare loop, exists above the sigmoid and the sigmoid-remnant (S' in Fig. 1(d)). This means that the sigmoid itself could not be erupted, but it should stay underneath the cusp structure. However, the field twist in the sigmoid is revealed by magnetic reconnection, making lines such as L1 and L2 in Fig. 2.

Sterling et al. [6] examined the morphological evolution from the sigmoid into cusps and arcades by the SXT observations, and they concluded that the cusp-producing fields may be overlying the sigmoid fields in the pre-flare phase. Our simulation is well consistent with their observation, and can naturally explain the overlying process of the cusp structure.

4. Conclusion

We have made the first simulation, which is able to reproduce both the formation of sigmoids and the onset of arcade eruption [7]. The results are consistent with the observation as well as with the prediction of the reversed-shear flare model [3], and strongly suggest that magnetic reconnection on the shear inversion layer plays a crucial role for the flaring activity in the Solar corona.

References

[1] Kusano, K., Yokoyama, T., Maeshiro, T. and Sakurai, T. 2003 Annihilation of magnetic helicity: a new model for Solar flare onset. *Adv. Space Res.* **32**, 1931–1936.

[2] Yokoyama, T., Kusano, K., Maeshiro, T. and Sakurai, T. 2003 Relation between magnetic helicity injection and flare activities in active region NOAA 8100. *Adv. Space Res.* **32**, 1949–1952.

[3] Kusano, K., Maeshiro, T., Yokoyama, T. and Sakurai, T. 2004 The trigger mechanism of Solar flares in a coronal arcade with reversed magnetic shear. *Astrophys. J.* **610**, 537–549.

[4] Sato, T. 2004 The Earth Simulator: roles and impacts. *Parallel Comput.* **30**, 1279–1286.

[5] Rust, D. M. and Kumar, A. 1996 Evidence for helically kinked magnetic flux ropes in Solar eruptions. *Astrophys. J.* **464**, L199–L202.

[6] Sterling, A. C., Hudson, H. S., Thompson, B. J. and Zarro, D. M. 2000 *Astrophys. J.* **532**, 628–647.

[7] Kusano, K. 2005 Simulation study of the formation mechanism of sigmoidal structure in the Solar corona. *Astrophys. J.* **631**, 1260–1269.

https://doi.org/10.1017/S0022377806005423 Published online by Cambridge University Press