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Study of Magnetic Helicity and Magnetohydrodynamic Relaxation in Solar Flare Processes

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Abstract

The solar coronal activities, such as solar flares, are believed to arise as a result of photospheric plasma motion, which supplies magnetic free energy as well as magnetic helicity into the solar corona. In this paper, we investigated the physical relationship between magnetic helicity and the coronal activity, based on the three-dimensional numerical simulations and on the vector magnetograph observations. We found that magnetic helicity flow across the solar surface has a patchy structure, in which the right-handed helicity and the left-handed helicity were almost simultaneously injected within an active region. Furthermore, it was also revealed, in the various flare events, that the initial brightening of TRACE 1,600 Å image was located at a region where magnetic shear is sharply reversed on the photosphere. Motivated by these observations, we carried out the numerical simulations, in which the magnetic shear in a magnetic arcade is reversed by a slow foot-point motion. It was demonstrated by the simulations that the resistive instability growing on the shear inversion layer can lead to the eruption of large-scale plasmoid through the interaction of two different kinds of magnetic reconnections. These results strongly suggest that the solar coronal activity and solar flares are a consequence of the magnetohydrodynamic relaxation process driven by the cancellation of the oppositely sheared magnetic fluxes.

Keywords:

solar flare, the Sun, MHD, magnetic reconnection

1. Introduction

For the last decade, several satellite observations by Yohkoh, SOHO, and TRACE have revealed that the solar corona is a dynamic plasma system, in which various types of energetic activity always proceed. Particularly, solar flares are powerful explosion in the solar corona, powered by the sudden release of the magnetic energy accumulated in the coronal magnetic field. Although there are many evidences that magnetic reconnections play a key role in flare processes, the triggering mechanism of flares still remains to be solved.

Since magnetic shear and sigmoid structure are often observed in flare productive active regions by the magnetogram and the soft-X ray observations, respectively, magnetic helicity is widely believed to be an important quantity for understanding the trigger mechanism of solar flares. The objective of this paper is to briefly review our recent study of magnetic helicity in solar flare processes. In particular, the relationship between magnetic helicity in the solar corona and the trigger mechanism of solar flares will be discussed based on the vector magnetogram observation and the observation-based numerical simulations.

2. Measurement of magnetic helicity flux

Since the measurable magnetic field in the sun is limited only on the photospheric and the chromospheric levels, we cannot directly measure magnetic helicity contained in the solar corona. On the other hand, according to Berger and Field's formula [1], the gauge-invariant relative helicity should be defined by the volume integral,

$$H = \int (\boldsymbol{A} + \boldsymbol{A}_P) \cdot (\boldsymbol{B} - \boldsymbol{B}_P) \mathrm{d}V ,$$

and the flux across a plane S can be described by

$$\dot{H} = 2 \int_S \boldsymbol{E} \times \boldsymbol{A}_P \cdot \mathrm{d}\boldsymbol{S} , \qquad (1)$$

where $\boldsymbol{A}$ and $\boldsymbol{A}_P$ are vector potentials of magnetic field $\boldsymbol{B}$ and current free field $\boldsymbol{B}_P$, which have common boundary condition of the normal component on S, respectively. It means that, if the electric field $\boldsymbol{E}$ on the solar surface can be measured in

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addition to the magnetic field, we could derive the magnetic helicity flux into the solar corona from the sun. Recently, Kusano *et al.* developed the new methodology, which enables to derive the electric field from the vector magnetogram observations [2]. The principle of the new measurement is based on the induction equation of the normal component on the solar surface,

$$\partial \boldsymbol{B}_n / \partial t = [\nabla \times (\boldsymbol{V} \times \boldsymbol{B})]_n \, . \tag{2}$$

Because the magnetogram observation can provide the information of the magnetic field vector $\boldsymbol{B}$ as well as the variation $\partial \boldsymbol{B}_n/\partial t$, the velocity $\boldsymbol{V}$ can be derived as a solution from the inverse problem of the induction equation (2). However, it is not a well-defined problem, because an infinite number of the solutions is possible. The uncertainty comes from the fact that the induction equation (2) cannot determine the velocity component orthogonal to the vertical plane, which contains the magnetic field line. Therefore, the velocity vector $\boldsymbol{V}$ has to be derived from (2) after determining the orthogonal velocity, which is tangential to the solar surface. We showed that it can be obtained by applying the correlation tracking technique onto the sequential data of magnetograms. The proposed procedure can always provide the consistent electric field, even though the derived velocity vector $\boldsymbol{V}$ is not the same as the real plasma velocity.

Using this new method, Maeshiro *et al.* [3] found that the absolute intensity of the magnetic helicity flux well correlates with the averaged energy flux of the soft-X ray radiation, based on the data analyses of the seven different active regions appearing on the photosphere from the year 1997 to 2000. This result indicates that magnetic helicity is indeed responsible for the energetic activity in the solar corona. However, the detail analyses of each flare event implied that there were no clear correlation between the amplitude of injected helicity and the onset of flares [4]. For instance, in Fig. 1, we can see that the solar flare, which was observed by Yohkoh HXT, occurred in a region away from the area (labeled with ‘A’), in which magnetic helicity was most actively injected. This is a negative result for the simple model that the over-injection of magnetic helicity can trigger solar flares, and suggests that some other properties should be relevant to the onset of flares rather than the amount of magnetic helicity.

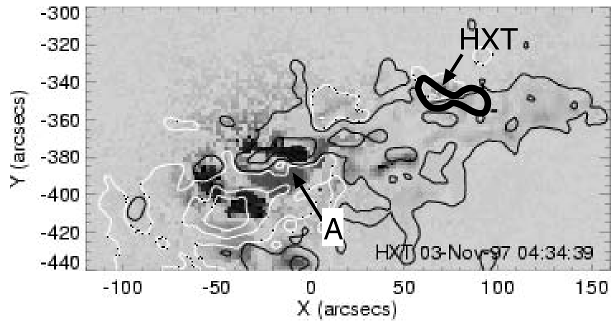

Fig. 1 A map of active region NOAA 8100 at 04:34:39 UT, Nov. 3, 1997. Gray scale indicates intensity of helicity flow, and thin contours (white and black) represent the magnetic field component along the line-of-sight observed by SOHO/MDI. Thick contour is hard-X ray intensity of solar flare observed by Yohkoh HXT. Region where magnetic helicity is most intensively injected is labeled with ‘A’.

On the other hand, our measurement of magnetic helicity revealed also that the structure of helicity injection in active regions was highly complicated both in time and space, and that even the sign of helicity flux often changed within a single active region [2]. Motivated by the results, we recently proposed a new hypothesis that annihilation between the positive and negative magnetic helicities is responsible for the release of magnetic energy and also for the trigger of solar flares [5]. Magnetic helicity is a quantity having either positive or negative sign, which represents the right-handed linkage or the left-handed linkage of magnetic fluxes, respectively. Therefore, if the positive and negative helicities coexist within an active region, magnetic reconnection can cancel magnetic helicity by merging the flux systems of opposite helicities. Since the reconnected field may relax to the helicity-free state, it is likely that the free energy corresponding to the magnetic helicity of mixed signs is efficiently released through the helicity annihilation process.

In fact, we found that the brightening in some solar flares extended from a point where the magnetic shear is steeply reversed, based on the correlation analyses between TRACE 1,600 Å images and the vector magnetogram observations [6]. Since the bright areas in TRACE 1,600 Å images could correspond to the foot-points of the field lines, which are subject to energy liberation, these results strongly support the helicity annihilation hypothesis.

3. Numerical simulation

In order to examine the helicity annihilation hypothesis, we developed the three-dimensional numerical simulation model [7]. The simulations were carried out by applying the foot-point shear motion, which reverses the pre-loaded magnetic helicity, on the vicinity of magnetic neutral line in the arcade configuration. As a result, it was clearly demonstrated that the reversal of magnetic helicity can cause a large scale eruption of the magnetic arcade through a series of two different kinds of magnetic reconnections. The physical mechanism is explained as follows: First, the resistive tearing mode instability grows on the helicity inversion surface, on which the axial magnetic field along the magnetic arcade is reversed. Secondly, the resistive tearing mode instability drives magnetic reconnection, which annihilates the positive and negative axial magnetic fluxes. Thirdly, the flux annihilation is followed by collapse of the magnetic arcade into the reconnection point, and then the vertical current sheet is generated. Fourthly, the second reconnection starts on the new current sheet, and drives the explosive up-welling flow, as seen in Fig. 2a. Finally, the total system reaches a loss-of-equilibrium state, and the whole magnetic arcade is erupted upward (see Fig. 2b).

These processes are understood as a chain-reaction, in which the resistive magnetohydrodynamic (MHD) instability (tearing mode) brings about a loss-of-equilibrium dynamics (eruption). In this model, the onset of solar flares can be explained as a result of mutual excitation between two different reconnections, which grows on the helicity inversion surface and on the current sheet generated by the internal collapse seen in Fig. 2a. Because two reconnections drive each other, the eruptive dynamics may start quickly, even though the growth rate of the original instability (tearing mode) is much slower than the MHD time-scale.

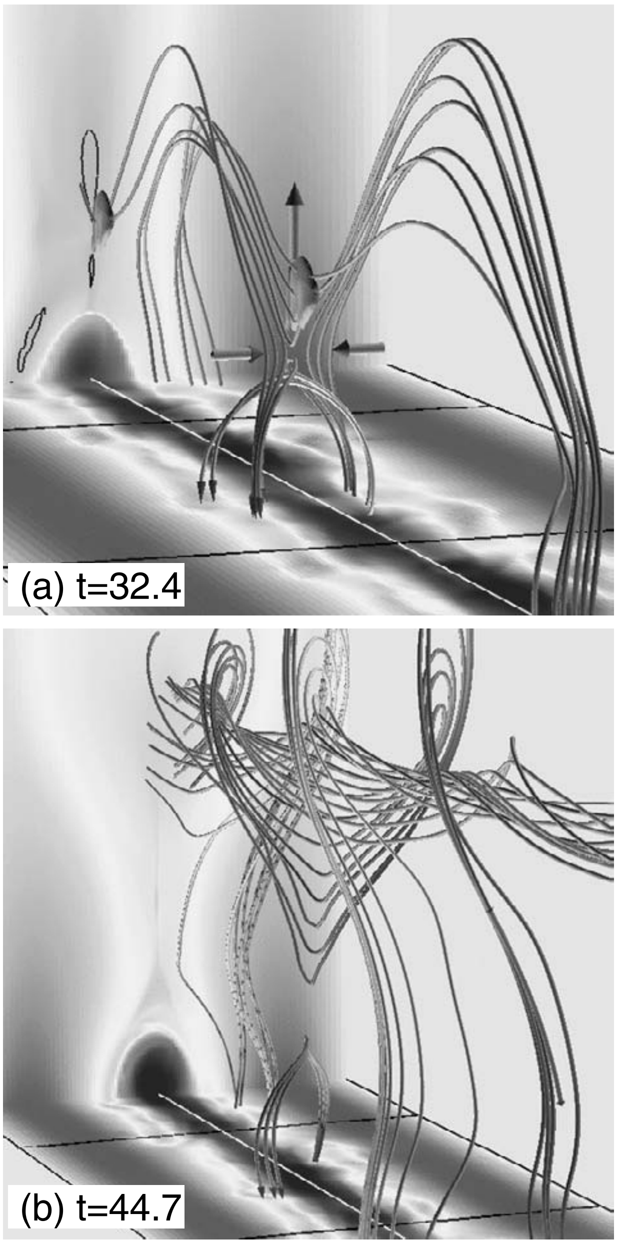

Fig. 2 Three-dimensional structure of the magnetic field lines in the eruptive phase calculated by the numerical simulation [5]. (a) Sheared loop field lines are collapsed into the center of arcade, as a result of the annihilation of the axial magnetic field parallel to the magnetic arcade axis, and they are reconnected. The up-stream jet region is plotted by the iso-value surface, in which the up-welling velocity is faster than 10% of the characteristic Alfvén speed. The typical flow structure is illustrated by thick arrows. (b) The large scale plasmoid is ejected upward.

It was also found from the simulation results that the original instability growing on the helicity inversion layer may cause the MHD energy relaxation in the embedded region bounded by the helicity inversion surface in advance of the large scale eruption. Figure 3 indicates the vertical distribution of the averaged shear parameter

$$\langle \alpha \rangle = \left\langle \frac{\boldsymbol{B} \cdot \nabla \times \boldsymbol{B}}{\boldsymbol{B} \cdot \boldsymbol{B}} \right\rangle ,$$

where the bra-ket denotes the average along the magnetic arcade axis. Here, we can see that $\langle \alpha \rangle$ is greatly decreased in the lower part ($z < 0.1$) for the early phase ($t = 8.8$). It is a result of the shear reversal due to the foot-point motion imposed near the magnetic neutral line. After the relaxation phase ($t = 30.5$), however, $\langle \alpha \rangle$ in the negative shear region ($z < 0.2$) is dramatically flattened.

According to the Taylor's theory, the absolute value of the shear parameter in the relaxed state must be smaller than the smallest eigenvalue of the curl operator [8,9,10]. The limitation of α arises as a result of transition of the linear force-free field from the so-called *coupled* state into the *mixed* state in the words of Taylor [8]. In our model, since the size of the revered shear region is $L = 0.2$ in the non-dimensional unit, and thus the corresponding eigenvalue is approximately given by $2\pi/L = 31.4$. In fact, $\langle \alpha \rangle$ in the negative helicity region at $t = 30.5$ has a value close to α_0 as seen in Fig. 3. It is an evidence of the Taylor-type relaxation. Furthermore, we can see in Fig. 4 that the magnetic field lines form the inverse S-shape structure after the energy relaxation.

Sigmoidal structure, which showed the S- or the inverse

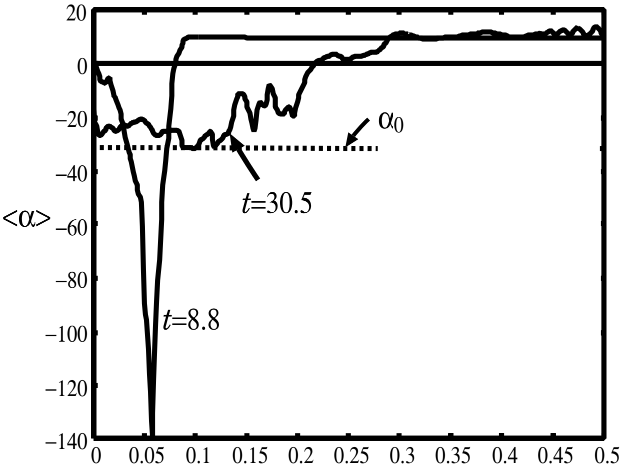

Fig. 3 Vertical distribution of the averaged α calculated by the three-dimensional simulation. Dashed line indicates the smallest eigenvalue $\alpha_0 = -31.4$ corresponding to size of the reversed shear region.

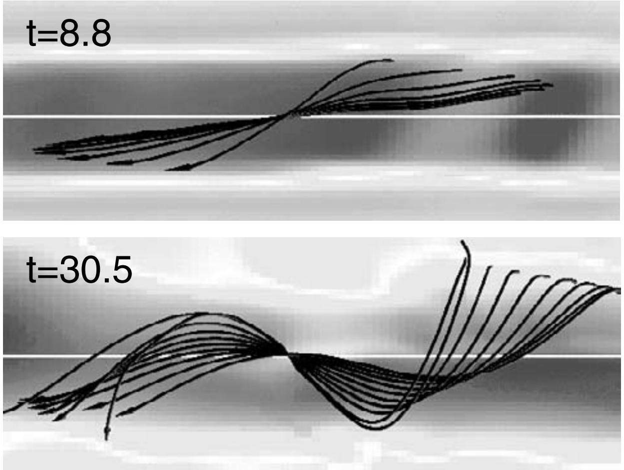

Fig. 4 Top views of the magnetic field lines in the inside of the reversed shear region before (t = 8.8) and after (t = 30.5) the MHD energy relaxation.

S-shapes corresponding to the sign of magnetic helicity, was often observed by soft-X ray observation of active regions. Since sigmoidal structures sometimes appeared prior to solar flares and coronal mass ejection (CME) events, it was pointed out that sigmoids could be a precursor of eruption in the solar corona. The numerical results, that the MHD energy relaxation forms the inverse S-shape field line preceding the large scale eruption, is consistent with the observations. It implies that the MHD energy relaxation, which is similar to the self-sustainment activity of the reversed-field pinch experiments, could be realized also in the solar corona, and that the coronal activities, in particular solar flares, are understood as a consequence of that.

4. Conclusion

In this paper, based on the vector magnetogram observations and the numerical simulations, we have demonstrated that the reversal of magnetic shear in the coronal magnetic field may cause a large scale eruption of a magnetic arcade and the MHD energy relaxation process. The physical mechanism of flare onset is explained as a chain-reaction, in which the resistive MHD instability (tearing mode) brings about a loss-of-equilibrium dynamics (eruption). The simulation results are well consistent with the observations of magnetic field and X-ray images. However, it is still an open problem how generally is this model applicable to various types of energetic events. Therefore, further investigation is required to carefully examine the relationship between the magnetic shear structure and the coronal activity.

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