MAGNETIC RECONNECTION MODEL OF CORONAL X-RAY JETS

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ABSTRACT

We review our magnetic reconnection model of the coronal X-ray jets. Two-dimensional numerical simulations are performed by solving the resistive magnetohydrodynamic (MHD) equations. The plasma of an X-ray jet is accelerated and heated by reconnection between the emerging flux and a pre-existing coronal field. Many observed characteristics of X-ray jets could be successfully reproduced. Morphologically, the two observed types of jets, two-sided-loop type and anemone-jet type, were well reproduced. Here, the two-sided-loop type is a pair of horizontal jets (or loops), which occurs when an emerging flux appears in a quiet region where the coronal field is approximately horizontal. In contrast, the anemone-jet type is a vertical jet, which takes place when an emerging flux appears in a coronal hole where the coronal field is vertical or oblique. Quantitatively, the velocity, temperature, thermal energy, kinetic energy, and other parameters obtained in the simulation are in good agreement with the observations. We also discuss the Alfvén wave generated by the reconnection process. The simulation results show that the amount of Alfvén wave energy is $\approx 3\%$ of the total energy released by the magnetic reconnection.

Key words: Sun: flares — jets — Alfvén wave — plasmas — MHD

1. INTRODUCTION

Solar coronal X-ray jets are a new phenomenon discovered by Yohkoh. It is a collimated flow of hot — a few million degree, plasma in the corona. The discovery of X-ray jets leads us to recognize that the corona is much more dynamic than had been expected. Figure 1 shows examples of the jets (Shibata et al. 1994). It is seen that the jets are ejected from flaring regions. Indeed, almost all X-ray jets are associated with small flares (e.g. subflares or microflares) in X-ray bright points, emerging flux regions, and active regions. This relation is also seen (not always) in larger flares and coronal mass ejections. This may suggest that some common mechanism is working in large range of energy scales. In this sense, the study of the X-ray jets is not only for themselves but also for understanding the fundamental physical nature of the corona. The general discussion of this unified view in various classes of ejections and flaring phenomena is given in Shibata (1998).

Figure 1. Examples of two types of solar coronal X-ray jets observed by the Yohkoh soft X-ray telescope (after Shibata et al. 1994) and schematic pictures of their reconnection model. In the anemone-jet, the active region at the footpoint of the jet looks like a sea-anemone. In two-sided-loop type, a pair of jets appears at both sides of emerging flux along the nearly horizontal field.

Physical conditions of X-ray jets are as follows (Shimojo et al. 1996; see also Shibata 1998). The frequency of occurrence is over twenty jets per month. Length is 10,000 — 400,000 km. Velocity is 10 — 400 km s$^{-1}$. Kinetic energy is $10^{26}$ — $10^{28}$ erg. Often a small flare occurs separately (by a few thousand km) from the exact footpoint of a jet. Some events of both X-ray jets and Hα surges are found (Canfield et al. 1995; Okubo et al 1996). The relationship between the jets and the magnetic activities are discussed in Shimojo et al. (1998). They found that, in the footpoint of the jets, the magnetic configuration is usually (more than 72%) mixed polarity. For some events, an increase or a decrease of magnetic flux at

the footpoint are found. These results suggest that the generation mechanism of X-ray jets related to the magnetic activity.

It is found that there are two typical types of jets ejected from emerging flux regions (Fig. 1). One is called anemone-jet type. In this case the jet is vertical or oblique, and usually occurs in coronal holes. The other type is called two-sided-loop type. In this case, the jets are horizontal, and occur in quiet regions. Based on these observations, a phenomenological model is proposed (Fig 1; Shibata et al. 1994). In this model, jets are ejected by magnetic reconnection between pre-existing coronal magnetic field and new magnetic field in the case of anemone jet type, emerging flux reconnect with pre-existing oblique coronal field in coronal holes. One of the hot plasma outflow goes up to become a hot X-ray jet. In the case of two-sided jet type, emerging flux reconnect with pre-existing horizontal coronal field in quiet regions. The hot plasma outflow becomes a pair of hot X-ray jets.

In this proceeding, we review our MHD simulations of X-ray jets based on the magnetic reconnection model (Yokoyama & Shibata 1995, 1996). We also discuss the Alfvén wave generated by the reconnection event. The application of this model is the acceleration of the high speed solar wind (600 - 900 km s\(^{-1}\)) which is relatively faster than the winds in the other region (\(\approx 450\) km s\(^{-1}\)). Parker (1991) suggested a model in which 20% of the energy released by reconnection events in the solar corona is transferred as a form of Alfvén wave. The energy of this wave becomes a heat in some dissipation mechanism in the outer corona. Due to the generated pressure gradient force, the flow is accelerated to fast solar wind. We estimated the energy of Alfvén wave from our numerical simulations and compared with the Parker’s assumed value of 20%.

Here we note that our simulation does not include the heat conduction nor radiative cooling. This means that the effect of evaporation is not included. And due to the numerical limitation, we do not use a realistic parameters for e.g. temperature, density, magnetic field strength etc. However, we believe that the qualitative evolution of the phenomena can be described in this simulation. The complementary simulation which aims at this aspect is discussed by Shibata & Yokoyama (1998) in detail although he assumed a one-dimensional jet model.

2. MHD SIMULATION OF X-RAY JETS

The numerical simulation is performed by solving the two-and-a-halldimensional MHD equations with uniform gravity, with no radiative cooling nor heat conduction. The plasma is assumed to have anomalous resistivity, whose functional form is taken to be \(\eta = 0 \) for \( v_d \geq v_t \) and \( \eta \propto (v_d/v_t - 1)^2 \) for \( v_d < v_t \), where \( v_d \equiv u/\rho \) is the non-dimensional (relative ion-electron) drift velocity, \( \rho \) is the non-dimensional mass density, \( J \) is the current density, and \( v_t \) is threshold above which anomalous resistivity sets in.

Figure 2 shows the initial conditions for the simulations. Each panel in this figure corresponds to the horizontal coronal field case and oblique coronal field case, respectively. The initial plasma consists of three stratified layers in magnetohydrostatic equilibrium in the \(zz\) plane. From top to bottom; the corona, the chromosphere/photosphere, and the convection zone. There are two parts of initial magnetic field. One is horizontal localized flux sheet in the convection zone. The other is coronal field, which is horizontal in this case and oblique in the other case. The flux sheet in the convection zone is unstable to the Parker’s magnetobuoyancy instability. We impose a small perturbation in this region and see what happens.

The times are in units of \(\tau \equiv H/C_s \approx 20\) sec, and the length is in units of where \(H \) and \(C_s \) is pressure scale height and sound speed in the photosphere/chromosphere. The parameters used in this simulation are as follows; initial coronal and chromospheric/photospheric temperatures is 25 (which is somewhat low, but has a weak effect on the result) and unity, respectively; vertical range of chromosphere/photosphere is 8 (1,600 km); plasma beta in the corona and in the horizontal magnetic sheet in the convection zone is 0.2 and 4.0, respectively.

Figure 3 shows the results of the case of horizontal field. Gray-scale map of left-hand-side indicates temperature and the right-hand-side indicates log-scaled density.
Initially, the magnetic flux in the convection layer rises to become a loop due to the Parker instability. When the top of the rising loops enter the coronal level, reconnection takes place between the loop top and the coronal field. A pair of hot plasma jets, heated by reconnection process, is ejected. These jets are identified to the two-sided-loop type of coronal X-ray jets. With hot horizontal jets, another interesting feature is seen. That is the magnetic island which confines cool and dense plasma, originally from the chromosphere. This ejection may be observed as an Hα ejection.

Figure 4 shows the results of the case of oblique field. In this case, the hot plasma, heated by magnetic reconnection process, goes up to become an oblique hot jet. Note that the jet is not directly ejected from the X-point of the reconnection. But it is decelerated at the site where the reconnection outflow collides with the field lines in the side. Through the detailed investigation, we found that a fast-mode MHD shock is formed here. The pressure becomes high behind this shock. Then the plasma is accelerated again by the pressure gradient force. In addition to the hot jet, another ejection of cool plasma is seen as well. This cool plasma is the chromosphere plasma, which is carried up with the expanding loops. It is ejected by the slingshot effect due to reconnection and forms this cool jet. Another interesting feature in this simulation is the hot loops at the right side. It is pointed that observation shows that often a small flare occurs separately from the exact footpoint of a jet. This hot loop may be the observed one.

3. GENERATION OF ALFVÉN WAVE

In this section, the generation of the Alfvén wave by the magnetic reconnection process is discussed. The
Figure 4. Simulation results for the oblique-coronal-field case. The remaining notation is the same as in figure 9.

The numerical model is almost the same as the oblique-coronal-field case shown in the previous section. But we added the third (y-) component to the flux sheet in the convection zone. This is perpendicular to the computational domain. The magnetic strength of the y-component equals to the x-component, so that the field direction of the flux sheet is 45 degree away from the computational domain.

Figure 5 shows the results. The plotted quantities
Figure 5. The propagation of waves. The plotted value is the velocity perpendicular to the initial coronal field. Color map of left-hand-side indicates the component parallel to the computational domain, and the right-hand-side indicates the component perpendicular to the figure. Lines indicate magnetic field lines and arrows indicate velocity.

are the velocities perpendicular to the initial coronal field. The color map of the left-hand-side panels indicates the component in the $x$-$z$-plane, $V_x$, and that of the right-hand-side panels indicates the component perpendicular to the plane, $V_y$. The propagation of Alfvén waves along the coronal field can be seen in this figure. These waves are excited in two kinds of processes. First, there is a propagating wave along the coronal field line in $V_y$ plot of Figure 5. When the reconnection occurs, the reconnected field lines have a kink because there is a shear between the emerging loops and the coronal field. This kink will propagate away as an Alfvén wave. Second, in Figure 5, a propagation of isotropic wave can be seen. It is a fast-mode magnetosonic wave excited by the compression of the plasma at the collision site of the reconnection outflow. In the wave front, there is a spot which locally has higher amplitude. This is the front of Alfvén wave that is excited at the same time with the fast-mode wave. The propagating speed of this Alfvén wave is almost equal to the fast-mode wave. But the Alfvén wave can propagate only along the magnetic field line.

We can check if these waves are really Alfvén wave by investigating the propagating speed. Figure 6 are one-dimensional plots along the initial coronal field between point $A(x = 0, z = 0)$ and $B(x = -150, z =$
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Figure 6. Evolution of one-dimensional plot along the line between points A\( (z = 0, z = 0) \) and B\( (z = 150, z = 150) \). In the right panels, the solid lines indicate the Alfvén wave speed and the dashed lines indicate the slow-mode magnetosonic wave speed.

Some propagating profiles can be seen. The solid line indicates the Alfvén velocity and the dashed line indicates the velocity of slow-mode magnetosonic wave. The propagating speeds of the profiles clearly fit with the Alfvén velocity.

Figure 7. Amplitude of the Alfvén wave as a function of time monitored at point \((x, z) = (-85, 85)\). Measured quantities are the components perpendicular to the initial coronal fields but in the computational domain (with subscript \(L \)) or also perpendicular to the domain (with subscript \(y \)) of the velocity and the magnetic field strength.

Next, we measure the amplitude and energy of excited Alfvén waves. From Figure 7, it is shown that the amplitude normalized with coronal Alfvén speed \( (V_A = 9.8) \) is about 0.1. This value is large because this value corresponds to 100 \( \text{km}^{-1} \) in the real corona which have not yet been observed. This may be justified by the fact that the generated Alfvén wave in the simulation is impulsive and non-steady although the measured amplitudes are based on the observation with long-time exposure.

Figure 9 is a plot of the energy flux of Alfvén wave crossing through the upper bound of the simulation box. The total energy of Alfvén wave can be obtained by integrating this in time. It is compared with the various energies released by the magnetic reconnection in this figure. The ratio of energy of Alfvén wave to the thermal energy is obtained as 0.027, or about 3 %. This value is smaller than Parker’s estimation. But it is noted that this study is still a preliminary level and the conclusion is not strong so far.

4. Summary

The summary of the numerical simulations of the X-ray jets based on the magnetic reconnection model (see Figure 10) is given as follows:

1. A hot and a cool jet are ejected.
2. A fast-mode MHD shock is formed at the collision site of the reconnection jet. At the shocks, the jets are compressed, and change direction along the field lines.
3. The energy of Alfvén wave generated by the reconnection event in the corona is about 3 % of the released energy.

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Figure 10. Schematic pictures of the simulation results of the magnetic reconnection between an emerging flux and a coronal field producing X-ray jets. (left) The horizontal-field case and (right) The oblique-field case.

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