MHD Simulations of the Internal Shocks in Magnetic Reconnection Jet in the Solar Flare: Possibility of the Particle Acceleration

S. Tanuma[1] and K. Shibata,[1]
(1) Kwasan Observatory, Kyoto University, Yamashina, Kyoto 607-8471, Japan

Abstract

The solar atmosphere is filled with the high-energy particles. The satellites such as Yohkoh and RHESSI observe the X- and gamma-ray emissions from them. They are accelerated in solar flares. The their origin is, however, not fully known yet. In this paper, we examine how the magnetic reconnection creates the fast shocks, by performing two-dimensional numerical resistive magnetohydrodynamic simulations. As the results, we find that the current sheet becomes thin by tearing instability, and it collapses to Sweet-Parker current sheet. The thin current sheet becomes unstable to the tearing instability again. The fast reconnection starts immediately after the plasmoid ejection, which are created by the secondary tearing instability. The internal shocks are created inside the reconnection jet due to the non-steady plasmoid-ejection. In the next phase, the magnetic reconnection jet oscillates in the current sheet, which is due to Kelvin-Helmholtz-like instability, or turbulent reconnection. The reconnection jet collides with two standing slow shocks, so that the fast shocks are created by oblique shocks. The fast shocks created by the magnetic reconnection are possible sites for the particle acceleration in the solar flare.

1. Introduction

The solar environment is filled with a large number of high-energy particles. The satellites such as Yohkoh and RHESSI observe the hard X-and gamma-ray emissions from the solar flares, especially “impulsive flares”(called “Masuda flare”)[1]. They are considered to be accelerated in the diffusion region, standing slow shocks, or fast shock at the loop top in the solar flares[4]. The origin of hight energy particles is, however, not fully known yet. In this paper, we suggest that internal shocks are created in the reconnection jet, and they are possible cite for the particle acceleration in the solar flare. We examine how the magnetic reconnection creates the multiple fast shocks, by performing two-dimensional(2D) numerical resistive magnetohydrodynamic(MHD) simulations[2,3].

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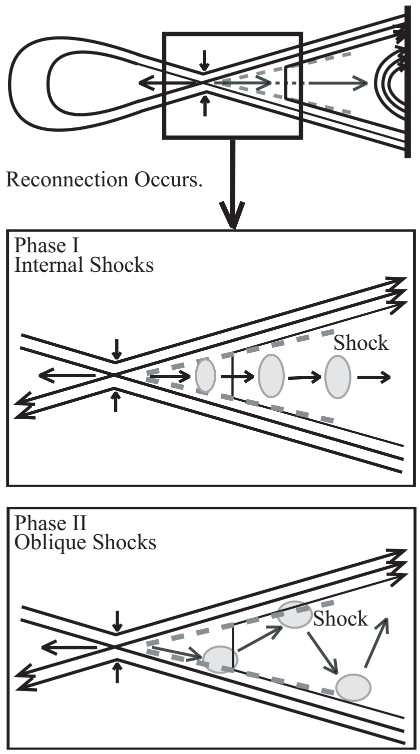

Fig. 1. The schematic illustration of solar flare. The magnetic field inflates to solar corona from solar surface. Magnetic reconnection occurs, so that the magnetic energy is converted toward thermal and kinetic energies. We suggest that the multiple fast shocks are created in the reconnection jet(called "downflow"). They are possible site for the particle acceleration in the impulsive flares[1].

2. Numerical Simulations

As the initial condition, we assume the simplest current sheet created by the magnetic field $[B_x = \tanh(z/H),\ B_z = B_y = 0]$. The plasma $\beta = pg/(B_x^2/8\pi) = 0.2$, so that the Alfvén velocity is $V_A \sim 2.45\times$ sound velocity. We assume the small grid $(dx, dz) = (0.13, 0.013)$(uniform). The simulation region size is $L_x \times L_z = 208.0 \times 20.8$. The number of grid is $(N_x, N_z) = (1600, 1600)$. We assume the anomalous resistivity model, defined as following: The resistivity is $\eta = 0$ (if $v_d < v_c$), and $\eta \propto (v_d/v_c - 1)^2$ (if $v_d > v_c$), where $v_d \equiv J/\rho$ is the non-dimensional drift velocity (The resistivity would increase because the plasma turbluence or some instability would occur when the electron velocity increases very much, for example, as fast as sound velocity). We also assume that the resistivity does not increase above $\eta_{max} = 1$. The magnetic Reynolds number is $R_m = V_A L_x/\eta_{max} \sim 500$.

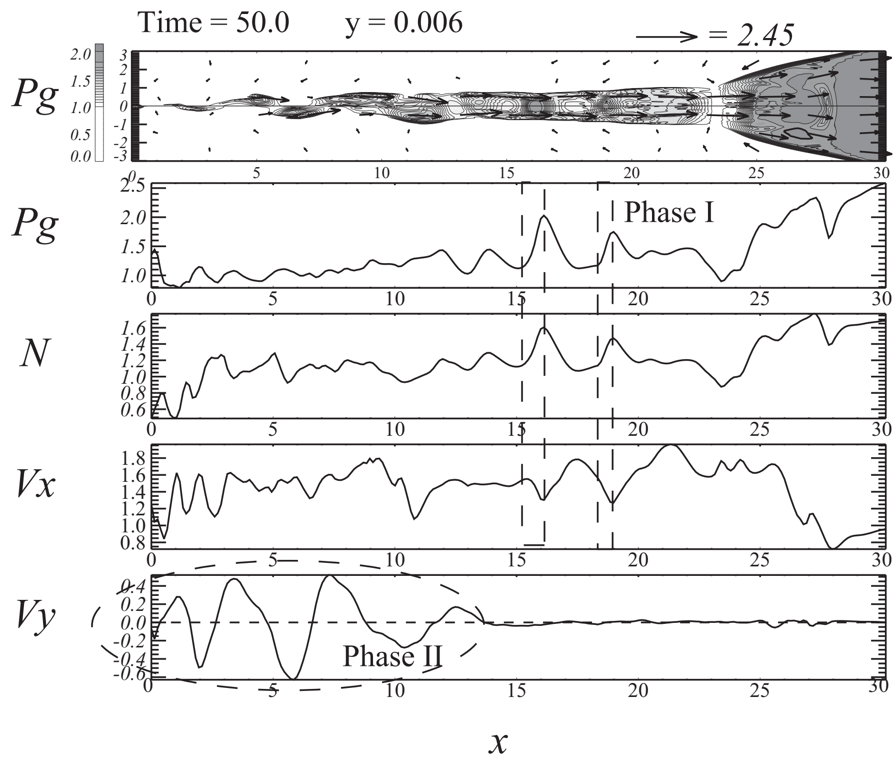

Fig. 2. The profiles of reconnection jet. The diffusion region ("X-point") is around $(x, z) = (0, 0)$. The gas flows into diffusion region and standing slow shocks. We find that the internal shocks are created in the jet. (Phase I)The internal shocks are created due to the secondary tearing instability. (Phase II)In a later phase, the reconnection jet starts to oscillate, which would be due to Kelvin-Helmholtz(-like) instability. The jet collides with high pressure gas to create multiple fast shocks. along the reconnection jet[1].

3. Results

We put small perturbation on the electric resistivity at the center of current sheet for a short time. As the results, we find that the current sheet evolves as following phases[2,3]: (i)The current sheet becomes thin by tearing instability in its nonlinear phase. (ii)It collapses to Sweet-Parker current sheet. (iii)The thin current sheet becomes unstable to the tearing instability again (which is called "secondary tearing instability"). (iv)The anomalous resistivity sets in, immediately after the ejection of large plasmoid, which are created by the secondary tearing instability. The fast(Petschek-like) reconnection starts. The magnetic energy is converted toward the thermal and kinetic energies in a non-steady manner.

We find two types of multiple fast shocks are created in the reconnection jet along the current sheet(figures 1 and 2). (a)The internal shocks are created inside the reconnection jet due to the non-steady plasmoid-ejection, which is created by the secondary tearing instability. The intervals of internal shocks are almost equal to the wavelength of secondary tearing instability. (b)In the next phase, the magnetic reconnection jet starts to oscillate in the current sheet, which would be due to Kelvin-Helmholtz(-like) instability, or turbulent reconnection. The reconnection jet collides with high pressure gas (two standing slow shocks), so that the multiple fast shocks (oblique shocks) are created along the jet. They are also standing shocks.

4. Discussion

The fast shocks created by the magnetic reconnection are possible sites for the particle acceleration in the solar flare. We can calculate the number of accelerated particles, by assuming it is equal to flux to the fast shocks. It is $dN/dt = LdV_AN \sim 10^{36}$ s^{-1}, where L and d are length of reconnection jet($\sim 10^{10}$ cm) and width of flare loop($\sim 10^9$ cm), V_A is Alfvén velocity ($\sim 10^7$ cm s^{-1}), N is number density of electrons ($\sim 10^{10}$), because the simulation results shows that the multiple fast shocks are created at whole reconnection region. The above value(10^{36} s^{-1}) is one or two orders of magnitude larger than the value derived by hard X-ray observation. It suggests that the efficiency of particle acceleration would be much less than unity, or that the fast shocks are created only near the diffusion region.

5. Conclusions

We perform 2D MHD simulations of the magnetic reconnection, by assuming the simple current sheet, and assuming the smallest grid. As the results, we find that the fast reconnection occurs after the current sheet thinning and secondary tearing instability. During the reconnection, two types of multiple fast shocks are created inside the reconnection jet. It would be due to the ejection of plasmoids created by the secondary tearing instability, and due to oscillation of jet by Kelvin-Helmholtz-like instability, respectively. We suggest that these internal shocks are possible site for the particle acceleration in the solar flare.

References

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