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Proton Acceleration in a Single-Loop Disrupted during Collision of Two Moving Solitary Magnetic Kinks

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We investigate a new model of single-loop flare based on the fact that a magnetic flux tube with axial current can be explosively disrupted during collision of two moving solitary magnetic kinks (MoSMaK), particularly paying attention to an acceleration mechanism of high energy protons. At this time, we investigate a model which flow cross-section is not same as the collision cross-section. By using three-dimensional electromagnetic fields obtained from a resistive three-dimensional MHD equations during the single-loop flare, we investigate the orbit of many protons to obtain their energy spectra. We found that the protons can be accelerated to γ-ray emitting energies. The protons are accelerated mainly in one direction along the loop by the electric field produced near the three-dimensional localized current associated with the magnetic reconnection process in the disrupted loop.

Keywords : single-loop flare, proton acceleration, moving solitary magnetic kink

1 Introduction

When energetic protons accelerated during impulsive flares collide with solar atmosphere, excited nuclei emit prompt nuclear de-excitationlines, as well as secondary neutrons and positrons that results in the delayed 2.223 MeV neutron-capture and 511 KeV positron-annihilation line emission. In most strong flare events the time profile of the prompt gamma-ray line emission is observed to be very similar to that of the bremsstrahlung hard X-rays emitted by energetic electrons. This suggests that the acceleration and propagation of the flare-accelerated protons and electrons are closely related.
However, the location, size and geometry of the accelerated proton collision region remains unknown until now. Recent paper by Hurford et al. (2003) presents the first gamma-ray images of a solar flare taken from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) for the X4.8 flare of 2002 July 23. The result shows that the centroid of the 2.223 MeV image was found to be displaced by 20 $\pm$ 6 arcsec from that of the 0.3-0.5 MeV implying a difference in acceleration and /or propagation between the accelerated electron and proton population near the Sun. The fact that proton-associated gamma-ray source does not coincide with the electron-bremsstrahlung sources suggests that the protons would be accelerated in one direction by the DC electric field and could subsequently interact in spatially separated sources. Therefore it is now important to investigate in details the proton acceleration processes for different types of flare.
Among *Confined/impulsive flares* single-loop flares occur in a single loop. We consider single-loop flares an elementary case of the class of confined/impulsive flares.
There are two next studies as a background of our model. The first is an article by Furusawa and Sakai (2000). They investigated the collision process of two flux tubes and they showed that shock waves can be excited from a region where two magnetic flux tubes with weak electric current collide with each other. They also showed that plasma up-flows are generated along the flux tubes, when two magnetic flux tubes collide with X-type configuration.
The second is an article by Nishi and Sakai (2002). They investigated head-on and rear-end collision process of dense plasma blobs moving along a magnetic flux tube with axial current, by using a resistive 3-D MHD code. They found a new nonlinear elementary excitation called "moving solitary magnetic kink" (MoSMaK) that can be excited near the interface of colliding plasma blobs.The MoSMaK is characterized with an isolated magnetic flux ring and a pair of counter-rotating vortex rings.
From these studies, we investigate a new model of

single-loop flare based on the fact that a magnetic flux tube with axial current can be explosively disrupted during collision of two moving solitary magnetic kinks. And we will attention to high energy protons more than 1MeV which seems to be provided by observation and will inspect it.
In this study, we use MHD equations in order to calculate magnetic fields and electric fields. After that we do test particle simulation of protons, using electric fields and magnetic fields given by MHD equations.

2 Basic equations and simulation model

2.1 Basic equations and numerical scheme

To solve the following resistive MHD equations, we employ recently proposed *Artificial Wind* (AW) numerical scheme[4] with splitting over the spatial coordinates. The AW scheme is based on the fact that the fundamental physical invariance (Galilean or, more generally, Lorentz invariance) allows one to solve the governing equations in different steadily moving frames. Tests of ideal MHD simulation show that the AW scheme captures all the structures of MHD waves correctly without producing noticeable oscillations. The following conservative MHD equations are numerically integrated:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho V_i) = 0, \quad (1)$$

$$\frac{\partial(\rho V_i)}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho V_i V_j + (p + B^2)\delta_{ij} - 2B_i B_j\right] = 0, \quad (2)$$

$$\frac{\partial B_i}{\partial t} + \frac{\partial}{\partial x_j}(V_j B_i - V_i B_j) = \frac{1}{R_m}\frac{\partial^2 B_i}{\partial x_j^2}, \quad (3)$$

$$\frac{\partial}{\partial t}(\frac{\rho V^2}{2} + \frac{p}{\gamma - 1} + B^2) + \frac{\partial}{\partial x_i}\left[V_i(\frac{\rho V^2}{2} + \frac{\gamma p}{\gamma - 1} + 2B^2) - 2B_i B_j V_j + q_i\right] = 0, \quad (4)$$

where ρ ,V_i,p_i and B_i are the density, velocity, pressure and magnetic field, respectively; γ is the adiabatic constant, R_m is the magnetic Reynolds number; δ_{ij} is a unity tensor; and q_i is the dissipative energy flux. The density , pressure, velocity, and magnetic field are normalized to ρ_0, p_0, $\sqrt{p_0/\rho_0}$, and $B_0 = \sqrt{8\pi p_0}$, respectively.
We admit the dissipative hydrodynamic flux in the form

$$\lambda = 1/(3R_m) \quad (5)$$

The magnetic Reynolds number $R_m = 1.3 \times 10^3$.

2.2 Simulation model

We consider a model of a single-loop flare based on the fact that a magnetic flux tube with axial current can be explosively disrupted during collision of two moving solitary magnetic kinks (MoSMaK) as shown in Fig. 1. The system size is $(x, y, z,) = (200\Delta, 200\Delta, 300\Delta)$. The center of flows are $(x, z) = (95, 50), (105, 50)$, respectively.

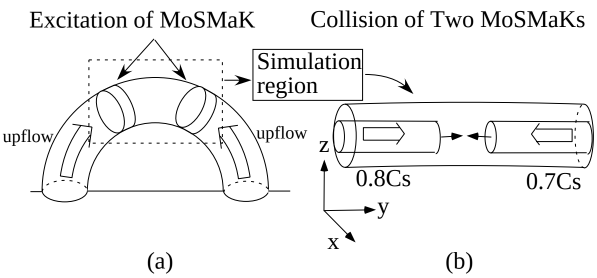

Figure 1: (a) Schematic picture of a single loop flare that is triggered during collision of two moving solitary magnetic kinks(MoSMaKs) excited at the collision fronts between upflows and loop plasma. (b)Simulation region and coordinate system.

We take the magnetic flux as follows.

$$B_\theta = q(\frac{r}{a})B_0 e^{(-\frac{r}{a})^2} \quad (6)$$

$$B_z = B_0 e^{(-\frac{r}{a})^2} \quad (7)$$

where $r = \sqrt{(x - x_c)^2 - (z - z_c)}$. The center of the flux tube is placed at $(x_c, z_c) = (100, 100)$. The twist parameter q is set to 1.0 and $B_0 = 1.0$. The pressure, density and velocity is as

$$p = (\frac{q^2}{2} - \frac{q^2 r^2}{a^2} - 1)e^{-2(\frac{r^2}{a^2})} + p_0 \quad (8)$$

$$\rho = p + \{0.5\rho_c(1 - \tanh(\frac{y - y_1}{3}))e^{-(\frac{r_{c1}}{10})^2} + 0.5\rho_c(1 + \tanh(\frac{y - y_2}{3}))e^{-(\frac{r_{c2}}{10})^2}\} + 50e^{(-\frac{z}{100})} \quad (9)$$

$$V_x = 0 \quad (10)$$

$$V_y = \{0.4V_{y1}(1-\tanh(\frac{y-y_1}{3}))e^{-(\frac{r_{c1}}{10})^2}$$

$$-0.5V_{y2}(1-\tanh(\frac{y-y_1}{3}))e^{-(\frac{r_{c2}}{10})^2}\} \quad (11)$$

$$V_z = 0.4e^{(-\frac{r}{20})}e^{(-(\frac{y-100}{100})^4)} \quad (12)$$

where $p_0 = 1.0$, $y_1 = 50$, $y_2 = 150$, $\rho_c = 10$, $V_{y1} = 0.8C_s$, and $V_{y2} = 0.7C_s$, $r_{c1} = \sqrt{(x-95)^2-(z-z_c)}$, $r_{c2} = \sqrt{(x-105)^2-(z-z_c)}$. In this way, we give the plasma flow of an opposite direction along a magnetic flux tube. Then two MoSMaKs are generated on a border of the moving plasma and the stationary plasma. In addition these collide. This is a new model which we present.

3 Simulation results

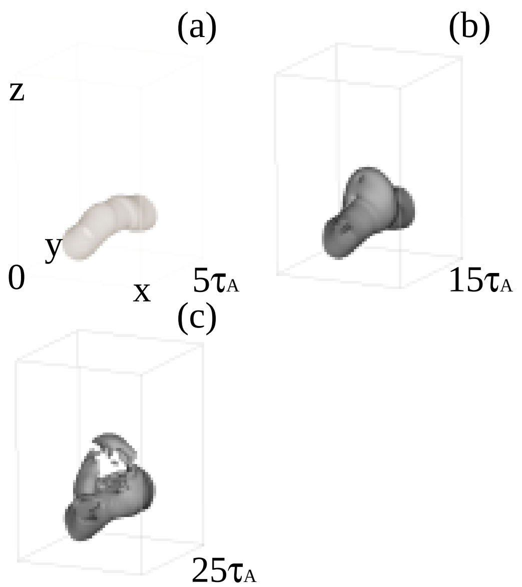

Figure 2: The time evolution of the isosurface of total magnetic field intensity with $|B| = 0.3$ during collision of two MoSMaKs at three different times (a) just before the collision, (b) just after the collision, (c) disruption of a loop.

Firstly,we present our simulation results of MHD simulation. Figs.2-(a),(b) and (c) show the time evolution of the isosurface of total magnetic field intensity with $|B| = 0.3$. Each times are (a) at $5\tau_A$, (b) at $15\tau_A$, and (c) at $25\tau_A$. These show that two MoSMaKs occur and collide and eventually the magnetic flux tube is disrupted. For the test particle simulation, we use the electromagnetic fields at $25\tau_A$.

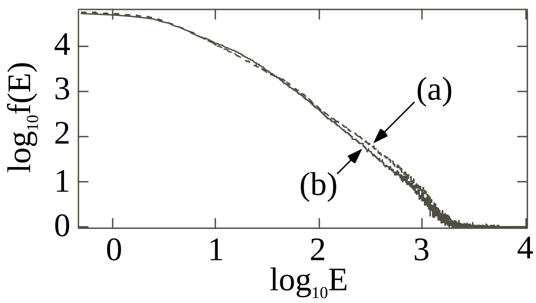

Figure 3: Proton energy spectra (a) head-on collision (dotted line), (b) head-on collision with small collision cross-section (solid line)

Next we present the test particle simulation results and investigated them. Fig.3 shows proton energy spectra. (a) is previous case (head-on collision) with dotted line. (b) is this time case (head-on collision with small collision cross-section) with solid line. In this time case, proton energy is more than 10MeV. But number of protons decrease compared with previous case.

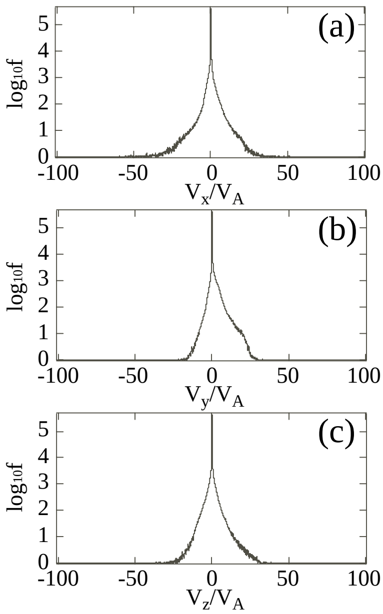

Figure 4: Proton velocity distribution functions of (a) the x-direction, (b) y-direction, and (c) z-direction.

Fig.4 shows proton velocity distribution functions: (a) in the x-direction, (b) in the y-direction, and (c) in the z-direction. In the x-direction and the z-direction, protons are accelerated symmetrically. On other hand, in the y-direction, protons are accelerated mainly in positive y-direction. Therefore protons are accelerated mainly in one direction along the loop, because the y-direction is along the loop.

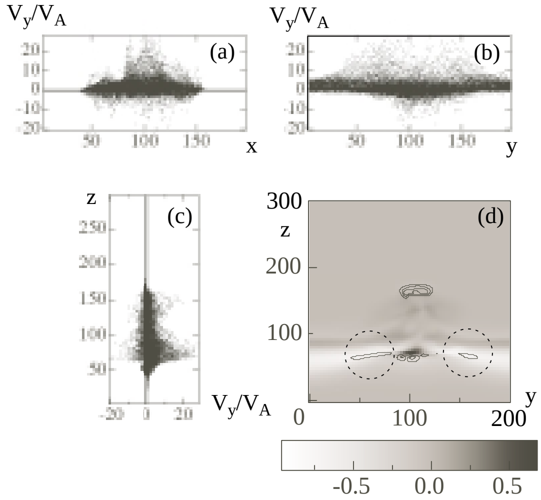

Figure 5: (a) The phase diagram of protons in the x-V_y, (b) in the y-V_y, and (c) in the z-V_y. (d) Spatial distribution of the magnetic fields B_y in the y-z plane on $x = 100$. The counter of the electric field intensity with E_y is overplotted.

Finally, we investigate the electric field and magnetic field during the acceleration in the y-direction. Figs.5 (a)-(b)-(c) show the phase diagram of protons in the x-V_y, y-V_y, and z-V_y. These show that protons are accelerated mainly in the regions surrounded with dotted lines. Fig.5 (d) shows spatial distribution of the magnetic field intensity with B_y in the y-z plane on $x = 100$ and the counter of the electric field intensity with E_y is overplotted. In this figure, strong electric fields are located at four regions which are in the upper part of a loop, the lower part of a collision side center and the both sides which region is sandwiched.
In the upper part of a loop, E_y is strong, but B_y is weak. In addition, we confirmed that the direction of total magnetic field is perpendicularly almost to total electric field. So protons are not accelerated efficiently.
In the lower part of a collision side center, E_y is strong, and B_y is also strong. We confirmed that the directions of the total magnetic field and the total electric field are not perpendicular, but are not parallel. Therefore, protons are accelerated a little.
In the regions surrounded with dotted lines, it is realized that the magnetic fields and the electric fields are parallel and both are together strong. Therefore, in the regions surrounded with dotted lines, protons are accelerated very efficiently along the magnetic field.

4 Conclusions

We investigated a model of single-loop flare based on the fact that a magnetic flux tube with axial current can be explosively disrupted during collision of two moving solitary magnetic kinks (MoSMaK). We found that the protons are accelerated more than 10MeV, even though the collision cross-section of flows becomes small. However, number of accelerated protons decrease then. The protons are accelerated mainly in one direction along the loop. A form of an electric field and amagnetic field is somewhat difference, and, the mechanism of the protons acceleration is the same almost.
This model seems to be consistent with the observation that γ-ray image seems to be one region. We hope further observations of solar flares on the γ-ray image to understand the proton acceleration mechanism.

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