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

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Abstract

A new model of single-loop flare is investigated 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. By using three-dimensional electromagnetic fields obtained from a resistive three-dimensional magnetohydrodynamic (MHD) equations of the single-loop flare, the orbit of many protons is studied to obtain their energy spectra. It is shown that the protons can be accelerated to γ-ray-emitting energies (> 1 MeV) with double power-law spectra up to about 25 MeV. There appears a breaking point of the index of the power-law spectra from 1.8 to 2.1 near 10 MeV. 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:

solar flare, single loop flare, proton acceleration, solitary magnetic kink

1. Introduction

Recent paper by Hurford *et al.* [1] 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±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 populations 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 flares [2-3].

Recently Sakai *et al.* [4] 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 three-dimensional MHD code. They have found a new nonlinear elementary excitation mechanism of a “moving solitary magnetic kink” (MoSMaK) that is generated 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. They studied the collision process of two MoSMaKs along a straight magnetic flux tube. It was shown that a twisted magnetic flux tube can be explosively disrupted during the collision of two MoSMaK’s, resulting in strong emission of magnetosonic waves.

In this paper 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. 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 (> 1 MeV) with double power-law spectra. 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.

2. Simulation results

We use two methods of simulation to obtain the energy spectra of the protons accelerated in a single-loop disrupted during collision of two MoSMaks. Firstly we caluculate the electromagnetic fields by means of a three-dimensional resistive MHD simulation of a single-loop flare. Next we obtain the orbits of many protons under the electromagnetic fields obtained from the MHD simulation.

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We investigate the collision process of two MoSMaKs propagating along a bent magnetic flux tube. We present the resistive MHD simulation results for the plasma beta (β = 0.05) at the center of the loop to obtain the electromagnetic fields by using the resistive MHD equations. Here we take a long system size in the z-direction as N_z = 300 and $N_x = N_y$ = 200. The magnetic flux tube is assumed to be in an equilibrium state. We used the magnetic Reynolds number $R_m = 1.3 \times 10^3$.

In Fig. 1 we present the time evolution of the isosurface of total magnetic field intensity with $|\boldsymbol{B}|$ = 0.3 (the magnetic field is normalized by magnetic field intensity at the center of the loop) during collision of two MoSMaKs for β = 0.05 at four different times: (a) at 5 τ_A (just before the collision), (b) at 15 τ_A (just after the collision), (c) at 25 τ_A and (d) at 45 τ_A (disruption phase of a loop), where τ_A is the transit time of Alfvén wave across the loop radius.

To find which time phase after the disruption the protons can be effectively accelerated, we investigated the proton energy spectra by using the electromagnetic fields obtained from the MHD simulation at three different time steps after the collision of two MoSMaKs. It is found that the protons can be accelerated most effectively at 25 τ_A. As shown in Fig. 2, the energy spectra of the protons at $\omega_{ci}t$ = 1500 (ω_{ci} is the ion cyclotron frequency) are characterized by double power law whose index is about 1.8 and 2.1 for both cases of β = 0.05 (dotted line) and β = 0.5 (solid line). Since the aim of this study is to investigate the acceleration of protons in a single-loop solar flare, we establish physical links between the scaling of the basic parameters in the simulations and solar flare conditions. As the initial given value of $A = V_A/c$ = 1/300 (V_A is the Alfvén velocity at the center of the loop and c is the velocity of light), the Alfvén velocity is about 1000 km/s. Also, the proton thermal velocity is assumed to be equal to 0.1 V_A, or 100 km/s, which corresponds to the energy of ~ 100 eV. The maximum proton energy is about 25 MeV. There appears a breaking point of the index from 1.8 to 2.1 near 10 MeV. The acceleration time $\omega_{ci}t$ = 1500 of the protons is about 10^{-3} s and quite rapid compared with the MHD time scale $\tau_A = a/V_A$ = 10 s, if we take an ion-cyclotron frequency of 1.34×10^6 rad/s for a magnetic field of 140 G and the loop radius of $a = 10^9$ cm.

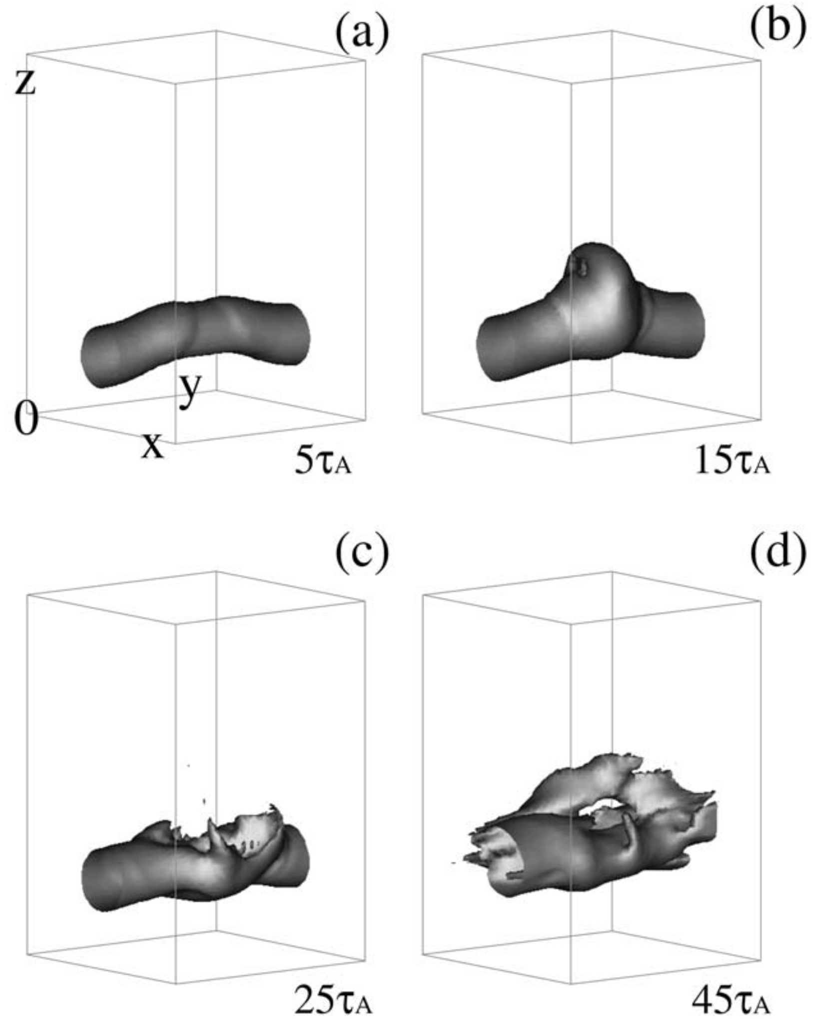

Fig. 1 The time evolution of the isosurface of total magnetic field intensity with $|\boldsymbol{B}|$ = 0.3 during collision of two MoSMaKs for β = 0.05 at four different times: (a) just before the collision, (b) just after the collision, (c) and (d) disruption of a loop.

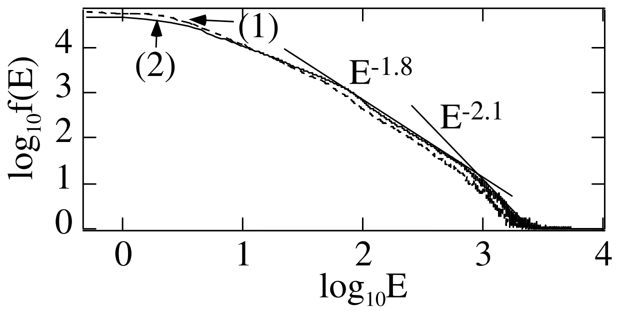

Fig. 2 Proton energy spectra at $\omega_{ci}t$ = 1500, showing double power law whose index is about 1.8 and 2.1 (1) for β = 0.05 (dotted line) and (2) for β = 0.5 (solid line). $E = (V_x^2 + V_y^2 + V_z^2)/V_A^2$.

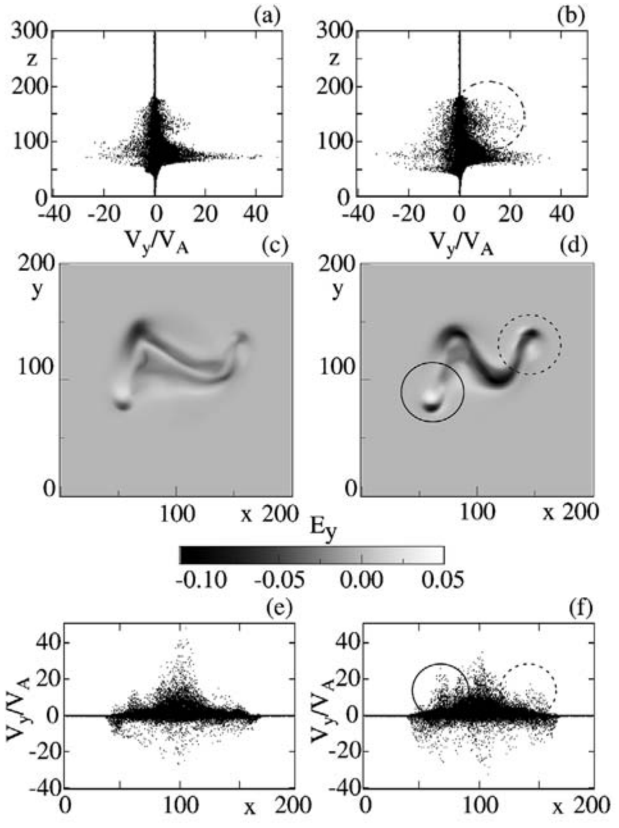

Fig. 3 (a) The phase diagram of protons in the $z - V_y$ plane for β = 0.05 at $\omega_{ci}t$ = 1500. (b) The phase diagram of protons in the $z - V_y$ plane for β = 0.5 at $\omega_{ci}t$ = 1500. The region of dot-dashed circle shows that protons located near upper part of disrupted loop are accelerated for β = 0.5. (c) Spatial distribution of the electric field E_y in the *x-y* plane on z = 130 at 25 τ_A for β = 0.05. (d) Spatial distribution of the electric field E_y in the *x-y* plane on z = 130 at 25 τ_A for β = 0.5. (e) The phase diagram of protons in the $x - V_y$ plane for β = 0.05 at $\omega_{ci}t$ = 1500. (f) The phase diagram of protons in the $x - V_y$ plane for β = 0.5 at $\omega_{ci}t$ = 1500. Solid circles and dotted circles in (d) and (f) correspond each other.

Next we investigate the acceleration mechanism of the high-energy protons for the case of β = 0.05. The proton velocity distributions are almost isotropic, while in the *y*-direction, the velocity distribution is asymmetric and the protons are accelerated mainly in positive *y*-direction. To understand the reason why the protons are accelerated in positive *y*-direction, we investigated the electric field structure where the protons are effectively accelerated. In Figs. 3(a) and 3(b) we show the phase diagram of protons in the $z - V_y$ plane at $\omega_{ci}t$ = 1500 for β = 0.05 and for β = 0.5, respectively. The region of dot-dashed circle in Fig. 3(b) shows that protons located around z = 130 near the upper part of the disrupted loop are accelerated mainly in the positive *y*-direction up to $V_y = 25\ V_A$ only for β = 0.5. To understand the proton acceleration in the upper part for β = 0.5, in Figs. 3(c) and 3(d) we show the spatial distribution of the electric field E_y in the *x-y* plane on z = 130 at 25 τ_A for β = 0.05 and β = 0.5, respectively. In Figs. 3(e) and 3(f), we also show the phase diagram of protons in the $x - V_y$ plane at $\omega_{ci}t$ = 1500 for β = 0.05 and for β = 0.5, respectively. The solid circles and dotted circles in Figs. 3(d) and 3(f) correspond each other. From the comparison of these regions we conclude that the protons located near the upper part of the disrupted loop for β = 0.5 can be effectively accelerated due to locally strong electric field E_y. The reason why the elecctric field near the upper part of the disrupted loop becomes strong is due to the fact that the loop with β = 0.5 can be strongly deformed to the upper part as well as inside the loop, therefore there occur current sheets where magnetic reconnection is possible.

3. Conclusions

We investigated 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. By using three-dimensional electromagnetic fields obtained from a resistive three-dimensional MHD equations during the single-loop flare, we investigated the orbit of many protons to obtain their energy spectra. We found that the protons can be accelerated to γ-ray-emitting energies (> 1 MeV) with double power-law spectra up to about 25 MeV. There appears a breaking point of the index of the power-law spectra from 1.8 to 2.1 near 10 MeV. The acceleration time $\omega_{ci}t$ = 1500 of the protons is about 10^{-3} s and quite rapid compared with the MHD time scale $\tau_A = a/V_A$ = 10 s, if we take an ion-cyclotron frequency of 1.34×10^6 rad/s for a magnetic field of 140 G and the loop radius of $a = 10^9$ cm. 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. We studied the loop disruption for two different plasma beta in the center of the loop; β = 0.5 and β = 0.05. In a high beta case (β = 0.5), the disruption of the loop is more violent than that of β = 0.05. We found that the proton acceleration for the case of β = 0.5 occurs mainly at two different regions; one is inside the loop and the other is in the upper part of the disrupting loop. However, the energy spectra of protons are very similar for both cases.

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