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Chaotic Reconnection Due to Mixing of the Vortex-Current Filaments

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Abstract

We propose a new reconnection mechanism "chaotic reconnection". The basic mechanism of the chaotic reconnection is examined by means of numerical simulations of collision between two vortex-current filaments. We conclude the chaotic reconnection is a faster process than the traditional resistive non-chaotic reconnection.

Keywords:
solar flare, chaos, magnetic reconnection, MHD, vortex-current filament

1. Introduction

Nowadays many researchers share a common aspect that the magnetic reconnection is a fundamental process in the solar flare [1]. Now it is accepted in most cases that the electric resistivity plays a minor role and most of the theoretical works on the reconnection to date deal with the time scale problem [2]. Here we shall propose a new fast reconnection mechanism "chaotic reconnection" of the vortex-current filaments in the three-dimensional space.

In Sec. 2, we give simulation results of collision between two straight vortex-current filaments and diagnosis via the Lyapunov exponents. The collision means the strong interaction between two filaments.

In Sec. 3, we show the basic mechanism of the chaotic reconnection. The mechanism is revealed by the evaluation of the reconnection rates and we conclude the chaotic reconnection is a faster process than the traditional resistive non-chaotic reconnection which has the simple configuration of the magnetic field.

2. Simulation Results

We have introduced the vortex-current filament model in our previous papers [3,4]. The vortex-current filament consists of the electric current and the vorticity inside it. As basic equations, we use the ideal MHD equations with gravity. Integrating the equation of motion over the small volumeelement, we obtain a macroscopic force balance equation correct to $O(\rho^{-2})$ where ρ is a local radius of curvature of the filament. The velocity of the filament $\partial \boldsymbol{R}/\partial t$ is given in the follwing form with the cutoff Biot-Savart integral correct to $O(\rho^{-1})$: [3]

$$\left(\frac{\partial \boldsymbol{R}}{\partial t}\right)_{\perp} = -\frac{J}{\kappa}(\boldsymbol{B}_E)_{\perp} + (\boldsymbol{u}_E)_{\perp} + \frac{\mu_0 J^2}{4\pi\kappa}\int \frac{(\boldsymbol{R}-\boldsymbol{x})\times \mathrm{d}\boldsymbol{x}}{\left(|\boldsymbol{R}-\boldsymbol{x}|^2+\alpha^2 a^2\right)^{3/2}} - \frac{\kappa}{4\pi}\int \frac{(\boldsymbol{R}-\boldsymbol{x})\times \mathrm{d}\boldsymbol{x}}{\left(|\boldsymbol{R}-\boldsymbol{x}|^2+\beta^2 a^2\right)^{3/2}} + \frac{\pi a^2}{\kappa}\boldsymbol{g}\times \boldsymbol{s} + \mathrm{O}(\rho^{-2}). \qquad (1)$$

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Illustration of the initial conditions of the simulation is given in Fig. 1. The most crucial parameter in our simulations is symmetry of the initial configuration of the filaments. The symmetry of the initial configuration is determined by an initial angle θ between the two filaments projected on the $x-z$ plane shown in Fig. 1. The values of the initial angle are chosen as $\pi/2$, 2 arctan (1/2) and zero which are called types (a), (b) and (c), respectively. The most symmetrical case is $\theta = 0$ and the most asymmetrical case is $\theta = \pi/2$.

We show typical results of simulations in Fig. 2. For all the types, the filaments are attracted each other and collide. Although the results for types (a) and (b) show complicated configuration near the collisional region, the result for type (c) shows non-complicated configuration. This is because the initial configurations of the types (a) and (b) are more asymmetrical than that of the type (c).

The time evolution of the instantaneous Lyapunov exponent is shown in Fig. 3. The largest peak for type (c) is due to the collision where the two filaments fully overlaps with each other. We consider that the other peaks at that time for types (a) and (b) are caused by the same reason. After the collision, the exponents only for types (a) and (b) are positive. We, therefore, conclude that the chaotic configuration is induced by the collision of the two filaments with initially low-symmetrical configuration.

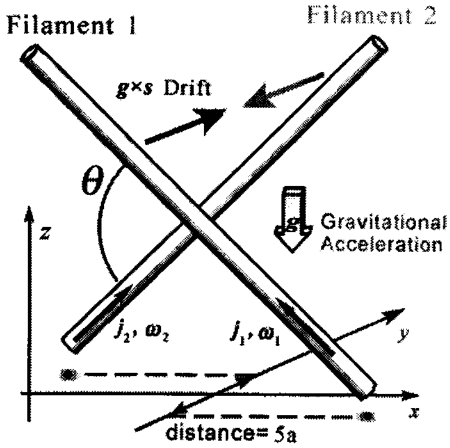

Fig. 1 Illustration of the initial conditions of the simulation is shown.

3. Chaotic Reconnection

We consider when the filament 1 approaches the filament 2 and the electric currents and the vorticities inside the filaments are antiparallel to each other respectively, the net electric current and vorticity must be nearly zero. This means the filaments should locally annihilate each other in that region. Here we introduce a three-dimensional space averaging. The three-dimensional space averaging is a kind of mixing. It is well known that the mixing increases the entropy of the system and this implies that the mixing is an irreversible process. Thus the space averaging is considered to introduce a dissipation process into the system artificially. We calculate the three-dimensional space-averaged distribution of the electric currents from the results shown in Fig. 2 numerically and trace the trajectories by its distribution. The results are shown in Fig. 4.

For types (a) and (b) in Fig. 4, the macroscopic filaments, which mean the reconstructed filaments obtained by tracing the distribution of the electric current, are reconnected with each other. The reconnection is due to the chaotic configuration induced by the collision of the two filaments in low-symmetry system. Thus it is obvious that the reconnection is not observed for type (c) because the initial configuration is symmetrical and the configuration does not evolve into a chaotic one. We call this reconnection mechanism "chaotic reconnection" henceforth [5].

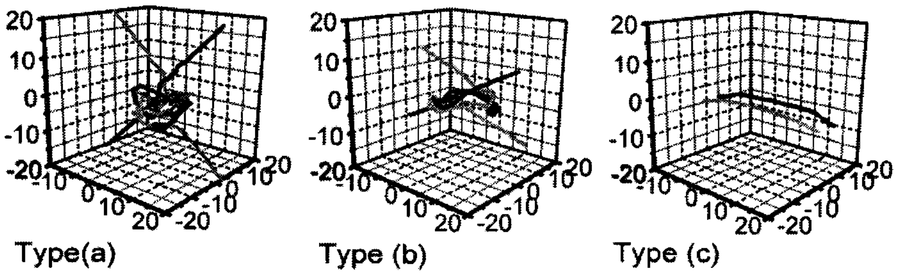

Fig. 2 Snap shots of the configuration of the filaments at $T = 75 \times 10^4 \Delta t$ are shown.

One can estimate the efficiency of the reconnection process by a reconnection rate. We assume the reconnection rate $R_f(t)$ of the chaotic reconnection is given by the following form:

$$R_f(t) = D(t)\Omega(t, \theta), \quad (2)$$

where $D(t)$ is a traditional non-chaotic reconnection rate determined by the resistive dissipation process of the system. The notation $\Omega(t, \theta)$ represents a normalized overlapping volume between the filaments per unit volume. The value of $D(t)$ is usually zero for the case of ideal MHD and positive for the case of non-ideal MHD. It is well known that a kind of dissipation process is needed for the mangetic reconnection. Thus a dissipation process, space averaging, is introduced in the present work because $D(t)$ should be finite.

Here we introduce another mesoscopic enhancement factor, normalized overlapping volume, to solve the time scale problem of the fast reconnection. The term mesoscopic means the scale which is describable by MHD but much less than the scale length of the phenomena while the collisionless process is microscopic. We consider the large $\Omega(t, \theta)$ yields the fast reconnection. Unnormalized overlapping volume is calculated from the time-developed configuration of the filaments numerically and is normalized by the non-chaotic overlapping volume which is determined by the initial configuration.

Evolution of the normalized overlapping volume $\Omega(t, \theta)$ is plotted in Fig. 5. For each type, there is a peak at $T = 25 \times 10^4$ or so and these peaks are due to the collision. In later time the values of the normalized overlapping volume become large for types (a) and (b) while zero for type (c). The large value of the normalized overlapping volume is rapidly achieved by the chaotic dynamics of the filaments based on the ideal MHD and the "diffusion regions" are formed anywhere in the collisional region along the tangled filaments. Then the reconnection rate $R_f(t)$ becomes sufficiently large if the factor $D(t)$ in Eq. (2) has a nonzero value. Thus we conclude the chaotic reconnection is a faster process than the traditional resistive reconnection owing to the enhancement by the large normalized overlapping volume. It is the main mechanism of the chaotic reconnection in the three-dimensional space. If the overlapping volume $\Omega(t, \theta)$ is small, the reconnection time scale is the same as that of the traditional resistive non-chaotic reconnection which is determined only by the factor $D(t)$.

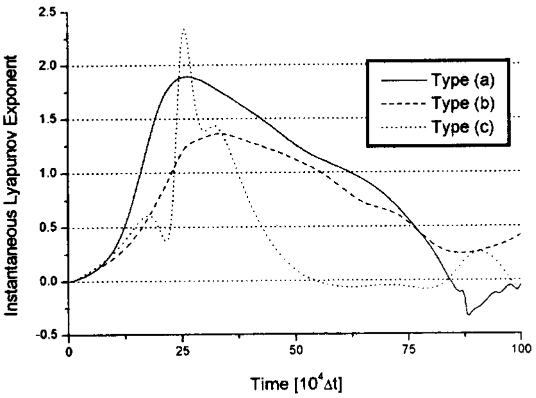

Fig. 3 Evolution of the instantaneous Lyapunov exponents are shown.

4. Conclusions

In this work we have proposed a new fast reconnection mechanism, "chaotic reconnection" of the vortex-current filaments in the three-dimensional space. Note that the basic dynamics are based on the nonlinear ideal MHD in which the time scale is mainly determined by the Alfvén transit time, although we have introduced

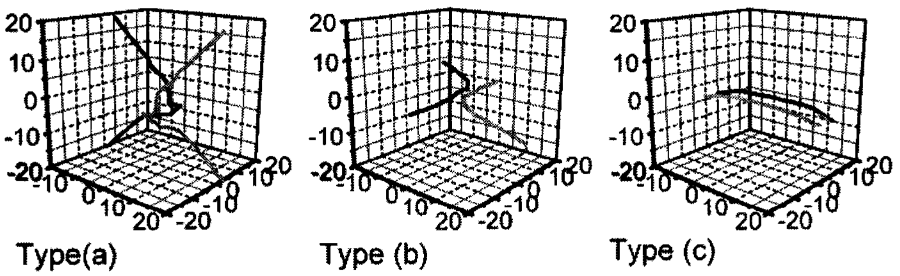

Fig. 4 Trajectory of the three-dimensional space-averaged distribution of the electric current is shown. Original data are given in Fig. 2.

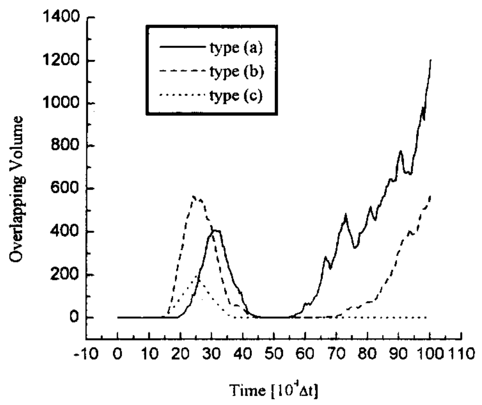

Fig. 5 Evolution of the normalized overlapping volume $\Omega(t, \theta)$ is plotted.

a dissipation process, i.e. three-dimensional space averaging. We must extend the present model to the realistic one and apply our model to the solar flare. Further progress in understanding chaotic reconnection dynamics requires the fully three-dimensional MHD simulations in the high magnetic Reynolds number.

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