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Instability of the Sweet–Parker–like reconnecting current layer

Marina Skender[1] and Giovanni Lapenta[1]

Centrum voor Plasma Astrofysica, Katholieke Universiteit Leuven,
Celestijnenlaan 200B bus 2400, 3001 Leuven, Belgium
Marina.Skender@wis.kuleuven.be

Abstract. A two−dimensional reconnecting current sheet is studied numerically in magnetohydrodynamics approach with the aim of getting more insight on the nature of the instability taking place. At studied value of Lundquist number $S = 10^4$ and Reynolds number $R = 10^4$ a Sweet–Parker–like current sheet is observed to form, followed by the fragmentation, which leads to the fast reconnection. The Sweet–Parker–like current sheet does not reach the stationary state characteristic of the Sweet–Parker reconnection. Rather, it evolves very slowly and is therefore identified as a quasiequilibrium current sheet. It has increasing ratio of the length and width (aspect ratio) whose maximum is found to correspond with the detected fragmentation. This qualitative scenario is confirmed for the simulations with the initial Harris and force–free equilibria applied, for the periodic and open–boundary conditions with uniform and non–uniform grid prescribed, respectively, and for varying sizes of the numerical system.

Key words: quasiequilibrium current sheet, impulsive bursty reconnection, tearing–mode instability, aspect ratio

1 Introduction

Magnetic field reconnection is a fundamental plasma process, which converts magnetic energy into kinetic and thermal energy. When two highly conductive plasma systems with oppositely directed magnetic field components are placed in contact, an electric current sheet develops in between. In the electric current sheet the magnetic field lines break and reconnect [1]. Magnetic reconnection can create fine–scale structure and filamentation, large electric fields and shock waves which can accelerate particles. It is considered to be a major mechanism for energy release in large–scale solar phenomena, stellar flares, planetary and cometary magnetospheres, as well as in tokamak disruptions.

In the Sweet−Parker (SP) model [2],[3] reconnection takes place in a diffusion region of length L and width l. Magnetized plasma enters the diffusion region while the reconnected plasma flows out of the system along the current sheet and the stationary state is established. SP model is characterized by a relatively low rate of reconnection, M_e, scaling with the magnetic Reynolds number, R_m, as $M_e = R_m^{-1/2}$.

Furth, Killeen and Rosenbluth [4] studied resistive linear tearing instability, in which a wavelike perturbation is applied to the whole plasma in a static configuration. Following the theory of resistive linear tearing instability, the current sheet would be practically always unstable and also leading to faster reconnection. Bulanov *et al.* [5] considered a current sheet with a finite thickness l, and found that the effect of the outflow stabilizes the tearing instability.

In the study by Priest [6], a sufficiently long diffusion region unstable to tearing is suggested to precede impulsive bursty reconnection, characterized by a high reconnection rate. Forbes and Priest [7] formulated a criterion for development of this onset with such tearing. It was confirmed to take place in many numerical experiments, *e.g.* [8],[9],[10],[11].

The advancement of observational technology provided more direct evidence of magnetic reconnection on the Sun. Theoretical considerations which take into account the width of the current sheet are of particular value for interpreting large−scale solar eruptive phenomena, *e.g.* [12]. In the study of Lin *et al.* [13] the width and the electrical resistivity of the current sheet developed between a coronal mass ejection and the associated flare are estimated. It is indicative of a relatively thick current sheet, with a large−scale turbulence operating within. Vršnak *et al.* [14] made a rough assessment of the size of a similarly situated current sheet.

The study presented here shows conclusively that at a comparatively low resistivity value, in the system of Lundquist number $S = 10^4$, a finite sized reconnecting current sheet does not reach the stationary state of SP. Rather, it evolves very slowly, presumably at diffusion times, and eventually enters a phase of impulsive bursty reconnection. The aspect ratio of the slowly evolving current sheet is seen to grow until it reaches a maximum.

2 Evolution of the current sheet in two numerical systems

A two−dimensional reconnecting current sheet is studied by utilizing the particle–in–cell FlipMHD code, which solves the set of equations for viscous and resistive MHD flow [15], [16]. Two differently set numerical systems are considered: One with initial Harris and the other with force−free equilibrium, and with periodic and open boundary condition applied, respectively.

2.1 Harris equilibrium and periodic boundary condition applied

The typical case with the initial Harris equilibrium set, following the setup of the GEM challenge [17], is presented. The periodic boundary conditions are chosen in the direction along the current sheet and the uniform grid is prescribed. The physical size of the system in each direction is labeled as L_x, L_y, and L_z. The initial equilibrium is two−dimensional and independent of the y−coordinate.

Resistivity, η, is defined through the Lundquist number $S = 10^4$, $S = LV_A/\eta$, with the length and Alfvén speed set to $L = V_A = 1$, and viscosity, μ, is given by Reynolds number $R = 10^4$, $R = LV_A/\mu$. In the study presented here the size of the physical box is $L_x/L = 80$ and $L_z/L = 80$, with 960×960 Lagrangian markers arrayed in a grid of 320×320.

Initial Harris current sheet is along the x−axis and the z−axis is across it. The initial perturbation of the system creates a tearinglike instability, which is is observed to form an evolving current sheet of a finite length and width [18],[19].

The evolving current sheet is characterized by a low reconnection rate, cf. Fig. 1(a): During $t/\tau_A \leq 300$ the reconnection rate is $\sim 4 \cdot 10^{-4}$ which is ~ 25 times lower than the reconnection rate a stationary state SP−current sheet would have, $M_{SP} \approx 10^{-2}$.

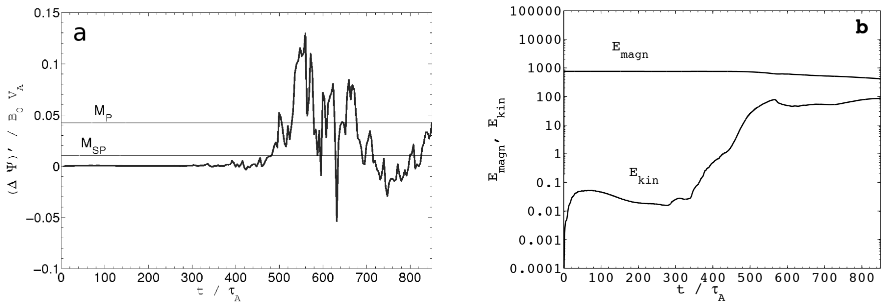

Fig. 1. (a) Reconnection rate as a function of time. Reconnection rate is computed as the time derivative of the reconnected flux, which is obtained as the difference of the maximal and minimal out−of−plane component of the vector potential along the current sheet, $A_y^{max}(z) - A_y^{min}(z)$, through the X−point. The lower horizontal line corresponds to the reconnection rate a stationary SP−current sheet would have, $M_{SP} \approx 1/\sqrt{S} = 10^{-2}$. The higher horizontal line depicts the maximal fast reconnection rate a stationary Petchek current sheet would have (cf. [20],[21]), $M_P \approx \pi/8 \ln S$. Quasiequilibrium current sheet is characterized by the reconnection rate lower than that of a stationary SP−current sheet. The phase of the impulsive bursty reconnection is characterized by a distinctively higher reconnection rate. **(b)** Magnetic energy and global kinetic energy as a function of time. During the quasiequilibrium phase of the evolution the global kinetic energy (lower curve) is much smaller than the magnetic energy (upper curve). Energy is normalized according to $L_A = V_A = 1$.

Moreover, at a comparatively low resistivity value corresponding to $S = 10^4$, we did not infer the scaling of SP any more (cf. [22]), which is consistent with the solely time−dependent reconnection found by Loureiro [23]. This suggests that at a relatively low resistivity value the current sheet does not reach the SP−stationary state, but it rather evolves slowly through a series of quasiequilibria. The quasiequilibrium current sheet is characterized by the global kinetic energy being being much less than the magnetic energy, cf. Fig.1(b).

The quasiequilibrium current sheet is seen to finally undergo the fragmentation [22] and subsequently enter the phase of impulsive bursty reconnection. In

Fig. 1(a) a distinctive increase of the reconnection rate after $t/\tau_A \sim 450$ can be inferred, which characterizes impulsive bursty phase of the evolution of the current sheet. The aspect ratio of the current sheet is found to reach a maximum, after which it decreases (cf. [22]).

2.2 Force−free initial equilibrium and open boundary condition applied

The case with initial force−free equilibrium set, following [24], open boundary conditions applied, and the nonuniform grid in the direction across the current sheet is presented. The size of the physical box is again $L_x/L = 80$ and $L_z/L = 80$, with 960×960 Lagrangian markers arrayed in a grid of 320×320. This level of accuracy results in converged solutions, as proved by testing with increasing the time step and the grid spacing. Lundquist and Reynolds numbers are taken, at adopted values $S = 10^4$ and $R = 10^4$, respectively.

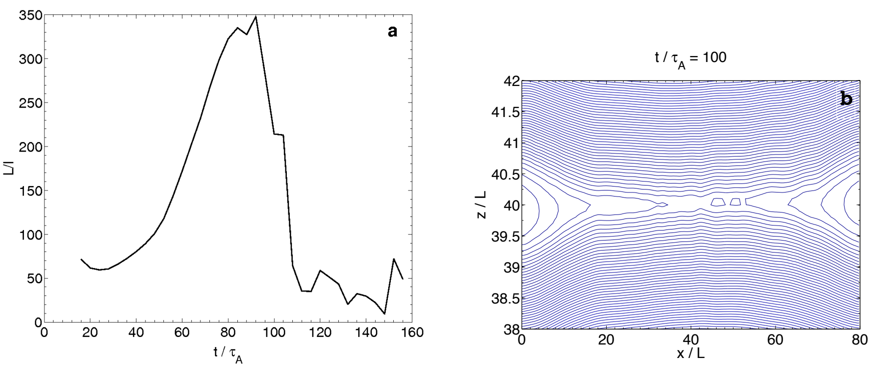

Fig. 2. (a) Aspect ratio as a function of time. Aspect ratio of the quasiequilibrium current sheet reaches a maximum value at $t/\tau_A \sim 100$, just before the fragmentation starts. **(b)** Out−of−plane component of the vector potential A_y at $t/\tau_A = 100$, when the fragmentation of the current sheet becomes apparent.

In this version of the simulation, with different initial and boundary conditions and different type of grid, qualitatively the same scenario is found: formation of a quasiequilibrium current sheet, whose aspect ratio increases in the attempt to reach the SP−stationary state, the instability which overtakes and fragments the system, leading it to the phase of the impulsive bursty reconnection.

In this setup the quasiequilibrium current sheet is found to be thinner and longer during its evolution prior to the fragmentation. The aspect ratio reaches a maximum, as seen in Fig. 2(a), at $t/\tau_A \sim 100$. The aspect ratio is calculated from the size of the current sheet inferred as the region where the out–of–plane component of the current is more than 85% of the maximal j_y. The maximal aspect ratio is in this version of the simulation immediately succeeded by the fragmentation of the current sheet, as can be seen in Fig. 2(b).

The periodic boundary condition applied in the first numerical setup presented here limits lengthening of the current sheet by pushing the outflow backward, therefore making the aspect ratio reach its maximum earlier before the fragmentation starts taking place, cf. [22]. In the case of the open boundary condition applied, as presented in the second numerical setup here, there is no countering effect which limits lengthening of the quasiequilibrium current sheet, *i.e.* the length of the current sheet is limited only by the size of the box, and therefore the aspect ratio increases all the time, until the fragmentation starts taking place.

3 Summary and discussion

Evolution of a two−dimensional quasiequilibrium current sheet is studied numerically in MHD approach. Two different numerical setups are employed: in the first the periodic boundary condition, uniform grid and the initial Harris equilibrium are applied, while in the second configuration the open boundary condition, non−uniform grid and a force−free initial condition is prescribed.

Evolution of the current sheet in the two different numerical setups follows qualitatively the same scenario: slowly evolving current sheet is formed after perturbing the initial equilibrium state, it reconnects at a rate much slower than the stationary SP model has, it becomes fragmented and eventually it enters a phase of impulsive bursty reconnection.

The aspect ratio of the quasiequilibrium current sheet is found to increase until it reaches a maximum value. In the configuration with the periodic boundary condition applied the lengthening of the current sheet is restricted, which causes the aspect ratio to reach its maximum earlier before the fragmentation. The configuration with the open boundary condition applied enables the lengthening of the current sheet limited only by the size of the box, which has a consequence of the maximal aspect ratio being reached immediately prior to the fragmentation of the system.

In the simulations presented here the adopted Lundquist number is $S = 10^4$, for which the reconnected flux of the quasiequilibrium current sheet is not inferred to scale as SP current sheet [22]. This result suggests that at comparatively small values of resistivities in the system the current sheet does not reach the stationary state, which is consistent with the finding of solely time−dependent reconnection by Loureiro [23].

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