Self-Feeding Turbulent Magnetic Reconnection on Macroscopic Scales

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Within a MHD approach we find magnetic reconnection to progress in two entirely different ways. The first is well known: the laminar Sweet-Parker process. But a second, completely different and chaotic reconnection process is possible. This regime has properties of immediate practical relevance: (i) it is much faster, developing on scales of the order of the Alfvén time, and (ii) the areas of reconnection become distributed chaotically over a macroscopic region. The onset of the faster process is the formation of closed-circulation patterns where the jets going out of the reconnection regions turn around and force their way back in, carrying along copious amounts of magnetic flux.

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Reconnection is one of the most active areas of research in plasma physics [1,2]. Reconnection is believed to be a crucial engine of energy conversion in astrophysical objects such as the environment of black holes [3] and stars [2] and in laboratory experiments [4]. In reconnection, magnetic field lines break and reconnect changing their topological connectivity [1] and in the process convert magnetic energy into kinetic and thermal energy. Explaining how reconnection can be an active agent for energy exchanges in macroscopic systems requires addressing two fundamental problems.

The first problem is that the detailed study of reconnection leads to the conclusion that reconnection is a very localized process developing in tiny regions (called diffusion regions) within the overall system. However effective such a localized process may be, still how can it affect large fractions of the system energy? There is a need to explain how a vast area of magnetic field and energy can undergo such a process when it takes place on very small scales. A suggestion [5,6] has been made that reconnection might take place in large areas in the form of a cluster of many diffusion regions filling a significant area of the domain. This proposal is very attractive, but evidence for such a process is still lacking, either as direct observational evidence or as simulation demonstration.

A second difficulty is to achieve the required rate of reconnection. Reconnection requires dissipative processes usually not present in a simple description of the plasma as a resistive fluid: the level of resistivity present in the system is vastly insufficient to explain the observed rates. Reconnection can be fast on the microscopic scales [7] or when the process of reconnection is driven by flows [1] (spontaneously generated in the system or created externally).

We report here a possible mechanism capable of inducing a turbulent (meant here simply to imply a chaotic process) reconnection region encompassing a large scale portion of a macroscopic system and where reconnection aliments itself requiring no external flows to keep a fast rate of reconnection.

Reference systems considered.—For simplicity we consider two types of systems initially in a 1D equilibrium state described either as a balance of magnetic and plasma pressure (the so-called Harris sheet):

$$\mathbf{B}(z) = B_0\{\tanh(z/L), 0, 0\}; \qquad p(z) = p_0 \operatorname{sech}(z/L), \tag{1}$$

or as a force-free equilibrium in a uniform plasma:

$$\mathbf{B}(z) = B_0\{\tanh(z/L), \operatorname{sech}(z/L), 0\}; \qquad p(z) = p_0. \tag{2}$$

To follow a now standard procedure that facilitates comparison with previously published works, the evolution of the system is initiated by an initial perturbation chosen according to the so-called GEM challenge [7]: $\delta A_y = \epsilon B_0 L \cos(2\pi(x - L_x/2)/L_x)\cos(\pi z/L_z)$, with $\epsilon = 0.1$. We consider the 2D plane $(x, z) \in [0, L_x] \times [-Lz/2, L_z/2]$ where reconnection develops.

The aim of the present Letter is to consider macroscopic processes (on scales much larger than the ion inertial length); therefore, the fluid MHD approach is appropriate, compared with the kinetic approach valid at all scales but relevant only at small scales below what is considered here. We use the FLIP3D-MHD code [8], based on the viscoresistive MHD equations and including an energy equation and an ideal equation of state with adiabatic index $\gamma = 5/3$. The simulations reported below have different system sizes (listed in each case) but all have grid spacing $\Delta x/L$, $\Delta z/L = 1/12$ and time step $\Delta t/\tau_A = 0.05$ (with the Alfvén time $\tau_A = L/v_A$). This level of accuracy results in converged solutions, as tested by comparing simulations with a time step or grid spacing increased separately by a factor of 2. Periodic boundary conditions are used along x to try to mimic similar events happening in nearby regions of the system, as proposed in the mechanism suggested in Ref. [6]. In z, the so-called no-slip conditions (i.e., no parallel flow is allowed and the boundary is impermeable to the plasma; the magnetic field remains parallel to the wall) are used. This choice of the boundary conditions

could impede the flow patterns that will be analyzed below, reducing the rate of reconnection compared with an open system. For this reason we have conducted simulations with varying vertical box size ($L_z = 40$, 60, 80, 100, 120) and we have compared with open boundary conditions (as in Ref. [9]). The results are not affected, qualitatively or quantitatively, proving that the boundary in z is far enough from the reconnecting layer as not to affect the evolution. Viscosity and resistivity are uniform and are expressed via the Reynolds (R) and Lundquist (S) numbers [1].

The evolution of the topology of the magnetic surfaces and of the stream function is monitored. The intersection of the magnetic surfaces in the plane of a 2D system are easily obtained as contour lines of the component of the vector potential along the ignorable direction (y in our choice of coordinate system): A_y [1]. The stream function ψ is a fluid quantity that plays a similar role for the streamlines that A_y plays for the magnetic surfaces [1].

Two stage system evolution.—The system evolves in two phases. Figure 1 shows the evolution of the reconnected flux (i.e., the amount of magnetic flux that has passed through the reconnection process) from its initial configuration with only open field lines starting on one vertical boundary and exiting the other to its final state with a new topology including field lines connected to the same vertical boundary at both ends (referred to as closed; see Fig. 2 below). The reconnected flux is eventually collected towards the two ends of the system ($x = 0$, L_x) of the system because of the choice of periodic boundary conditions and of the initial perturbation (symmetric and strongest in the center).

The reconnected flux (that causes the presence of the new closed field lines) is measured as described in the textbook procedure for 2D systems [1]: the out of plane vector potential A_y is computed and on the mid axis ($z = 0$) its maximum and minimum are computed, their difference, initially zero, provides the amount of flux in the closed field lines, caused by reconnection.

To show the robustness of the processes discussed, different equilibria and dissipations are used. For both types of equilibria, there is one slow reconnection phase followed by a vastly faster process where almost all reconnection happens.

The evolution shown in Fig. 1 presents clearly two phases. At first, the flux is very slowly reconnected and the details of the the growth (slope of the curve) and its duration vary widely with viscosity and resistivity (measured by R and S). The second phase is much faster and is rather insensitive to both viscosity and resistivity.

We focus here on the transition between the slow phase and the fast phase showing that it is linked to the formation of a self-feeding process where the fast flow out of the reconnection regions is recycled into the inlet of the reconnection region causing a feedback loop where the reconnection process feeds on itself. Furthermore, we

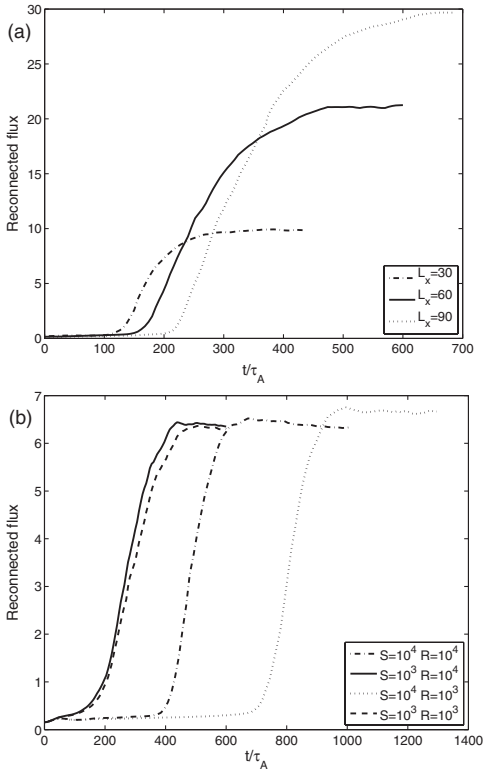

FIG. 1. Reconnection rate for two types of equilibria. Note the different vertical and horizontal scales in panel (a) and (b). Panel a: Harris sheet, Eq. (1). Different horizontal system sizes are used: $L_x/L = 30$, 60, 90, with the same vertical size ($L_z/L = 120$), viscosity (Reynolds number, $R = 10^4$) and resistivity (Lundquist number, $S = 10^4$). Panel (b): Force-free, Eq. (2). Different viscosity (Reynolds number, R) and resistivity (Lundquist number, S) are used: $R = 10^3$, $10^4$and $S = 10^3$, 10^4, for the same system size: $L_x/L = 30$, $L_z/L = 40$.

show that the process is chaotic leading to multiple short lived reconnection regions popping up randomly, frequently and at multiple locations simultaneously. Even though the process is dynamical and active with a continuous creation and destruction of reconnection sites, the overall rate remains remarkably steady: the reconnected flux increases monotonically during the fast reconnection phase shown in Fig. 1, despite the dynamical physics behind it.

Each phase needs resistivity as its core dissipative mechanism: in a complete kinetic description this feature would change the details of the rate of reconnection in each phase but the overall transition between the two phases is not a process dependent on the presence of resistivity or on its value. Similarly viscosity is not a key element. Let us turn the attention now on this mechanism allowing the transition from slow to fast reconnection.

Self-feeding and the nature of faster reconnection.—The transition to the fast reconnection process is characterized by the transition from a state where the outflow from a single reconnection region remains localized near the central horizontal axis of the system to a state where the

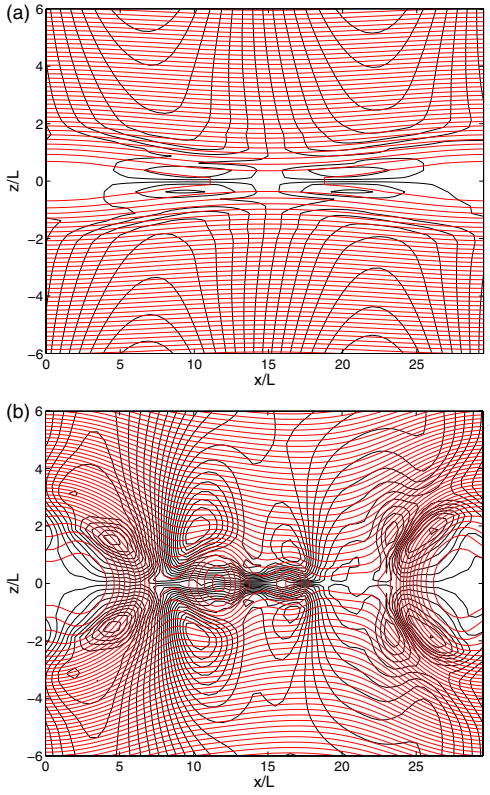

FIG. 2 (color online). Magnetic topology and flow pattern at two times: during the slow phase (a: $t/\tau_A = 100$) and during the fast phase (b: $t/\tau_A = 200$). In red: intersection of the magnetic surfaces with the plane of the simulation. In black: contours of the stream function, corresponding to the circulation lines everywhere tangent to the flow speed. Results from the Harris equilibrium run with $L_x/L = 60$, $L_z/L = 120$, $R = 10^4$ and $S = 10^4$. Blow up around the central axis.

outflow spills into the bulk of the system and forms a circulation loop out of the reconnection region and directly into it. Figure 2 shows the plasma circulation at different times, as measured by the stream function of the plasma. At the early time during the slow reconnection phase, the jets from the one and only reconnection site caused by the initial perturbation remains bound to the axis in the outflow region. At the later time during fast reconnection, loops are formed in the plasma flow that link the outflow with the inflow to the reconnection region. The fast reconnection process is accompanied by a direct circulation pattern between the inlet and outlet of the reconnection sites. It is as if a pipe was feeding the plasma exiting at fast speeds from the reconnection region back into the inflow: but at each passage, the flow brings in new magnetic field lines that become decoupled with the plasma in the reconnection region and contribute to the global reconnection on large scales.

In the fast reconnection phase, the reconnection process changes nature. The Sweet-Parker (SP) layer [2] present during the slow phase of reconnection becomes destabilized and multiple islands form. In between islands, x points form where each reconnection site is driven by its own self-feeding circulation pattern (as well as by neighboring reconnection sites [10]). In the fast phase, the reconnection process resembles more the x-point configuration of driven reconnection than the y-point configuration of spontaneous SP reconnection [2], thereby enabling the faster rate.

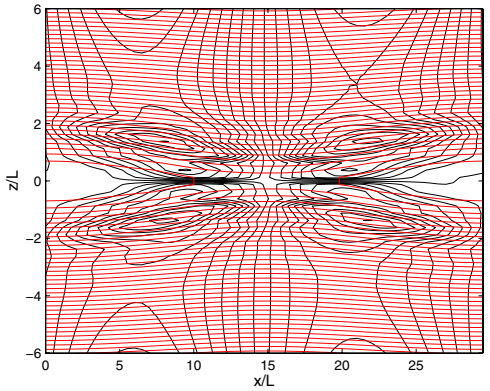

FIG. 3 (color online). Magnetic topology and flow pattern shown for the same case as in Fig. 2, but at a time right before the start of the fast phase ($t/\tau_A = 150$).

In smaller systems (smaller than reported here), the process described above is inhibited by the limited size in the horizontal direction. Under those circumstances, the SP layer may become unstable to secondary islands (as reported in Ref. [11] for the so-called GEM challenge) but the transition to the chaotic stage of reconnection is possible only in large macroscopic systems, as shown above.

The transition between slow and fast reconnection is linked to the formation of these self-feeding circulation patterns: during the slow phase the flows have not yet formed the self-feeding patterns. The results support the view that the formation of the circulation pattern precedes the onset of faster reconnection. Figure 3 shows the magnetic topology and flow pattern at a time when reconnection is still progressing slowly. Clearly the pattern is forming. The observation of subsequent frames (visible in movies) shows the first formation of the self-feeding loops during the slow phase, its subsequent strengthening until eventually the reconnection rate takes off strongly. There is a time interval when even though the speed of reconnection has not increased yet, the circulation pattern is already forming, thereby preceding the onset of faster reconnection. This fact suggests (but does not prove) that the circulation pattern is indeed the cause of fast reconnection and not one of its effects.

The destabilization of the outflowing jets from the laminar reconnection phase and the formation of the self-feeding loops is due to the interaction of the newly reconnected plasma with the magnetic flux already accumulated in the outflow region. This process is more effective for smaller systems where less room is available for the reconnected flux. Indeed, as L_x/L is increased from 30 to 60

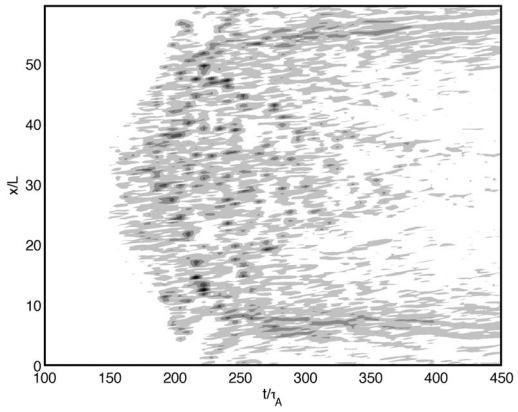

FIG. 4. Evolution in space (vertical axis) and time (horizontal axis) of the magnetic islands. Results from the Harris run with $L_x/L = 60$, $L_z/L = 120$, $R = 10^4$, and $S = 10^4$. Note that a limited temporal span is shown.

to 90, the time to onset increases linearly. Furthermore, the destabilization of the flows and the onset of faster reconnection is delayed if the outflow is impeded by dissipations (lower R) or by the presence of an out of plane magnetic field (as in the case of the initial force-free equilibrium) that diverts part of the kinetic energy gained in the reconnection region towards the out of plane direction.

Multiplicity of reconnection sites.—The self-feeding process described above is not steady: the islands are continuously created and destroyed in a chaotic process. Figure 2(b) shows a pattern of different reconnection regions in proximity of different islands and self-feeding circulation patterns each with its own size, some are emerging others are dying off to be replaced continuously by new ones. For comparison, the slow phase of reconnection [see Fig. 2(a)] has just one single long SP layer, a well-known feature of slow laminar reconnection [2].

Figure 4 shows the space-time evolution of the magnetic islands in the central horizontal plane of the simulation with $L_x = 60$. Magnetic islands correspond to regions of increased curvature of the out of plane component of the vector potential: darker regions in the plot correspond to regions of increased $|\partial^2 A_y/\partial x^2|$. Other typical indicators of reconnection (e.g. reconnection current or reconnection electric field) lead to similar plots, not reported. Different reconnection regions and different islands are continuously created with a limited life span. At any given time, there is the contemporary presence of multiple reconnection sites. The reconnection process is very dynamical and chaotic, even though the overall accounting of the amount of flux processed by reconnection progresses steadily (as shown in Fig. 1).

We point out two crucial differences of the chaotic reconnection region, compared to previously considered turbulent scenarios. First, the transition towards a turbulent reconnection process is spontaneous and it is not initiated by imposing turbulent fields or flows [12]. Second, the chaos considered here is intrinsic of the fluid model and bears no relationship with the microscale (kinetic) turbulence embodied by the so-called anomalous resistivity: here resistivity is fixed and uniform, the independence of the rate of reconnection from resistivity is caused by the mechanism produced by the self-feeding closed-circulation loops.

Recapitulation.—Results are reported above using two different types of equilibria: Harris and force-free equilibria. In both cases the system given a standard initial perturbation goes through two stages. The first is the well-known SP laminar reconnection [2] that crawls on the resistive time scales. The second phase takes off at later times, depending on the parameters and the initial equilibrium, and corresponds to a faster and turbulent reconnection process. The chaotic stage is anticipated by the destabilization of the outflowing reconnection jets which turn back towards the reconnection region and form a conveyor-belt closed-circulation loop that carries quickly new magnetic flux at the reconnection point where it becomes decoupled from the flow and contributes to the overall macroscopic reconnection process. The flow pattern and the current layer become chaotic with recurrent changes of number and locations of reconnecting points and magnetic islands. The process of reconnection becomes fast as it is driven by the incoming flow due to the self-feeding of the closed-circulation patterns.

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