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# Magnetic Reconnection: MHD and Beyond

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**Abstract.** A new paradigm is suggested for 3D magnetic reconnection where the interaction of reconnection processes with current aligned instabilities plays an important role. According to the new paradigm, the initial equilibrium is rendered unstable by current aligned instabilities (lower-hybrid drift instability first, drift-kink instability later) and the non-uniform development of kinking modes leads to a compression of magnetic field lines in certain locations and a rarefaction in others. The areas where the flow is compressional are subjected to a driven reconnection process on the time scale of the driving mechanism (the kink mode). In the present paper we illustrate this series of events with a selection of simulation results.

## INTRODUCTION

We consider a new paradigm for 3D magnetic reconnection where the interaction of reconnection processes with current aligned instabilities plays an important role. The new paradigm is suggested by kinetic models where the lower-hybrid drift instability (LHDI) and kink modes (KM) [15, 8] drive field lines together and promote the onset of reconnection [14]. The new paradigm is suggested by MHD models where the presence of velocity shear induces a Kelvin-Helmholtz instability (KHI) that drives reconnection by locally compressing field lines [5, 6, 11, 12, 16].

According to the new paradigm, reconnection in 3D is eminently a naturally driven process. The driving force is determined by the instabilities developing in the current aligned direction. For the typical magnetotail configuration with the current in the dawn dusk direction ($y$) and the field mostly in the tailward direction ($x$) and the gradients mostly in the north-south direction ($z$), the tearing instability develops in the $(x,z)$ plane. The collisionless tearing instability has long been considered the best hope to explain reconnection onset. However, accurate studies have not yet resolved the issue of the instability of the tearing mode in actual realistic magnetotail configurations. Most of the results seem to conclude that the tearing mode is stable in realistic configurations and that reconnection onset has other causes [17].

The new paradigm for 3D reconnection cited above deals with the issue of reconnection onset. It is a new explanation of how reconnection can start, of what mechanism breaks the frozen in condition in the first place. In a spatially varying magnetic field configuration (such as the Earth magnetotail [15] or a corona arcade [16]) or in presence of spatially varying flow shear (such as at different latitudes along the magnetopause [6, 11]) the non-uniform development of kinking modes leads to compression of magnetic field lines in certain locations and rarefaction in others. The areas where the flow is compressional are subjected to a driven reconnection process on the time scale of the driving mechanism (the kink mode). In the new paradigm, two main physics processes must be considered.

First, the kink modes, including both the KHI and the drift kink instability (DKI) [13, 7], can drive field lines together, causing a localized compression that drives field lines to reconnect [6].

Second, new oblique modes are excited and contribute to the process of reconnection [14].

This new paradigm is distinct but complementary to the other recent remarkable progress in understanding fast reconnection through the role played by the Hall physics [2]. The Hall fast reconnection that has attracted so much recent attention is relevant to the fully developed reconnection process in the non-linear phase. The progress in that area has brought about understanding of the fast reconnection rates observed naturally. But still leaves us at a loss in trying to understand reconnection onset. It is the new paradigm for the role of current aligned instabilities that gives us the tools to understand onset of reconnection.

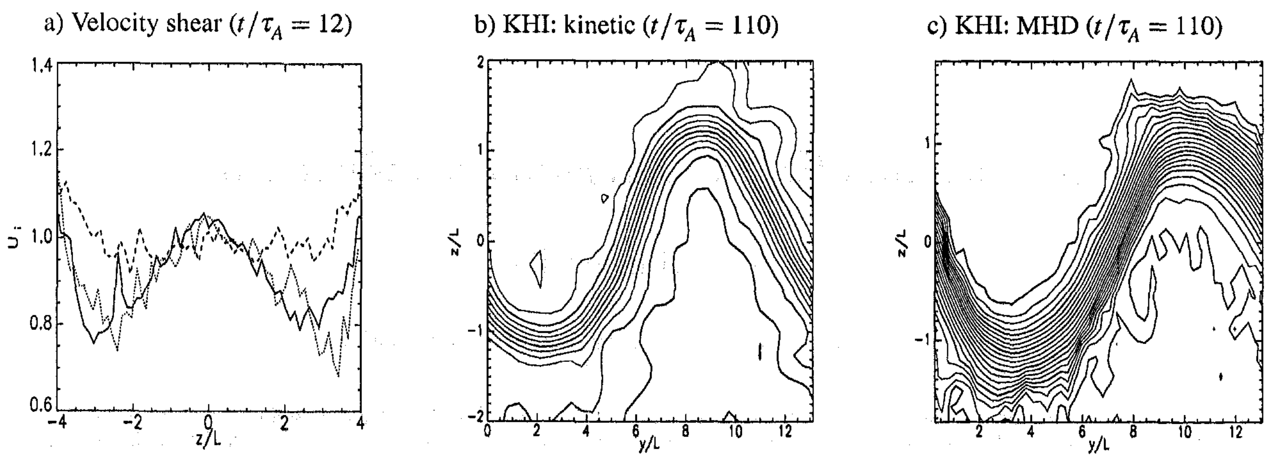


**FIGURE 1.** Harris equilibrium with $u_i/v_i = 1$, $m_i/m_e = 180$. Velocity shear (a) produced by the LHDI in a kinetic simulation ($t/\tau_A = 12$). Three different temperature ratios are considered: $T_i/T_e = 10$ (solid); $T_i/T_e = 4$ (dotted); $T_i/T_e = 2$ (dashed). Contour plot of $B_x(y,z)$ at the end of two simulation ($t/\tau_A = 110$): b) a fully kinetic simulation with no initial shear; b) a MHD simulation with an initial shear equal to the shear observed in the kinetic simulation after saturation of the LHDI. Details in (Lapenta and Brackbill, 2002).

## PHYSICAL SYSTEM

The Earth's magnetotail is described with the Birn's empirical profile chosen to best fit the actual magnetotail [1]. The system is simulated using the Vlasov-Maxwell model. In the present work, relativistic effects will be neglected. The Vlasov-Maxwell system is solved using the CELESTE 3D implicit particle in cell code. A detailed description of the implicit moment method used in CELESTE 3D can be found in the review paper [3] and the details of the implementation can be found in [18].

For comparison, we will also consider simulations conducted with the 3D MHD code FLIP–MHD [4].

## VELOCITY SHEAR

The initial equilibrium considered above is unstable to a number of current aligned instabilities, propagating along $y$. Two are of particular importance for understanding reconnection onset: the lower hybrid drift instability (LHDI) and kinking modes (KM).

Recent simulation work [15, 8] has shown that the early dynamic of current sheet is dominated by the LHDI. It has been observed [15, 8] that the nonlinear evolution of the LHDI changes the initial density and current profile and modifies the initial flat velocity profile by creating a velocity shear. Figure ?? shows the velocity profile after saturation of the LHDI. The creation of a robust velocity shear is evident. It sould also be noted that the LHDI growth rate and saturation level is directly proportional to the $\sqrt{T_i/T_e}$ just like the velocity shear observed in Fig. ??, an indication that the velocity shear is caused by the LHDI.

It is interesting to note that the process of creation of velocity shear by the LHDI is reminiscent of the creation of zonal flows [10] observed in tokamaks in relation with the L-H transition [9].

Once a velocity shear is created in the short time scales of the LHDI a much slower fluid instability arises, the Kelvin-Helmholtz instability (KHI). The process can be modeled very simply using MHD. Figure 1-a shows a fully kinetic simulation where the velocity shear is created initially by the LHDI and is destabilized later by the KHI. At the end of the simulation the distinctive kinking caused by the KHI is observed. Figure 1-b shows a simple MHD simulation with the same initial equilibrium used for the kinetic simulation but with the addition of an initial velocity shear equal to the velocity shear formed naturally by the LHDI in the kinetic simulation. Clearly, the comparison of Fig. 1-a and Fig. 1-b proves that the evolution following the creation of shear is purely a fluid instability. However, note that in the kinetic simulation the velocity shear arises naturally while in the MHD simulation the shear is artificially introduced as an initial condition.

## RECONNECTION ONSET

The evolution of the KHI and the kinking of the initial current sheet has an important consequence on reconnection onset. The presence of kinking causes the compression of the field lines in some regions and the rarefaction in others. Compression of field lines can drive reconnection. Such mechanism has already been observed in MHD simulations of the evolution of the KHI and tearing instability [5, 12] for application to the Earth magnetopause [6, 11] and to the solar corona [16]. The present paper is the first instance where the same mechanism is observed in the magnetotail.

In the references just cited, the mechanism was proposed in presence of externally driven shears (driven by the solar wind in the case of the magnetopause [6] or driven by the photosphere in the case of the corona [16]). In the magnetotail we suggest that, instead, the shear is created naturally by the LHDI without requiring any external action. Once the current sheet is thin enough for the LHDI to cause the velocity shear the chain of events sets in place and causes the onset of reconnection. The only required external action is the transfer of flux from the dayside to cause the thinning of the magnetotail.

An illustration of how the KHI can drive reconnection onset is presented in Fig. 2. A typical magnetotail (Fig. 2-a) described by eq. (??) is rendered unstable to the KHI by the velocity shear induced by the LHDI. The KHI moves the current sheet up and down, compressing field lines in some regions and rarefying in others. A region of field line compression is evident in the northern side of the near Earth tail in Fig. 2-b. Eventually, field line compression drives reconnection (Fig. 2-c). Note that a 2D simulation of the same initial configuration cannot capture the presence of the KHI and the mechanism just proposed would not be observed. Indeed, in a 2D simulation of the equilibrium shown in Fig. 2-a, the tearing mode is stable due to the electron compressibility [17] and reconnection never sets in. Only 3D simulations can capture the chain of events proposed in the new paradigm for naturally driven reconnection onset.

## CONCLUSIONS

A new scenario for magnetotail reconnection has been presented. The scenario is based on a sequence of three events.

First, the LHDI grows and saturates changing the initial equilibrium. A consequence of this change is the creation of a velocity shear that renders the equilibrium unstable to the KHI.

Second, the KHI grows and kinks the current sheet causing regions of compression of field lines.

Third, local compression drives field lines together and causes the onset of reconnection. Once reconnection is started by the driving force of the KHI it can progress via the action of the Hall term mediated fast reconnection process of recent discovery [2].

## ACKNOWLEDGMENTS

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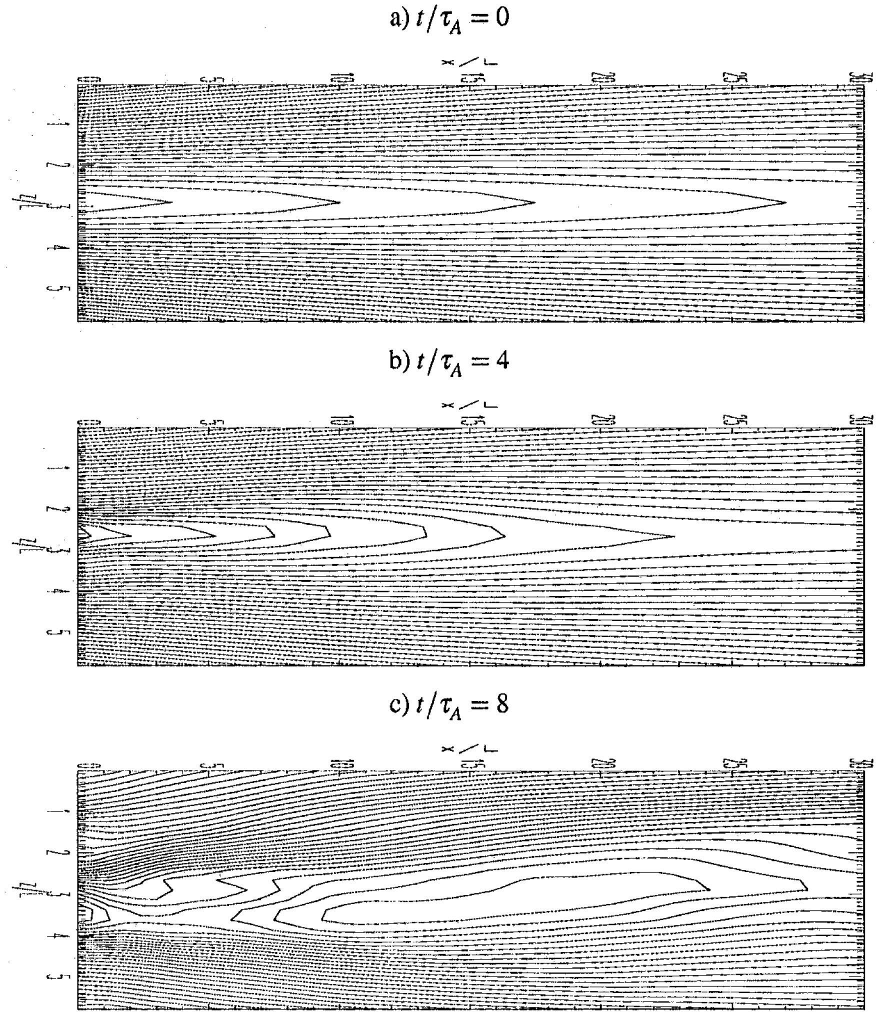


**FIGURE 2.** Cross section of the flux surfaces for a 3D MHD simulation at $y = L_y/2$ and three different times: initial ($t/\tau_A = 0$), $t/\tau_A = 4$, $t/\tau_A = 8$.

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