Final Report on DoE Grant No. DE-FG02-05ER54824, 2005-2006 ($40,000)

Title : *Collisionless Reconnection Research at Center for Magnetic Self-Organization*

This was a one-year grant. The main purpose of the grant was to initiate the affiliation of the University of New Hampshire with the Center for Magnetic Self-Organization---the NSF/DoE Frontier Physics Center. The following tasks were completed:

1. Collisionless reconnection in an electron-positron plasma

The conditions under which collisionless plasmas exhibit fast nonlinear reconnection have been a dominant subject of research over a few decades. Under standard approximations, collisionless hydrogen plasmas, consisting of electrons (of mass m_e and charge $-e$) and protons (of mass m_i and charge e), can be shown to obey the generalized Ohm's law

$$\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c} = \frac{m_e}{ne^2}\left[\frac{\partial \mathbf{J}}{\partial t} + \nabla\cdot(\mathbf{J}\mathbf{v}+\mathbf{v}\mathbf{J})\right] - \frac{\nabla\cdot\overleftrightarrow{\mathbf{P}}_e}{ne} + \frac{\mathbf{J}\times\mathbf{B}}{nec}, \qquad (1)$$

discussed in textbooks, where $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field, $\mathbf{v}$ is the plasma flow velocity, c is the speed of light, $\mathbf{J}$ is the current density, $\overleftrightarrow{\mathbf{P}}_e$ is the electron pressure tensor, and n is the electron and ion densities. In recent years, it has been shown, primarily by means of simulations based on fluid, hybrid as well as particle-in-cell (PIC) methods, that the Hall current and electron pressure terms in the generalized Ohm's law (1) play an important role in realizing fast reconnection. It has been suggested that this is because of a separation of spatial scales between electron and ion flows, which, in turn, causes a separation of scales between the thin current sheet and the reconnection electric field produced in the reconnection layer. Whereas electrons contribute primarily to the current density in the thin current sheet, which has a characteristic width of the order of the electron skin depth, ions decouple from electrons over a broader spatial scale of the order of the ion skin depth (when the equilibrium guide field is zero), and control the reconnection rate. It has also been suggested that there is a strong link between fast reconnection and the excitation of whistler waves produced by the Hall current at small scales. Unlike Alfvén waves, whistler waves have a dispersion relation that depends quadratically on the wave number, and hence their phase velocity increases linearly with increasing wave number (or decreasing spatial scale).

In this task, we study the problem of fast reconnection in electron-positron (or pair) plasmas. There has been growing interest in pair plasmas for their applications to astrophysical as well as laboratory plasma physics. Important astrophysical applications include extragalactic jets and winds and jets from pulsars. Recent laboratory experiments of electron-positron plasmas have offered significant new insights into beam-plasma instabilities, and new experiments on magnetically confined toroidal devices are under way.

In addition to the various applications mentioned above, studies of magnetic reconnection in electron-positron plasmas present a new opportunity to examine critically the question of the ingredients that are essential in realizing regimes of fast magnetic reconnection. In a pair plasma, the electron and ion skin depth parameters are identical. We demonstrate, by means of PIC simulations, that fast reconnection occurs in a pair plasma without a separation of spatial scales between electron and positron flows, and without the intervention of the Hall current which cancels out exactly in the generalized Ohm's Law. Due to this cancellation, whistler waves do not exist in pair plasmas. Despite the absence of the Hall current and whistler waves, our numerical results provide clear evidence of fast collisionless reconnection due to the localization caused by the off-diagonal components of the pressure tensors, which produce an effect analogous to a spatially localized resistivity.

Paper published: N. Bessho and A. Bhattacharjee, Physical Review Letters **95**, 245001 (2005).

2. Nonlinear evolution of the g-mode

The nonlinear development of the g-mode (also known as the magnetic Rayleigh-Taylor or the Parker instability) is a problem of great interest in astrophysical as well as laboratory plasma physics. The instability has been generalized to include the effects of line tying, which can be modeled by assuming that the magnetic fields lines are anchored in perfectly conducting rigid walls. Of great interest is a recent prediction that if the threshold for the instability is crossed in a small region of space, the instability would grow near-explosively in the nonlinear regime, in the manner of a finite-time singularity, destabilizing neighboring metastable regions. The process has been called "detonation". It has been suggested that the mechanism for detonation is generic, and extensions of the theory have been applied to phenomena in fusion as well as space plasmas, including edge-localized modes (ELMs) and disruptions in tokamaks, and substorm onset at the near-Earth magnetotail.

The prediction of detonation has been obtained by reductive perturbation theory, applied to the equations of ideal MHD. The asymptotic ordering scheme upon which the perturbation theory is based breaks down eventually in the detonation phase. Therefore, it appears important to study the phenomenon in the context of the primitive ideal MHD equations without the constraints imposed by an ordering scheme. Such a study will enable us pursue two objectives: first, to test the predictions of perturbation theory, and second, to continue the solution into regimes where the ideal MHD equations hold but the ordering scheme may not. Our principal focus is on the intermediate nonlinear regime, which is defined as the regime that lies between the linear regime of ideal exponential growth and the late nonlinear regime when the ideal MHD model needs to be modified to include kinetic effects, dissipation, and transport.

One of our principal findings is that detonation is generally absent in direct numerical simulations of the nonlinear g-mode based on the primitive ideal MHD equations. Instead, we provide numerical evidence that the intermediate nonlinear development is characterized by the formation of convection-induced discontinuities. Fingers do form, qualitatively consistent with the analytical predictions of the detonation theory, but instead of producing finite-time singularities, they tend to produce shock-like, coherent propagating structures. While such nonlinear solutions can have discontinuous spatial derivatives (in the absence of dissipation and kinetic effects), they grow exponentially at approximately the linear growth rate and remain bounded at all finite times.

Paper published: P. Zhu, A. Bhattacharjee, and K. Germaschewski, Physical Review Letters **96**, 065001 (2006) [*Erratum*: **96**, 129901 (2006)].