GEM Magnetic Reconnection Challenge

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Abstract.

The Geospace Environmental Modeling (GEM) Reconnection Challenge project is presented and the important results, which are presented in a series of companion papers, are summarized. Magnetic reconnection is studied in a simple Harris sheet configuration with a specified set of initial conditions, including a finite-amplitude, magnetic-island perturbation to trigger the dynamics. The evolution of the system is explored with a broad variety of codes, ranging from fully electromagnetic particle in cell (PIC) codes to conventional resistive magnetohydrodynamic (MHD) codes, and the results are compared. The goal is to identify the essential physics which is required to model collisionless magnetic reconnection. All models which include the Hall effect in the generalized Ohm's law produce essentially indistinguishable rates of reconnection, corresponding to nearly Alfvénic inflow velocities. Thus, the rate of reconnection is insensitive to the specific mechanism which breaks the frozen-in condition, whether resistivity, electron inertia or electron thermal motion. The reconnection rate in the conventional resistive MHD model, in contrast, is dramatically smaller unless a large localized or current dependent resistivity is used. The Hall term brings the dynamics of whistler waves into the system. The quadratic dispersion property of whistlers (higher phase speed at smaller spatial scales) is the key to understanding these results. The implications of these results for trying to model the global dynamics of the magnetosphere are discussed.

Introduction

Magnetic reconnection plays an important role in the dynamics of the magnetosphere in facilitating the entry of particles and energy from the solar wind into the magnetosphere at the magnetopause and in allowing magnetospheric topology to change in response to the direction of the interplanetary magnetic field (IMF) direction. The dissipation region, where the frozen-in flux constraint is broken, controls the rate of reconnection in a resistive magnetohydrodynamic (MHD) description [*Biskamp,* 1986]. At small values of resistivity the dissipation region forms an elongated Sweet-Parker layer and the rate of reconnection is very low, with an inflow velocity v_i into the x-line which scales like

$$v_i = \frac{\delta}{\Delta} v_A << v_A \tag{1}$$

where δ and Δ are the width (controlled by resistivity) and length (macroscopic) of the dissipation region, respectively, and v_A is the Alfvén velocity [*Parker,* 1957; *Sweet,* 1958]. This relation follows from continuity and the Alfvén limit on the ion outflow velocity.

In the magnetosphere the classical collision rate is very small and the inertia of electrons allows the frozen-in flux constraint to be broken [*Laval et al.,* 1966; *Vasyliunas,* 1975]. This occurs as the electrons become demagnetized either as a result of their thermal [*Laval et al.,* 1966] or inertial [*Dungey* , 1988] Larmor radius. From the fluid perspective the demagnetization of the electrons produces a non-gyrotropic pressure which can balance the reconnection electric field in the kinetic Ohm's law [*Vasyliunas,* 1975; *Lyons and Pridmore-Brown,* 1990; *Cai et al.,* 1994; *Kuznetsova et al.,* 1998],

$$\frac{4\pi}{\omega_{pe}^2}\frac{d\mathbf{j}}{dt} = \mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B} - \frac{1}{nec}\mathbf{j}\times\mathbf{B} + \frac{1}{ne^2}\nabla\cdot\vec{\vec{p_e}} - \eta\mathbf{j}, \tag{2}$$

where $\vec{\vec{p_e}}$ is the electron pressure tensor. Equation (2) is simply the electron equation of motion rewritten in terms of the traditional MHD terms ($\mathbf{E}$ and $\mathbf{v}\times\mathbf{B}$) plus the Hall ($\mathbf{j}\times\mathbf{B}$), pressure and electron inertial terms. The scale length around the x-line where the electrons become demagnetized is of the order of the electron skin depth c/ω_{pe} or slightly larger, depending on the electron temperature.

The electron demagnetization region is much smaller than the ion inertial length c/ω_{pi}, below which the Hall terms in the kinetic Ohm's law become important. The dynamics of the system at the scale of the electron dissipation layer is therefore inextricably linked to Hall physics and not to conventional MHD physics. The exploration of the implications of this is one of the keys to understanding magnetic reconnection in collisionless plasma. At scale lengths above c/ω_{pi} all of the non-MHD terms in (2) can be neglected and the MHD description is valid. At scale lengths below c/ω_{pi} the motion of electrons and ions decouple [*Sonnerup,* 1979] and it was established that the resulting currents generated from the relative electron and ion motion produce a characteristic quadrupole out-of-plane magnetic field pattern [*Terasawa*, 1983]. Later it was shown that this inner region is governed by the so-called electron MHD equations, in which the dominant waves are whistler rather than Alfvén waves and the ion motion can essentially be neglected [*Mandt et al.,* 1994].

The first indications that the whistler dynamics would fundamentally alter the rates of reconnection compared with the MHD model came from sensitivity studies of the rate of reconnection to the strength of the dissipative effect which breaks the frozen-in condition, either resistivity or electron inertia. In hybrid simulations with resistivity [*Mandt et al.,* 1994], two-fluid simulations [*Ma and Bhattacharjee,* 1996; *Biskamp et al.,* 1997] and particle simulations [*Shay and Drake,* 1998; *Hesse et al.,* 1999a] the rate of magnetic reconnection was found to be insensitive to the strength of the dissipation. Moreover, in contrast with the macroscopic Sweet-Parker current sheet from MHD theory the narrow current layers defining the dissipation region remain microscopic in length. When the Hall effect is eliminated from the simulations, the macroscopic current sheet reappears, the reconnection rate is drastically reduced and the reconnection rate becomes sensitive to the electron inertia [*Biskamp et al.,* 1997]. The Hall effect is therefore a critical ingredient in determining collisionless reconnection rates. It was suggested that the insensitivity of the reconnection rate to the mechanism which breaks the frozen-in condition results from the quadratic dispersion character of whistlers [*Shay and Drake,* 1998]. The phase velocity of the whistler is inversely proportional to scale length so the electron flux out of the dissipation region, the product of the velocity times the width of the layer, is independent of the layer width. When the initial axial guide field is large, the kinetic Alfvén wave plays a similar role, facilitated by the pressure term in Ohm's law.

Since the reconnection rate is insensitive to the level of electron dissipation in models which include the Hall effect, the ions must control the rate of reconnection. A natural question is therefore what is the minimal model required to produce accurate rates of reconnection? Such a question is pertinent to modeling the global dynamics of the magnetosphere where the storage and time step limitations on full particle simulations make this approach to global simulations prohibitive. Is a Hall MHD code with resistivity adequate to model magnetic reconnection? The goal of the GEM Reconnection Challenge Project is to answer this question and at the same time to pin down the role of electron dissipation and whistlers in controlling the rate of magnetic reconnection. Magnetic reconnection in 2-D in a simple Harris sheet equilibrium is investigated using a variety of simulation models, including MHD, Hall MHD, hybrid (particle ions and fluid electrons), and full particle. A specified set of parameters are chosen as are the dimensions of the computational domain, the boundary conditions and the initial amplitude and form of a seed magnetic island to initiate reconnection. The results of the simulations are then compared. The initial conditions and the important results are summarized in this paper. Details from the individual calculations are presented in companion papers in this journal [*Pritchett,* 1999; *Hesse et al.,* 1999b; *Shay et al.,* 1999; *Kuznetsova et al.,* 1999; *Birn and Hesse,* 1999; *Ma and Bhattacharjee,* 1999; *Otto,* 1999].

Equilibrium and initial conditions

The equilibrium chosen for the reconnection challenge problem is a Harris equilibrium with a floor in the density outside of the current layer. The magnetic field is given by

$$B_x(z) = B_0 \tanh(z/\lambda) \tag{3}$$

and the density by

$$n(z) = n_0 \mathrm{sech}^2(z/\lambda) + n_\infty \tag{4}$$

The electron and ion temperatures, T_e and T_i, are taken to be uniform in the initial state. The pressure balance condition gives $n_0(T_e + T_i) = B_0^2/8\pi$. The computation is carried out in a rectangular domain $-L_x/2 \leq x \leq L_x/2$ and $-L_z/2 \leq z \leq L_z/2$. The system is taken to be periodic in the x direction with ideal conducting boundaries at $z = \pm L_z/2$. Thus, the boundary conditions on the magnetic fields at the z boundaries are $B_z = \partial B_x/\partial z = \partial B_y/\partial z = 0$ with corresponding conditions on the electric fields and particle or fluid quantities.

The normalization of the space and time scales of the system is chosen to be the ion inertial length c/ω_{pi} and the ion cyclotron frequency Ω_i^{-1}, where $\omega_{pi}^2 = 4\pi n_0 e^2/m_i$ is evaluated with the density n_0 and the ion gyrofrequency $\Omega_i = eB_0/m_i c$ is evaluated at the peak magnetic field. In these units the velocities are normalized to the Alfvén speed v_A. In the normalized units, $B_0 = 1$ and $n_0 = 1$. Specific paramters for the simulations are $\lambda = 0.5$, $n_\infty/n_0 = 0.2$, $T_e/T_i = 0.2$, $m_i/m_e = 25$, $L_x = 25.6$ and $L_z = 12.8$. The grid spacing is left open since this may depend on the specific spatial differencing algorithm in each code. The resistivity or form of dissipation in codes without finite electron mass is also left open.

The initial magnetic island is specified through the perturbation in the magnetic flux,

$$\psi(x, z) = \psi_0 \cos(2\pi x/L_x) \cos(\pi z/L_z), \tag{5}$$

where the magnetic field perturbation is given by $\mathbf{B} = \hat{y} \times \nabla\psi$. In normalized units $\psi_0 = 0.1$, which produces an initial island width which is comparable to the initial width of the current layer. The rationale for such a large initial perturbation is to put the system in the nonlinear regime of magnetic reconnection from the beginning of the simulation. The linear growthrate of the tearing mode depends strongly on the particular model, whether it is a full particle model which includes the effect of electron thermal streaming or a hybrid model with resistivity. In the nonlinear regime it is expected that these differences will be reduced if the hypothessis is correct that the reconnection rate is insensitive to the electron dissipation mechanism. The inclusion of the linear phase of the tearing mode would only serve to obscure the expected underlying commonality between the various approaches.

Simulation Results and Discussion

The general conclusions of the GEM Reconnection Challenge are summarized here. Details can be found in the individual papers in this issue. The reconnection simulations have been carried out with a wide variety of tools, including full particle codes [*Hesse et al.,* 1999b; *Pritchett,* 1999; *Shay et al.,* 1999], hybrid codes with and without electron mass and the off-diagonal electron pressure tensor [*Kuznetsova et al.,* 1999; *Shay et al.,* 1999], Hall MHD (two-fluid) codes with and without the electron mass [*Ma and Bhattacharjee,* 1999; *Birn and Hesse,* 1999; *Otto,* 1999; *Shay et al.,* 1999] and MHD codes [*Birn and Hesse,* 1999; *Otto,* 1999]. The key results are displayed in Fig. 1 where the magnetic flux reconnection versus time is shown from simulations based on full particle, hybrid with finite electron mass, Hall MHD with a fourth order dissipation (discussed in more detail later) and MHD models. The reconnection electric field is the slope of the flux versus time curve. The striking result is that, with some caveats, all of the models which include the Hall effect produce essentially the same rates of reconnection, the reconnection electric field E_y having a peak value of $0.24 B_0 v_A/c$.

A caveat is that dissipation in the form of resistivity must be sufficiently small, or sufficiently localized, so as not to blur the narrow current layers which form in the vicinity of the x-line. Excess diffusion substantially reduces the rate of reconnection [*Birn and Hesse,* 1999; *Otto,* 1999]. There is also new evidence presented that within a given model the reconnection rate is insensitive to the electron dissipation mechanism (specifically the electron mass in full particle [*Hesse et al.,* 1999b; *Pritchett,* 1999] and hybrid [*Shay et al.,* 1999] simulations). In contrast to the models including the Hall physics, the reconnection rate in the MHD models depends on the level of dissipation, *i.e.*, the resistivity [*Birn and Hesse,* 1999; *Otto,* 1999], consistent with earlier calculations [*Biskamp,* 1986]. For all values of dissipation the MHD reconnection rate is smaller than that obtained from the two-fluid and kinetic models. The results for the MHD model in Fig. 1 are for $\eta = 0.005$. Very small resistivity leads to the expected Sweet-Parker current layers and associated slow reconnection while large resistivity causes strong diffusion of the current sheet, effectively suppressing reconnection. Localized and current dependent resistivity models lead to faster reconnection than uniform resistivity models but again remain slower than the models with Hall physics.

While the rates of reconnection in the models with Hall physics were essentially the same, there were substantial differences in the structure of the dissipation region, including the widths of the current layers and velocity outflows. Generally, the layers were broader in the particle models than in the fluid models as a result of the meandering orbits of the particles in the region of magnetic field reversal [*Laval et al.,* 1966]. For example, in the hybrid and Hall MHD simulations with electron mass the width of the electron current layer was close to the electon skin depth c/ω_{pe} [*Shay et al.,* 1999] but was larger by around a factor of two in the particle models [*Hesse et al.,* 1999b; *Pritchett,* 1999; *Shay et al.,* 1999]. The width of the jet of ions ejected from the dissipation region displayed a similar difference in the hybrid and Hall MHD models. The width of the ion jet was larger by around a factor of two in the particle and hybrid simulations in comparison with the two-fluid models, again as a result of the meandering orbits of ions. The differences, however, were not reflected in the reconnection rates, which were essentially identical.

Further data was also generated to try to pin down the physics underlying the insenstivity of the reconnection rate to the electron dissipation. If the whistler phase speed is the factor which limits the electron outflow velocity from the inner dissipation region (where the electron frozen-in condition is broken) the electron outflow velocity should scale like the whistler speed based on the electron skin depth. This corresponds to the electron Alfvén speed $v_{Ae} = \sqrt{B^2/4\pi m_e n}$. With decreasing electron mass the outflow velocity of electrons should increase. This trend has been clearly identified in particle simulations [*Hesse et al.,* 1999a; *Hesse et al.,* 1999b; *Pritchett,* 1999]. A series of simulations in the hybrid model confirmed the scaling of the outflow velocity with v_{Ae} and that the width of the outflow velocity scales with c/ω_{pe} [*Shay et al.,* 1999]. The flux of electrons from the inner dissipation region is therefore independent of the electron mass, consistent with the general whistler scaling argument.

As noted previously, excess dissipation in the Hall MHD models reduces the reconnection rate below the large values seen in particle models. On the other hand, large values of the resistivity are required in the simulations to prevent the collapse of the current layers to the grid scale. The reason is linked to the dispersion properties of whistler, which controls the dynamics at small scale. Including resistivity $\eta = m\nu_{ei}/ne^2$,

$$\omega = k^2\Omega_e c^2/\omega_{pe}^2 - i\eta k^2 c^2/4\pi, \tag{6}$$

Even as $k \to \infty$, the dissipation term remains small compared with the real frequency as long as $\nu_{ei} \ll \Omega_e$. There is no scale at which dissipation dominates propagation. The consequence is that current layers become singular unless the resistivity becomes excessive, even when electron inertia is retained. The resolution of the problem is straightforward. Dissipation in the magnetic field equation proportional to ∇^p with

$p \geq 4$ can be adjusted to cut in sharply around the grid scale and not strongly diffuse the longer scale lengths which drive reconnection. Such dissipation models are therefore preferable to resistivity in modeling magnetic reconnection with hybrid and two-fluid codes.

The key conclusion of this project is that the Hall effect is the critical factor which must be included to model collisionless magnetic reconnection. When the Hall physics is included the reconnection rate is fast, corresponding to a reconnection electric field in excess of $0.2 B_0 v_A / c$. For typical parameters of the plasma sheet ($n \sim 0.3/cm^3$ and $B \sim 20nT$), this rate yields electric fields of order $4mV/m$. Several caveats must, however, be made before drawing the conclusion that a Hall MHD or two-fluid code would be adequate to model the full dynamics of the magnetosphere. The conclusions of this study pertain explicitly to the 2-D system. There is mounting evidence that the narrow layers which develop during reconnection in the 2-D model are strongly unstable to a variety of modes in the full 3-D system. Whether the two-fluid model provides an adequate description of these instabilities and whether these instabilities play a prominent and critical role in triggering reconnection and the onset of substorms continues to be debated.

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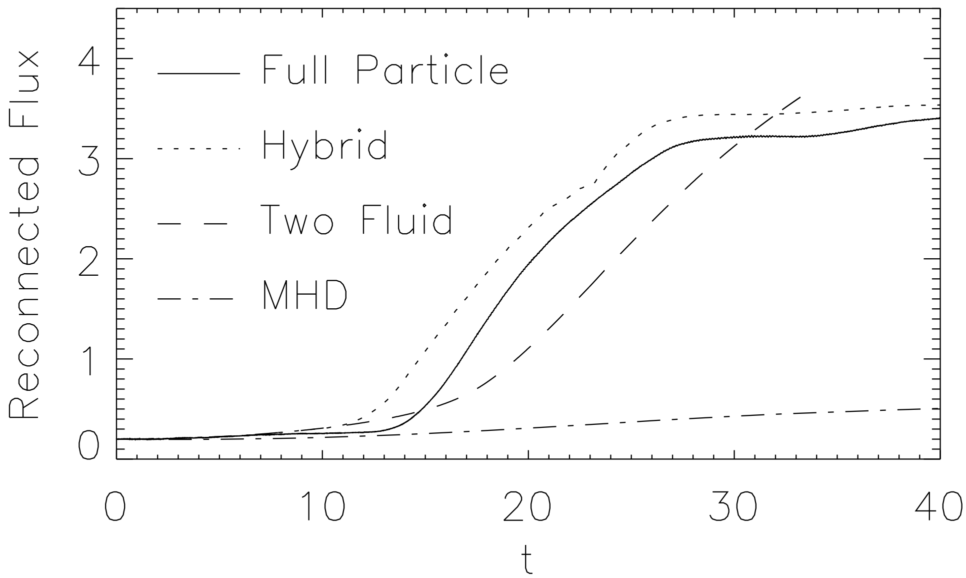

Figure 1. The reconnected magnetic flux versus time from a variety of simulation models: full particle, hybrid, Hall MHD and MHD (for resistivity $\eta = 0.005$).