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The hall effect in magnetic reconnection: Hybrid versus Hall-less hybrid simulations

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[1] To understand the role of the Hall effect during fast magnetic reconnection, hybrid simulations with and without the Hall term in the generalized Ohm's Law are compared, as done originally by Karimabadi et al. (2004). It is found that reconnection with the Hall term is fast, but reconnection in the so-called Hall-less hybrid simulations is Sweet-Parker like (slow) when the resistivity is constant and uniform. These results re-affirm the importance of the Hall term in allowing fast reconnection in the hybrid model.
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1. Introduction

[2] The first self-consistent model of magnetic reconnection was the Sweet-Parker model [*Sweet*, 1958; *Parker*, 1957], in which electron-ion collisions break the frozen-in constraint. Laboratory experiments in collisional plasmas provide observational support for this model [*Trintchouk et al.*, 2003; *Furno et al.*, 2005]. However, this Sweet-Parker reconnection is "slow", meaning that the diffusion region expands in length, becoming comparable to the system size, which throttles the reconnection rate. As such, Sweet-Parker reconnection is not fast enough to explain observed energy release rates in reconnection events of space physics interest such as solar eruptions, nor can it explain how reconnection occurs in a collisionless plasma such as the magnetosphere.

[3] Understanding the physics allowing reconnection to be fast is crucial. In "fast" reconnection the diffusion region length is not coupled to the system size, leading to an energy release rate consistent with observations. It has been suggested [*Mandt et al.*, 1994; *Shay et al.*, 1999] that the Hall term is critical to make reconnection fast. The Hall term operates at sub-ion gyroradius scales and describes the decoupling of ions from the magnetic field when their gyro-orbit is comparable to gradient scales in the magnetic field. *Mandt et al.* [1994] and *Rogers et al.* [2001] argued that collisionless (Hall) reconnection is fast because of the dispersive nature of the whistler and kinetic Alfvén waves introduced by the Hall term.

[4] The importance of the Hall effect was shown in the GEM Challenge study [*Birn et al.*, 2001, and references therein], which compared fluid, two-fluid, hybrid, and particle-in-cell (PIC) simulations. All simulations containing Hall physics had a similar (fast) reconnection rate, while the simulation without the Hall effect was much slower. The Hall model has had wide success explaining observations in the magnetosphere [*Nagai et al.*, 2001; *Øieroset et al.*, 2001; *Mozer et al.*, 2002; *Runov et al.*, 2003; *Borg et al.*, 2005; *Phan et al.*, 2007] and laboratory experiments [*Ren et al.*, 2005; *Cothran et al.*, 2005; *Frank et al.*, 2006; *Yamada et al.*, 2006], and there is indirect evidence that the Hall effect is important in solar and stellar coronae [*Cassak et al.*, 2008].

[5] There have been significant challenges to the Hall reconnection model and specifically to the argument that dispersive waves shorten the current layer and facilitate fast reconnection. In one case, *Karimabadi et al.* [2004] performed hybrid simulations in which the Hall term was manually removed from the generalized Ohm's law. In these so-called Hall-less hybrid simulations, the rates of reconnection were found to be fast, calling the Hall model into question.

[6] In a second challenge, PIC simulations with open boundary conditions were performed, and it was found that the electron current layer continuously increased in length and was limited only by the formation of secondary magnetic islands [*Daughton et al.*, 2006]. Thus, dispersive waves were insufficient to limit the length of the electron current layer but fast reconnection was possible due to the periodic ejection of secondary islands. This model is reminiscent of earlier MHD models of turbulent reconnection where secondary islands break up the Sweet-Parker current layer and facilitate fast reconnection [*Matthaeus and Lamkin*, 1986; *Kliem*, 1995; *Lazarian and Vishniac*, 1999; *Lapenta*, 2008]. Subsequent large scale periodic simulations [*Shay et al.*, 2007] and larger open boundary conditions [*Karimabadi et al.*, 2007; *Klimas et al.*, 2008] found long time periods with steady fast reconnection rates and steady electron current layer lengths. *Shay et al.* [2007] concluded that secondary magnetic islands are not necessary for fast reconnection, while *Karimabadi et al.* [2007] viewed the steady reconnection periods as transient and concluded that magnetic reconnection as a whole is time dependent due to secondary island formation. Although it is clear that secondary islands often form during magnetic reconnection, there is currently no consensus on the role they play in setting the reconnection rate.

[7] A surprising result of these simulations [*Shay et al.*, 2007; *Karimabadi et al.*, 2007] is that the electron diffusion region exhibits a two-scale structure along the outflow direction, an inner diffusion layer synonymous with previous two-fluid and hybrid results, and an extremely long outer layer (10s of c/ω_{pi} in length) containing a super-

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Alfvénic jet of electrons which are not frozen-in. Signatures of this extremely long outer electron diffusion region (greater than 60 c/ω_{pi}) have been observed in satellite measurements of reconnection in the Earth's magnetosphere [*Phan et al.*, 2007]. We emphasize that these new features are due to kinetic electron physics, which are not present in hybrid simulations.

[8] In this paper, we focus on the first challenge, that "ion kinetics" alone facilitate fast reconnection [*Karimabadi et al.*, 2004]. We perform a study of the role of the Hall effect by comparing hybrid and Hall-less hybrid simulations, similar to part of the study by *Karimabadi et al.* [2004]. In contrast to the previous work, we find that reconnection is slow (Sweet-Parker) in the absence of the Hall effect. The removal of the Hall effect during fast reconnection leads immediately to a collapsing of the current sheet to a Sweet-Parker layer. This reconfirms the importance of the Hall effect in producing fast reconnection in the hybrid model. Potential reasons for the discrepancy with *Karimabadi et al.* [2004] are discussed.

2. Hall-Less Reconnection Physics

[9] There are fundamental physics differences between the standard hybrid system (with particle ions and fluid electrons) and the Hall-less hybrid system, much more disparate than the differences between MHD and Hall-MHD. In a standard system, ions and electrons are frozen-in far from the neutral line. Ions within a gyroradius of the neutral line undergo stochastic orbits, decoupling from the magnetic field and electrons. Since $\mathbf{E} + \mathbf{u}_e \times \mathbf{B}/c \simeq 0$ in the region between the ion and electron gyroradii (with $\mathbf{u}_e$ the electron fluid velocity), the electrons remain frozen to the magnetic field. The electrons decouple only at electron gyroradius scales, and the magnetic topology can change in this region.

[10] In the Hall-less hybrid system, the ions undergo stochastic trajectories within a gyroradius of the neutral line, as in the standard system. However, in the absence of the Hall term, $\mathbf{E} + \mathbf{u}_i \times \mathbf{B}/c \simeq 0$ and the magnetic field remains frozen to the average ion velocity $\mathbf{u}_i$ until resistive scales are reached.

3. Simulations and Results

[11] We use the hybrid code P3D [*Zeiler et al.*, 2002] in 2 1/2 dimensions. The evolution equations are normalized to a length of the ion inertial scale $d_i = c/\omega_{pi}$, a velocity of the Alfvén speed $c_A = B_0/(4\pi m_i n_0)^{1/2}$, and a time of the ion cyclotron time $\Omega_{ci}^{-1} = (eB_0/m_i c)^{-1}$, where n_0 is the initial density outside the current sheet, B_0 is the asymptotic magnetic field strength, and m_i is the ion mass. This gives normalizations of electric fields, temperature, resistivity, and hyperviscosity as follows: $E_0 = c_A B_0/c$, $T_0 = mc_A^2$, $\eta_0 = 4\pi\ d_i c_A/c^2$, and $\eta_{4_0} = c_A d_i^3$ The ions are evolved in time t using

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i \tag{1}$$

$$\frac{d\mathbf{v}_i}{dt} = \mathbf{E}_{ION} + \mathbf{v}_i \times \mathbf{B} \tag{2}$$

where $\mathbf{x}_i$ and $\mathbf{v}_i$ are the positions and velocities of the individual protons and $\mathbf{B}$ is the magnetic field. The electric field used to update the ions $\mathbf{E}_{ION}$ is given by

$$\mathbf{E}_{ION} = -\left(\mathbf{u}_i - \frac{\mathbf{J}}{n}\right) \times \mathbf{B}. \tag{3}$$

where n is the density, $\mathbf{J} = \nabla \times \mathbf{B}$ is the current density, and $\mathbf{u}_i$ is the ion bulk flow velocity. The quantity in parentheses is the electron bulk flow velocity $\mathbf{u}_e$. The magnetic field is updated using

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}_{OHM} \tag{4}$$

$$\mathbf{E}_{OHM} = -\mathbf{u}_i \times \mathbf{B} + \frac{\mathbf{J}}{n} \times \mathbf{B} + \eta \mathbf{J} - \eta_4 \nabla^2 \mathbf{J} \tag{5}$$

where η is the resistivity and η_4 is a hyperviscosity. We emphasize that both explicit dissipation terms in the code have constant and uniform coefficients (i.e., they are not spatially localized). The contributions to the generalized Ohm's law (equation (5)) from electron inertia ($m_e = 0$) and the electron pressure gradient (the electron temperature $T_e = 0$) are omitted to isolate the effect of the Hall term. The code assumes quasi-neutrality. We refer to simulations using equations (1)–(5) as "standard" hybrid simulations.

[12] The Hall-less hybrid system is defined by removing the Hall term from equation (5), giving

$$\mathbf{E}_{OHM} = -\mathbf{u}_i \times \mathbf{B} + \eta \mathbf{J} - \eta_4 \nabla^2 \mathbf{J}. \tag{6}$$

It is important to note that the $\mathbf{J} \times \mathbf{B}$ term is not removed from the electric field used to step forward the ions $\mathbf{E}_{ION}$ because doing so would eliminate bulk forces on the ion fluid (see *Karimabadi et al.* [2004] for a thorough discussion). It has been shown that this prescription for removing the Hall term removes dispersive waves from the system [*Karimabadi et al.*, 2004]. The simulations using equation (6) instead of equation (5) are referred to as Hall-less hybrid simulations.

[13] The simulated domain is 204.8 × 102.4 with a 1024 × 512 grid (i.e., the grid scale is 0.2). There are initially 100 particles per cell loaded with an initial Maxwellian distribution having a uniform temperature 0.5. The background density is initially 1.0. We use $\eta = 0.015$ and $\eta_4 = 10^{-3}$. There is no initial out-of-plane (guide) magnetic field. The domain has periodic boundary conditions in all directions. The initial equilibrium is a double Harris sheet with an initial current sheet width of 1. A coherent perturbation in the y-direction to the magnetic field of amplitude 0.3 is used to initiate reconnection.

[14] First, we perform a standard hybrid simulation, which reveals known properties of reconnection. In the steady-state, the out-of-plane current J_z is opened out into a Petschek-type outflow jet, as shown at $t = 300$ in Figure 1a, an indication of fast reconnection. The reconnection rate E, computed as the time rate of change of magnetic flux between the X-line and the O-line, is shown in Figure 2a as a function of time. The steady value is $E \sim 0.03$, which is fast, but somewhat slower than typical values closer to 0.1 seen in

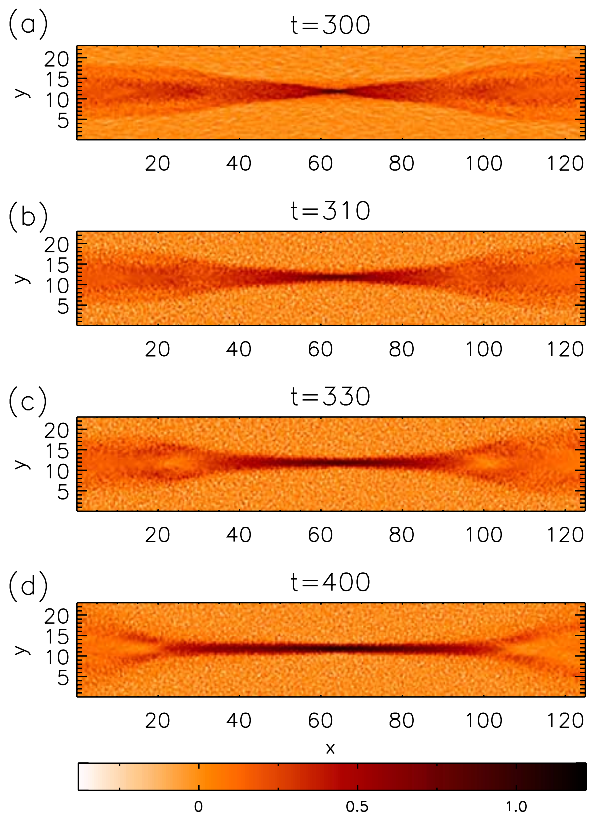

Figure 1. Plots of the out-of-plane current J_z during the transition from standard to Hall-less hybrid reconnection at (a) t = 300, (b) t = 310, (c) t = 330, and (d) t = 400.

collisionless reconnection simulations. This is due to the large value of the resistivity η employed in the simulations. Indeed, the transit time across the dissipation region is $\tau_{tr} \sim \delta/v_{in} \sim 1/0.03 \sim 30$, while the diffusion time across the layer is $\tau_d \sim \delta^2/\eta \sim 1/0.015 \sim 60$ (where δ is the thickness of the ion dissipation region and v_{in} is the ion inflow speed), revealing that diffusion is playing a non-negligible role during the reconnection process. When the same simulation is performed with $\eta = 0$, the reconnection rate is closer to 0.045. The hyperviscosity η_4 still plays the main role, however, for setting $\eta_4 = 0$ in the Hall runs leads to the current sheet collapsing down to grid scale lengths.

[15] Second, we perform a Hall-less hybrid simulation with the same parameters as the previous simulation. In this case, J_z has the signatures of slow (Sweet-Parker like) reconnection. (Very similar to Figure 1d, which is discussed later.) The current sheet elongates to the system size with no Petschek-type open outflow region. The reconnection rate is plotted in Figure 2b, and the steady-state value is $E \sim 0.015$, with a horizontal line marking the prediction from a standard Sweet-Parker analysis using parameters measured near the end of the simulation. The rate is considerably lower than in the standard hybrid run. We emphasize that the only difference between this simulation and the previous one is the omission of the Hall term in the Ohm's Law, which shows the importance of the Hall term in enabling fast reconnection.

[16] Note that from the parameters chosen, the predicted half-width δ_{SP} of a Sweet-Parker current layer is $\delta_{SP} \sim (\eta\ L/c_{Aup})^{1/2} \sim 0.77$, where L is the length of the current sheet from the X-line to one end of the current sheet and c_{Aup} is the Alfvén speed based on the upstream reconnecting magnetic field strength B_{up}. This thickness is smaller than the ion inertial scale, so if kinetic effects of the ions alone was sufficient for fast reconnection, as has been previously suggested [*Karimabadi et al.*, 2004], we presumably would not have seen slow reconnection. Setting $\eta = 0$ in the Hall-less case leads to the current sheet collapsing to the grid scale.

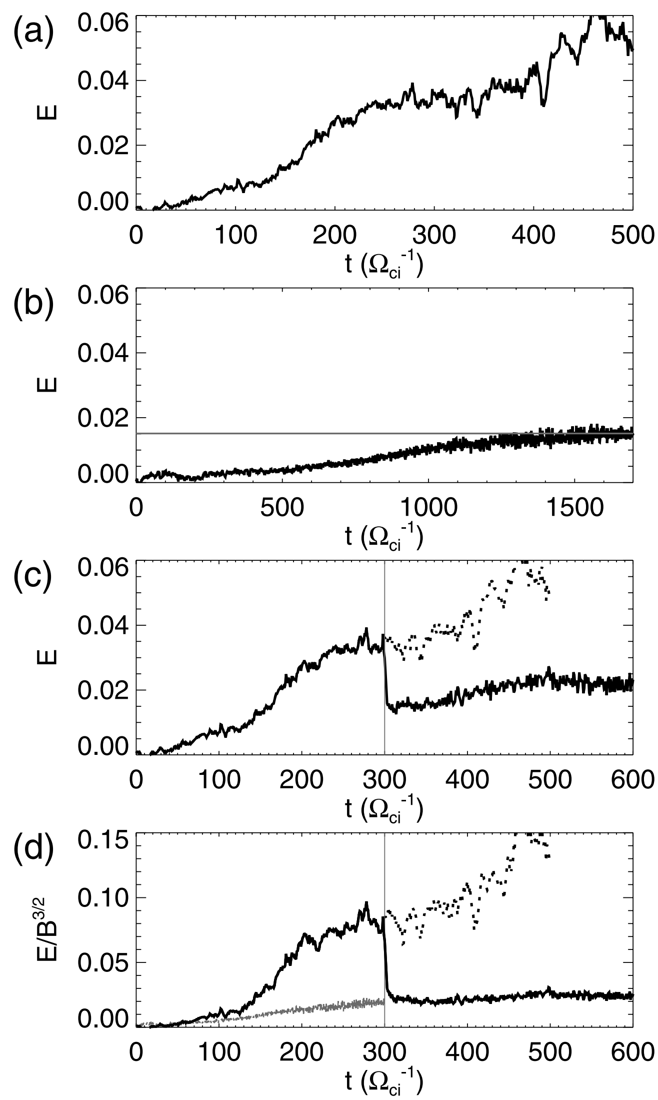

Figure 2. The reconnection rate E as a function of time t for various simulations: (a) a standard hybrid simulation, (b) a Hall-less hybrid simulation, with the horizontal line indicating the predicted Sweet-Parker value for this system, and (c) a standard hybrid simulation in which the Hall term is removed at t = 300 (denoted by the vertical line), with the gray dashed line denoting E for the standard hybrid simulation (from Figure 2a). (d) E normalized to $B_{up}^{3/2}$ in the standard hybrid (gray dashed line), Hall-less hybrid (gray solid line), and standard hybrid with the Hall term removed mid-run (black solid line) simulations. The time scale for the Hall-less data is rescaled in Figure 2d so that the final time of t = 1700 is shown at t = 300.

[17] Finally, to emphasize the role of the Hall term, we perform a standard hybrid simulation until the system reaches a steady state, then suddenly turn off the Hall term at t = 300 and continue the simulation with the Hall term disabled. The current sheet J_z after turning off the Hall term is plotted in Figure 1, with plots at t = 310 (Figure 1b), t = 330 (Figure 1c), and t = 400 (Figure 1d). The transition from the Petschek-type open outflow region to a Sweet-Parker type layer on a very fast time scale is clearly seen.

[18] The reconnection rate as a function of time for this run is plotted in Figure 2c. As soon as the Hall term is turned off, E drops to the Sweet-Parker value in less than 10 ion cyclotron times. The reconnection rate then gradually increases and finally levels off. The reason for the gradual increase is that when we suddenly turn the Hall term off, the reconnection suddenly changes from fast to slow. However, the plasma upstream of the dissipation region continues to flow toward the X-line at a fast rate. This causes an accumulation of the magnetic field upstream, leading to a higher reconnection rate. To remove the effect of the changing upstream magnetic field B_{up} during Hall-less reconnection, Figure 2d shows the reconnection rates from all three simulations normalized to the $B_{up}^{3/2}$ as a function of time. If the length of the diffusion region is not changing in time, this normalization should give a constant reconnection rate during Hall-less reconnection [*Parker*, 1957]. The upstream density changes very little during this time. When the upstream magnetic field is normalized away, the reconnection rate becomes rather steady. Figure 2d clearly shows that the reconnection rate after turning the Hall term off is in agreement with the Sweet-Parker value. The system remains in a steady-state of Sweet-Parker type reconnection for over 300 ion cyclotron times.

4. Discussion

[19] Our simulations reveal that while reconnection in the standard hybrid model is fast, reconnection in the Hall-less hybrid system is slow when a constant and uniform resistivity is employed. This clearly suggests that the Hall term plays a fundamental role in limiting the length of the current layer and facilitating reconnection in the hybrid model.

[20] We can also address the role of secondary island formation in our simulations. In the Hall-less hybrid simulations, a secondary island forms and is ejected out of the dissipation region. The production of the secondary island does not significantly disrupt the structure of the Sweet-Parker current sheet, nor does it greatly affect the reconnection rate. Thus, we see no evidence in this system that the formation of secondary islands facilitates fast reconnection, as has been suggested previously by *Daughton et al.* [2006] and *Karimabadi et al.* [2007] based on collisionless PIC simulations. However, as has been postulated with the long current sheets in resistive MHD simulations [*Matthaeus and Lamkin*, 1986], perhaps secondary island formation in extremely large Hall-less hybrid simulations would anomalously increase the reconnection rate. Resolving this issue will require extremely large and well resolved simulations.

[21] We also would like to emphasize that numerical resolution can significantly affect these simulations. In particular, we find that if the Hall-less current layer is not sufficiently resolved (with at least 4 grid cells across the dissipation region for the algorithm in use for these simulations), the current layer is unstable to secondary islands at the grid scale which seemingly substantially increases the reconnection rate. This is tested with simulations using the same grid scale (0.2) as the simulations described in the previous section but with a lower resistivity (η = 0.007). With the lower η, the predicted $\delta_{SP} \sim 0.52$, leaving only 2.5 grid cells per δ_{SP}. Simulations with this η in which the Hall effect is turned off mid-run reveal that a Sweet-Parker type current layer forms after the Hall term is disabled, but grid scale instabilities soon form. When the η = 0.007 simulation is redone with a grid scale of 0.1 (giving 5 cells across δ_{SP}), no grid scale effects occur and the reconnection remains steady at its slow Sweet-Parker rate. As such, ostensibly fast reconnection can occur if numerical resolution is insufficient, and care is needed to ensure that fast reconnection is not being caused by numerical effects.

[22] The present results disagree with *Karimabadi et al.* [2004], who claimed that ion kinetics alone are sufficient to make reconnection fast (i.e., reconnection in the Hall-less hybrid system is fast even in the limit of a uniform resistivity). We attribute the discrepancy to the fact that all of the simulations of reconnection performed in that study employed a localized resistivity, which itself is sufficient to produce fast reconnection even in MHD. To confirm this interpretation, we perform a Hall-less hybrid simulation with an ad hoc cosh-profile resistivity similar to that used by *Karimabadi et al.* [2004], and find that the reconnection is fast. As such, the hybrid system behaves much like the fluid system in that either the Hall term or an ad hoc localized resistivity is sufficient to make reconnection fast.

[23] In conclusion, consistent with the GEM Challenge result [*Birn et al.*, 2001], we find in hybrid simulations that the Hall term is required to produce fast reconnection when the resistivity is uniform. The kinetic dynamics of ions alone are insufficient to produce fast reconnection. We emphasize that hybrid simulations do not contain 3D effects, which may be playing a critical role during reconnection, nor kinetic electron physics, which has been shown to modify substantially the electron diffusion region.

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