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# The role of Hall currents on incompressible magnetic reconnection

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**Abstract**

Magnetic reconnection is one of the most important energy conversion processes in space plasmas. Theoretical models of magnetic reconnection have been traditionally developed within the framework of magnetohydrodynamics (MHD). However, in low density astrophysical plasmas as those found in the magnetopause and the magnetotail, the current sheet thickness can be comparable to the ion inertial scale and therefore the Hall electric field becomes non-negligible. The role of the Hall current is to increase the reconnection rate with respect to MHD predictions, which therefore poses a promising mechanism for fast reconnection. We present results from parallel simulations of the incompressible Hall MHD equations in $2\frac{1}{2}$ dimensions. We quantitatively evaluate the relevance of the Hall current in the reconnection process by performing a set of simulations with different values of the Hall parameter. We compute the corresponding reconnection rates as a function of time, and explore the spatial structure of the fields in the surroundings of the diffusion region. We quantify the increase of the reconnection rate as a function of the Hall parameter, and confirm the presence of a quadrupolar structure for the out-of-plane magnetic field.
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*Keywords:* Magnetic reconnection; Hall current; Solar wind and magnetosphere

## 1. Introduction

Magnetic reconnection is likely to be the main mechanism by which the energy stored in stressed magnetic fields can be converted into kinetic and thermal energy. It is believed to play a crucial role in different astrophysical environments such as the Earth's magnetopause Sonnerup et al. (1981), the Earth's magnetotail (here it is related to the release of magnetic energy, see e.g., Birn and Hesse (1996)), the solar atmosphere (related to the occurrence of flares, coronal mass ejections, and coronal heating, see e.g. Priest (1984), Gosling et al. (1995)), or the interplanetary medium (for instance, as a consequence of the interaction between magnetic clouds and the solar wind, see Farrugia et al. (2001), Schmidt and Cargill (2003)).

Hall currents can in turn play a significant role in the dynamics of low density and/or low temperature astrophysical plasmas, for which a one fluid description has been traditionally used. For instance, they can alter the dynamics of magnetic fields in dense molecular clouds, trigger instabilities in accretion disks or modify the efficiency of turbulent dynamos (Minnini et al., 2003). Due to the low density of the plasma in the solar wind and magnetosphere, the Hall currents can also be of importance during magnetic reconnection at the Earth's magnetopause, and some signatures of these Hall currents have been reported (Mozer et al., 2002). However, the quantitative importance of its contribution to magnetic reconnection is still being assessed in

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the literature (see for example: Craig et al. (2003) and Birn et al. (2001) and references therein).

Theoretical models of magnetic reconnection have been traditionally developed within the framework of magnetohydrodynamics (notably Parker (1957) and Petschek (1964)). Nevertheles, in recent years many analytical and computational efforts have been made to clarify the importance of the Hall effect in the reconnection process (Craig and Watson, 2003; Smith et al., 2004; Chacón et al., 2003; Dorelli and Birn, 2003; Dorelli, 2003).

In this paper, we study the importance of the Hall term in incompressible magnetic reconnection. We perform numerical simulations of an incompressible $2\frac{1}{2}$D Hall MHD code with different values of the dimensionless parameter $\epsilon$, which measures the relative importance of the Hall current.

In Section 2, we introduce the Hall MHD equations as well as the $2\frac{1}{2}$D configuration. The basis of the numerical model, boundary and initial conditions are presented in Section 3. Section 4 is devoted to the analysis of the role played by the Hall currents and Section 5 contains the summary of the results presented in this paper.

## 2. Hall MHD model

Highly conductive plasmas (i.e., $S \gg 1$) tend to develop thin and intense current sheets in their reconnection layers. Whenever the current width reaches values as low as $c/w_{\text{pi}}$ ($w_{\text{pi}}$ is the ion plasma frequency and $c$ is the speed of light), the standard Ohm's law needs to be extended, since it is not possible to neglect the Hall term (Ma and Bhattacharjee, 2001). For a fully ionized plasma of protons and electrons, the generalized Ohm's law can be written as:

$$\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B} = \frac{1}{\sigma}\boldsymbol{j} + \frac{1}{ne}\left(\frac{1}{c}\boldsymbol{j} \times \boldsymbol{B} - \nabla p_{\text{e}}\right), \tag{1}$$

where $n$ is the electron and proton density (under the quasi-neutrality hypothesis), $e$ is the charge of the electron, $\sigma$ is the electric conductivity, $\boldsymbol{v}$ is the plasma flow velocity, and $\boldsymbol{j}$ is the electric current density. Assuming incompressibility (i.e., $\nabla \cdot \boldsymbol{v} = 0$), the so-called Hall-MHD equations can be cast in their dimensionless form as:

$$\partial_t \boldsymbol{v} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} - \nabla p + \nu \nabla^2 \boldsymbol{v}, \tag{2}$$

$$\partial_t \boldsymbol{B} = \nabla \times [(\boldsymbol{v} - \epsilon \nabla \times \boldsymbol{B}) \times \boldsymbol{B}] + \eta \nabla^2 \boldsymbol{B}, \tag{3}$$

$$\nabla \cdot \boldsymbol{B} = 0 = \nabla \cdot \boldsymbol{U}. \tag{4}$$

In Eqs. (2)–(4), we have normalized $\boldsymbol{B}$ and $\boldsymbol{v}$ to the Alfvén speed $v_{\text{a}} = B_0/\sqrt{4\pi\rho}$ (where $B_0$ is a typical magnetic field intensity and $\rho$ is the mass density), the total gas pressure $p$ to $\rho v_{\text{a}}^2$, and longitudes and times, respectively, to $L_0$ and $L_0/v_{\text{a}}$. The dimensionless dissipation coefficients are the viscosity $\nu$ and the electric resistivity $\eta$ defined as

$$\eta = \frac{c^2}{4\pi\sigma}. \tag{5}$$

The dimensionless coefficient $\epsilon$ is defined as

$$\epsilon = \frac{c}{w_{\text{pi}} L_0}, \tag{6}$$

is a measure of the relative strength of the Hall effect. The dimensionless electron velocity is

$$\boldsymbol{v}_{\text{e}} = \boldsymbol{v} - \epsilon \nabla \times \boldsymbol{B}. \tag{7}$$

From Eq. (3) it is apparent that in the non-dissipative limit (i.e., $\eta \to 0$) the magnetic field remains frozen to the electron flow $\boldsymbol{v}_{\text{e}}$ rather than to the bulk velocity $\boldsymbol{v}$.

The incompressible Hall MHD simulations reported in this paper are carried out under the geometric approximation known as $2\frac{1}{2}$D (two and a half dimensions).

This approximation is based on the assumption that there is translational symmetry along the $\hat{z}$ coordinate (i.e., $\partial_z = 0$). Therefore, the solenoidal magnetic and velocity fields, can be represented as:

$$\boldsymbol{B} = \nabla \times [\hat{z} a(x, y, t)] + \hat{z} b(x, y, t), \tag{8}$$

$$\boldsymbol{U} = \nabla \times [\hat{z} \phi(x, y, t)] + \hat{z} u(x, y, t), \tag{9}$$

where $a(x, y, t)$ is the magnetic flux function and $\phi(x, y, t)$ is the stream function. In this approximation, the Hall MHD equations take the form:

$$\partial_t a = [\phi - \epsilon b, a] + \eta \nabla^2 a, \tag{10}$$

$$\partial_t b = [\phi, b] + [u - \epsilon j, a] + \eta \nabla^2 b, \tag{11}$$

$$\partial_t w = [\phi, w] + [j, a] + \nu \nabla^2 w, \tag{12}$$

$$\partial_t u = [b, a] + [\phi, u] + \nu \nabla^2 u. \tag{13}$$

The nonlinear terms are the standard Poisson brackets (i.e., $[p, q] = \partial_x p \partial_y q - \partial_y p \partial_x q$), $w = -\nabla^2 \phi$ is the $\hat{z}$-component of the flow vorticity and $j = -\nabla^2 a$ is the $\hat{z}$-component of the electric current density which vectorial expression can be written:

$$\boldsymbol{j} = \nabla \times b\hat{z} + j\hat{z}. \tag{14}$$

The set of Eqs. (10)–(13) completely describes the reconnection problem for this particular geometry. One of the most important consequences of including the Hall effect is the coupling between the $\hat{z}$-component of the fields to the scalar potentials $a$ and $\phi$. Note that if $\epsilon = 0$, then the system decouples and the solutions for $a$ and $\phi$ are determined by the solution of Eqs. (10) and (12), thus becoming completely independent from the $\hat{z}$ fields.

## 3. Simulation model

In the present paper, we study the Hall reconnection phenomena by means of the numerical integration of

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