AGU FALL MEETING
New Orleans | 11-15 December 2017

PARTICLE-IN-CELL SIMULATIONS OF ASYMMETRIC GUIDE-FIELD RECONNECTION: QUADRUPOLAR STRUCTURE OF HALL MAGNETIC FIELD

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SM13B-2365

INTRODUCTION

One of the most important processes that occurs in Earth's magnetosphere is known as magnetic reconnection (MR). This process can be symmetric or asymmetric, depending basically on the plasma density and magnetic field in both sides of the current sheet. A good example of symmetric reconnection in terrestrial magnetosphere occurs in the magnetotail, where these quantities are similar on the north and south lobes. In the dayside magnetopause MR is asymmetric, since the plasma regimes and magnetic fields of magnetosheath and magnetosphere are quite different. Symmetric reconnection has some unique signatures. For example, the formation of a quadrupolar structure of Hall magnetic field and a bipolar Hall electric field that points to the center of the current sheet. The different particle motions in the presence of asymmetries change these signatures, causing the quadrupolar pattern to be distorted and forming a bipolar structure. Also, the bipolar Hall electric field is modified and gives rise to a single peak pointing toward the magnetosheath, considering an example of magnetopause reconnection.

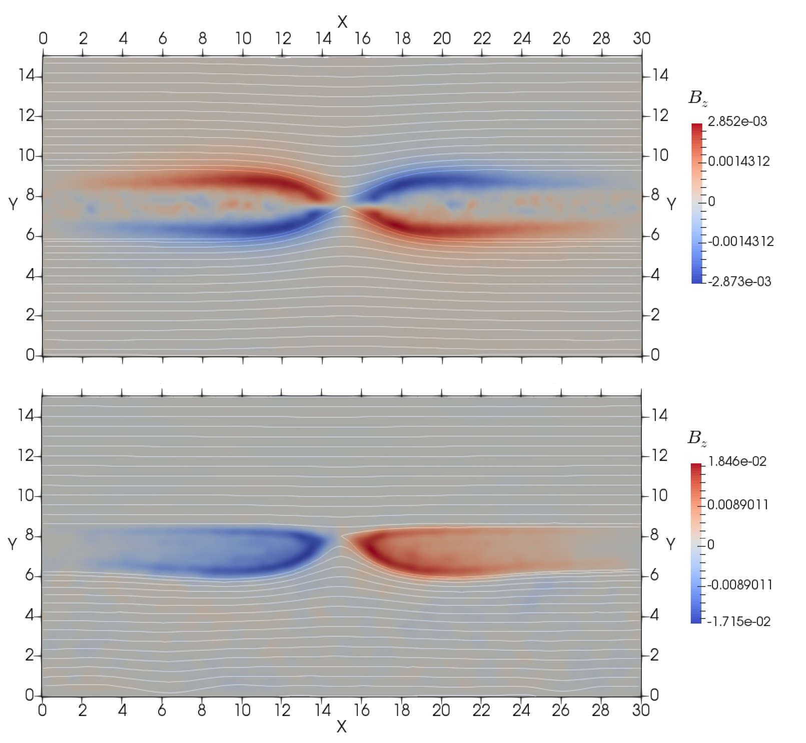

Figure 1: From the top to the bottom, the quadrupolar magnetic field out-of-plane from the symmetric case and the bipolar structure from the asymmetric case.

Figure 1 shows two examples of these structures. In the top panel is shown the out-of-plane magnetic field from a simulation of symmetric reconnection. The parameters used in the simulation are based on typical values of the magnetotail (Goldman et al., 2016). The bottom panel shows a simulation of asymmetric case, based on Mozer et al. (2008). We can see that the presence of asymmetry changes the Hall magnetic field's configuration due to the asymmetry of the Hall current in the ion diffusion region. Both simulations were made without a guide-field, i. e., $B_z = 0$.

MAGNETIC RECONNECTION WITH GUIDE-FIELD

The presence of a guide-field can distort the quadrupolar pattern, by giving a shear angle across the current sheet and altering the symmetric patterns. In Figure 2 we can see results of a simulation of symmetric MR with a guide-field at $\Omega_i t = 19.6$, made by Pritchett (2001). The quadrupolar pattern of Hall magnetic field B_y, is distorted (Fig. 2a), but still exists. There are two distinct regions: one of enhanced B_y that occupy the region inside the magnetic island and another region with reduced B_y that is concentrated along the separatrices. Also, the electron flows along the separatrices while the ion flows out of the diffusion region (Fig 2b and 2c).

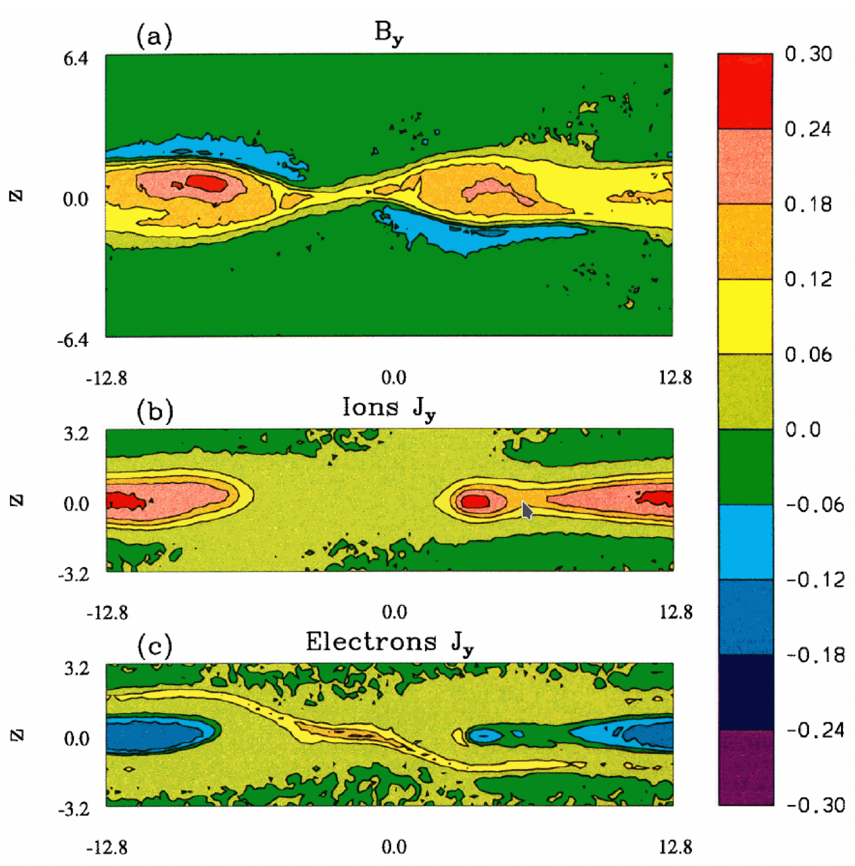

Figure 2: Simulation of a symmetric case with guide-field at $\Omega_i t = 19.6$ from Pritchett (2001). (a) Hall magnetic field, (b) ion current density J_{iy} and (c) electron current density J_{ey}.

Figure 3 shows an asymmetric MR simulation with guide-field (Pritchett & Mozer, 2009). The left panel shows the Hall electric field, E_x, strongly pointing to the magnetosheath. The right panel shows the Hall magnetic field, B_y, a little distorted by the guide-field but still mantaining its bipolar structure. The asymmetric characteristics are present even with the presence of the guide-field.

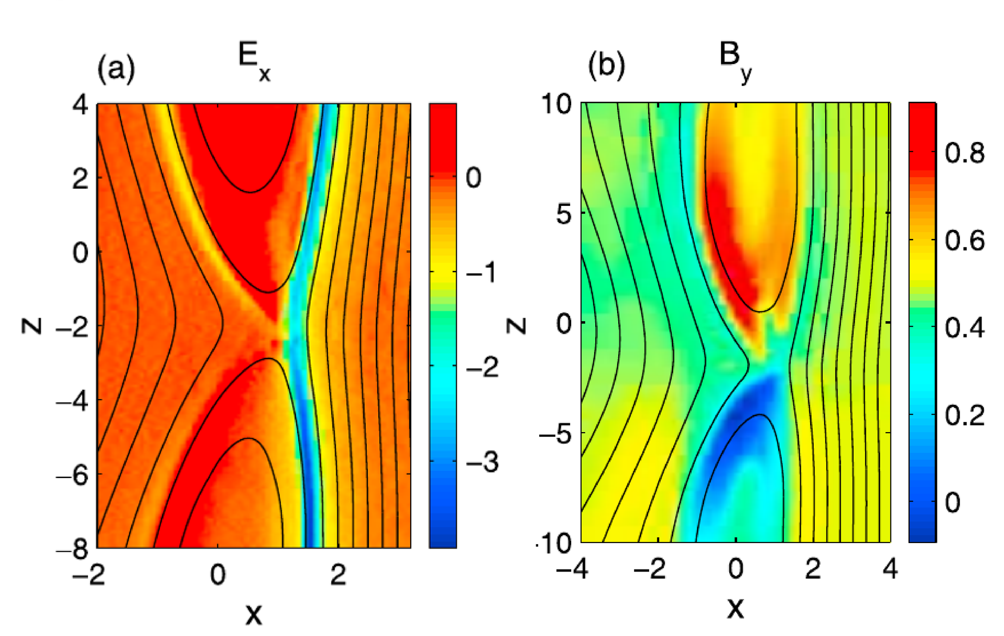

Figure 3: Simulation of a asymmetric case with guide-field at $\Omega_i t = 70$ from Pritchett & Mozer (2009). (a) Hall electric field E_x and (b) Hall magnetic field B_y.

MMS OBSERVATIONS

Recently, a quadrupolar structure was observed in an asymmetric guide-field MR event using Magnetospheric Multiscale (MMS) mission data (Peng et al., 2017).This event was detected on 3 december 2015, from 02:38:30 to 02:38:50 at the dayside magnetopause. It was observed the signatures of a symmetric RM with a guide-field, including the quadrupolar magnetic field and bipolar Hall electric field.

MMS OBSERVATIONS

Figure 4 shows an overview of the current sheet associated with this event. The components of the magnetic field in GSE coordinates are presented in Figure 4 (a). Figures 4 (b) - (e) shows, respectivily, the magnetic field magnitude, $|B|$, B_L, B_M^* and B_N in LMN coordinates. The component B_M^* is obtained after removal of the guide-field, $B_g = 12.5\,\text{nT}$. The ion and electron flows are presented in Figure 4 (f) and (g), respectivally.

Table 1 shows the ion density (N_i) and magnetic field (B_L) of this event on both sides of the current sheet, the Sun side and the Earth side. We can see clearly the density asymmetry, although the magnetic field is only about 16% stronger on the Earth side than on the Sun side.

Table 1: Observed parameters

	Sun side	Earth side
B_L	30 nT	35 nT
N_i	16 cm^{-3}	8 cm^{-3}
B_g	12.5 nT	

Figure 4 (d) shows a bipolar variation of B_M^*, which is interpreted as the quadrupolar Hall magnetic field of symmetric RM. Also was detected in this event the bipolar Hall electric field. However, this was an event of asymmetric reconnection. Therefore, the density asymmetry and the guide-field were not sufficient to form signatures of asymmetric reconnection.

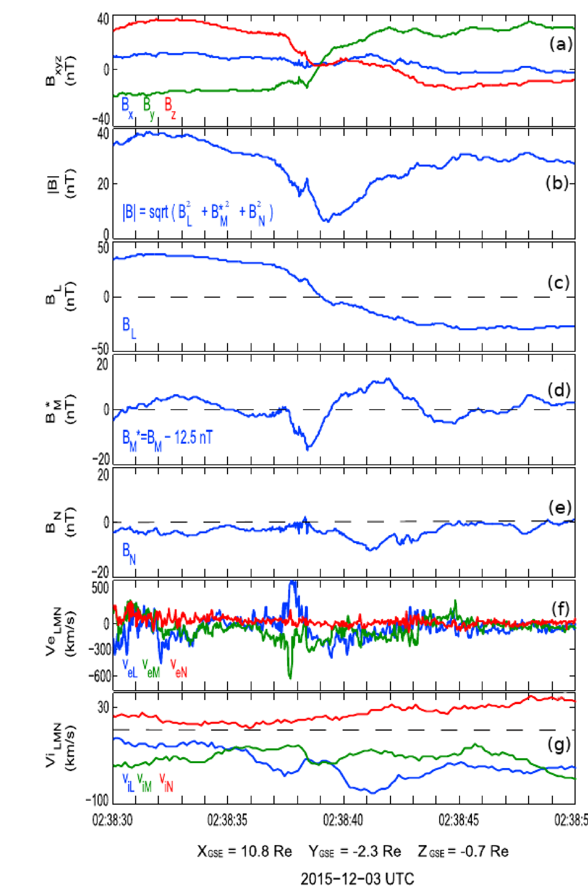

Figure 4: (a) Magnetic field components in GSE coordinates, (b) - (e) shows, respectivily, the magnetic field magnitude, $|B|$, B_L, B_M^* and B_N in LMN coordinates, (f) ion flow and (g) electron flow (from Peng et al. (2017).)

PARTICLE-IN-CELL SIMULATIONS

Using the particle-in-cell code iPIC3D (Markidis et al., 2010) with the MMS data from this event (Table 1) used to define input parameters, we found a quadrupolar structure of Hall magnetic field and a bipolar pattern of Hall electric field in ion scales. The code was modified to run asymmetric MR, based on Pritchett (2008). The normalized parameters used as initial conditions for the simulations were obtained from Table 1. The spatial grid was $20\,\mathrm{d_i}$ in x direction and $10\,\mathrm{d_i}$ in y direction with 600×300 cells. The time step was $\Delta t = 0.005$ during 100000 cycles. Figure 5 shows the magnetic field magnitude at $\Omega_i t = 0$. It was introduced a small perturbation to speed up the reconnection. The asymmetric density profile at $\Omega_i t = 0$ is presented in Figure 6.

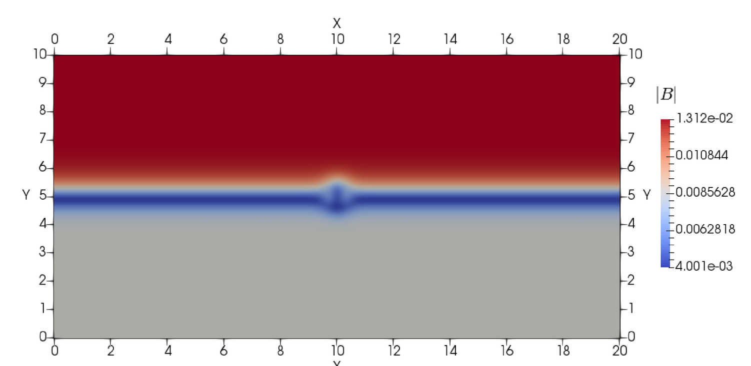

Figure 5: Magnetic field magnitude at $\Omega_i t = 0$.

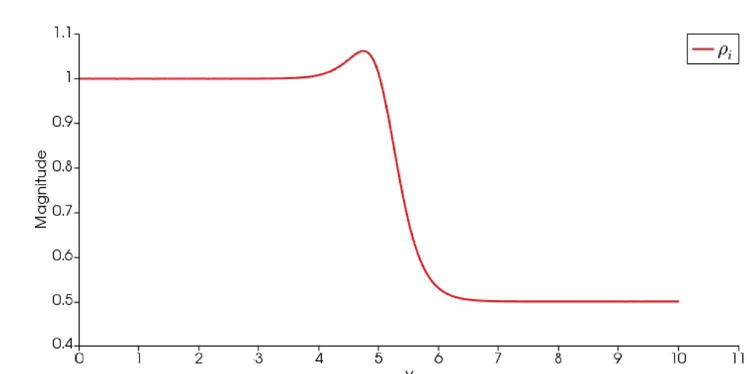

Figure 6: Density profile at $\Omega_i t = 0$.

The main results are presented in Figures 7 and 8. Figure 7 shows the Hall magnetic field (B_z at the top) and Hall electric field (E_y at the bottom) after 60000 cycles. It is clearly seen a distorted quadrupolar pattern of B_z compatible with symmetric RM with guide-field, as in Figure 2. Also, the Hall electric field has a bipolar structure, which is a characteristic of symmetric MR due to the charge separation between ions and electrons. In Figure 8 is shown the current density J_z of ions and electrons. We can see that the behavior is according Figure 2, the electron flows along the separatrices and the ion flows directed to the outflow region. These results shows that the simulation are in a good agreement with the MMS observations made by Peng et al. (2017).

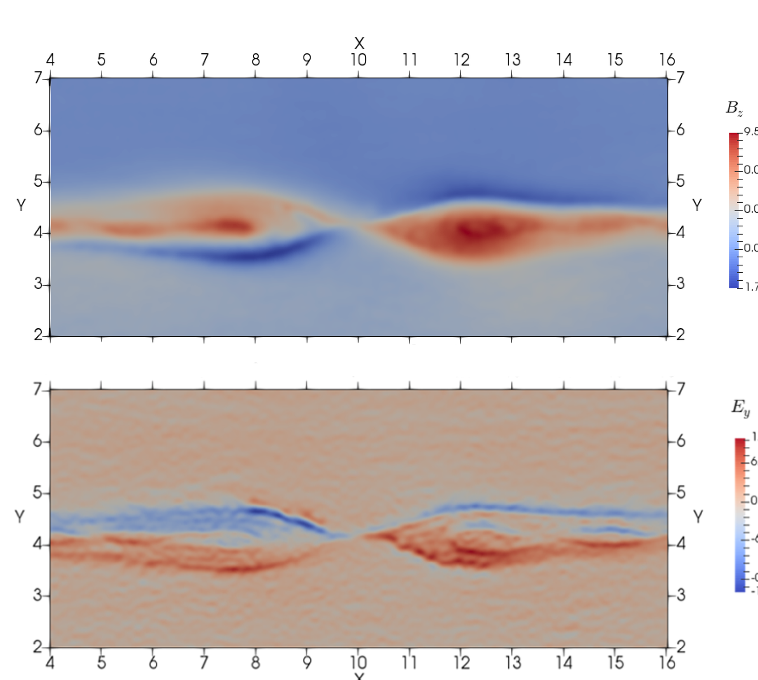

Figure 7: Top panel: quadrupolar pattern of Hall magnetic field B_z. Bottom panel: Hall electric field E_y.

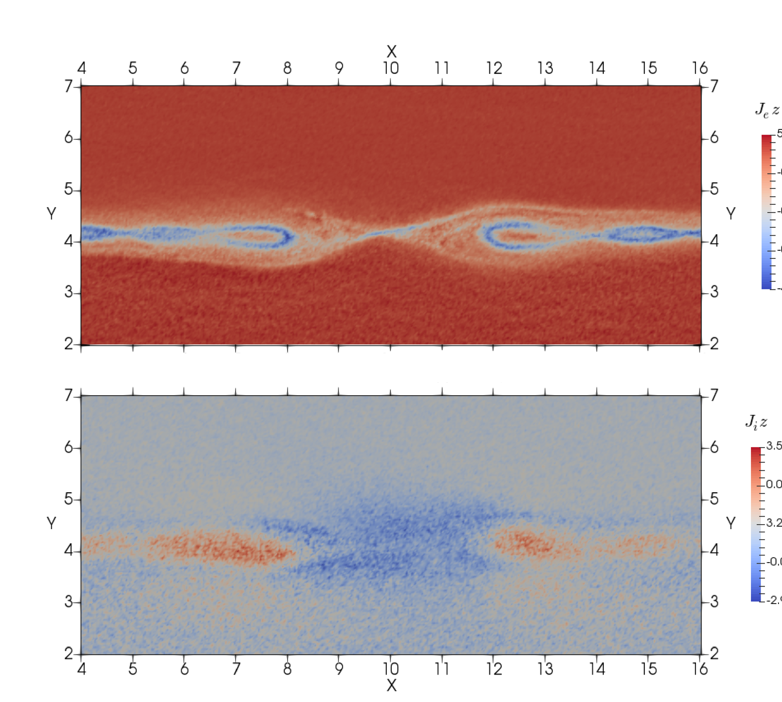

Figure 8: Out-of-plane current density J_z of electrons (top panel) and ions (bottom panel).

CONCLUSIONS

Our results are in an excellent agreement with the MMS observations, showing that it's not trivial to find a threshold between a symmetric and an asymmetric reconnection. Even with all the asymmetric parameters we still found the characteristics of symmetric guide-field reconnection. Previous simulations, such as Pritchett & Mozer (2009), have found that a guide-field distorts the RM region, but our simulations presented another scenario. Even with the guide-field and the density asymmetry the asymmetric structures were observed.

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ACKNOWLEGMENTS

INPE
CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico
CAPES