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The double layers in the plasma sheet boundary layer during magnetic reconnection

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Abstract

We studied the evolutions of double layers which appear after the magnetic reconnection through two-dimensional electromagnetic particle-in-cell simulation. The simulation results show that the double layers are formed in the plasma sheet boundary layer after magnetic reconnection. At first, the double layers which have unipolar structures are formed. And then the double layers turn into bipolar structures, which will couple with another new weak bipolar structure. Thus a new double layer or tripolar structure comes into being. The double layers found in our work are about several ten Debye lengths, which accords with the observation results. It is suggested that the electron beam formed during the magnetic reconnection is responsible for the production of the double layers.

1 Introduction

Magnetic reconnection is a very important progress in the space plasma, which change the magnetic field energy into kinetic energy of electrons and ions (Pritchett, 2001; Lu et al., 2010). In the previous works, more attentions are paid on the whistler waves (Fujimoto and Sydora, 2008; Deng and Matsumoto, 2001; Guo, 2011; Xiao et al., 2007, 2008, 2010) and electron acceleration (Fu et al., 2006; Huang et al., 2010; Pritchett, 2006). Recently, the electrostatic waves have been found in the simulation and observation. Through the simulation, Drake et al. (2003) reported that the electrostatic waves and electron holes are produced by the Buneman instability. In their simulation, the initial electron drift speed is above the threshold to trigger the Buneman instability except for a strong guide field. However, Fujimoto and Machida (2006) suggested that the electrostatic waves are excited by the electron two-stream instability which has a relationship with magnetic reconnection. Particularly, no guide field is used in their initial condition. And the observation (Li et al., 2009) proved that the guide field has no direct effect on the generation of the electrostatic wave in or around the reconnection diffusion region. These reported electrostatic waves appear with bipolar electric field and electron holes, while the signature of the double layers is a unipolar electric field. The charged particles will be accelerated, decelerated, or reflected by the electric field when they enter the double layer. The double layers are often observed in the downward current region of the auroral ionosphere (Ergun et al., 2001) in current-driven space plasma (Newman et al., 2001) in plasma sheet boundary layer (Ergun et al., 2009) and near the dipolarization fronts of bursty bulk flows which propagate earthward (Deng et al., 2010).

The tripolar electrostatic waves are one kind of electrostatic waves with three humps, which have been found in current layers (Li et al., 2013). The tripolar pulses have two positive and one negative peak in the electric field, or two negative peaks and one positive. These structures have been observed in the magnetosheath and solar wind. The tripolar electrostatic solitary waves can be interpreted as weak double layers (Li et al., 2013). Recently, in the region which is adjacent to the reconnection diffusion, Geotail observed the tripolar electrostatic solitary waves along the plasma sheet boundary layer region (Li et al., 2013; Pickett et al., 2009). All of the above suggests that double layers are universal in many active plasma regions. It has been suggested that the tripolar electrostatic waves is the couple of anti-propagating bipolar electrostatic waves. But no obvious details are given in the observations.

The electron beams have a closely relationship with electrostatic waves. Especially, magnetic island is considered to has an important effect on the production of electron beams. This structure will be formed between X lines in multiple X line reconnection (Wang et al., 2010; Hang et al., 2012). Then counterstreaming electrons will come from the left and rights sides of islands along the magnetic field lines. The periodic boundary condition used in the simulation is suitable for this environment. In this paper, the particle-in-cell simulation can be used to investigate the generation mechanism and a double layer during the magnetic reconnection will be studies and discussed.

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2 Simulation

The initial magnetic field distribution is set to be $B_x(y) = B_0 \tanh[(y - L_y/2)/\delta_0]$, where δ_0 is the half width of the initial current sheet. The particle densities read $n(y) = n_\mathrm{p}\mathrm{sech}^2[(y - L_y/2)/\delta_0] + n_\mathrm{b}$, where n_p and n_b represent the current sheet and background densities. δ_0 is equal to $0.5\lambda_\mathrm{i}$, where λ_i is the ion inertial length given by n_p. All of the particles have the initial Maxwellian velocity distributions. In the present simulation, the simulation size is $L_x \times L_y = 25.6\lambda_\mathrm{i} \times 12.8\lambda_\mathrm{i}$. The other parameters are $T_\mathrm{i}/T_\mathrm{e} = 5$, $n_\mathrm{b} = 0.1n_\mathrm{p}$, $m_\mathrm{i}/m_\mathrm{e} = 256$, $c/V_\mathrm{A} = 30$, where V_A is the Alfvén speed based on B_0 and n_p. The spatial resolution is $\Delta x = \Delta y = 0.05\lambda_\mathrm{i}$. The time step is $\Delta t\Omega_\mathrm{i} = 0.001$, where Ω_i is the proton cyclotron frequency. Along the x axis, the periodic boundary conditions are used, and the ideal conducting boundary conditions are used in the y direction. The particles will be reflected when they reach the boundary in the y direction. The magnetic and electric fields are calculated with a full explicit algorithm. About 6×10^6 particles per species are employed in the simulation. A small initial magnetic perturbation is superposed in the form which is the same as the references (Lu et al., 2013; Guo, 2014).

3 Simulation results

Figure 1a shows the electric field parallel to the local magnetic field $E_\parallel$ and magnetic field lines at $t\Omega_\mathrm{i} = 15.3$. Figure 1b shows the magnification of $E_\parallel$ in left-hand plane. The electric fields with polarized structures can be seen clearly in the diffusion region and plasma sheet boundary layer. These structures are almost along the magnetic field lines. As the magnetic reconnection proceeds, the polarized electric fields will also appear in the diffusion region, which have been discussed in our previous work (Guo, 2014). In this paper, we mainly discuss the evolution of electric fields with polarized structures in the plasma sheet boundary layer.

In order to reveal the evolution of the parallel electric fields $E_{\parallel}$, shown in Fig. 2 are the time evolutions of the $v_{\parallel} - x$ phase space distribution of electron and ion, the electric field $E_{\parallel}$ and density of particles (the black and red curves represent electron and ion respectively) at $t\Omega_i = 13.0$ (Fig. 2a), 13.5 (Fig. 2b), 14.0 (Fig. 2c) and 15.3 (Fig. 2d). The magnetic field line passes through $y/\lambda_i = 6.75$, where the magnetic field is nearly parallel to the x axis in the region $x/\lambda_i > 17$ or < 6. At $t\Omega_i = 13.0$, the obvious double layer with unipolar electric field can be seen clearly at about $x/\lambda_i = 21.0$. It has the width of about $0.4\lambda_i$. At this time, the electron thermal speed $v_{the} \sim v_{th0} = (2T_e/m_e)^{1/2} \sim 6.5V_A$, then $0.4\lambda_i \sim 29\lambda_{De}$, $\lambda_{De} = v_{the}/\omega_{pe}$ is the initial electron Debye length. Correspondingly, the densities of electron and ion have a hump and dip around $x/\lambda_i = 21.0$ respectively. At this time, the electron parallel velocity distribution can be regarded as composed with two counter streaming beams. The parallel velocity distribution of electron near $x/\lambda_i = 21.0$ appear to be composed of two electron beams with drift velocity $v_d/V_A \sim \pm 6.0$. The same evolution of electron parallel velocity appears at about $x/\lambda_i = 4.5$, whereas the double layer is not obvious.

At $t\Omega_i = 13.5$, a new double layer with a negative peak near $x/\lambda_i = 4.0$ is formed, while the double layer near $x/\lambda_i = 21.0$ has turn into bipolar structure. As the progress goes on, the velocities of electron beams trapped by the electrostatic structure increase. They nearly reach $v_d/V_A \sim \pm 10.0$ at $t\Omega_i = 14.0$ as shown in Fig. 2c. At this time, the unipolar structure near $x/\lambda_i = 4.0$ has become bipolar structure. The bipolar parallel electric field near $x/\lambda_i = 4.0$ continues to develop and a new double layer with a width of $0.2\lambda_i$ at about $x/\lambda_i = 3.5$ can be seen adjacent to this bipolar structure, as shown in Fig. 2d. Whereas the bipolar structure near $x/\lambda_i = 21.0$ is evolved into a tripolar structure.

As for ion, the evolution of ion is contrary to that of electron. The ions which enter the electrostatic structure are decelerated or reflected out of this region. Especially, the parallel electric field initially has unipolar structure, and then it turns to be bipolar. After that, a relatively weak bipolar structure come into being, it will couple with the former bipolar structure. And then, a new double layer is formed as shown in Fig. 3. In our

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simulation, the double layer seems to only propagate outward along the magnetic field for a short distance and then exist for a long time.

Figure 4 shows the time evolution of the electron flow velocity parallel to the magnetic field at $y/\lambda_i = 6.75$. The electron beam should be outflow according to its velocity. The electron beam appear at about $x/\lambda_i = 20.0$ at $t\Omega_i \sim 12.0$ where polarized electric fields form. There is another electron beam with negative velocity at about $x/\lambda_i = 4.0$ at $t\Omega_i \sim 13.0$. The delay of two electron beams can explain the different time of the double layers formation time. We suggest that the electron beam produced by magnetic reconnection should be responsible for the formation of the double layer. These electrons should be accelerated by whistler waves (Guo, 2011) or gain energy owing to the curvature drift in the stronger magnetic field region after they are accelerated near the x line (Hoshino et al., 2001) and so on. Next, we mainly discuss the beam in the left region near $x/\lambda_i = 4.0$. The beam propagates along the magnetic field toward left until nearly $t\Omega_i = 15.0$. Although the flow velocity is not equal to zero, it cannot propagate because it encounters the electron beam from left due to the periodic boundary. This evolution is consistent with that of parallel electric field shown in Fig. 2. The observations from reference (Ergun et al., 2009) suggest that the three primarily plasma environments where the double layers are often observed. The first is the plasma sheet boundary layer, the second is near the current sheet where $|B|$ is minimum, and the third is during bursty bulk flows events. In our simulation, the region where the double layers are found just locates in the plasma sheet boundary layer and the value of $|B|$ is about $0.4B_0$. All of the above suggest that the conditions where the double layer found in our simulation are consistent with observation environments. Of course, the bursty bulk flows events need to be studied carefully in the future because of the limited simulation conditions.

Figure 5 shows the evolution positions of electrons whose absolute parallel velocities $|v_{\parallel}/V_A|$ are larger than 9 at $t\Omega_i = 15.3$. They are located in the region $3.6 < x/\lambda_i < 4.0$ near $y/\lambda_i = 6.75$. The black points represent the electrons whose velocities $v_{\parallel}/V_A$ are larger than 9, while the red points represent the electrons whose velocities $v_{\parallel}/V_A$ are smaller than −9. Note the origin of these electrons with large velocities is the plasma

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sheet, as shown at $t\Omega_i = 0$. They are trapped by the islands due to the magnetic reconnection and move along the magnetic field. At $t\Omega_i = 15.0$, the black and red points shift toward each other almost on the same line. After the meeting at $t\Omega_i = 15.3$, the particles continue to move along the original direction.

4 Conclusions

In this paper, the evolutions of double layers during magnetic reconnection are studied by two-dimensional electromagnetic particle-in-cell simulation. The simulation results show that, the double layers appear in the plasma sheet boundary layer, which is excited by the electron beam produced during the magnetic reconnection. At first, the double layers come into being, and then these structures are evolved into bipolar structures. A relatively weak bipolar structure is excited, and then the two bipolar structures couple together, which leads to produce a new double layer. The double layers found in our simulation are about several ten Debye lengths, which accords with the observation results (Boström, 1992). But the double layers can only propagate for a short distance because two electrons counter-streaming are formed due to periodic boundary condition in the x direction. In the region with a double layer, the electron density decreases while the ion density increase, until the density of the latter is much larger than that of the former. However, even though we get some interesting results, there are still many questions that remain to be addressed. For instance, that is worth pursuing is to adopt observed values for the physical parameters in the same place to compare with our results. This approach is, however, beyond the scope of the present manuscript.

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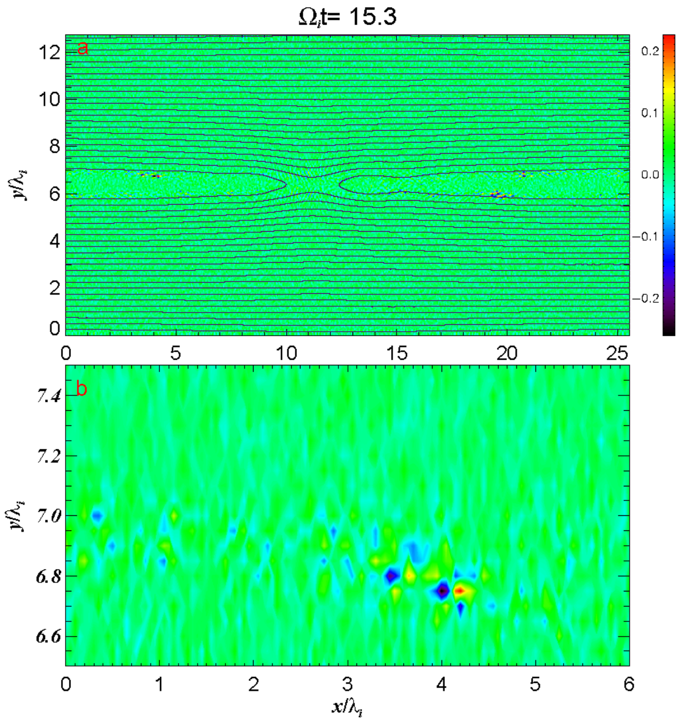

Figure 1. The electric field parallel to the local magnetic field $E_{\|}$ and magnetic field lines at $t\Omega_i = 15.3$ **(a)**; the magnification of the left-hand plane **(b)**.

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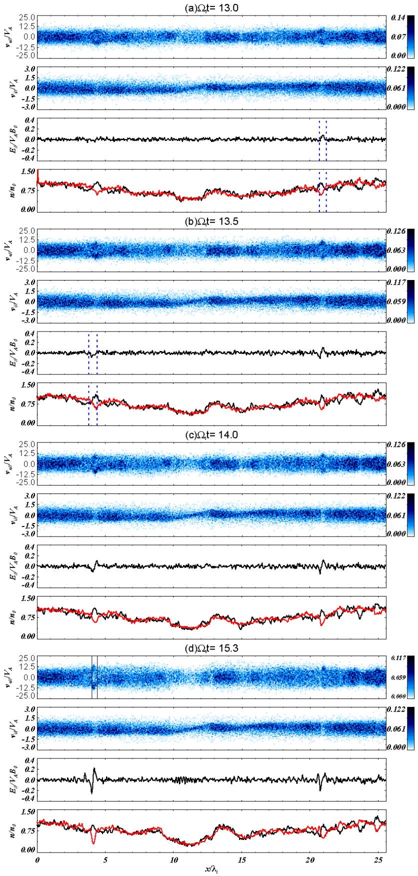

Figure 2. The time evolutions of the $v_{\parallel} - x$ phase space distribution of electron and ion, the electric field $E_{\parallel}$ and density of particles (the black and red curves represent electron and ion respectively) at Ω_i = 13.0 **(a)**, 13.5 **(b)**, 14.0 **(c)** and 15.3 **(d)**.

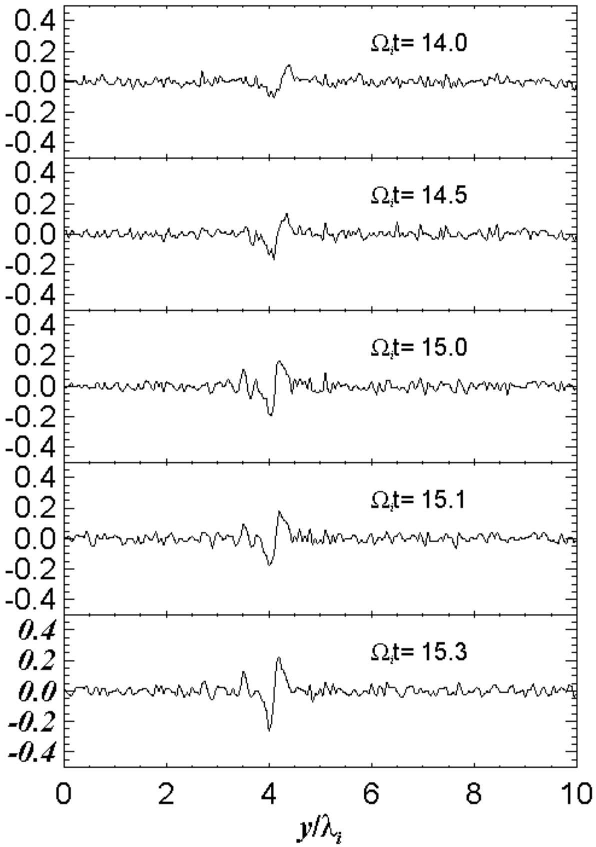

Figure 3. The time evolution of a new double layer.

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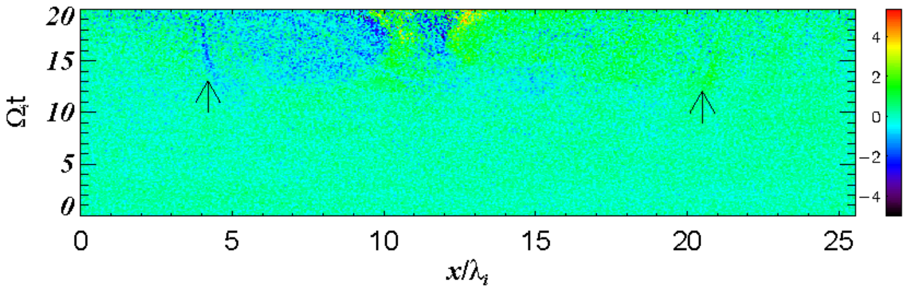

Figure 4. The time evolution of the electron flow velocity parallel to the magnetic field at $y/\lambda_i = 6.75$.

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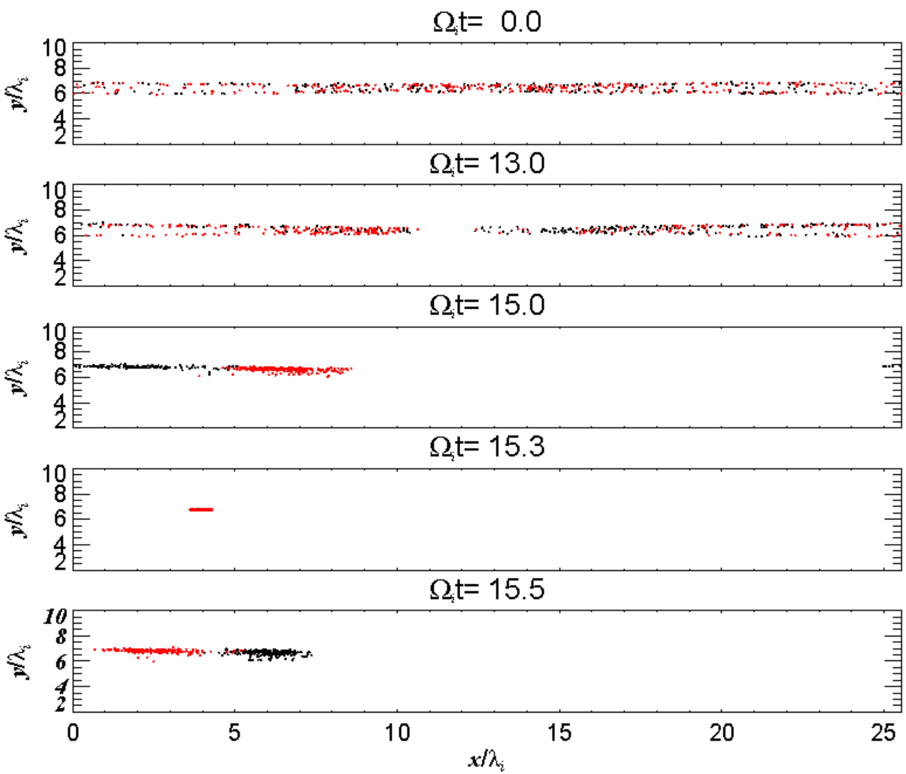

Figure 5. The evolution positions of electrons whose absolute parallel velocities $|v_{\parallel}/V_A|$ are larger than 9 at $t\Omega_i = 15.3$.

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