The double layers in the separatrix region during magnetic reconnection

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Abstract We studied the evolution of double layer which appears during the magnetic reconnection through two dimensional particle-in-cell simulation. The simulation results show that the double layer in the wake of electron hole is formed in the separatrix after magnetic reconnection. At first, a localized electron beam forms. Then the speed of electron beam increases as the magnetic reconnection goes on. When the speed is large enough, the electron beam excites the ion-acoustic instabilities, which results in the formation of double layers. The estimated spatial size of the double layer found in our work is about ten Debye lengths, and these structures propagate along the magnetic field with a velocity comparable to the ion acoustic speed, which accords with the observation results.

Keywords: the double layer, magnetic reconnection, particle-in-cell simulation

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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(EHs) 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. 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 (DLs) is a unipolar electric field. The electrons and ions will be accelerated, decelerated, or reflected by the electric field when they enter the double layer. The current-driven double layers have been carefully studied by using a series of one-dimensional Vlasov simulations.(Singh, 1980,1982, 2000) It is found that electron holes are a common feature of a strong double layer. The evolution of the electron beam accelerated by a double layer would contribute to continuously creating moving electron holes. Besides that, the double layer accelerate the ion beam to generate fluctuations above the ion cyclotron frequency in the 2.5dimensional particle-in-cell simulations. (Singh and Khazanov, 2003)

Electron holes are frequently observed by the spacecraft measurement during reconnection. Double layers are frequently observed in the auroral ionosphere. (Boström, 1992; Ergun et al., 2001) Only recently, Ergun et al. (2009) reported the double layers in the plasma sheet in the magnetotail. But, they could not confirm the relation between the double layers and reconnection in their work. Wang et al. (Wang et al., 2014) presented the first evidence of double layers during magnetic reconnection, and found that the double layers are moving away from X line at a velocity of about ion acoustic speed along the separatrix region. On the contrary, a series of electron holes moving toward the x line are observed in the wake of the double layer. In addition, the multiple DLs are also observed, which could be created in the simulation.(Singh et al.,2011)

The electrostatic waves have a closely relationship with electron beams. Previous simulation results by Hosino et al. (2001) show that electron beams form mainly close to the separatrix. Using three-dimensional simulation in the presence of a guide field, Prichett and Coroniti (2004) found the enhanced parallel electric field and electron velocity are confined to one pair of separatrix. In this case strong DLs can be generated at the reconnection site. The purpose of our study is to investigate the generation mechanism of the double layer during the magnetic reconnection without a guide field. Our results suggest that both the double layer and electron hole are found in our simulation. These polarized structure should be excited by the ion-acoustic instabilities.

2. Simulation Model

The initial magnetic field distribution is set to be $B_x(y) = B_0 \tanh[(y - Ly/2)/\delta_0]$, where δ_0 is the half width of the initial current sheet. The particle densities read $n(y) = n_p \mathrm{sech}^2[(y - L_y/2)/\delta_0] + n_b$, where n_p and n_b represent the current sheet and background densities. δ_0 is equal to $0.5\lambda_i$, 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 $L_x \times L_y = 25.6\lambda_i \times 12.8\lambda_i$. The other parameters are $T_i/T_e = 5$, $n_b = 0.1n_p$, $m_i/m_e = 256$, $c/V_A = 30$, where VA is the Alfvén speed based on B_0 and n_p. Then the ratio of ion gyro-frequency to plasma frequency is $\omega_{pi}/\Omega_i = c/V_A = 30$. The spatial resolution is $\Delta x = \Delta y = 0.05\lambda_i$. The time step is $\Delta t\Omega_i = 0.001$, 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 $E_{//}$ and magnetic field lines at $t\Omega_i = 15.3$. Figure 1b shows the magnification of $E_{//}$ in left-hand plane. We plot figure 1b as function of the electron Debye length instead of the ion inertial length. At this time, the electron thermal speed v_{the}~v_{th0}= $(2T_e/m_e)^{1/2}$ ～ $6.5V_A$. It is obvious that the electric fields with polarized structures are mainly located in the separatrix region. 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)

Shown in figure 2 are the $v_{//}$ - x phase space distributions of electron (a) and ion (b), and the electric field $E_{//}$ at y/λ_i=6.75(c). Figure 1(a) and (c) show clearly that there is an electron phase-space hole at x/λ_i～4.1. Besides that, a double layer with a width about $10\lambda_{De}$ lies at x/λ_i～3.5, which is in the wake of a electron hole, $\lambda_{De}=v_{the}/\omega_{pe}$ is the initial electron Debye length. Figure 2(d) is the parallel velocity distribution of electron $f(v_{e//})$ at about x/λ_i=4.1 and y/λ_i=6.75, which is corresponding to the electron hole shown in figure 2(a). This distribution appears an electron beam with $v_{e//}/V_A$~-12.0 and a broad peak centered around $v_{e//}/V_A$ ~10.0(flat-top distribution). On the other hand, the low velocity portion of the distribution is also dominated by an plateau formation. Figure 2(e) is the density distribution of electron along y axis at y/λ_i=3.5 where the double layer appear. Figure 2 (f) is the density distribution of electron along x axis at y/λ_i=6.75. Couple the (e) and (f), it is found that the density of electron where the double layer appears is lower than the surrounding along both x and y axis. Based on the observations, (Wang et al., 2013; 2014) the DL and electron hole are observed together. Then, our simulation results are basically consistent with the observations at least in the structure.

The magnetic field line passes through y/λ_i=6.75, where the magnetic field is nearly parallel to the x axis in the region x/λ_i <7. The plateau function means that the Buneman or ion-acoustic modes probably appear. Figure 3 is the wave spectrum of parallel electric field. The sampling region is 0< x/λ_i<6.4 and the time interval is 15.0<$t\Omega_i$< 15.5. It is found that the normalized wave number associated with the highest wave energy density is $k\lambda_{De}$～±0.8. These forward and backward modes are corresponding to the distribution shown in figure 2(d). During this period, the frequency of the dominant mode is far below the ion plasma frequency. All of the above suggests that the DL located in the separatrix region shown in figure 2(c) should be produced by the ion-acoustic instabilities.

Numerical simulations and observations have been performed during the past decade showing that DLs are highly variable structures moving with time. (Singh et al., 2005; Wang et al., 2014) Figure 4(a) is the time evolution of the polarized electric field shown in figure 1(b) at y/λ_i=6.75. The double layer in our simulation seems to only propagate outward along the magnetic field for a short distance. The propagation velocity can be estimated to be $0.2V_A$. While the double layer found in the separatrix near the X line shown in figure 4(b) can propagate for a long time and distance. The propagation velocity can be estimated to be $0.4V_A$. In fact, these two velocities are of the same order of the ion acoustic speed, although the former is a little small. The observation (Wang et al., 2014) also suggests that the DL propagates away from the X line at a velocity of about ion acoustic speed. That is, the results shown in figure 4 are very consistent with those observations. However, the DL found in the separatrix at a distance of several ion inertial length away from the X line shown in figure 1(b) cannot propagate for a long distance. A reasonable explanation for the figure 4(a) is due to the periodic boundary condition.

Previous simulation results about magnetic reconnection (Hosino et al., 2001; Prichett and Coroniti, 2004) show that electron beams form mainly close to the separatrix. In this condition, strong DLs can be generated at the reconnection site. These simulation results have been confirmed by the Cluster observations published by Vaivads et al. (2004). Figure 5 shows the time evolution of the electron flow velocity parallel to the magnetic field at y/λ_i=6.75. The localized electron beam with negative drift velocity propagates along the magnetic field toward left. At time $t\Omega_i\sim$ 12, this electron beam lies at $x/\lambda_i\sim$4.8, while the propagation stops at $x/\lambda_i\sim$4.1 due to the periodic boundary condition at time $t\Omega_i\sim$15.5. This evolution is consistent with that of parallel electric field shown in figure 4(a). Of course, the DL appears after the electron beam formed for a period of time. On the other hand, as the time goes on, the width of electron flow becomes smaller, while the beam velocity becomes larger. The figure shows that only when the velocity of electron beam reaches a certain value will excite the electrostatic waves. Compared with the figure 2, the electron beam just locates in the region where the electron hole appears. Our previous simulation results (Guo and Li, 2013) suggest that the ion-acoustic waves are always accompanied by electron beams. Considering the figure 2(d), thus it can be concluded that the localized electron beam excites the ion-acoustic instabilities, which results in the formation of DLs. However, the electron beam cannot drift for a long time due the periodic boundary, which lead the DL to cannot propagate long distance.

4. Conclusion

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 DLs appear in the separatrix, which are produced by the ion-acoustic instabilities. The DL found in our simulation is about ten Debye lengths and propagate out of the diffusion region with a velocity comparable to the ion acoustic speed. These results accord with the observation results. (Wang et al., 2014) The physical evolution process can be inferred from the following process. At first, the electrons are accelerated near the X line and then flow out of the diffusion region along the magnetic field. When the velocity of the electron beam is large enough, then the localized electron beam excites the ion-acoustic instabilities, which produced the DL. But the double layers at a few ion inertial length away from the X line can only propagate for a short distance, because the propagation of electron beam tends to stable due to periodic boundary condition. However, even though we get some interesting results, there are still many questions that remain to be addressed. For instance, a sufficiently long system will be used to study the propagation of DL in the future work.

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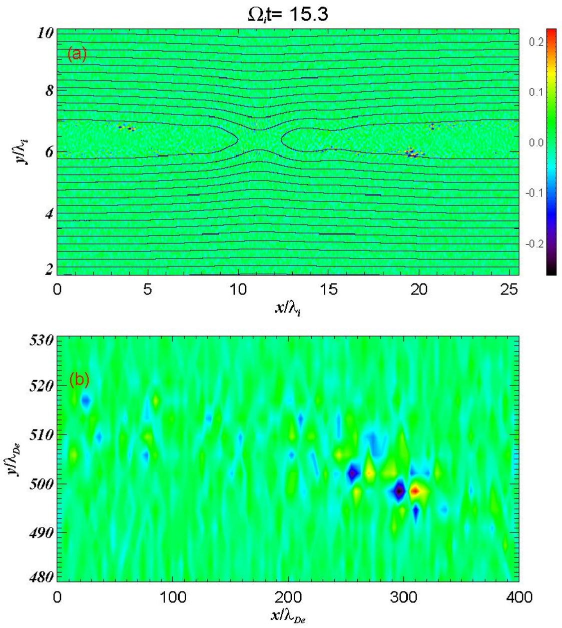

FIG. 1. The electric field parallel to the local magnetic filed $E_{//}$ and magnetic field lines at $t\Omega_i$ = 15.3(a); the magnification of the left-hand plane (b).

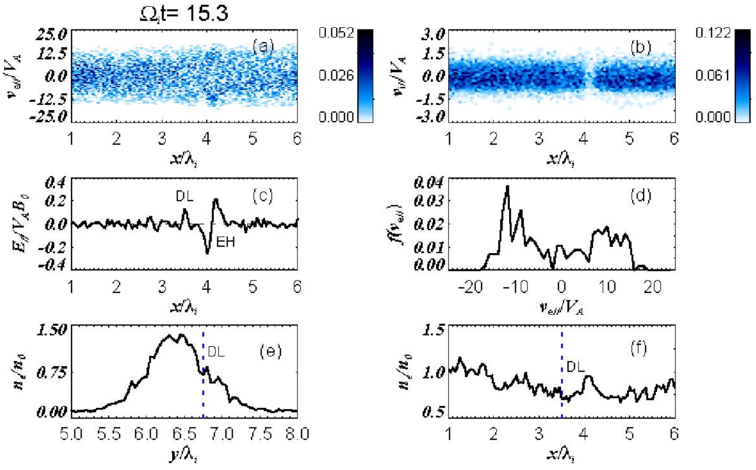

FIG. 2. The $v_{//}$ - x phase space distributions of electron (a) and ion (b), and the electric field $E_{//}$ at y/λ_i=6.75(c), the parallel velocity distribution of electron $f(v_{e//})$ at about x/λ_i=4.1 and y/λ_i=6.75(d), the density distribution of electron along y axis at y/λ_i=3.5 where the double layer appear (e) and the density distribution of electron along x axis at y/λ_i=6.75(f).

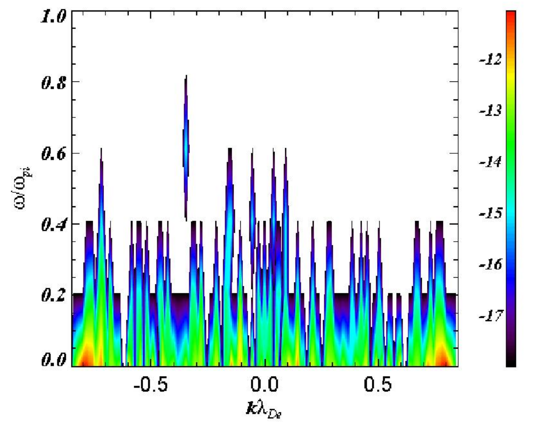

FIG. 3. The wave spectrum of parallel electric field. The sampling region is 0< x/λ_i<6.4 and the time interval is 15.0<$t\Omega_i$< 15.5.

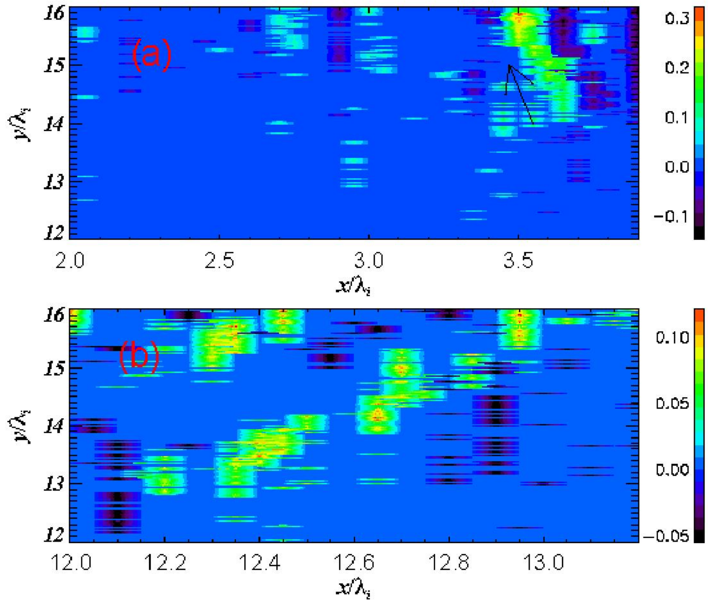

FIG. 4. The time evolution of the polarized electric field shown in figure 1(b) at y/λ_i=6.75 (a) and the double layer found in the separatrix near the X line (b).

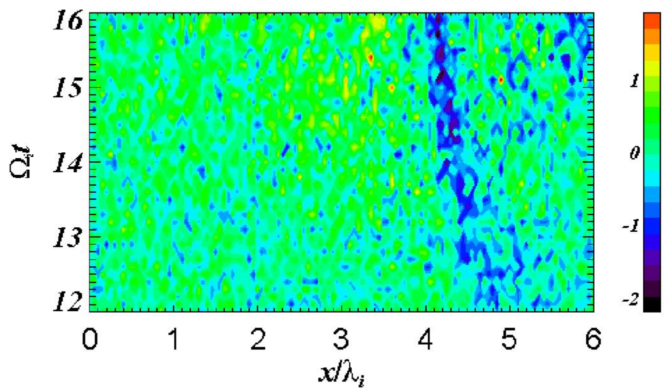

FIG. 5. The time evolution of the electron flow velocity parallel to the magnetic field at y/λ_i=6.75.