Effects of Ion-to-Electron Mass Ratio on Electron Dynamics in Collisionless Magnetic Reconnection *

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A $2\frac{1}{2}$-dimensional electromagnetic particle-in-cell (PIC) simulation code is used to investigate electron behaviour in collisionless magnetic reconnection. The results show that the ion/electron mass ratio (m_i/m_e) almost has no impact on the reconnection rate, however it can significantly affect electron behaviour in the diffusion region. For the case with larger mass ratio, the width of electron current sheet becomes smaller and the outflow region along the separatrix is smaller, hence the peak of the electron outflow speed is essentially larger. Density cavities and the parallel electric field $E_{//}$ along the separatrix can be found in the case with larger mass ratio, which may have significant influences on the acceleration and heating of the electrons near the X point.

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Magnetic reconnection is a fundamental plasma transport process because it plays an important role in the Earth's magnetosphere, solar corona, and laboratory plasma.[1,2] It rapidly converts magnetic energy into kinetic and thermal energy of electrons and ions. Recent studies show that electron behaviour is important to magnetic reconnection, and many physical phenomena have been thought to be related to the energetic electrons accelerated in the magnetic reconnection.[3,4] Usually an artificial ion-to-electron mass ratio (m_i/m_e), which ranges from 25 to 100, is used in particle-in-cell (PIC) simulations to study the electron behaviour due to limitation of computing resources.[5−7] It was found that the mass ratio cannot change the large scale phenomena, such as the reconnection rate. However, the mass ratio has significant effects on electron behaviour in the diffusion region. With the increasing ion-to-electron mass ratio, the electron diffusion region reduces and the maximum electron outflow speed increases. The results have also been verified by the implicit kinetic simulation with the real mass ratio ($m_i/m_e = 1836$).[8] Recently, the electron acceleration in the magnetic reconnection is investigated with particle-in-cell simulations,[9,10] where the mass ratio $m_i/m_e = 100$ is used. The results exhibited that the induced electric field in the diffusion region plays an important role in the electron acceleration. In this Letter, electron behaviour in collisionless magnetic reconnection is studied with a $2\frac{1}{2}$-dimensional electromagnetic PIC simulation code in which different mass ratios are considered. The density cavities and the parallel electric field can appear along the separatrix in the case with a larger mass ratio, which is rarely reported in previous studies.

In the particle simulations, the electromagnetic fields are defined in grids, and they are updated by the Maxwell equations. The ions and electrons are taken as discrete particles, and they are advanced in the electromagnetic fields according to their equations of motion.[11] In this study, the electromagnetic fields are calculated with a full explicit algorithm, and the relativistic effect is also considered in studying the motion of the particles.

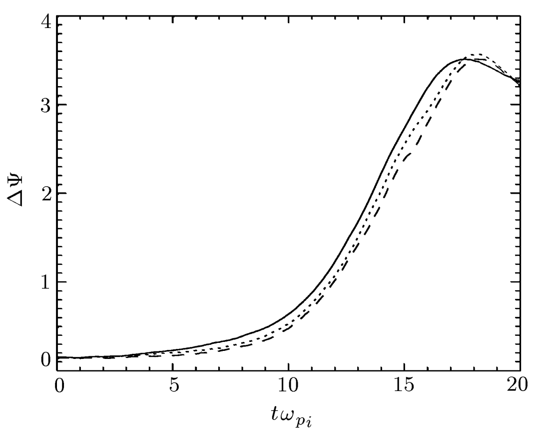

Fig. 1. Reconnected flux (normalized to B_0c/ω_{pi}) for $m_i/m_e = 25$ (solid line), $m_i/m_e = 64$ (dotted line), and $m_i/m_e = 256$ (dashed line).

The initial configuration for the present study is a Harris neutral sheet in the x, y plane. The initial magnetic field is $\boldsymbol{B} = B_{0x}(y)\boldsymbol{x}$, with

$$B_{0x}(y) = B_0 \tanh \frac{y - y_0}{\delta}, \quad (1)$$

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where B_0 is the asymptotic magnetic field, and δ is the half-width of current sheet, y_0 is the centre of current sheet. The ion and electron densities read

$$n(y) = n_0 \mathrm{sech}^2((y - y_0)/\delta) + n_b, \tag{2}$$

where n_0 and n_b represent the current sheet and background densities, which correspond to Harris and background particles, respectively. The Harris particles drift in the z direction, and the drift speeds of electrons and ions satisfy $V_{e0}/V_{i0} = -T_{e0}/T_{i0}$($T_{i0}$ and T_{e0} are the uniform temperatures of ions and electrons). Both the background electrons and ions have no drift speed, and their temperatures are the same as their corresponding Harris particles.

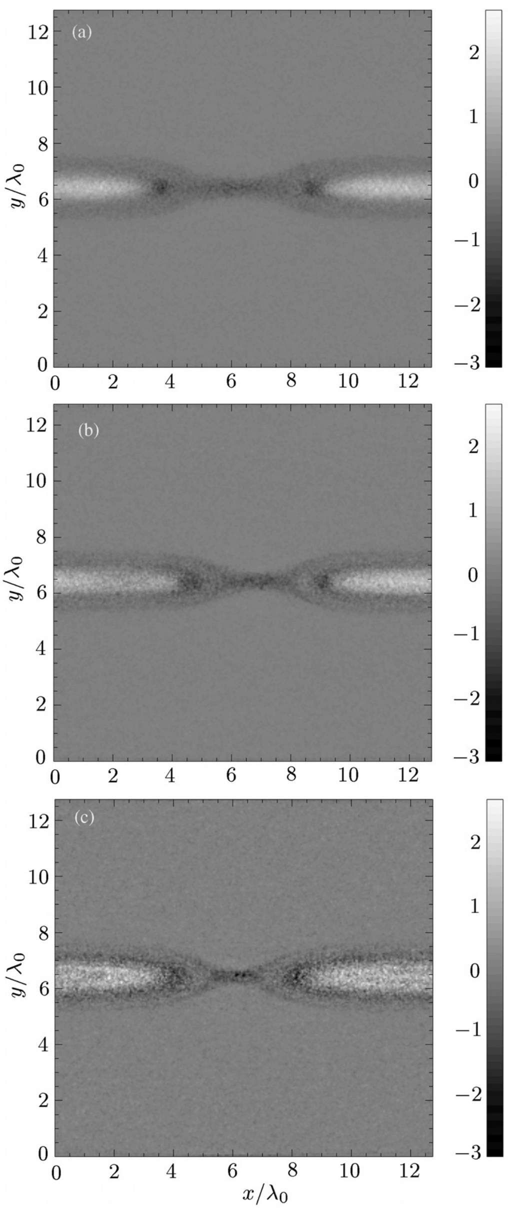

Fig. 2. Out-of-plane electron current density (normalized to en_0V_A) at $\omega_{pi}t = 13$ for $m_i/m_e = 25$ (a), $m_i/m_e = 64$ (b) and $m_i/m_e = 256$ (c).

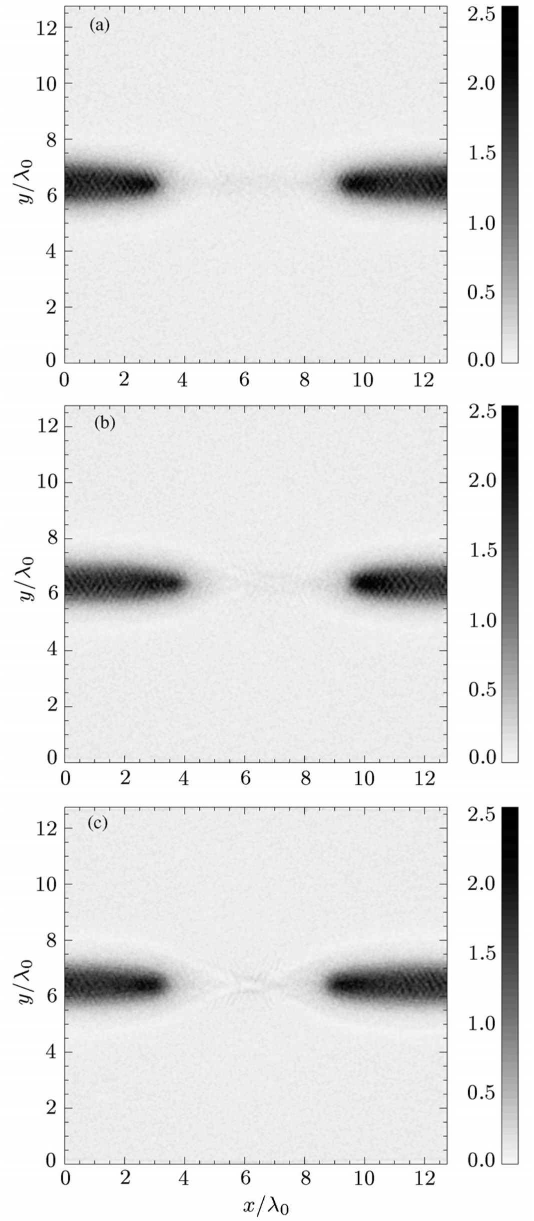

Fig. 3. Two-dimensional plots of the electron density at $\omega_{pi}t = 14.5$ for $m_i/m_e = 25$ (a), $m_i/m_e = 64$ (b) and $m_i/m_e = 256$ (c).

The half-width of the current sheet is $\delta = 0.5c/\omega_{pi}$, and its centre is located at $y_0 = 6.4c/\omega_{pi}$, where c/ω_{pi} is the ion inertial length defined on the current sheet density n_0. The background density $n_b = 0.1n_0$, and the ratio of temperature of ions to electrons is $T_{i0}/T_{e0} = 5$. The mass ratios are $m_i/m_e = 25, 64, 256$ and the plasma β is 0.1. We employ $N_x \times N_y = 256 \times 256$ grids, and the cell size is $\Delta x = \Delta y = 0.05c/\omega_{pi}$. The time step is taken to be $\Omega_i t = 0.001$, where Ω_i is the ion cyclotron frequency depended on B_0. The speed of light is chosen as $c/V_A = 30$, where V_A is the Alfvén speed based on B_0 and n_0. Periodic boundary conditions for particles and fields are used in the x direction. Simple wave reflection boundary conditions for electromagnetic fields are employed in the y

direction, and particles are reflected after they reach the boundary. In the simulations, an initial magnetic island is specified by the perturbation in the magnetic flux,

$$\Psi(x,y) = \Psi_0 \cos[2\pi(x - L_x/2)/L_x] \cdot \cos[2\pi(y - L_y/2)/L_y], \quad (3)$$

where Ψ is the vector potential component A_z, the value chosen for Ψ_0 is $\Psi_0/(B_0 c/\omega_{pi}) = 0.05$.

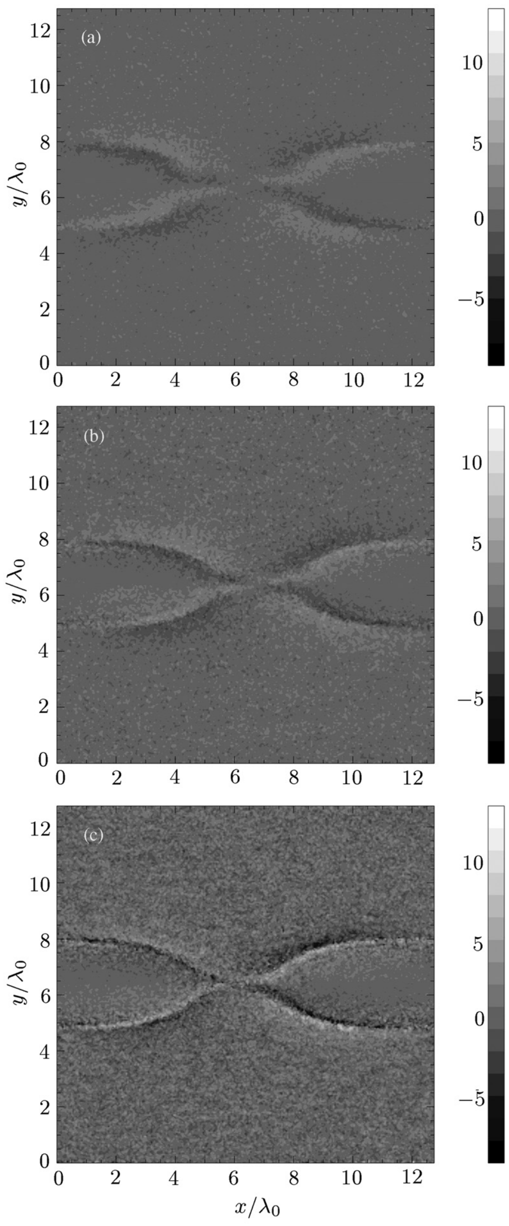

Fig. 4. Two-dimensional plots of the electron parallel velocity at $\omega_{pi}t = 14.5$ for $m_i/m_e = 25$ (a), $m_i/m_e = 64$ (b) and $m_i/m_e = 256$ (c).

Figure 1 shows the evolution of the reconnected flux for three cases with different mass ratios: $m_i/m_e = 25$, $m_i/m_e = 64$, and $m_i/m_e = 256$. To evaluate the reconnection rate, the flux difference between the X and O points, $\Delta\Psi$, is used. It can be seen that the reconnected flux are nearly the same in the three cases, all the cases show that the rapid growth begins at about $\omega_{pi}t \approx 10$ and saturates at about $\omega_{pi}t \approx 18$, which indicate that the ion to electron mass ratio has little effect on the gross reconnection rate.

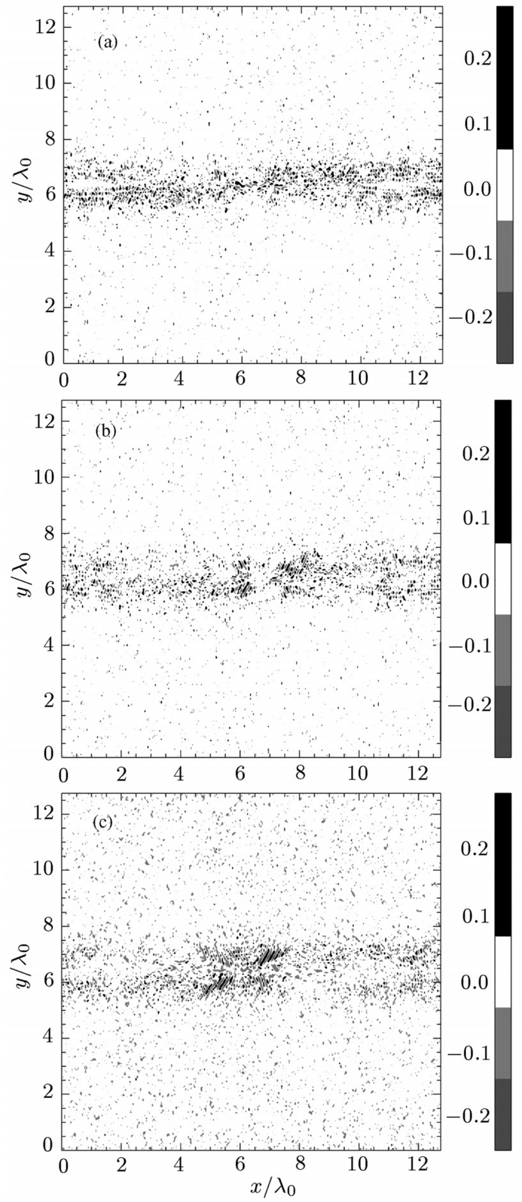

Fig. 5. Two-dimensional plots of the electric field parallel to the magnetic field at $\omega_{pi}t = 14.5$ for $m_i/m_e = 25$ (a), $m_i/m_e = 64$ (b) and $m_i/m_e = 256$ (c).

Figure 2 shows the electron out-of-plane current for three different mass ratios. In comparison, the current sheet near the X point is thinnest (in the y direction) and narrowest (in the x direction) in the case with mass ratio $m_i/m_e = 256$. In addition, the maximal value of the electron current (normalized to en_0V_A) for the mass ratio $m_i/m_e = 256$ is about 3.0, and it is 2.0 for the mass ratio $m_i/m_e = 25$.

Figure 3 shows the plot of the electron density at

$\omega_{pi}t = 14.5$ for three different mass ratios. In the case of $m_i/m_e = 256$, there are obvious density cavities along the entire separatrix, while there are no such density cavities for the case $m_i/m_e = 25$. Figure 4 shows a two-dimensional plot of the electron parallel velocity. Compared to the electron density cavities shown in Fig. 3, the electron density cavities locate in the region where the electrons flow along the separatrix. With a larger ion/electron mass ratio, the width of high-speed electron flow along the separatrix becomes smaller, and hence the peak of the electron outflow speed is larger.[7,12]

Figure 5 is the contour of electric field parallel to the magnetic field. It is obvious that the parallel electric field $E_{//}$ along the separatrix appear clearly for the mass ratio $m_i/m_e = 256$, which will accelerate and heat electrons along the local magnetic field toward X line. That is, it is not only electric field component perpendicular to the simulation plane and located at the centre of diffusion region can accelerate and heat electrons, but also the parallel electric field plays an important role in the acceleration and heating of electrons when smaller electron mass is applied in the simulation.

In this study, we employ a $2\frac{1}{2}$-dimensional electromagnetic PIC simulation code to study the electron behaviour in collisionless magnetic reconnection. The results show that the mass ratio has a negligible effect on the reconnection rate. However, the mass ratio has a significant effect on the electron dynamics in the diffusion region. The electron out-of-plane current sheet near the X point is thinner and narrower for larger mass ratio. Density cavities generated along the separatrix in the simulation with larger mass ratio (such as $m_i/m_e = 256$). Also, the electric field parallel to magnetic field appears with smaller electron mass, which will accelerate and heat the electron toward the X line. We obtain some interesting results when mass ratio is 256. Of course, the physical mass ratio should be 1836, and we only consider the low beta plasma. These effects are considered are our future investigations.

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