Whistler Mode Waves 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 the wave phenomena in the plasma sheet of collisionless magnetic reconnection. The results show that these waves have the following characteristics: they are right-hand circularity polarized, with propagation direction nearly parallel to local magnetic field, and frequency between 0.07 and 0.17 times of local electron cyclotron frequency. Therefore we conclude that such waves are Whistler waves, and their possible excitation mechanisms are also discussed.

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Magnetic reconnection is a fundamental plasma transport process in plasmas in which magnetic energy is rapidly converted into plasma energy, and it plays an important role in the dynamics of magnetosphere, the solar corona, and the laboratory experiments.[1] Early theories of magnetic reconnection including the Sweet–Parker model and the Petschek model are usually based on resistive MHD and postulate that Alfvén waves play a key role in driving reconnection: the waves accelerate the plasma in the out-flow region of current sheet, which is limited by the corresponding Alfvén speed.[2,3] However, recent studies show that the Hall term is a critical ingredient in determining collisionless reconnection rates, and a multi-scale structure based on ion scale length is developed in the dissipation region.[4] At scale lengths larger than the ion inertial length $\lambda_0 = c/\omega_{pi}$ (ω_{pi} is the ion plasma frequency), the ions are accelerated away from the X-line and eventually reach the Alfvén speed; in this region the MHD description is valid. At scale lengths below λ_0, the motion of electrons and ions decouples, and the Hall effect which is caused by the relative motion of electrons and ions produces a characteristic of quadrupole pattern for the out-of-plane magnetic field. This characteristic is considered as a main signature in Whistler-mediated reconnection, and in this region the Whistler modes rather than Alfvén waves are the dominant waves. Both the out-of-plane magnetic field pattern and Whistler waves have been recently observed in the current sheet by the GEOTAIL spacecraft.[5,6]

In this Letter, we employ a $2\frac{1}{2}$-dimensional electromagnetic PIC simulation code to study the Whistler waves in collisionless magnetic reconnection. In the particle simulations, the particles can be anywhere in the simulation domain while the electric and magnetic fields are defined in the grids.[7] The particles are advanced according to the well-known Boris algorithm. The electromagnetic fields are obtained by integrating the time-dependent Maxwell equations with an explicit algorithm, and charge conservation is guaranteed by a correction to the electric fields.

The Harris neutral sheet equilibrium with the main field directed along the x axis and gradients along the y axis is chosen as the initial configuration. The initial magnetic field is $\boldsymbol{B}_0 = B_{0x}(y)\boldsymbol{e}_x$, with

$$B_{0x}(y) = B_0 \tanh((y - y_0)/w), \tag{1}$$

where B_0 is the asymptotic magnetic field, and w is the half-width of current sheet, y_0 is the centre of current sheet. The proton and electron densities are

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

where n_0 and n_b represent the current sheet and background density, which correspond to Harris and background particles, respectively. The Harris particles drift in the z direction, which satisfies $V_{e0}/V_{i0} = -T_{e0}/T_{i0}$ (where T_{e0} and T_{i0} are the uniform electron and proton temperatures of the Maxwellian particle distributions). The background particles have no drift, and the background temperatures for the electrons and protons are assumed to be the same as T_{e0} and T_{i0}, respectively.

The half-width of the current sheet is $w = 0.2c/\omega_{pi}$ and its centre is located at $y_0 = 6.4\lambda_0$, where $\lambda_0 = c/\omega_{pi}$ is the ion inertial length defined on the peak Harris density n_0. The background density $n_b = 0.1n_0$, the temperature ratio is $T_{e0}/T_{i0} = 0.2$, and the mass ratio is $m_i/m_e = 25$. We employ $N_x \times N_y = 128 \times 128$ simulation grids, and the cell size is $\Delta x = \Delta y = 0.1c/\omega_{pi}$. The time step is taken to be $\Omega_i t = 0.002$, where Ω_i is the proton cyclotron frequency based on B_0. The speed of light is chosen

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** To whom correspondence should be addressed. Email: qmlu@ustc.edu.cn as $c/V_A = 15$, 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 specularly reflected if they reach the boundary. There are 429824 particles which are used for electron and ion respectively.

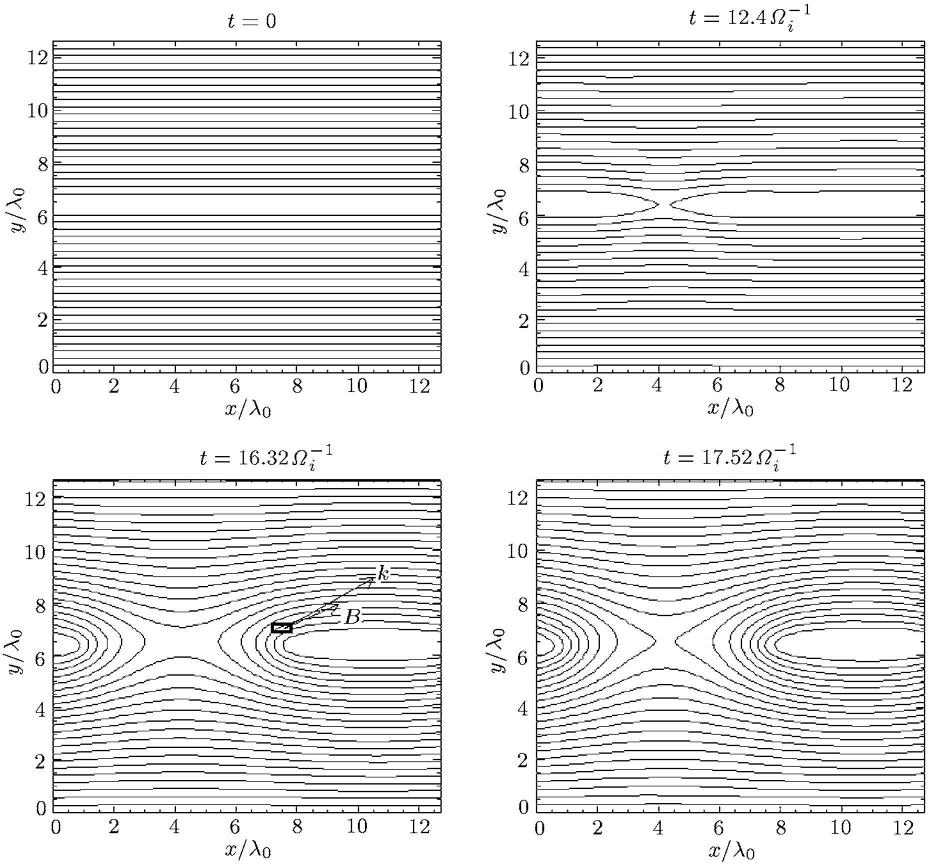

Fig. 1. Magnetic field lines at different times. The blank rectangle indicates the region where the wave is detected; the arrows represent the directions of the magnetic field and propagation respectively.

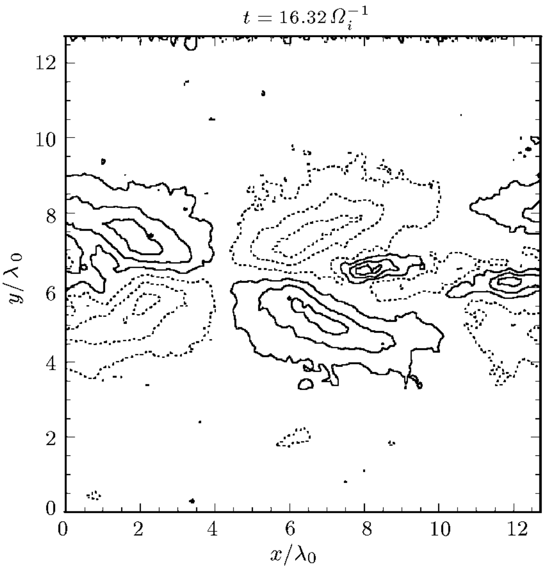

Fig. 2. Contours of out-of-plane B_z field. The solid lines mean that B_z has positive value while the dashed lines denote the negative value.

Figure 1 shows the magnetic field lines in the xy plane at different times; the process of magnetic reconnection can be seen clearly from the figure. The magnetic field lines begin to reconnect in the centre of the simulation domain at about $t = 10.0\Omega_i^{-1}$, and at about $t = 12.4\Omega_i^{-1}$ a magnetic island is formed. The process of magnetic reconnection saturates at about $t = 17.52\Omega_i^{-1}$, and the half-width of magnetic island is about $2.4c/\omega_{pi}$. Figure 2 describes the contours of the out-of-plane B_z field at $t = 16.32\Omega_i^{-1}$, which is just before the saturation time. In the figure, the solid lines mean that B_z has positive value while the dashed lines denote negative value. The characteristics of quadrupole pattern for the out-of-plane magnetic field can be easily found, which is due to the electron Hall current. These characteristics have been considered as an important signature for magnetic reconnection mediated by Whistler waves.

In order to investigate the wave phenomena in the plasma sheet layer which is a non-uniform plasma system, the Morlet wavelet analysis method is used in our simulations. The wavelet transformation is a powerful tool to analyse time series containing non-stationary power with different frequency.[8] Figure 3(a) is the wavelet power spectrum of the time series of B_z at the point $x = 7.6\lambda_0$, $y = 7.0\lambda_0$ which is in the plasma sheet layer using the Morlet wavelet analysis, and Fig. 3(b) shows the power spectrum of the same time series with the FFT method. It can be found that there are wave phenomena between $t = 15\Omega_i^{-1}$ and $t = 22\Omega_i^{-1}$; their frequency is between $2.0\Omega_i$ and $4.8\Omega_i$. In this position, the amplitude of local magnetic fields is about 1.14, and we can calculate that the wave frequencies are between 0.07 and 0.17 local electron cyclotron frequency. The propagation direction of these waves can be determined with minimum variance analysis, which has been marked in the magnetic field lines of Fig. 1 when $t = 16.32\Omega_i^{-1}$; the direction of the local magnetic field has also been marked in the figure. It turns out that the wavevector of the waves $\boldsymbol{k}$ is nearly parallel to the local magnetic field, and the angle between them is about 6°. Their polarity can be determined by the hodograph of the electric field in Fig. 4, which is right-hand circularly polarized with respect to the wavevector $\boldsymbol{k}$. In short, these waves are right-hand circularity polarized, with propagation direction nearly parallel to the local magnetic field, and frequency between 0.07 and 0.17 times the local electron cyclotron frequency. Therefore, we can conclude that these waves are Whistler waves. The area where the Whistler waves can be found in the simulation domain is denoted in the magnetic field lines of Fig. 1 when $t = 16.32\Omega_i^{-1}$, and it is in the plasma sheet layer.

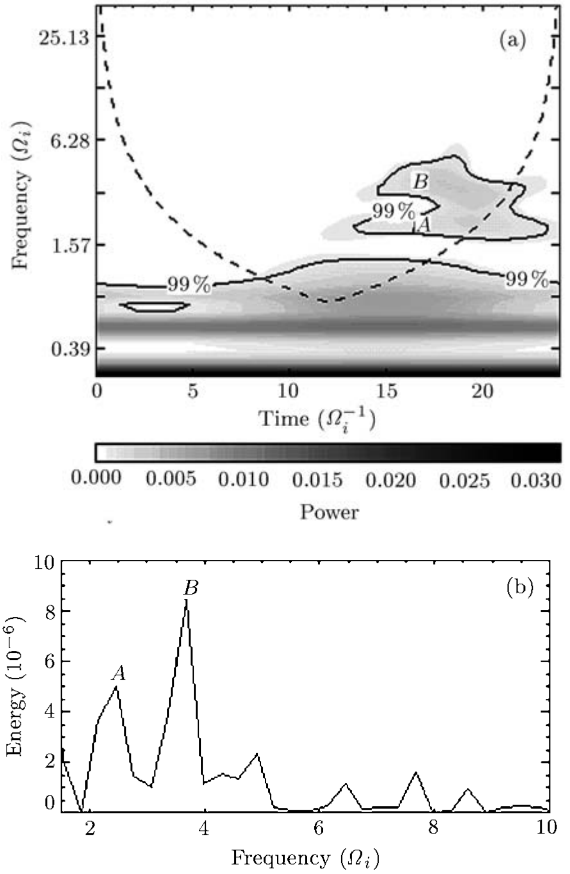

Fig. 3. (a) Local wavelet power spectrum of the time series of $\boldsymbol{B}_z$ using the Morlet wavelet. The left axis is the Fourier frequency. The bottom axis is time (the unit is Ω_i^{-1}). The thick dashed contour encloses the regions of greater than 99% confidence. The region below that indicates the cone of influence, where the edge effects become important. The frequency of region A and B is about $2.6\Omega_i$ and $3.9\Omega_i$ respectively. (b) The power spectrum of the same series, i.e. energy of the wave versus frequency, obtained with the FFT method.

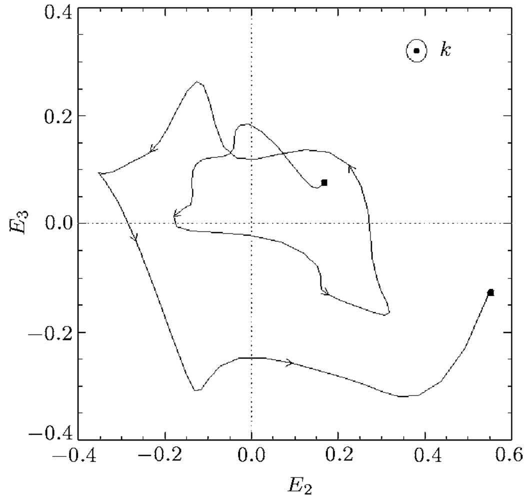

Fig. 4. Hodograph of the electric field. E_2 and E_3 are the two orthogonal axes which are perpendicular to the $\boldsymbol{k}$ vectors of the Whistler mode waves.

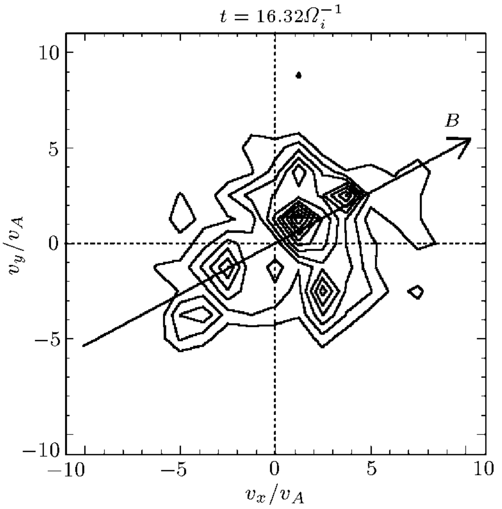

Fig. 5. In-plane velocity distribution of electrons. The arrow represents the direction of $\boldsymbol{B}$.

Figure 5 is the in-plane velocity distribution of electrons in the black rectangle in Fig. 1; it consists of three parts: the first is the main part, the second and third are the beam electrons which are parallel and anti-parallel to local magnetic field with average flow velocities about $5\,V_A$.

In summary, we have employed a $2\frac{1}{2}$-dimensional electromagnetic PIC simulation code to study the wave phenomena in plasma sheet layer of collisionless magnetic reconnection. These waves are right-hand circularity polarized, with propagation direction nearly parallel to local magnetic field, and frequency between 0.07 and 0.17 times the local electron cyclotron frequency. According to these characteristics, we conclude that these waves detected in plasma sheet layer are Whistler waves. A possible mechanism for the excitation of these waves might be beam electrons through electron cyclotron resonance.[9]

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