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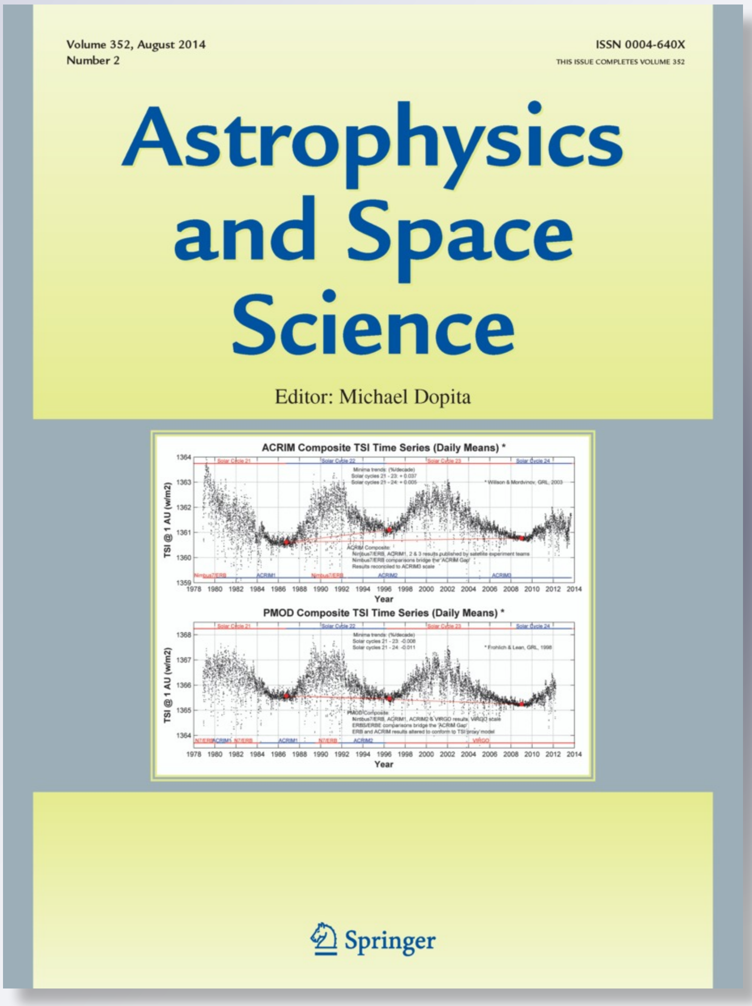
Astrophysics and Space Science
An International Journal of Astronomy, Astrophysics and Space Science

ISSN 0004-640X
Volume 352
Number 2

Astrophys Space Sci (2014) 352:565-570
DOI 10.1007/s10509-014-1923-x



Springer

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DOI 10.1007/s10509-014-1923-x

ORIGINAL ARTICLE

Dissipation of an electron phase-space hole and its consequence on electron heating

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Received: 4 January 2014 / Accepted: 7 April 2014 / Published online: 15 April 2014

Abstract An electron phase-space hole (electron hole) is considered to be unstable to the transverse instability. In this paper, two-dimensional (2D) electrostatic particle-in-cell (PIC) simulations are used to explore the dissipation process of a one-dimensional (1D) electron hole in a weakly magnetized plasma and its consequence on electron heating, which consists of two stages. In the first stage, the electron hole is still kept as a quasi-1D structure, however, with the excitation of the transverse instability and the generation of the perpendicular electric field, the electrons are scattered and then heated along the perpendicular direction in the electron hole. In the second stage, the quasi-1D electron hole is broken into several 2D electron holes. The temperature of the electrons outside of these 2D electron holes also increase, and at last the velocity distribution of the electrons become almost isotropic in the whole simulation domain. Our results provide a new dissipation mechanism of an electron hole.

Keywords Electron phase-space hole · Electron heating · Transverse instability · Dissipation

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1 Introduction

Recent decades of satellite observations have revealed the ubiquitous existence of electron phase-space holes (electron holes) in different space environments, such as the bow shock (Bale et al. 1998), the solar wind (Mangeney et al. 1999) and the magnetosphere (e.g. Matsumoto et al. 1994; Ergun et al. 1998; Cattell et al. 2002; Andersson et al. 2009). The observational characteristics of electron holes are the bipolar structures of their parallel electric field. These holes have also been observed in laboratory plasma, for example, in magnetized plasma surrounded by a waveguide (Saeki et al. 1979) and unmagnetized laser-generated plasma (Sarri et al. 2010). Electron holes are always associated with processes such as double layers (Ergun et al. 2001), the bow shock (Bale et al. 1998) and magnetic reconnection (Cattell et al. 2005), which makes electron holes a reliable indicator of strongly nonlinear behavior in plasmas.

Theoretically, electron holes are considered to be stationary Bernstein-Greene-Kruskal (BGK) solutions of the Vlasov and Poisson equations (e.g. Bernstein et al. 1957; Chen et al. 2005; Ng and Bhattacharjee 2005; Muschietti et al. 1999). Particle-in-cell (PIC) simulations have demonstrated that electron holes can be formed during the nonlinear evolution of electron bi-stream instabilities (e.g. Morse and Nielson 1969; Oppenheim et al. 1999; Goldman et al. 1999; Wu et al. 2012) or the Buneman instability (Newman et al. 2001; Drake et al. 2003; Shimada and Hoshino 2003), which can persist for a sufficiently long time in one-dimensional (1D) simulations (Omura et al. 1994; Lu et al. 2005a, 2005b). However, recent studies have shown that electron holes are always related to electron heating (Shimada and Hoshino 2003; Dieckmann et al. 2000). By performing three-dimensional (3D) PIC simulations, Drake et al. (2003) found that in magnetic reconnection with a strong guide field electron holes are formed during the nonlinear evolution of the Buneman instability, and the intense transverse electric field are produced in these electron holes due to the coupling with lower hybrid waves, which lead to strong electron scattering and heating. The resulting anomalous resistivity is indicated to play an important role in releasing magnetic energy rapidly during magnetic reconnection. Che et al. (2010) further demonstrated that electron holes with different phase velocities are formed during magnetic reconnection with a guide field, which can scatter the electrons more efficiently. With 1D PIC simulation Shimada and Hoshino (2003) found that the electrons are heated by electron holes formed in the shock transition region through the process of electron-ion coupling. Therefore, electron heating by electron holes may have relevance to other physical processes in plasma, such as reconnection and shock. Recently, electron holes are found to be unstable to the transverse instability (Muschietti et al. 2000; Lu et al. 2008; Wu et al. 2010). In electron holes, perturbations can produce transverse gradients of the electric potential, and then the trapped electrons are focused into regions that already have a surplus of electrons. Such a process can result in larger transverse gradients of the potential and more focusing of the trapped electron until the transverse instability finally occurs (Muschietti et al. 2000). The observed unipolar structure of the parallel cut of the perpendicular electric field associated with electron holes is considered to be generated due to the combined actions between the transverse instability and the stabilization by the background magnetic field (Lu et al. 2008; Wu et al. 2010). In this paper, we propose a mechanism for the dissipation of an electron hole due to the transverse instability. The perpendicular electric field is then generated, which can scatter and heat the electrons.

2 Simulation model

We carry out 2D electrostatic PIC simulations with periodic boundary conditions to examine the electron heating during the evolution of an electron hole (Decyk 1995; Lu and Cai 2001). In the simulations, only electron dynamics are included, while ions are motionless and form a neutralizing background. A homogeneous magnetic field $\mathbf{B}_0$ is along the x direction. We describe the potential structure which represents an electron hole in the co-moving frame along the background magnetic field $\mathbf{B}_0$ as

$$\phi(x) = \psi \exp\left[-0.5(x-L)^2/\Delta_\parallel^2\right] \tag{1}$$

where $\Delta_\parallel$ and L are the half width and center position of the electron hole, respectively, ψ is the amplitude of the potential structure. This potential structure is homogeneous in the transverse direction, and it is supported by a clump of trapped electrons in the electron hole. The trapped electrons gyrate in the background magnetic field while they bounce back and forth in the parallel direction. The motions of a trapped electron are determined by the ratio of the electron gyrofrequency $\Omega_e = eB_0/m_e$ to the bounce frequency $\omega_b = \sqrt{\psi/\Delta_\parallel^2}$ (Muschietti et al. 2000). The initial electron distributions can be calculated by the BGK method self-consistently, which has already been given by Muschietti et al. (1999). It is

$$F(x, v_x, v_y, v_z) = F_1(w)\exp\left[-0.5\left(v_y^2+v_z^2\right)/T_e\right] \tag{2}$$

where T_e is the electron temperature, $w \equiv v_x^2 - 2\phi(x)$ is twice the parallel energy and

$$F_1(w) = \frac{\sqrt{-w}}{\pi\Delta_\parallel^2}\left[1 + 2\ln\left(\frac{\psi}{-2w}\right)\right] + \frac{6+(\sqrt{2}+\sqrt{-w})(1-w)\sqrt{-w}}{\pi(\sqrt{2}+\sqrt{-w})(4-2w+w^2)} \quad \text{for } -2\psi \le w < 0 \tag{3a}$$

$$F_1(w) = \frac{6\sqrt{2}}{\pi(8+w^3)} \quad \text{for } w > 0 \tag{3b}$$

Equations (3a) and (3b) describe the distributions of the trapped and passing electrons, respectively. The trapped electron distribution has a hollowed out shape, while the passing electron distribution has a flattop shape.

In this model, the density is normalized to the density n_0 outside the electron hole. The velocities are expressed in units of the electron thermal velocity $v_{Te} = (T_e/m_e)^{1/2}$. The dimensionless units used here have space in Debye length $\lambda_D = (\varepsilon_0 m_e v_{Te}^2/n_0 e^2)^{1/2}$, time in the inverse of the plasma frequency $\omega_{pe} = (n_0 e^2/m_e\varepsilon_0)^{1/2}$, and potential in $m_e v_{Te}^2/e$. Cell size units $\lambda_D \times \lambda_D$ are used in the simulations, and the time step is $0.02\omega_{pe}^{-1}$. There are average 20×20 particles in each cell, and the number of cells is 64×64.

In our simulation, the initial potential of the electron hole is characterized by $\psi = 2.0$, $\Delta_\parallel = 3.0$ and $L = 32$. Hence, the bounce frequency of trapped electrons in the electron hole is $\omega_b = 0.47$. The electron gyrofrequency is taken as $\Omega_e = 0.47$, so that $\omega_b/\Omega_e = 1$. Initially, we loaded the electron distribution functions according to Eqs. (2) and (3a), (3b) in our simulation. These distributions will support the potential of the electron hole.

3 Simulation results

Figure 1 shows the time evolution of electric field energy, the increase of electron kinetic energy and the total energy. From the top to the bottom, the parallel electric field energy

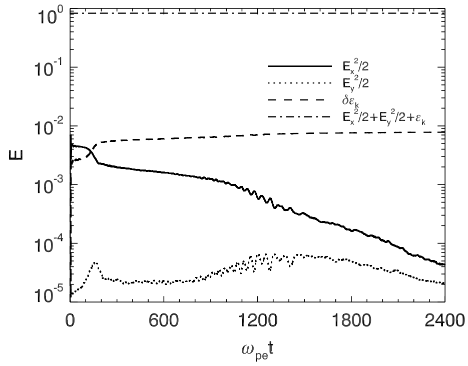

Fig. 1 The time evolution of the total energy (*dash-dotted line*), the electric field energies $1/2E_x^2$ (*solid line*), $1/2E_y^2$ (*dotted line*) and the increase of electron kinetic energy $\delta\varepsilon_k$. Both the electric energy and electron kinetic energy are normalized by $n_0 m_e v_{Te}^2/\varepsilon_0$

$1/2E_x^2$ (solid line), the perpendicular electric field energy $1/2E_y^2$ (dotted line), the increase of electron kinetic energy $\delta\varepsilon_k$ (dashed line) and the total energy (dash-dotted line) are displayed. It can be found that the total energy in our simulation is well conserved. The change of total energy is less than 0.01 % in this case. Both the electric energy and electron kinetic energy are normalized by $n_0 m_e v_{Te}^2/\varepsilon_0$. Before about $\omega_{pe}t = 120$, the parallel electric field energy has little change. With the excitation of the transverse instability at about $\omega_{pe}t = 120$, the parallel electric field energy begins to decrease and the perpendicular electric field begins to increase rapidly. The transverse instability in electron holes is a self-focusing type of instability. Any transverse gradients can focus the trapped electrons into regions that already have a surplus of electrons, which results in larger transverse gradients and more focusing. Then the undulation of these transverse density gradients leads to strong perpendicular electric fields in electron holes. The electron holes begin to kink and finally break into several segments. In weakly magnetized plasma, the transverse instability is the reason which causes the decay of electron holes (Muschietti et al. 2000; Lu et al. 2008; Wu et al. 2010). After about $\omega_{pe}t = 240$, the electron kinetic energy and the energy of the electric field change little. We can also find that during the dissipation process of the electron hole, most energy is transferred into the electron kinetic energy.

Detailed analysis shows that with the excitation of the transverse instability, the electric field forms a regular structure, and the electrons are heated. The evolution of the electric field and electron temperatures are shown in Fig. 2, which plots the electric fields (a) E_x, (b) E_y and electron temperatures (c) T_x, (d) T_y, (e) T_z at the time $\omega_{pe}t = 0$, 1000, 1600 and 3000. Here, electric fields are normalized by $(n_0 m_e v_{Te}^2/\varepsilon_0)^{1/2}$, and electron temperatures are normalized by $m_e v_{Te}^2$. The electron temperatures in every grid

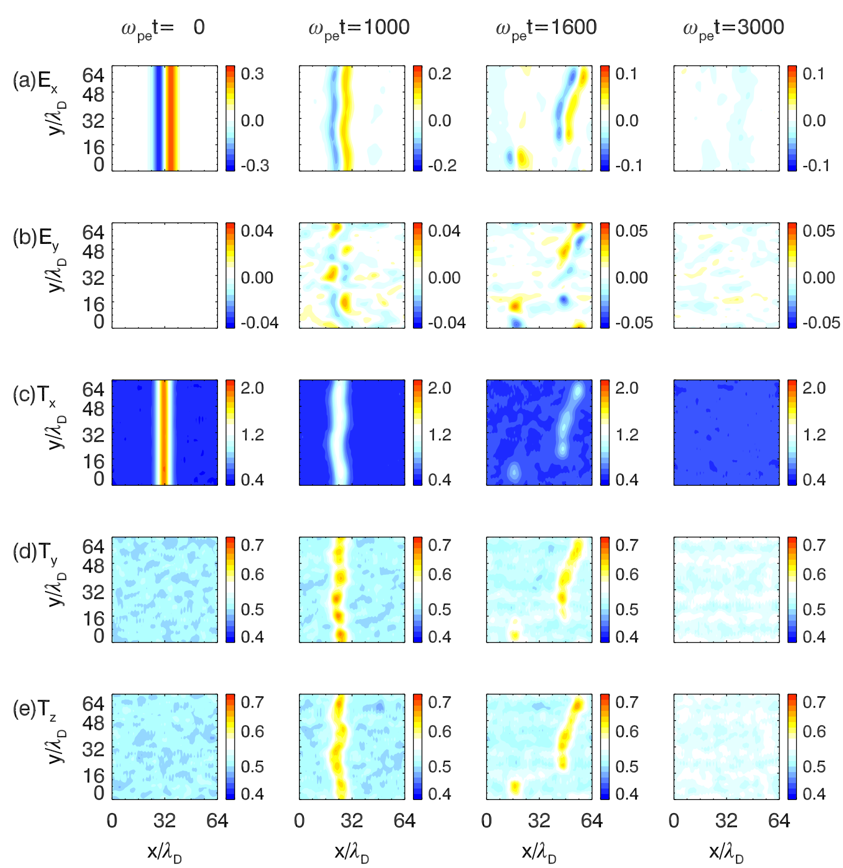

Fig. 2 From the *top* to the *bottom*, they are (**a**) E_x, (**b**) E_y, (**c**) T_x, (**d**) T_y, (**e**) T_z at the time $\omega_{pe}t = 0$, 1000, 1600 and 3000

cell are calculated with the following equation: $T_{x,y,z} = m_e\langle(v_{x,y,z} - \langle v_{x,y,z}\rangle)^2\rangle$ (where the bracket $\langle\bullet\rangle$ denotes an average over one grid cell). Initially, in the electron hole, the parallel velocity of trapped electrons has a hollowed out shape distribution while that of the passing electrons has a flattop shape distribution. Therefore, the electrons in the electron hole have a larger parallel temperature T_x than that outside of the electron hole. However, we should point out that in such a situation the temperature T_x is not a good quantity to describe the electron hole. The transverse instability begins to be excited at about $\omega_{pe}t = 120$ with the decrease of E_x^2 and increase of E_y^2. With the excitation of this instability, the electron hole becomes kinked, and this kinked potential produces a bipolar perpendicular electric field E_y (see the parallel cut of E_y at the time $\omega_{pe}t = 1000$). When the passing electrons cross this kinked hole, E_y can accelerate or decelerate electrons which can make the v_y of passing electrons more randomly. Such scattering will soon happen in v_z due to the gyration. At the same time, due to the scattering of the perpendicular electric field E_y the electron perpendicular temperatures T_y and T_z increase in the electron hole, while the electron parallel temperature T_x decreases. However, the electron temperatures outside of the electron hole change little. When the transverse instability is sufficiently strong, it begins to destroy the electron hole. The kinked electron hole is finally broken into several 2D electron holes, which are isolated in both the x and y directions. In these 2D electron holes, the parallel cut of the perpendicular electric field E_y has a unipolar structure, while the parallel cut of the parallel electric field E_x is still kept as a bipolar structure. During the broken process of the electron hole, with the decrease of the electron temperatures inside these 2D electron holes, the electron temperatures outside of these electron holes increase slowly. At last, these 2D electron holes are too weak to be observed, and the electron temperatures become almost isotropic and homogeneous in the whole simulation domain. The evolution of the electron temperatures can be distinguished more clearly in Fig. 3, which displays the three components of the electron temperatures T_x, T_y, and T_z at $\omega_{pe}t = 0$, 200, 1000, 1600 and 3000, respectively. Here, the temperatures are the average values along the y direction. The evolution of the electron temperatures can be divided into two stages. In the first stage, although the transverse instability has already been excited, the electron hole still has a quasi-1D structure. The electron perpendicular temperatures T_y and T_z in the electron hole increase rapidly, while the parallel temperature T_x decreases. We think that the increase of the energy of the perpendicular electric field, which begins at about $\omega_{pe} = 1000$ (shown in Fig. 1), indicates that the electron hole is being broken into several 2D electron holes. At about this time, the perpendicular temperatures T_y and T_z in the electron hole attain their maximum values, which is about 1.4 times that of their initial values. The second stage begins at about $\omega_{pe} = 1000$, as

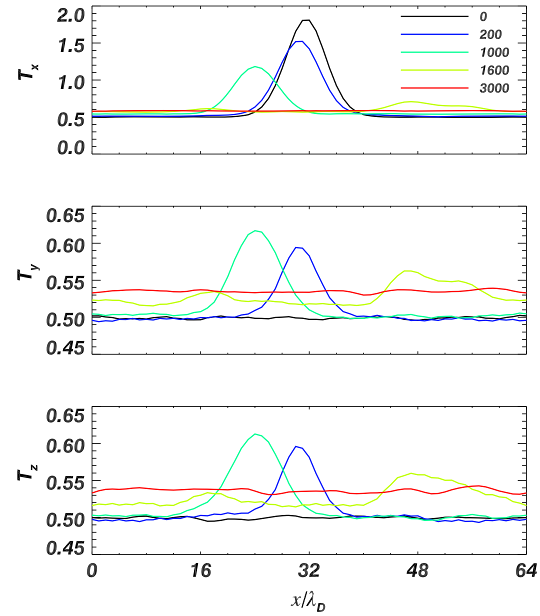

Fig. 3 The three components of temperature average along the y direction T_x, T_y and T_z at the time $\omega_{pe}t = 0$, 200, 1000, 1600 and 3000

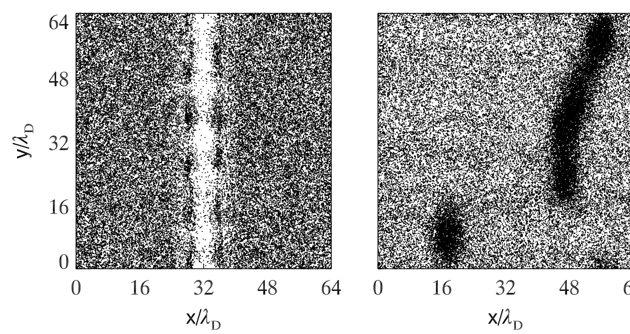

Fig. 4 The *right panel* shows positions of electrons which gained energy $\Delta\varepsilon > 1.0$ at the time $\omega_{pe}t = 1600$ while the *left panel* shows initial positions of these electrons

the quasi-1D electron hole is broken into several 2D electron holes, the electron temperatures outside of the electron holes begin to increase, while the electron temperatures in the electron holes begins to decrease. At last, the velocity distribution of the electrons becomes almost isotropic in the simulation domain. At the time $\omega_{pe} = 3000$, T_x, T_y, and T_z almost have the same average value. And the electron temperature is about 1.1 times that of their initial values.

To understand the process of electron heating, we try to trace the electrons which gain energy during the decay of the electron hole. At first, we calculate the increase of the kinetic energy $\Delta\varepsilon$ of each electron and pick up these electrons with $\Delta\varepsilon > 1.0$ from $\omega_{pe}t = 0$ to $\omega_{pe}t = 1600$. Then, we trace their positions back to $\omega_{pe}t = 0$. In Fig. 4, the left panel displays the initial positions of these particles at $\omega_{pe}t = 0$, while the right panel plots the positions of these electrons at

Table 1 Given the case number, the background magnetic field B_0, the maximum value of the perpendicular temperature T_y and the time when the maximum values are reached

Number	B_0	$\max(T_y)$	$\omega_{pe}t$
1	0.47	0.66	220
2	0.1	0.82	70
3	0.3	0.74	200
4	0.7	0.64	1000
5	2.0	0.53.	2800
6	5.0	0.53	3000

$\omega_{pe}t = 1600$. From the left panel, we can find that most of these electrons are located outside the electron hole. When passing through the kinked electron hole, these electrons are scattered by the perpendicular electric field and heated in the perpendicular direction. Therefore, these passing electrons are at first heated in the electron hole. As the time goes on, these passing electrons gain more and more energy in such a process, which leads to the increase of the temperature outside electron holes.

4 Conclusions and discussion

In summary, by performing 2D electrostatic PIC simulations, we investigate the dissipation of a 1D electron hole and its consequences on electron heating. The results show that the electron hole is dissipated due to the transverse instability. In general, the dissipation process of the electron hole can be divided into two stages. In the first stage, the electron hole becomes kinked and the intense perpendicular electric field is generated in the electron hole due to the transverse instability. The electrons are scattered by the perpendicular electric field when they pass through the electron hole, and are then heated in the perpendicular direction, while the electron temperature outside of the electron hole almost doesn't change. In the second stage, the electron hole is broken into several 2D electron holes, and the electron temperature outside of these electron holes increases. At last, almost the electric field energy is transferred to the thermal energy. The velocity distribution of the electrons is nearly isotropic and homogeneous in the whole simulation domain. The transverse instability of an electron hole is considered to be suppressed with the increase of the background magnetic field, which will also reduce the efficiency of electron heating during the dissipation of the electron hole. We have investigated some other cases with the same parameters except for the background magnetic field and check the maximum of the perpendicular temperature during the evolution. The results at different background magnetic field are shown in Table 1. With the increase of the background magnetic field, the heating process will happen slower and the increase of perpendicular temperature in the kinked electron hole is much smaller.

In our simulation, we only investigate the dissipation of one 1D electron hole, and found that most of the electric field energy is transferred into the thermal energy. However, satellite always observes a series of electron holes in a small region (Matsumoto et al. 2003; Cattell et al. 2005). Therefore, the energy density of the electric field corresponding to electron holes should be higher than that in our simulation, and the electron heating due to the dissipation of the electron holes may be much more efficient. In this paper, we propose a new mechanism for the dissipation of an electron hole, which will result in the anomalous resistivity. The dissipation of electron holes and its consequence of electron heating may play an important role in other physical processes in plasma. For example, it is considered that the fast magnetic reconnection is realized due to the anomalous resistivity, and both simulations and observations have found the existence evidence of electron holes in magnetic reconnection. The dissipation of electron holes may provide the anomalous resistivity, which is necessary in fast magnetic reconnection.

Acknowledgements This research was supported by 973 Program (2012CB825602, 2013CBA01503), the National Science Foundation of China (NSFC) under grants 41174124, 41274144, 41331067, 41121003, Ocean Public Welfare Scientific Research Project, State Oceanic Administration People's Republic of China (No. 201005017), CAS Key Research Program KZZD-EW-01, the Fundamental Research Funds for the Central Universities (WK2080000010), and the Specialized Research Fund for State Key Laboratories.

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