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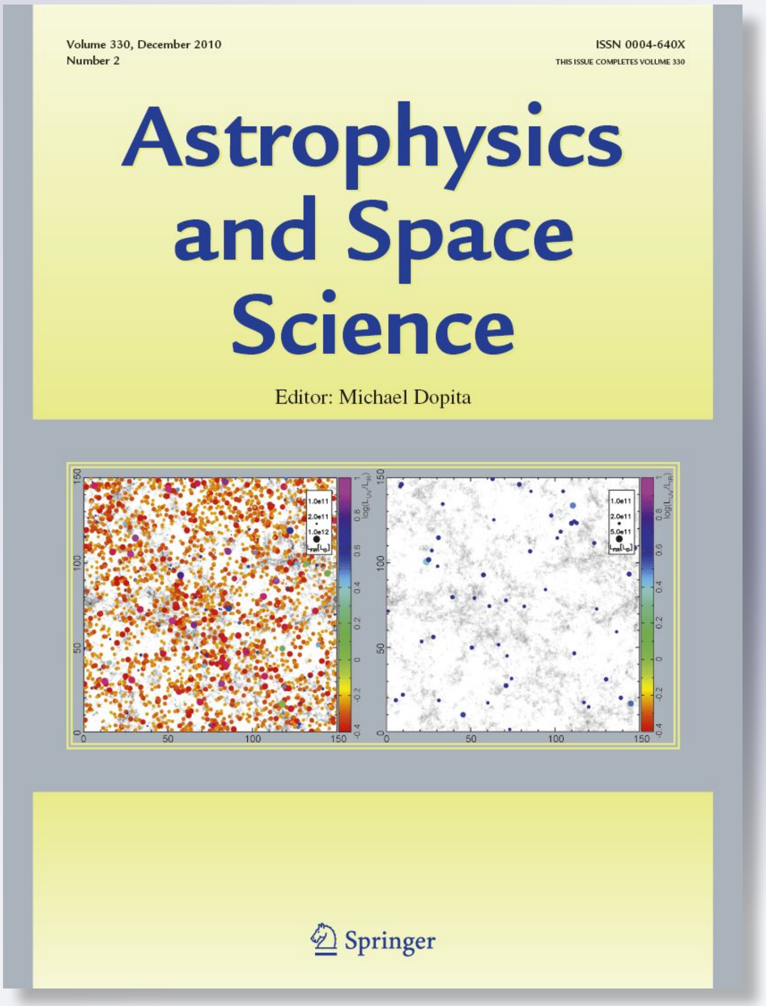

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ORIGINAL ARTICLE

The magnetic structures of electron phase-space holes formed in the electron two-stream instability

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Abstract It is well known that the parallel cuts of the parallel and perpendicular electric field in electron phase-space holes (electron holes) have bipolar and unipolar structures, respectively. Recently, electron holes in the Earth's plasma sheet have been observed by THEMIS satellites to have detectable fluctuating magnetic field with regular structures. Du et al. (2011) investigated the evolution of a one-dimensional (1D) electron hole with two-dimensional (2D) electromagnetic particle-in-cell (PIC) simulations in weakly magnetized plasma ($\Omega_e < \omega_{pe}$, where Ω_e and ω_{pe} are the electron gyrofrequency and electron plasma frequency, respectively), which initially exists in the simulation domain. The electron hole is unstable to the transverse instability and broken into several 2D electron holes. They successfully explained the observations by THEMIS satellites based on the generated magnetic structures associated with these 2D electron holes. In this paper, 2D electromagnetic particle-in-cell (PIC) simulations are performed in the x–y plane to investigate the nonlinear evolution of the electron two-stream instability in weakly magnetized plasma, where the background magnetic field ($\mathbf{B}_0 = B_0\vec{\mathbf{e}}_x$) is along the x direction. Several 2D electron holes are formed during the nonlinear evolution, where the parallel cuts of E_x and E_y have bipolar and unipolar structures, respectively. Consistent with the results of Du et al. (2011), we found that the current along the z direction is generated by the electric field drift motion of the trapped electrons in the electron holes due to the existence of E_y, which produces the fluctuating magnetic field δB_x and δB_y in the electron holes. The parallel cuts of δB_x and δB_y in the electron holes have unipolar and bipolar structures, respectively.

Keywords Electron phase-space hole · Magnetic structure · Particle-in-cell stimulation · The transverse instability

1 Introduction

Electron phase-space holes (electron holes) have often been detected in different regions of the Earth's magnetosphere (Matsumoto et al. 1994; Ergun et al. 1998a; Franz et al. 1998; Bale et al. 1998; Cattell et al. 2002; Pickett et al. 2004) and the solar wind (Mangeney et al. 1999). In electron holes, the parallel cut of the electric field parallel to the ambient magnetic field has bipolar structures, while the signals of the electric field perpendicular to the ambient magnetic field are unipolar (Ergun et al. 1998a, 1998b; Franz et al. 1998). Electron holes are stationary Bernstein-Greene-Kruskal (BGK) solutions of the Vlasov-Poisson equations (Bernstein et al. 1957; Muschietti et al. 1999; Chen et al. 2005; Ng and Bhattacharjee 2005) and considered to be related to nonlinear Landau damping (Ng et al. 2006). Recently, electron holes in the Earth's plasma sheet, where the plasma is weakly magnetized ($\Omega_e < \omega_{pe}$, where Ω_e and ω_{pe} are the electron gyrofrequency and electron plasma frequency, respectively), have been observed by THEMIS satellites to have detectable fluctuating magnetic field (Andersson et al.

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2009). The parallel cuts of the fluctuating magnetic field have unipolar structures in both the parallel and perpendicular directions. Du et al. (2011) investigated the evolution of a one-dimensional (1D) electron hole in weakly magnetized plasma with two-dimensional (2D) electromagnetic particle-in-cell simulations, which initially exists in the simulation domain. The electron hole is unstable to the transverse instability (Muschietti et al. 2000; Lu et al. 2008; Wu et al. 2010) and broken into several 2D electron holes (isolated along both the parallel and perpendicular directions), which can last for thousands of plasma periods. The trapped electrons in these electron holes suffer the electric field drift due to the existence of the perpendicular electric field, and then the current perpendicular to the background magnetic field is produced. The fluctuating magnetic field parallel to the background magnetic field, whose parallel cut has unipolar structures in the electron holes, is proposed to be generated by such kind of the current. The fluctuating magnetic field perpendicular to the background magnetic field, whose parallel cut also has unipolar structures in the electron holes, is explained based on the Lorentz transforming of a moving quasi-electrostatic structure (Andersson et al. 2009; Du et al. 2011).

It has been known that counter-streaming electron beams can generate the electron two-stream instability, and electron holes can be formed during its nonlinear evolution (Roberts and Berks 1967). Both 1D and 2D electrostatic PIC simulations have been performed to study the nonlinear evolution of the electron two-stream instability, and the electrostatic structures of the formed electron holes are investigated thoroughly (Omura et al. 1994; Mottez et al. 1997; Lu et al. 2005a, 2005b; Goldman et al. 1999; Oppenheim et al. 1999; Umeda et al. 2006). In 2D simulations, the structures of the electron holes are found to be governed by the combined actions between the transverse instability and the stabilization by the background magnetic field (Lu et al. 2008). In weakly magnetized plasma, the electron holes formed during the electron two-stream instability are found to have 2D structures. In these electron holes, the parallel cut of the perpendicular electric field has unipolar structures, while the parallel cut of the parallel electric field has bipolar structures (Lu et al. 2008; Wu et al. 2010). In this paper, we perform 2D electromagnetic PIC simulations to further study the magnetic structures associated with electron holes formed during the nonlinear evolution of the electron two-stream instability in weakly magnetized plasma.

This paper is organized as follows. In Sect. 2, we described the simulation model. The simulation results are presented in Sect. 3. At last, the discussion and conclusions are given in Sect. 4.

2 Simulation model

A 2D electromagnetic PIC code with periodic boundary conditions is employed in our simulations (Fu et al. 2006). The simulation system is taken in the x–y plane with a uniform magnetic field $\mathbf{B}_0$ along the x direction. In this code ions are assumed to be infinitely massive and their dynamics are excluded. Essentially we consider two electron beam components. The initial velocity distributions of the two electron components are both Maxwellian. Initially, these two electron components have the same density ($n_{e1} = n_{e2} = 0.5n_0$), the same temperature ($T_{e1} = T_{e2} = T_e$). The drift velocities of these two electron components are equal in magnitude (V_b) but opposite in direction, which are parallel to the background magnetic field.

In the simulations, the dimensionless units used here have the density in the total unperturbed density n_0 ($n_0 = n_{e1} + n_{e2}$), the velocity in the electron thermal velocity $v_{T_e} = (T_e/m_e)^{1/2}$. We normalized space by the Debye length $\lambda_D = (\varepsilon_0 T_e/n_0 e^2)^{1/2}$, and time by the inverse of the electron plasma frequency $\omega_{pe} = (n_0 e^2/m_e\varepsilon_0)^{1/2}$. The electric field is expressed in unit of $m_e\omega_{pe}v_{T_e}/e$ and the magnetic field is expressed in unit of $m_e\omega_{pe}/e$. In addition, current densities are normalized by $\varepsilon_0 m_e\omega_{pe}^2 v_{T_e}/e$, the potential by T_e/e, and the energy by $n_0 T_e/\varepsilon_0$.

Grid size units $\lambda_D \times \lambda_D$ are used in the simulations, and the time step is $0.02\omega_{pe}^{-1}$. There are 400 particles for each electron component in every cell, and the number of cells used in the simulations is 256 × 256. In our model, we choose the light speed as $c/v_{T_e} = 20.0$, $V_b = 2.0v_{T_e}$, and $\Omega_e/\omega_{pe} = 0.6$.

3 Simulation results

In this paper, our main interests are focused on the electromagnetic signatures associated with the electron holes formed during the nonlinear evolution of the electron two-stream instability in weakly magnetized plasma. Figure 1 shows the overall evolution of the electric field energies E_x^2, E_y^2 and the fluctuating magnetic field energy $\delta B^2 = \delta B_x^2 + \delta B_y^2 + \delta B_z^2$. At about $\omega_{pe}t = 20$, with the excitation of the two-stream instability, the electric field energy E_x^2 begins to grow rapidly. When the electric field energy E_x^2 is sufficiently large, nonlinear kinetic effects develop and parts of particles are trapped by the electrostatic waves. Then the electric field energy E_y^2 and the fluctuating magnetic field energy δB^2 begin to increase, and their generation mechanisms will be discussed later. At about $\omega_{pe}t = 40$, E_x^2 reaches its maximum value, while the electric field energy E_y^2 and the fluctuating magnetic field energy δB^2 attain their maximum values a little later.

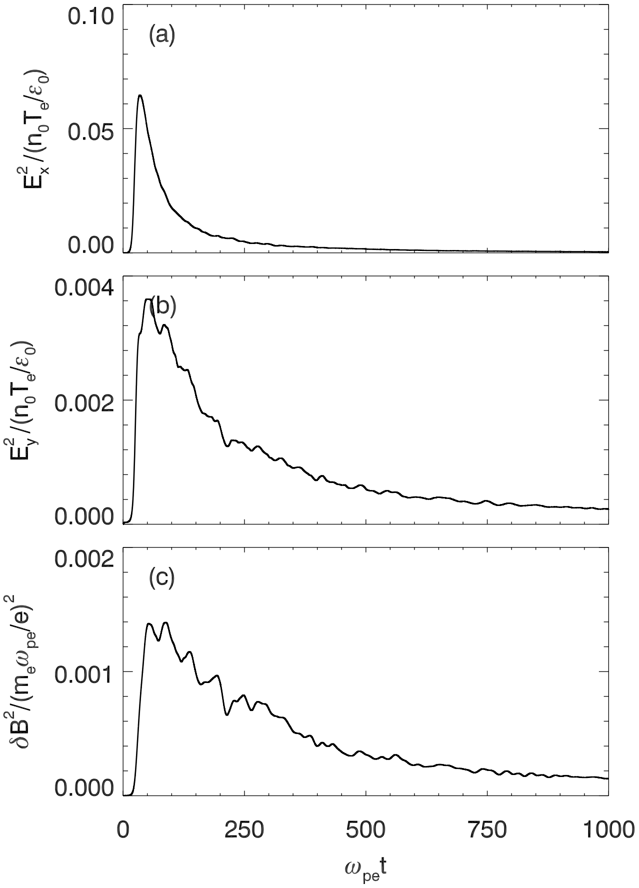

Fig. 1 The time evolution of the electric field energies (**a**) E_x^2, (**b**) E_y^2, and (**c**) the fluctuating magnetic field energy $\delta B^2 = \delta B_x^2 + \delta B_y^2 + \delta B_z^2$. The electric field energies are normalized by $n_0 T_e/\varepsilon_0$, and the magnetic field energies are normalized by $(m_e\omega_{pe}/e)^2$

The evolution of the electromagnetic field is shown in Fig. 2, which plots (a) E_x, (b) E_y, (c) δB_x, (d) δB_y, and (e) δB_z at $\omega_{pe}t = 40, 400$, and 820, respectively. With the excitation of the two-stream instability, monochromatic waves are firstly excited and have a substantial degree of coherence perpendicular to the background magnetic field, as described at the time $\omega_{pe}t = 40$. After the saturation of the two-stream instability, the nonlinear dynamic behaviors dominate the evolution. These monochromatic waves begin to merge with each other at the point with the closest approach between two waves. At last, several 2D electron holes, which are isolated in both the parallel and perpendicular directions, are formed, and their parallel cut of E_x has bipolar structures. These 2D electron holes are the results of combined actions between the transverse instability and stabilization by the background magnetic field, and they may have positive or negative propagation speed along the background magnetic field, or almost stay stationary. As time goes on, such 2D electron holes became weaker and weaker. At the time $\omega_{pe}t = 820$, some electron holes are too weak to be observed.

In order to analyze the electromagnetic signatures of the electron holes in detail, we select the electron hole in $96\lambda_D < x < 160\lambda_D$ and $32\lambda_D < y < 96\lambda_D$ at $\omega_{pe}t = 400$ (the region encircled by red line in Fig. 2). Figure 3 plots (a) E_y, (b) V_{Ez}, (c) j_z, and the fluctuating magnetic field (d) δB_x, (e) δB_y, (f) δB_z of the selected electron hole. V_{Ez} is the z component of the electric field drift velocity $\mathbf{V}_E \approx \mathbf{E} \times \mathbf{B}_0/B_0^2$, and the current j_z is calculated by summing the contributions of all particles in the simulations. Obviously, the parallel cut of E_y is observed to have unipolar structures, which is consistent with the results in 2D electrostatic PIC simulations (Lu et al. 2008). Such unipolar structures have also been obtained in previous theoretical works on multi-dimensional BGK modes (Chen and Parks 2002; Muschietti et al. 2002). At the same time, the fluctuating magnetic fields associated with the electron hole also have regular structures. δB_x has unipolar structures and the value of δB_x is always positive in the electron hole. δB_y has quadrupole structures, whose parallel cut is bipolar. The parallel cut of δB_z has unipolar structures, while the value of δB_z is positive in the upper part of the electron hole and negative in the lower part. The formation of the fluctuating magnetic fields δB_x and δB_y in an electron hole can be described as follows: due to the existence of the perpendicular electric field E_y, the trapped electrons in the electron hole will suffer the electric field drift along the z direction, which can be expressed as $v_{Ez} \approx -E_y/B_0$. Therefore, the current along the z direction is formed in the electron hole (Ions, which cannot be trapped in the electron hole with positive potential, may also suffer electric field drift in the electron hole. However, their drift motions are too complicated to be described by a simple expression because their gyroradii are larger than the spatial scales of the electron hole and their effects on the current along the z direction are negligible.), which then generates the fluctuating magnetic field δB_x and δB_y associated with the electron hole. In these electron hole, the value of j_z is positive in the upper part and negative in the lower part. Therefore, the fluctuating magnetic field δB_x is enhanced in the center of the 2D electron hole with positive values, while δB_y has quadruple structures. The structures of the fluctuating magnetic field δB_z can be interpreted based on the Lorentz transforming of a moving quasi-electrostatic structure (Andersson et al. 2009). The fluctuating magnetic field δB_z can be described as

$$\delta B_z = \frac{v_{EH}}{c^2} E_y, \qquad (1)$$

where v_{EH} is the propagation speed of the electron hole, which is parallel to the background magnetic field $\mathbf{B}_0$. Therefore, a propagating electron hole will generate the fluctuating magnetic field δB_z with the same structures as E_y, whose parallel cut has unipolar structures. In this run, the propagation speed of the selected electron hole is about $v_{EH} = 1.0 v_{T_e}$, and δB_z is estimated to be about $0.0025 E_y$ based on (1), which is consistent with our simulation results.

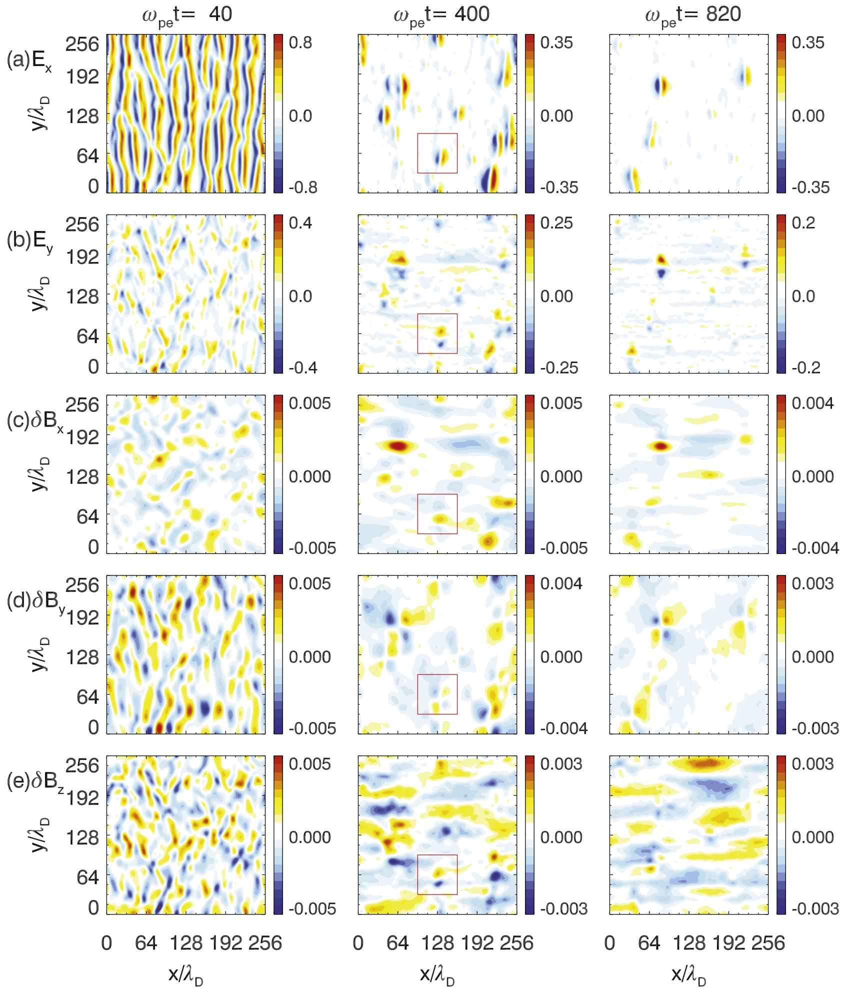

Fig. 2 Panels (**a**)–(**e**) display the electric field components (**a**) E_x, (**b**) E_y, and the fluctuating magnetic field components (**c**) δB_x, (**d**) δB_y, (**e**) δB_z at $\omega_{pe}t = 40$, 400 and 820. The *area encircled by red line* is shown in Fig. 3

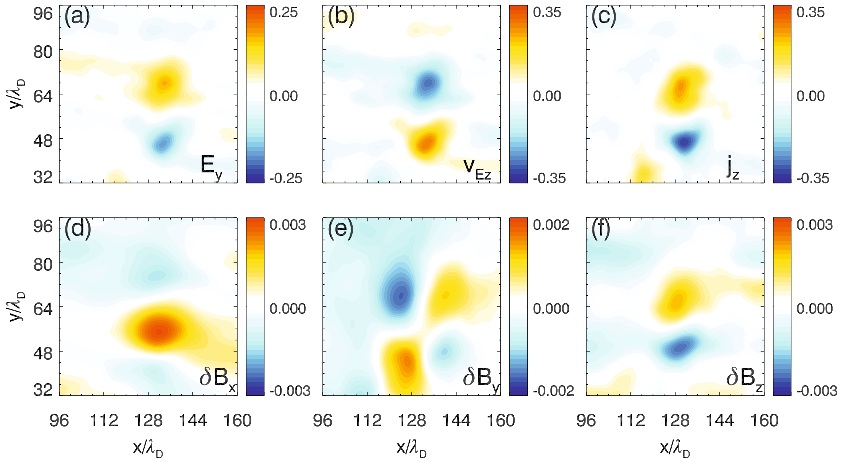

Fig. 3 The electric field component (**a**) E_y, the drift velocity (**b**) v_{Ez}, the current (**c**) j_z and the fluctuation magnetic field components (**d**) δB_x, (**e**) δB_y, (**f**) δB_z at $\omega_{pe}t = 400$ in the domain $96\lambda_D < x < 160\lambda_D$ and $32\lambda_D < y < 96\lambda_D$

4 Discussion and conclusions

The magnetic structures of the 2D electron holes have already been investigated by Du et al. (2011) with 2D electromagnetic PIC simulation in weakly magnetized plasma. In their simulations, an initial 1D electron hole is assumed to exist in the simulation domain. The 1D electron hole is broken into several 2D electron holes due to the transverse instability, and the magnetic structures associated with these electron holes have regular structures. In this paper, we performed 2D electromagnetic PIC simulations to study the structures of the fluctuating magnetic field associated with electron holes formed during the nonlinear evolution of the electron two-stream instability in weakly magnetized plasma. Several 2D electron holes are formed during the nonlinear evolution, which can last for about one thousand plasma periods. In these 2D electron holes, in addition to the bipolar structures of the parallel electric field E_x, there still exists the unipolar structures of the perpendicular electric field E_y due to the transverse instability. The fluctuating magnetic field δB_x and δB_y are produced by the current in the z direction due to the electric field drift of the electrons, whose parallel cuts have unipolar and bipolar structures, respectively. This is consistent with results in Du et al. (2011). Therefore, as proposed by Andersson et al. (2009) and Du et al. (2011), the unipolar structures of the fluctuating magnetic field in the perpendicular direction as observed by THEMIS satellites can be explained by the Lorentz transforming of a moving quasi-electrostatic structure when the moving speed is sufficiently large.

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