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Electrostatic Structure of the Electron Phase-space Holes Generated by the Electron Two-stream Instability with a Finite Width*

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Abstract Space satellite observations in an electron phase-space hole (electron hole) have shown that bipolar structures are discovered at the parallel cut of parallel electric field, while unipolar structures spring from the parallel cut of perpendicular electric field. Particle-in-cell (PIC) simulations have demonstrated that the electron bi-stream instability induces several electron holes during its nonlinear evolution. However, how the unipolar structure of the parallel cut of the perpendicular electric field formed in these electron holes is still an unsolved problem, especially in a strongly magnetized plasma ($\Omega_{\rm e} > \omega_{\rm pe}$, where $\Omega_{\rm e}$ is defined as electron gyrofrequency and $\omega_{\rm pe}$ is defined as plasma frequency, respectively). In this paper, with two-dimensional (2D) electrostatic PIC simulations, the evolution of the electron two-stream instability with a finite width in strongly magnetized plasma is investigated. Initially, those conditions lead to monochromatic electrostatic waves, and these waves coalesce with each other during their nonlinear evolution. At last, a solitary electrostatic structure is formed. In such an electron hole, a bipolar structure is formed in the parallel cut of parallel electric field, while a unipolar structure presents in the parallel cut of perpendicular electric field.

Key words Electron phase-space hole, Two-stream instability, PIC simulation

Classified index P 353

0 Introduction

Since Geotail satellite, which focused on the Earth's magnetotail, observed Electrostatic Solitary Waves (ESWs) in 1994[1], plenty of observing evidences flow out for various space environments, such as the foreshock region of the bow shock[2], the auroral region[3], the solar wind[4], the magnetosheath[5], and the separatrix region of magnetic reconnection[6−8]. These observed ESWs have common features that besides the parallel cut of parallel electric field has a bipolar structure, its perpendicular component has a unipolar structure[9,10].

ESWs are modeled as a format of electron phase-space hole by Bernstein *et al.*[11]. These structures can be calculated from the Vlasov and Poisson equations as the stationary solutions of the Bernstein-Greene-Kruskal (BGK) model[12,13]. Particle-in-cell (PIC) simulations in one-dimension (1D) have confirmed that the electron bi-stream instability would induce ESWs of several electron holes in the simulation domain during its nonlinear evolution, and the parallel cut of electric field in the parallel component at these ESWs has a bipolar structure[14−22]. Also,

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the electron velocity distributions in these ESWs consist of trapped and passed particles, and there is a hole in the phase space, which is consistent with the results of Bernstein *et al.*[14,18,23,24]. Recently, with two-dimensional (2D) PIC simulations, ESWs are found to swing due to the effect of transverse instability[25−27]. The transverse instability is demonstrated to be a kind of self-focusing instability: perturbations in ESWs lead to the electric potentials' transverse gradients, which focuses the trapped electrons into the areas with the superfluous electrons, and then the transverse instability occurs[28]. In a weakly magnetized plasma ($\Omega_{\rm e} < \omega_{\rm pe}$, where $\Omega_{\rm e}$ is defined as electron gyrofrequency and $\omega_{\rm pe}$ is defined as plasma frequency), the transverse instability will break a 1D electron hole into several 2D electron holes. In these 2D electron holes, the parallel cut of the electric fields in the parallel component and perpendicular cut of the electric field in the perpendicular components have bipolar and unipolar structures, respectively[25].

In a strongly magnetized plasma, the parallel cut of the parallel electric field has a bipolar structure in an electrons hole, however, whether a unipolar structure of the perpendicular electric field can be formed in an electron hole during the electron two-stream instability is still unknown[25]. In this paper, the nonlinear evolution of the electron two-stream instability with a finite width is investigated with the help of 2D electrostatic PIC simulations. It is found that besides the bipolar structure of parallel electric field, the unipolar structure of electric field in the perpendicular component can also be formed in an electron hole.

1 Simulation Model

In this paper, 2D electrostatic PIC simulations with periodic boundary conditions in x and y directions are performed to investigate the nonlinear evolution of electron bi-stream instability in a strongly magnetized plasma[29]. In the electrostatic simulation model, we set a uniform background magnetic field along the x direction. Our simulations also employ two different electron components with an initial drift velocity between them, and the Maxwellian distribution is satisfied for these two different electron components, which have the same thermal velocity $v_{\rm te}$ ($v_{\rm te} = \sqrt{k_{\rm B}T_{\rm e}/m_{\rm e}}$, where $T_{\rm e}$ is the electron temperature). The drift velocity $V_{\rm d}$ between the two components is $4.0\,v_{\rm te}$, *i.e.* $V_{\rm d} = 4.0\,v_{\rm te}$, which is along the x direction. The time, distance and velocity are normalized by $\omega_{\rm pe}^{-1}$ ($\omega_{\rm pe} = \sqrt{n_0e^2/m_{\rm e}\varepsilon_0}$, and n_0 is the total electron number density), Debye length $\lambda_{\rm D}$ ($\lambda_{\rm D} = (\varepsilon_0 T_{\rm e}/n_0e^2)^{-1/2}$), and $v_{\rm te}$, respectively. The electric field is normalized by $m_{\rm e}\omega_{\rm pe}v_{\rm te}/e$. The cell size is $\lambda_{\rm D}\times\lambda_{\rm D}$, and the time step $\Delta t = 0.02\omega_{\rm pe}^{-1}$. The simulation uses a scale of grids of 512×256. The mass ratio of ion to electron $m_{\rm i}/m_{\rm e} = 1836$, and $\Omega_{\rm e}/\omega_{\rm pe} = 2$ and 10.

2 Simulation Results

In this paper, four cases are performed: in Case A and C, the electron beam initially flows in the parallel direction with an infinite width; while in Case B and D the initial electron beam has a finite width of $32\,\lambda_{\rm D}$, and it only exists in the region of $112\lambda_{\rm D} < y < 144\lambda_{\rm D}$. In Case A and B, $\Omega_{\rm e}/\omega_{\rm pe} = 2$, and in Case C and D, $\Omega_{\rm e}/\omega_{\rm pe} = 10$.

Figure 1 presents the time evolutions of the electric field components E_x and E_y at $\omega_{\rm pe}t = 400$, 1000, and 1924 for Case A. Nearly monochromatic waves are firstly excited. Then, these waves coalesce with each other. At $\omega_{\rm pe}t = 1000$, from the distribution of E_x, it can be found that there are only two electrostatic solitary structures in the simulation area. At the same time, in these solitary structures, E_y forms a streaked structure. At $\omega_{\rm pe}t = 1924$, there is only one electrostatic solitary structure for E_x in the simulation domain, and the streaked structure of E_y occupies the whole simulation domain. Such a process of the formation of the solitary electrostatic structure for E_x and excitation of streaked structure for E_y

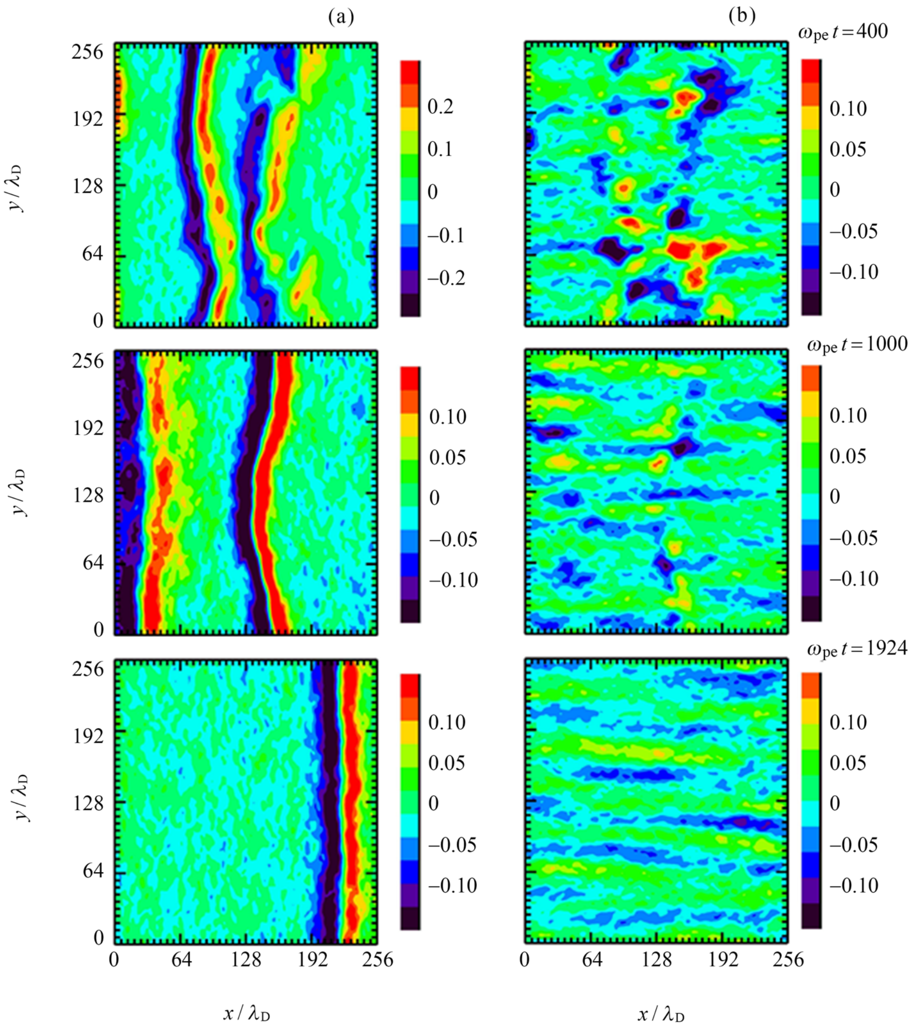

Fig. 1 Time history of the electric field components E_x (a) and E_y (b) at $\omega_{pe}t = 400$, 1000, 1924 for Case A

have been described previously in detail by Lu *et al.*[25], which is considered to be associated with electrostatic whistler waves emitted in the solitary structure. Obviously, the parallel cut of the electric field in the parallel component in the electron hole has a bipolar structure, however, the unipolar structure for the parallel cut of the electric field in the perpendicular component cannot be observed.

Figure 2 plots the time evolution of the electric field components E_x and E_y at $\omega_{pe}t = 400, 1000, 1788$ for Case B. Initially, from E_x, we can find that nearly monochromatic waves are excited in the region where the electron beam exists. Then, as in Case A, these waves also coalesce with each other. At $\omega_{pe}t = 1000$, from E_x, we can find that there is only one electrostatic solitary structure, where E_y has a negative value in the lower part but a positive value in the upper part. Such structures of E_x and E_y can be seen more clearly at $\omega_{pe}t = 1788$, and they could last for more than one thousand electron plasma periods. Figure 3 plots the parallel cut of E_x and E_y along $y = 136\lambda_D$ and $y = 120\lambda_D$ at $\omega_{pe}t = 1788$ for Case B. Obviously, in the solitary structure, a bipolar structure is formed in the parallel cut of the electric field in the parallel component, and a unipolar structure presents in the parallel cut of the perpendicular electric field. E_y has a positive value in the solitary structure along about $y = 136\lambda_D$, and it has a negative value along about $y = 120\lambda_D$. This is easy to be understood, because an electron hole has a positive potential. When the

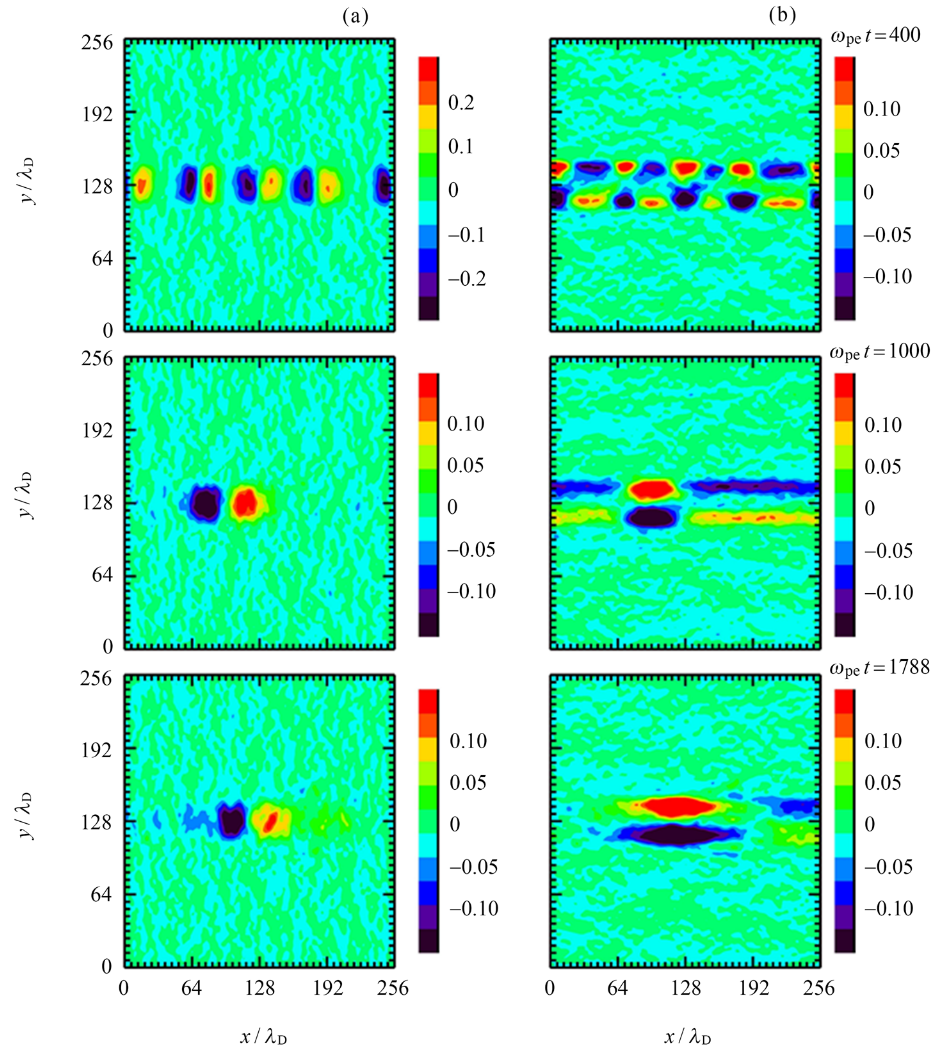

Fig. 2 Time history of the electric field components E_x (a) and E_y (b) at $\omega_{pe}t = 400$, 1000, 1788 for Case B

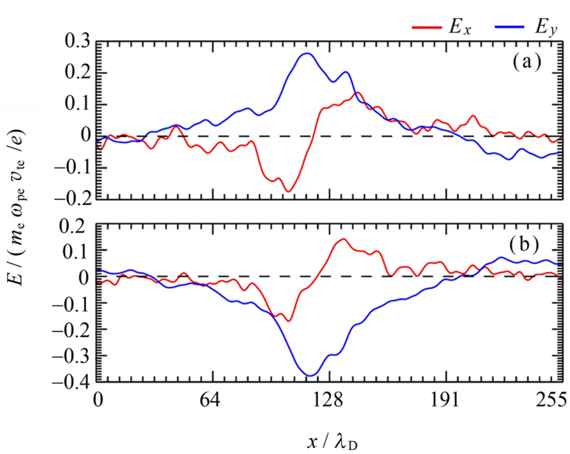

Fig. 3 Profiles of E_x and E_y along $y = 136\lambda_D$ (a) and $y = 120\lambda_D$ (b) at $\omega_{pe}t = 1788$ for Case B

electron beam has a finite width, the positive potential also has a finite width along the y direction in the electron hole. Therefore, E_y has a negative value in the lower part but positive value in the upper part of the electron hole.

Figure 4 and 5 show the time evolution of electric field E_x and E_y at $\omega_{pe}t = 400$, 1000, 2000 for Case C and D, respectively. Similar to Case A and B, from E_x, we can find that one solitary structure is formed at last. However, only when the electron beam has a finite width, the parallel cut of the electric field E_y has a unipolar structure in the solitary structure. Therefore, we can conclude that in strongly magnetized plasma during the nonlinear evolution

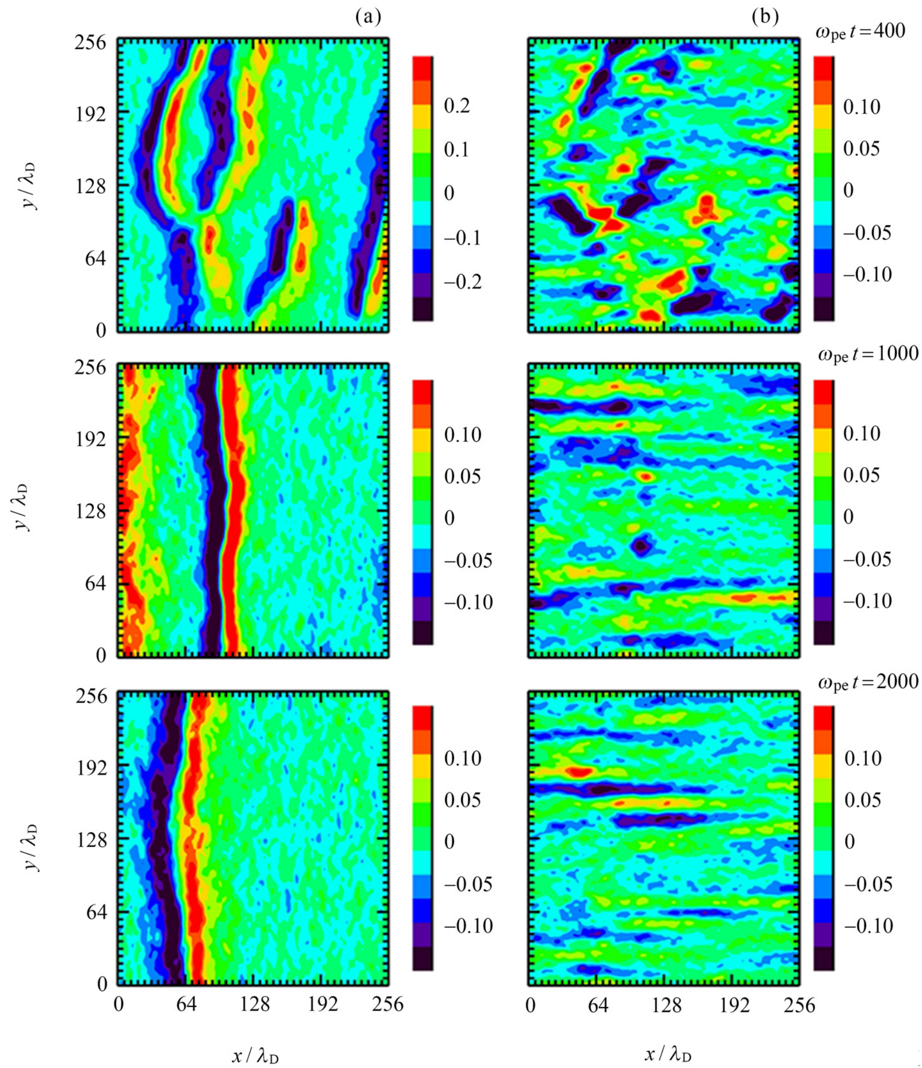

Fig. 4 Time history of the electric field components E_x (a) and E_y (b) at $\omega_{pe}t = 400$, 1000, 2000 for Case C

stage of the electron bi-stream instability with a finite width, a solitary electrostatic structure can be formed, where the parallel cuts of the electric fields in the parallel and perpendicular directions have a bipolar and unipolar structures, respectively.

3 Conclusions and Discussion

In this paper, with a 2D electrostatic PIC simulation model, the electron two-stream instability's nonlinear evolution in strongly magnetized plasma is investigated, and the results of the electron beam existing in the whole simulation domain are compared with that of the electron beam with a finite width. Our results show that the evolution of the parallel electric field is similar, and the solitary electric structure is formed at the late stage of the simulation through the coalescence of the excited waves, where the parallel cut of the electric field in parallel component has a bipolar structure. However, the evolution of the electric field in the perpendicular component is different. In cases where the electron beam exists in the whole simulation domain, the electric field in the perpendicular component forms a streaked structure. In cases where the electron beam has a finite width, the parallel cut of the electric field in the perpendicular component has a unipolar structure in the solitary electrostatic structure.

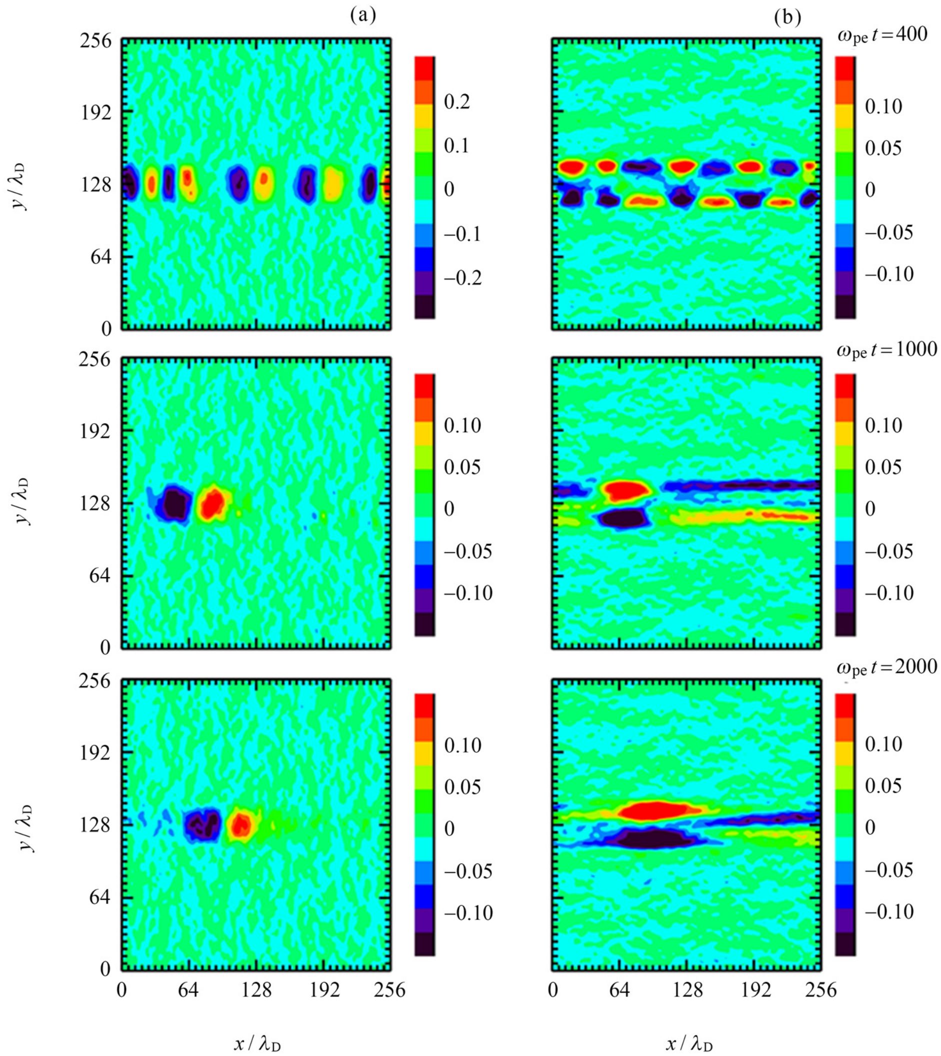

Fig. 5 Time history of the electric field components E_x (a) and E_y (b) at $\omega_{pe}t = 400$, 1000, 2000 for Case D

Satellite observations have shown that ESWs usually have a bipolar structure of the electric field in the parallel component and a unipolar structure of the electric field in the perpendicular component[9,10]. Our simulation results have demonstrated that the formed ESWs during their nonlinear evolution may have a bipolar structure of the electric field in the parallel component and a unipolar structure of the electric field in the perpendicular component when the electron two-stream instability has a finite width. The electron beams generated in geophysical environment, for example in magnetic reconnection, usually have a finite width[30−32]. Therefore, our results may explain the observed structures of both the parallel and perpendicular component of the electric fields in geophysical environment.

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