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The excitation and trapping of electron plasma waves by electron and ion holes

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Abstract

The dynamics of electron and ion holes in an electron–ion plasma is studied by means of Vlasov simulations. It is found that electron holes (EHs) repel ions owing to the positive EH potential, creating an ion density cavity which accelerates the EH, which can be trapped at ion density maxima. Colliding ion holes (IHs) produce non-isothermal electron distributions which excite Langmuir waves due to a streaming instability, and Langmuir waves can be trapped in an ion hole.

About a quarter century ago, Schamel presented a theory for electron holes (EHs) and ion holes (IHs) [1–3], where a vortex distribution is assigned for the trapped particles, and the integration over the distributions in velocity space gives the particle densities as a function of the electrostatic potential, which is calculated self-consistently from Poisson's equation. The dimensionless Vlasov equation

$$\frac{\partial f_j}{\partial t} + v\frac{\partial f_j}{\partial x} - \frac{m_e q_j}{e m_j}\frac{\partial \phi}{\partial x}\frac{\partial f_j}{\partial v} = 0. \tag{1}$$

describes the dynamics of the particle distribution f_j of the particle species j (where

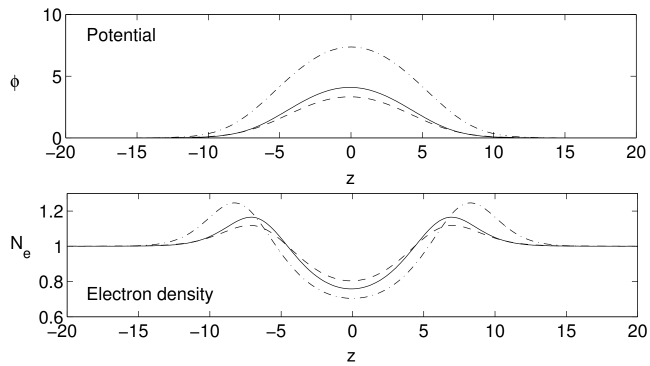
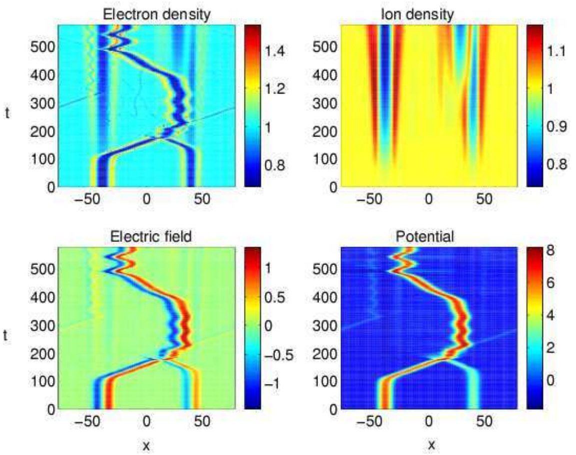
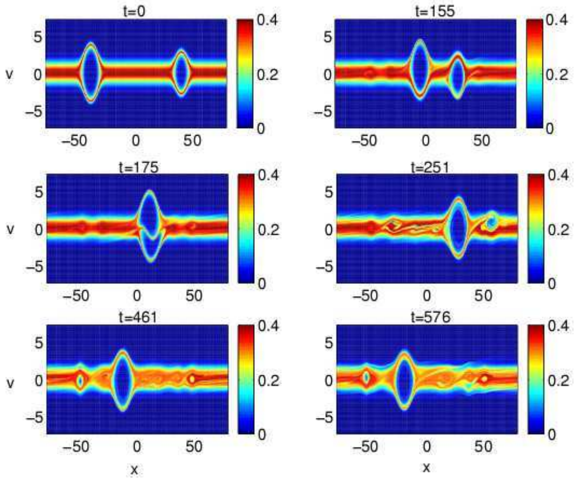


Figure 1: The potential and electron density, associated with a standing electron hole ($M = 0$) with the trapping parameters $\beta = -0.7$ (solid lines) and $\beta = -0.5$ (dash-dotted lines), and a moving electron hole ($M = 0.5$) with $\beta = -0.7$ (dashed lines) in plasmas with ion density ($N_i = 1$). (From Ref. [4]).



(a) The electron density (upper left panel), ion density (upper right panel), electric field (lower left panel) and potential (lower right panel) of the two electron holes, as function of space x and time t. Initially, the left EH has a trapping parameter $\beta = -0.5$, while the right EH has a trapping parameter $\beta = -0.7$.

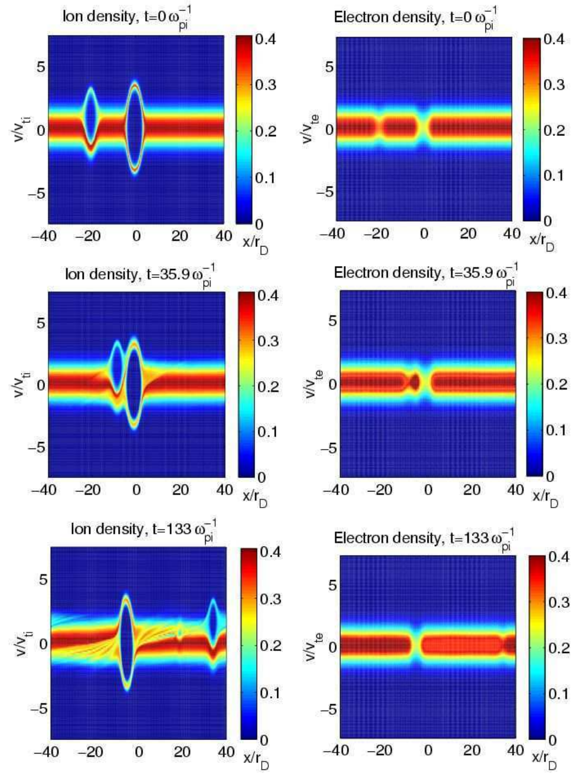


(b) The electron distribution for two electron holes at time $t = 0$ (upper left panel), $t = 155$ (upper right panel), $t = 175$ (middle left panel), $t = 251$ (middle right panel), $t = 461$ (lower left panel) and $t = 576$ (lower right panel).

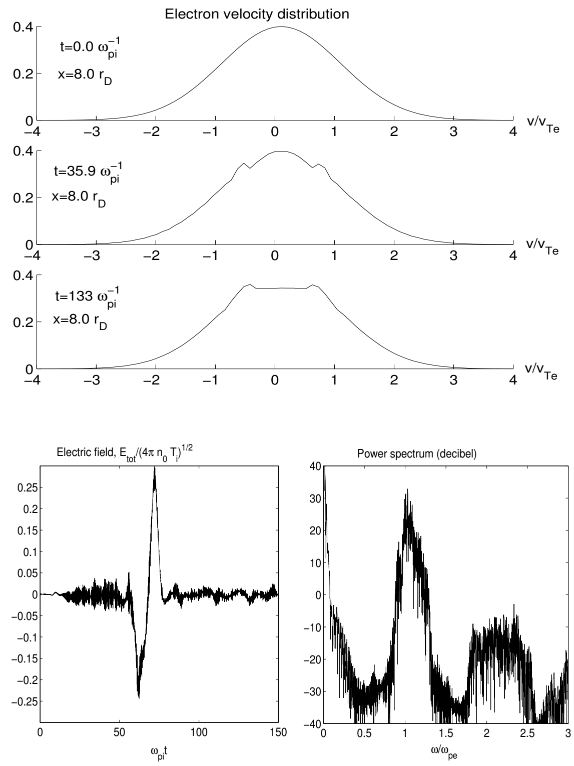
Figure 2: Two electron holes interacting with the oxygen ion background. (From Ref. [4].)

j equals e for electrons and i for ions), m_j is the mass, $q_e = -e$ ($q_i = e$) for electrons (ions), and e is the magnitude of the electron charge. The solution of Poisson's equation gives the EHs and IHs depending on the Mach number M and on a trapping parameter β. This model is here used to provide initial conditions to numerical simulations of EHs and IHs [4, 5], by means of a Vlasov simulation code [6]. In Fig. 1, we have illustrated potential and density for EHs, for a few sets of parameters, whereas in in Fig. 2, we have studied interactions between two EHs with each other and with oxygen ions. We can see that the EHs create local ion density cavities which after some time eject the EHs [Fig. 2(a)], which collide and merge into a new EH that is trapped at a local ion density maximum at $x \approx 30$; see Fig. 2(a). After $t \approx 400$, a new ion density cavity is created which ejects the EH in the negative x direction, to be trapped an ion density maximum located at $x \approx -30$. A few snapshots of the electron phase space density is depicted in Fig. 2(b).

The interaction between two IHs is depicted in Figs. 3 and 4. Figure 3(a) displays



(a) The distribution function for the ions (left panels) and electrons (right panels) of two colliding ion holes, before the collision at times $t = 0\,\omega_{pi}$ (upper panel) and $t = 35.9\,\omega_{pi}$ (middle panel), and after the collision at $t = 133\,\omega_{pi}$ (lower panel). The color bar goes from dark blue (small values) to dark red (large values).



(b) The electron velocity distribution at $x = 8\,r_D$, for $t = 0\,\omega_{pi}^{-1}$, $t = 35.9\,\omega_{pi}^{-1}$ and $t = 133\,\omega_{pi}^{-1}$ (upper three panels). The electric field at $x = 8.0\,r_D$ as a function of $\omega_{pi}t$ (lower left panel) and the power spectrum of the electric field as a function of ω/ω_{pe} (lower right panel).

Figure 3: Two colliding ion holes. (From Ref. [5].)

the ion and electron distribution functions for the two colliding IHs. In the initially Maxwellian distribution, beams are created at $v \approx \pm 0.6\,V_{Te}$, slightly before collision, whereafter a flat-top distribution with two maxima is created after collision; see the right panels of Fig. 3(a) and the upper panlels of Fig. 3(b). In the collision, electrons are accelerated by the IH potentials, and form electron streams leaving the trapped region between the IHs. These streams undergo a streaming instability and excite high-frequency Langmuir waves, which is illustrated in the lower panels of Fig. 3(b): High-frequency Langmuir waves are excited at time $t \approx 10\,\omega_{pi}^{-1}$. The large-amplitude bipolar electric fields of the IH appear as it crosses $x = 8.0\,r_D$ at time $t \approx 50$–$80\,\omega_{pi}^{-1}$. The frequency spectrum of the electric field (the right panel), reveals that the oscillations

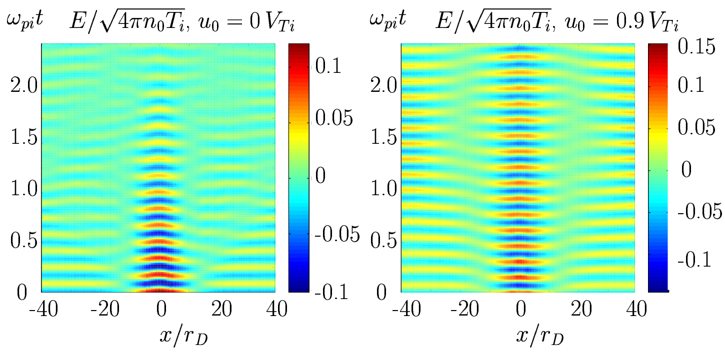


Figure 4: Normalized Langmuir wave Electric field $E/\sqrt{4\pi n_0 T_i}$ (the bipolar electric field has been removed from the data) as a function of the normalized space x/r_D and time $\omega_{pe}t$. The Langmuir wave is trapped in the ion hole which is initially centered at $x/r_D = 0$, and moving with the speed $u_0 = 0\,V_{Ti}$ (left panel) and $u_0 = 0.9\,V_{Ti}$ (right panel). (From Ref. [5]).

have frequency components close to the electron plasma frequency. Fig. 4 shows the trapping of Langmuir waves in an ion hole for a new set of simulations, where initially Langmuir waves are excited at the IH. The trapped waves have a frequency slightly lower than the electron plasma frequency, in line with previous investigations [7].

In summary, we have performed a numerical study, showing that electron holes can be acclelrated by the self-created ion density cavity, and that electron holes can be trapped at ion density maxima. Colliding ion holes acclelerate electrons due to the negative ion hole potentials, and the accelerated electrons form streams which excite high-frequency Langmuir waves. We are hoping that forthcoming observations from the FAST [8] and CLUSTER [9] missions should be able to verify the predictions of our computer simulations of electron and ion holes.

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[1] H. Schamel, Plasma Phys. **13**, 491 (1971); *ibid.* **14**, 905 (1972).
[2] S. Bujarbarua and H. Schamel, J. Plasma Physics **25**, 515 (1981).
[3] H. Schamel, Phys. Rep. **140**, 161 (1986); Phys. Plasmas **7**, 4831 (2000).
[4] B. Eliasson and P. K. Shukla, Dynamics of Electron Holes in an Electron-Oxygen Ion plasma, Phys. Rev. Lett. **92**, (in press, 2004);
[5] B. Eliasson and P. K. Shukla, Phys. Rev. Lett. **92**, 095006/1-4 (2004)
[6] B. Eliasson, J. Sci. Comput. **16** 1 (2001); J. Comput. Phys. **190**, 501 (2003).
[7] P. K. Shukla and B. Eliasson, JETP Lett. **77**, 647 (2003).
[8] C. W. Carlson *et al.*, Geophys. Res. Lett. **25**, 2013 (1998).
[9] See, for example, Annales Geophysicae **19**, pp. 1195–1730 (2001).