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Coherent wave forms in the auroral upward-current region

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Abstract. With the help of 1D PIC simulations we show that observations of high frequency electric wave spectra in the auroral upward current region can be reproduced. Using distribution functions suggested by the measurements we find that in the nonlinear state ion-acoustic waves and the electron two-stream (Langmuir) waves dominate the spectrum. In the absence of cold electrons electron-acoustic waves are not excited initially but appear only at late time. They are the result of formation of a two-temperature electron plasma by nonlinear interaction when the other instabilities have saturated being less important for the formation of electron holes and the particle dynamics than the two-stream instability.

The physical processes in the auroral upward current region have in the last decades been to a large extent clarified [for an recent extended review cf. *Paschmann et al.*, 2003]. This has been made possible by the availability of high resolution measurements of the plasma and field parameters in situ both in space and time by spacecraft like Viking, Polar, Freja, and FAST. In particular, FAST has provided information from the center of the auroral ‘inverted-V’ acceleration region showing that the upward current region is dominated by hot ring-like electron distributions, field-aligned electric potential differences, upward going ion beams and a fast downward electron beam while very little cold plasma is present. Wave observations showed that under these conditions auroral kilometric radiation is excited around and below the non-relativistic electron-cyclotron frequency Ω_{ce} and that this excitation is accompanied by the presence of intense electrostatic wave activity of broadband spectral appearance. This activity is rather intense and may lead to the formation of localized wave packets and so-called electron holes. The nature of these packets has not yet been finally confirmed. Analytical theories are available which attribute them either to ion-cyclotron modes, or to ion-acoustic respectively electron-acoustic waves since it is quite reasonable to assume that they both can be excited under the conditions of the auroral upward current region. The importance of clarifications of the very processes here lies in the fact that they have direct relevance to particle acceleration and thus to the main heating and energy loss processes involved in the emission of escaping auroral kilometric radiation and the transport of energy toward the ionosphere in form of Poynting and electron fluxes. It also is important in order to infer about the nature and mechanism of generation of the quasi-stationary electrostatic potential drops which lead to the acceleration and heating of the auroral particle component, lifting the ionosphere up into an

escaping energetic-ion beam and scattering electrons back down toward the ionosphere as has been observed in high-resolution spectra of the particle component [*McFadden et al.*, 2003; *Pottelette et al.*, 2004].

In this Letter we present numerical simulations of electrostatic wave generation in one dimension parallel to the magnetic field for conditions similar to those found in the auroral upward current region. The motivation of such simulations has been given by the above referred observations. Their main intention is to identify the dominant wave modes in the upward current region and to investigate whether the electron-acoustic wave mode is actually of the importance which it has been given in previous theories. In particular we wanted to find out whether it will under the favorable conditions in the upward current region rise to large amplitudes and be strong enough to trap electrons such that electron holes might form. Such electron-acoustic electron holes, which in theoretical approaches have been proposed to exist [*Dubouloz et al.*, 1991, 1993; *Berthomier et al.*, 2000, 2003; *Singh and Lakhina*, 2001; *Singh et al.*, 2001; *Shukla et al.*, 2004], have been made responsible for generation of the auroral kilometric radiation [e.g., *Pottelette et al.*, 1999].

We performed several simulation runs using a one-dimensional relativistic electromagnetic full particle code with periodic boundary conditions. The upward current region is often modelled by four plasma components with different drift velocities parallel to the magnetic field : a downward precipitating electron beam, a downward going hot main electron component, a cold rarefied electron background, and an upward going ion beam, respectively. Although we performed several runs, we present here results mainly from one of those runs. The physical parameters used in the simulation run shown, chosen as being reasonable in the upward current region [*Pottelette et al.*, 1999], are $u_b = 6 \times 10^4 \text{ km s}^{-1}$,

$u_h = 3 \times 10^3 \text{ km s}^{-1}$, $u_i = -10^2 \text{ km s}^{-1}$, $T_b = 500 \text{ eV}$, $T_h = 100 \text{ eV}$, $T_i = 8 \text{ eV}$. Here, u_j denotes the drift velocity, and T_j the temperature. The ion-to-electron mass ratio has been set to $m_i/m_e = 400$, and the beam-to-ion density ratio is taken as $n_b/n_i = 0.01$. The ratio of electron cyclotron-to electron plasma frequency inferred from measurements is $\Omega_e/\omega_{pe} = 10$. The simulation is restricted to a wave propagation angle $\theta = 0$ parallel to the ambient magnetic field \mathbf{B}_0 . Only two electron components (the precipitating beam $j = b$ and a hot main $j = h$ electron population) as well as one single ion component ($j = i$) are included in the case presented in this Letter. The results of this run do not differ much from what is obtained when a cold rarefied electron background is in addition taken into account. The effect of such a cold electron component will be discussed later. The technical parameters of the simulation are as follows: The grid size is $\Delta x \approx 0.31 \lambda_{De}$, the number of grid points is $ng = 8192$, the number of particles in one cell is 100 for each species, and the time step is $\Delta t = 0.00625 \omega_{pe}^{-1}$, respectively. Waves are only allowed to propagate along the magnetic field, i.e. along the x -axis.

Fig. 1a shows the initial velocity distribution function. The electrostatic linear dispersion relation,

$$1 + \sum_j \frac{2\omega_{pj}^2}{k^2 v_j^2} [1 + \zeta_j Z(\zeta_j)] = 0, \quad (1)$$

predicts the excitation of electron-beam and ion-acoustic instabilities, with the growth rate of the ion-acoustic instability much less than that of the beam instability, where ω_{pj} denotes the plasma frequency, $\zeta_j = (\omega - ku_j)/kv_j$, v_j the thermal velocity for species j , and $Z(\zeta_j)$ is the plasma dispersion function. As expected, the $\omega - k$ power spectrum based on the time interval $0 < \omega_{pe} t < 512$ in Fig. 2a exhibits a well pronounced peak $\omega/\omega_{pe} \sim 1, ku_b/\omega_{pe} \sim 1$ on the Langmuir wave branch labelled L which is due to the

beam instability. In addition, second harmonic ($2L$) and beat waves (*beat*) of the beam-generated Langmuir waves (L) are found. Finite intensities are also obtained on the ion acoustic (IA') branch although the frequency resolution for IA' waves is not sufficient. Moreover, waves at an almost constant frequency near the electron plasma frequency (straight horizontal line L') are excited.

Figure 1c shows electron phase space plots at a time when the beam instability develops to its nonlinear state. A sequence of electron holes are formed then. The lower panel Fig. 1d views the final state of the particle phase space when the electron components have been strongly heated by nonlinear wave-particle interaction and a broad electron distribution evolves. Figure 1b shows the final electron distribution at this time exhibiting a plateau and a long energetic tail which extends up to 2.5 times the initial beam speed. The high-resolution insert in this panel shows that the low-energy maximum of the distribution function has developed a slightly double-humped shape at late time.

Since the ion acoustic instability has a small linear growth rate (the linear growth time is estimated to $\sim 3 \times 10^3 \omega_{pe}^{-1}$), the IA' waves cannot have risen to large amplitude at the end of the simulation time through the linear process. The most plausible explanation for their occurrence is thus that they are the result of the decay instability of the beam-generated Langmuir waves. Large-amplitude Langmuir waves (L) decay into another Langmuir-like wave (L') and an ion acoustic like wave (IA') by the process $L \rightarrow L' + IA'$ [e.g., *Forme*, 1993]. In this case the resonance conditions of the wave-wave interaction are written as $\omega_L = \omega_{L'} + \omega_{IA'}$ and $k_L = k_{L'} + k_{IA'}$, where ω_j, k_j are the frequency and wavenumber of the parent ($j = L$) and the daughter ($j = L', IA'$) waves, respectively. The above condition

forms a parallelogram in $\omega - k$ diagram as shown in Fig. 3, which is consistent with what is observed in Fig. 2a.

In the late nonlinear stage, the L' waves accumulate more and more energy while the L waves lose their energy as seen in Fig. 2b which is based on the time interval $1536 < \omega_{pe}t < 2048$. As shown below, these L' waves play an important role in the nonlinear electron heating. In addition to a typical plateau formation due to the interaction between L waves and beam electrons, a high energy tail is generated in the late nonlinear stage (Fig. 1b). This tail has been produced through the nonlinear interaction between some electrons and the L' waves which have larger phase velocity than the L waves. We have confirmed that this high energy tail is not observed when the ions are assumed to be immobile so that the L' waves as well as the IA' waves are not excited in such a case.

Interestingly, in Fig. 2b small amplitude waves labelled EA are unexpectedly observed at later time in the simulation. These waves are presumably of electron acoustic nature which are generated by the nonlinear evolution of the electron distribution. In the late nonlinear stage, the main electron distribution function exhibits two bumps as can be seen in the framed area of Fig. 1b which is the expansion of the background picture. One of the bumps at $v_{ex}/u_b \sim 0$ disappears when the ion-acoustic IA' waves are absent, i.e. when the ions are artificially kept immobile. The peak velocity of the other bump roughly coincides with the phase velocity of the beat waves ($v_{ph}/u_b \sim 0.08$). Hence, those bumps have been produced by wave-particle interactions mediated by the beat and ion acoustic IA' waves. As a result, the system effectively consists of two electron components. In such a system, the electron-acoustic wave mode can survive as a normal mode [e.g., *Gary and Tokar*, 1985; *Watanabe and Taniuti*, 1977; *Singh and Lakhina*, 2001], although its amplitude will

not be large since there is not sufficient free energy to drive it hard in which case nonlinear effects as have been proposed [e.g., *Berthomier et al.*, 2000, 2003; *Shukla et al.*, 2004] will not arise.

The electron-acoustic mode could be linearly unstable also in the initial state if a cold rarefied electron component would additionally be included and the hot electron component had a finite drift velocity relative to the cold one. In studies of the upward current region the cold component is in most cases neglected as it is hard to measure though sometimes there have been indications [*Pottelette et al.*, 1999] of its presence. However, the electron acoustic instability usually does not dominate when other instabilities like the electron-beam instability and the ion-acoustic instability are simultaneously present. The electron-beam instability is strong enough to have much higher growth rates and higher saturation levels than the electron-acoustic instability in the parameter regime of the simulation. We have confirmed that there is not an essential difference between the results of the above run and the run which includes cold rarefied background electrons from the outset.

The ion-acoustic instability, if present, also yields higher saturation levels than the electron-acoustic instability. According to our simulation results (not shown here), the dominant saturation mechanism of the electron-acoustic instability is trapping of cold electrons while that of the ion-acoustic instability consists in trapping of hot electrons. Estimating the saturation levels of the electrostatic potential energy for those two mechanisms we find $e\phi_{ea} \sim (m_e/2)v_h^2(n_c/n_h)$ for the electron acoustic instability and $e\phi_{ia} \sim (m_e/2)v_h^2$ for the ion acoustic instability, respectively. Hence $\phi_{ea}/\phi_{ia} \sim n_c/n_h < 1$, where v_h indicates the hot-electron thermal velocity, and n_c is the cold electron density. Thus it

becomes clear that the electron-acoustic instability will not be so important in such a system. It is, however, interesting that the electron-acoustic mode becomes visible in the late nonlinear stage under certain conditions as our above simulations have shown. In the long-term evolution of the electron-beam plasma system one therefore expects also weak electron-acoustic waves to be present though their intensities will be weak and the waves dynamically not very important. In particular, it is not obvious that they might form electron-acoustic holes structuring the electron particle component and cause strong electron acceleration [Dubouloz *et al.*, 1992, 1993] or electron trapping [Shukla *et al.*, 2004].

In summarizing the simulations we note that the precipitating energetic electron beam generates strong Langmuir waves (L) and their second harmonics ($2L$), and beat waves (*beat*) via the beam instability. In addition, the intense L waves initiate three wave decay processes which lead to the appearance of other Langmuir like waves (L') at about constant frequency and in a large range of wave numbers, and to low-frequency ion-acoustic like waves (IA'). The former waves L' are important as they have larger phase velocities than the originally excited L waves. They thus interact with high-energy electrons and lead to the production of the high-energy tail on the electron distribution function. Most interestingly, weak electron-acoustic waves (EA) appear in the late nonlinear stage where the electron distribution function becomes double-humped and EA waves overcome the damping.

In this chain of processes taking place in the upward current region ion-acoustic waves have the slowest phase velocity, typically the order of hundred km s^{-1} . Since FAST passes the auroral region at about 6 km s^{-1} , it mainly observes the time rather than spatial variations of these waves. Figure 4a shows on the right the spatially averaged frequency

spectrum for the simulation run discussed in the present paper. The corresponding time period is $0 < \omega_{pe}t < 4096$. The strongest peak in the spectrum indicates the Langmuir waves L (and L' which are hidden in the spectrum by the width of the L line). The second-strong peak at lower frequency belongs to the ion acoustic IA' waves, and the small third high frequency peak is at the position of the $2L$ waves. Electron-acoustic EA waves no longer possess a sharp peak as mentioned above. The time variation of the electrostatic field observed at a certain position of the simulation box is shown on the left in Fig. 4a. It exhibits a nicely coherent structure of modulated wave packets with the frequency of the envelope oscillation corresponding to ion-acoustic IA' waves, and the carrier waves being sustained by the L and L' waves. This coherent wave form is produced by the nonlinear coupling between L , L' , and IA' waves in the course of the decay instability ($L \rightarrow L' + IA'$). Figure 4b shows the corresponding measurements of the wave form (left panel) and frequency spectrum (right panel) obtained by FAST on January 30, 1997 (FAST orbit 1750) as given by *Pottelette et al.* [1999] in their Figure 2. According to the observations, the total plasma frequency was ~ 12 kHz, and the peak at $\sim 5 - 6$ kHz was assumed to be due to the electron-acoustic instability. If this would have been the case, the coherent wave form would be interpreted as the result of the nonlinear interaction between the electron-acoustic and ion acoustic waves whose peak frequency is ~ 200 Hz. The simulation results suggest instead that the total plasma frequency is rather around $\sim 5 - 6$ kHz indicating a lower total density of $\sim 0.7 - 0.8 \text{ cm}^{-3}$, a conclusion which is supported by the observations of other authors [*Delory et al.*, 1998; *Ergun et al.*, 1998a, 1998b, 1998c; *Carlson et al.*, 1998; *McFadden et al.*, 1998, 2003; *Strangeway et al.*, 1998] of strongly reduced background densities, and by the general uncertainty in the plasma

density measurements. In this light the similarity in the simulations and observations in Fig. 4a and Fig. 4b in the wave measurements is interpreted such that the two major spectral peaks correspond to the IA' at frequency ~ 200 Hz and L as well as L' waves at $\sim 5-6$ kHz with the coherence being due to the nonlinear interaction between these waves. The spectral peak at 12 kHz belongs in this case to the second harmonics $2L$ of L waves. Compared to the FAST observations the simulations still show discrepancies. The first of is that the peak intensities of the IA' and $2L$ waves in the simulation are rather weaker than the observed intensities; the second is that the observed emission lines are rather broader than the simulated ones. The latter might depend on the set-up of the simulation and possibly also the limited length of the simulation which should be reflected in the weak level of EA waves. One might expect that at longer simulation times more Langmuir energy is transferred into the EA domain thereby broadening the IA' peak towards higher frequencies while the increasing intensity of EA waves will in addition heat the electrons stronger. In addition, one-dimensionality of the simulations might give a strong restriction to the simulation results. Presence of oblique waves could modify the frequency spectrum. A more quantitative evaluation of these aspects will be done by means of two-dimensional simulation code in the near future.

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References

Berthomier, M., R. Pottelette, M. Malingre, and Y. Khotyaintsev, Electron-acoustic solitons in an electron-beam plasma system, *Phys. Plasmas*, 7, 2987-2994, 2000.

- Berthomier, M., R. Pottelette, L. Muschietti, I. Roth, and C. W. Carlson, Scaling of 3D solitary waves observed by FAST and POLAR, *Geophys. Res. Lett.*, *30*, 2148, doi: 10.1029/2003GL018491, 2003.
- Carlson, C. W. et al., FAST observations in the downward auroral current region: Energetic upgoing electron beams, parallel potential drops, and ion heating, *Geophys. Res. Lett.*, *25*, 2017-2020, 1998.
- Delory, G. T., R. E. Ergun, C. W. Carlson, L. Muschietti, C. C. Chaston, W. Peria, J. P. McFadden, and R. Strangeway, FAST observations of electron distributions within AKR source regions, *Geophys. Res. Lett.*, *25*, 2069-2072, 1998.
- Dubouloz, N., R. Pottelette, M. Malingre, and R. A. Treumann, Generation of broadband electrostatic noise by electron acoustic solitons, *Geophys. Res. Lett.*, *18*, 155-158, 1991.
- Dubouloz, N., R. A. Treumann, R. Pottelette, and M. Malingre, Turbulence generated by gas of electron acoustic solitons, *J. Geophys. Res.*, *98*, 17415-17422, 1993.
- Ergun, R. E., C. W. Carlson, J. P. McFadden, F. S. Mozer, L. Muschietti, and I. Roth, Debye-scale plasma structure associated with magnetic-field-aligned electric fields, *Phys. Rev. Lett.*, *81*, 826-829, 1998a.
- Ergun, R. E. et al., FAST satellite observations of large-amplitude solitary structures, *Geophys. Res. Lett.*, *25*, 2041-2044, 1998b.
- Ergun, R. E. et al., FAST satellite observations of electric field structures in the auroral zone, *Geophys. Res. Lett.*, *25*, 2025-2028, 1998c.
- Forme, F. R. E., A new interpretation on the origin of enhanced ion acoustic fluctuations in the upper ionosphere, *Geophys. Res. Lett.*, *20*, 2347-2350, 1993.

- Gary, S. P., and R. L. Tokar, The electron-acoustic mode, *Phys. Fluids*, *28*, 2439-2441, 1985.
- McFadden, J. P. et al., Electron modulation and ion cyclotron waves observed by FAST, *Geophys. Res. Lett.*, *25*, 2045-2048, 1998.
- McFadden, J. P., C. W. Carlson, R. E. Ergun, F. S. Mozer, L. Muschietti, I. Roth, and E. Moebius, FAST observations of ion solitary waves, *J. Geophys. Res.*, *108*, 8018, doi:10.1029/2002JA009485, 2003.
- Paschmann, G., S. Haaland, and R. A. Treumann, Auroral Plasma Physics, *Space Sciences Series of ISSI*, *15*, Kluwer Academic Publishers, 2003.
- Pottelette, R., R. E. Ergun, R. A. Treumann, M. Berthomier, C. W. Carlson, J. P. McFadden, and I. Roth, Modulated electron-acoustic waves in auroral density cavities: FAST observations, *Geophys. Res. Lett.*, *26*, 2629-2632, 1999.
- Pottelette, R., R. A. Treumann, and E. Georgescu, Crossing a narrow in altitude turbulent auroral acceleration region, *Nonlin. Proc. Geophys.*, *11*, in press, 2004.
- Singh, S. V., and G. S. Lakhina, Generation of electron-acoustic waves in the magnetosphere, *Planet. Space Sci.*, *49*, 107-114, 2001.
- Singh, S. V., R. V. Reddy, and G. S. Lakhina, Broadband electrostatic noise due to nonlinear electron-acoustic waves, *Adv. Space Res.*, *28*, 1643-1648, 2001.
- Shukla, P. K., A. A. Mamun, and B. Eliasson, 3D electron-acoustic solitary waves introduced by phase space electron vortices in magnetized space plasmas, *Geophys. Res. Lett.*, *31*, L07803, 10.1029/2004GL019533, 2004.
- Strangeway, R. J. et al., FAST observations of VLF waves in the auroral zone: Evidence of very low plasma densities, *Geophys. Res. Lett.*, *25*, 2065-2068, 1998.

Watanabe, K. and T. Taniuti, Electron-acoustic mode in a plasma of two-temperature electrons, *J. Phys. Soc. Japan*, 43, 1819-1820, 1977.

Figure 1. Initial (a) and final (b) electron distribution functions and electron phase space plots at the end of the linear phase (c) and in the final nonlinear state (d).

Figure 2. $\omega - k$ dispersion spectra of the wave electric field E_x obtained in the simulation for the periods (a) $0 < \omega_{pe}t < 512$ and (b) $1536 < \omega_{pe}t < 2048$.

Figure 3. Schematic $\omega - k$ dispersion plot of the decay instability $L \rightarrow L' + IA'$ when the parent Langmuir wave L decays into another Langmuir L' and an ion-acoustic daughter wave IA' .

Figure 4. Comparison between (a) the simulation results and (b) FAST observations [Pottellette *et al.*, 1999]. Left panels: Wave forms. Right panels: Wave power spectra.







