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Simulations of three-dimensional auroral solitary structures with realistic boundary conditions

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Abstract. The fast solitary structures, which are observed frequently on the auroral field lines, are analyzed with the help of test-particles and particle-in-cell simulations with realistic, open boundary conditions. Since the evolution of the solitary structures is related to the changes in the trajectories of the supporting, trapped electrons, we employ a series of simulations to investigate the conditions for the stability of these structures.

1 Introduction

With the improved time resolution of the measured electromagnetic fields in space that became available on recent spacecraft, (for instance, Polar with 8000 samples/sec and Fast with 2000000 samples/sec) it became possible to simultaneously obtain detailed profiles of the highly nonlinear structures (Mozer et al, 1997; Ergun et al, 1999), as well as a reasonably good distribution function of the electrons (Carlson et al, 1998). Similar structures may have been observed in the geomagnetic tail by the Geotail (Matsumoto et al., 1994) and in the solar wind by the Wind (Bale et al, 1998) satellites. Of particular interest are the newly observed spiky nonlinear structures, that move generally in the anti-Earth direction with a large velocity of several thousands km/s, which is of the order of electron thermal velocity spread. These localized, large-amplitude structures are supported by the inhomogeneous, non-thermal, trapped electron populations, while they modulate the trajectories of the passing electrons. They form a basic plasma entity and may describe the mechanism by which two distinct plasma regions communicate between themselves. The evolution and stability of these spikes depends on the adjustment of the trapped population to perturbations and to externally modified parameters.

The passing electrons are the main indicators of the spikes since they respond instantaneously to any localized electric field and the changes in both the upgoing and downgoing electron fluxes characterize the electromagnetic properties of the spikes. The recent observations at low altitudes (FAST) of solitary structures, which move along the auroral magnetic field lines, indicate the existence of two different parallel potential profiles for the nonlinear spikes. Generally, the most intense spikes are observed as flat-top potential structures, in contrast to the standard Gaussian-like forms. In this potential form the (measured) parallel electric field is seen as separated reversed spikes, and the self-consistent electron density has a deficiency of electrons in the central part of the spike (electron hole) with a surplus at its edges.

Here, with the help of test-particles and particle-in-cell simulations we analyse the stability of the nonlinear pulses in three-dimensions. The evolution and stability of a specific spike depends on the adjustment of the trapped population to perturbations and to externally modified parameters. The strongest perturbations which affect the solitary spikes may be due to interaction with other spikes which move relatively to the analysed spike; when two spikes approach each other the supporting electron distributions intermingle and their mixture may cause a destruction or deformation of the spike(s).

2 Test-particle simulations

Most of the intense, fast propagating auroral potential structures can be described by a may be depicted along the parallel coordinate (ambient magnetic field) as a quasi-symmetric function with a flat- top and a sharp decline at the edges. In this potential form the (measured) parallel electric field is seen as separated reversed spikes, and the self-consistent electron density has a deficiency of electrons in the central part of the spike (electron hole) with a surplus at its edges. We use a separable form for the parallel dependence of the potential structure :

$$\Phi(x,r) = \phi_o G_o(x) R_o(r) \tag{1}$$

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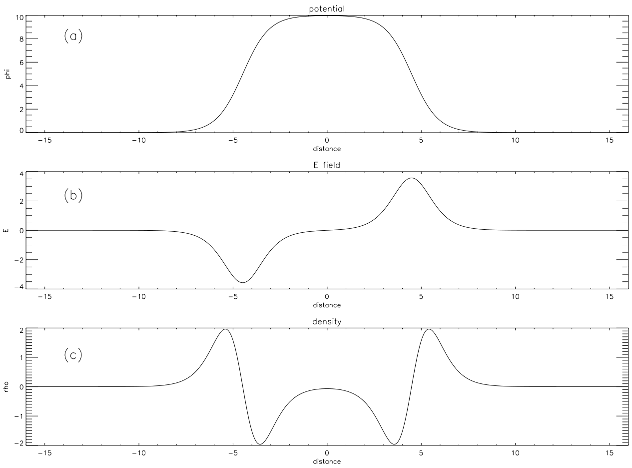

Fig. 1. **(a)** Potential structure, **(b)** parallel electric field and **(c)** self consistent charge density as a function of the parallel coordinate. $d = 4$, $\Delta_x = 1.3$.

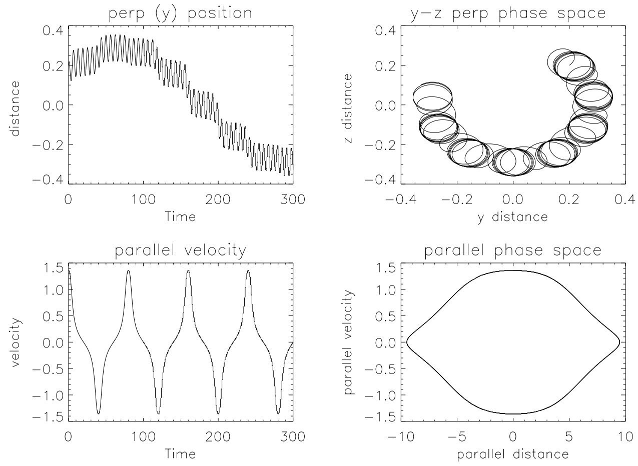

Fig. 2. Cuts in phase space variables in the presence of a single spike for an electron close to the separatrix. **(a)** perpendicular (y) coordinate vs time, **(b)** perpendicular coordinates phase space projection, **(c)** parallel velocity vs time, **(d)** parallel phase space projection. $\Delta_x = 1.3, \Delta_r = 4.0, d = 4.0, \phi_o = 1.0$. Initial conditions: $x = 0.0, v_x = 1.36, v_y = v_z = 0.05$

where x denotes the axial, parallel coordinate and $r^2 = (y^2 + z^2)$ is the perpendicular radial coordinate;

$$G_o(x) = [1 + \exp\ (-d/\Delta_x) \cosh(x/\Delta_x)]^{-1}$$

while the perpendicular form factor is taken as a Gaussian

$$R_o(r) = \exp\ [-r^2/\Delta_r^2]$$

The existence of a flat-top form requires formation of a particular charge density which supports the potential structures. Since the solitary structure exhibits a positive potential the supporting trapped distribution has deficiency of electrons at its center, i.e. it forms an "electron hole". Figure 1 shows the flat-top potential, together with the resulting well-separated, parallel bi-polar electric field components, as well as the self-consistent electron charge density. The electric field on Fig. 1b resembles the experimentally measured parallel field, while the potential structures as shown in Fig. 1a are supported by the self-consistent, phase space distribution functions which form the charge density on Fig. 1c.

To analyze the stability of the spikes and the effect of external perturbations on the trajectories of the trapped, magnetized electrons which self-consistently support the three-dimensional potential structures, we impose given external fields, as derived from Eq. 1 and follow representative electrons in phase space to discern the changes in their orbits under different external conditions. For each particle we propagate in time a six-dimensional vector which describes its phase space: $\boldsymbol{X} = (x, y, z, v_x, v_y, v_z)$. The set of the coupled equations

$$\dot{\boldsymbol{X}} = \boldsymbol{G}(\boldsymbol{X}) \tag{2}$$

where the vector $\boldsymbol{G}$ describes the changes in the phase space dynamics via the prescribed electromagnetic fields (external constant magnetic field and electric field derived from Eq. 1), is solved with an adaptive time step. The normalization used describes the time in units of inverse gyrofrequency and distances in Debye length. The results are displayed as a time series of a specific phase space variable (coordinate or velocity component) or a two-dimensional projections of the phase diagram.

Figures 2a-c show the phase space evolution of (a) the perpendicular coordinate with time, (b) the projection of the phase space on perpendicular coordinates, (c) the deformed oscillation in the parallel velocity and (d) the parallel phase space projection for an energetic electron close to the separatrtix with the initial values: $v_\perp = 0.07, v_\| = 1.38$. One observes a slight modification of the gyration-drift motion (Fig. 2a,b), and deformation of the parallel trajectories in the flat-top potential region and with increasing electron energies (Fig. 2c,d). Due to the relatively strong magnetization on the auroral field lines and the small perpendicular thermal spread, the gyroradius is much smaller than any perpendicular gradient of the spike's potential, and only weak coupling between parallel and perpendicular oscillations occur, indicating stability of an isolated spike.

3 Self-consistent simulations

In the three-dimensional code all the particle and field/potential quantities are functions of x, y, z, where x denotes the coordinate along the external field line. The dimensions of the system in the three directions are L_x, L_y, L_z, respectively. It is assumed that a potential profile made out of one or more spikes with specific characteristics has been formed and coexists with the populations of trapped and passing electrons. We follow then the evolution of the potential as determined by the full dynamics of the particles in an open-boundary, electrostatic, PIC code. In these simulations the boundary conditions along the external field line allow any given external flux of particles with an arbitrary distribution function, while those particles which leave the system are lost and ignored. The resulting total number of particles fluctuates in time, causing a (realistic) small fluctuation of the potential on the right boundary (the left boundary is kept at zero value). In the electrostatic approximation the line-integrated current component between two points is equal to the difference in time derivative of the potential at these two boundary points. Therefore the time varying value of the potential at the right boundary may be calculated from an integration of the parallel current (J_x) over any field line on the numerical grid starting from the left boundary. One may use these calculated values of the potential at each grid on the right boundary as a boundary condition for the solver of the Poisson equation, however, to ensure homogeneous boundary conditions we average the potential at $x = L_x$ over all y, z grid. This self-consistent, time-varying boundary conditions are very close to realistic conditions; they differ from most of the other boundary conditions implemented in auroral simulations. Generally, the time scales for the evolution of the solitary structures are hundreds or thousands times longer than the crossing time of an electron through the structures, hence repeated circulation of the same electrons in periodic simulations may inject some artificial effects. The simulation is carried out in the frame of one of the potential spikes so as to follow the evolution over long times without the spike moving out of the simulation box. Since here we concentrate on the particular evolution of an isolated spike, or interaction between two spikes at a close range, we do not require longer systems, as was done in other simulations. Therefore, with few millions of particles on a grid of 32x32x32 we obtain an excellent spatial resolution of 1000/λ_D^3. In the present set of simulations the ions are taken as a neutralizing fluid; in the given external parameters the electrons with a perpendicular temperature much smaller than the parallel temperature have a very small gyroradius and in the lowest order are tied to the magnetic field lines. For the perpendicular dimension we apply periodic boundary conditions, which are well justified for the strongly magnetized plasma with small gyroradii. In the runs presented, the cyclotron frequency is kept as equal to the plasma frequency, $\Omega_e = \omega_e$.

We test the behaviour of the primary spike when it is perturbed by another secondary, less intense, approaching spike. We create a primary, self-consistent Gaussian or flat-top (in the parallel direction) spike and adiabatically add an additional spike which moves very slowly towards the main investigated solitary structure (i.e. it approaches it while both of them are moving along the auroral field lines), while its amplitude is increased slowly to allow the trapped particles in the phase space to adjust themselves to the total potential. When the second spike reaches a sufficiently large amplitude ($\phi_1/\phi_o = 0.4$) and approaches the main structure within their parallel scale lengths at the time $40\omega_p^{-1}$, we allow the system to interact self consistently. The bottom of Figure 3 displays the two dimensional projection contours $\phi(x, y)$ of the three-dimensional potential $\phi(x, y, z)$ at a given value z when both spikes approach each other. The top of the figure

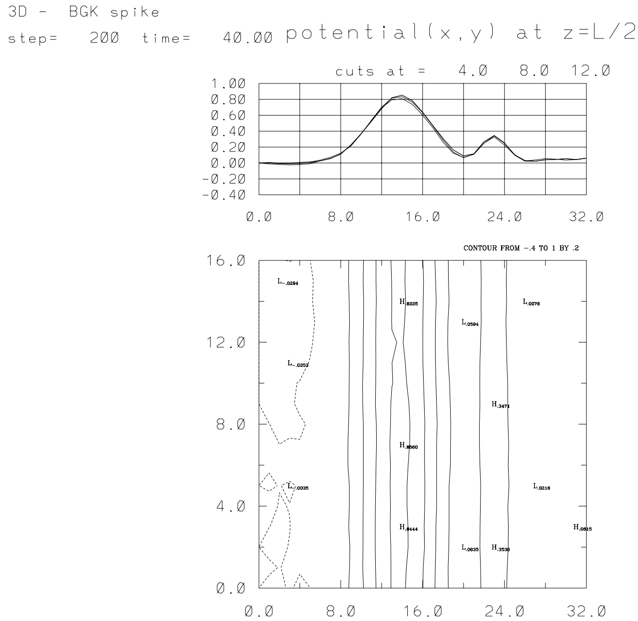

Fig. 3. Potential projection $\phi(x, z)$ and cuts $\phi(x)$ at $y = 8$ at the latest time of imposed approach of the secondary pulse. After that time a self-consistent interaction is allowed to take place.
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makes cuts of $\phi(x)$ for three values of y as noted.

We observe that after a short time (less than 25 plasma time periods) the smaller, perturbing spike disappears almost entirely, while the main spike gets a small boost in the direction of the motion of the perturbing spike. This destruction of the secondary spike is due to the phase space modifications in the trapped electrons. When the two spikes are sufficiently close, such that the distance between their centers is of the order of the sum of the parallel gradient scales of the respective potential structures, the more energetic electrons, close to the separatrix may tunnel out between the two structures. The electrons which support the main solitary structure, with a much higher density around its separatrix than those which support the (smaller) secondary spike, get an access to the secondary spike and in a very short time cause a major disruption of the delicate construction of the phase space densities which supports the spike. As they enter the secondary spike, they "fill" its electron hole; since the electrostatic potential structure responds instantaneously to the changes in phase space, the new electrons decrease the electron hole, the spike diminishes and the injected electrons become untrapped (passing electrons for the diminished secondary spike). Since the existence of a spike depends sensitively on the structure of the trapped particles, and the phase space density of the primary spike particles near the separatrix is much larger than in the smaller perturbing spike, the net injection of the additional electrons into the secondary spike adds the "missing" charge of the electron hole leading to a possible disappearence of the smaller, secondary hole and its potential spike. Additionally, those electrons which were trapped originally in the primary spike close to

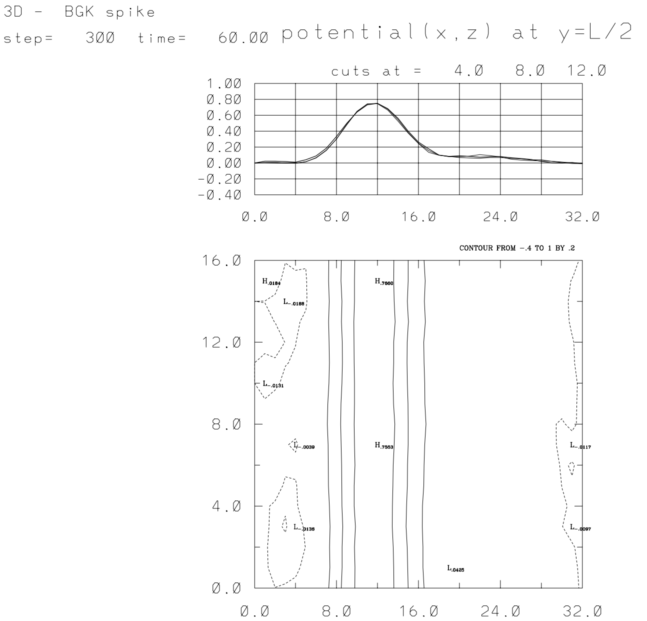

Fig. 4. Two-dimensional projection of the potential $\phi(x, z)$ for $y = 8$ and cuts $\phi(x)$ for three y values after the two spikes interact. One observes the disappearence of the smaller spike and average motion of the main structure opposite of the direction of the secondary spike.

the separatrix and became passing electrons with the demise of the secondary spike, carry with them significant momentum. Since this momentum was originally part of the primary spike, and there is no such loss of momentum of particles moving in the other direction, the main solitary structure starts moving in the opposite direction.

Figure 4 depicts the potential structure, similarly to the format of Fig. 3, after the two spikes approach each other and interact self-consistently (for 200 time steps). One observes a destruction of the secondary spike and an average drift of the main spike opposite to the original location of the secondary spike. Therefore, the interaction between spikes may be a source of the destruction of the less-intense spike; additionally, the interaction may accelerate or decelerate some of the fast, more intense solitary structures.

4 Summary

The robustness of the nonlinear spikes in three dimensions verifies their frequent observations by field crossing satellites. Although they presumably undergo deformations and collisions due to a spread of spikes' speeds along the field lines, these first results from the test particle and the self-consistent simulations indicate that they are stable and long-living.

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