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A numerical simulation of fast ionospheric Alfvén resonator excitation

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Abstract. It is commonly believed that the fast ionospheric Alfvén resonator (IAR) formed between the conductive layer of the ionosphere and the density gradient in the topside ionosphere plays a significant role in the dynamics of the topside ionosphere (Lysak (1986)). Here we present results from the two dimensional two fluid numerical model for excitation and propagation of inertial Alfvén waves in the ionosphere with different density distributions accounting for the ionospheric conductivity change due to feedback interaction with magnetic field aligned electric currents. Effects of IAR on the edges of discrete auroral structures are discussed in terms of the simulation results.

1 Observations

Quasiperiodic low frequency fluctuations are often observed at the edges of auroral structures. They are often accompanied by field-aligned electron bursts (Gelpi and Bering (1984), Ivchenko et al. (1999), Lynch et al. (1999)). Satellite observations seldom resolve the oscillations as satellites cross the oscillation region in a time short compared with the oscillation period. However, sounding rockets whose velocity is much less reveal the narrow-band character of these oscillations. Figure 1 shows Auroral Turbulence 2 Sounding rocket observations of electric and magnetic field oscillations accompanied by field aligned electron bursts.

Field-aligned electron bursts show time-of-flight energy dispersion pointing at the source region which is located at an altitude of several thousand kilometers. The electrons are thought to be accelerated by parallel electric field of inertial Alfvén waves (for a review see Stasiewicz et al. (2000)).

2 Statement of the problem

Observations of the fluctuations with a relatively narrow frequency band near 1 Hz suggest that the ionospheric Alfvén resonator may play a significant role in governing the waves. The ionospheric Alfvén resonator is bounded between the conducting ionosphere from below and plasma density gradient from above. It is expected that a feedback instability may operate in the resonator (Lysak (1991), Pokhotelov et al. (2000)).

We investigate whether the excitation of the ionospheric resonator is possible and favoured at the edges of auroral structures. The edges of the structures are characterized by the strong transverse gradients in the ionospheric conductivity, and, possibly, plasma density above the structures. Field aligned electric currents are generated at the conductivity gradients in the presence of a large scale convection electric field.

Several scenarios are studied using two dimensional two fluid hydrodynamics model similar to that of Lysak and Dum (1983).

3 The model

Following Lysak and Dum (1983) we assume that the aurora has mainly two-dimensional structure and the change of parameters with the longitude will be omitted. Two-dimensional shear Alfvén waves in a cold plasma are considered. If the field aligned current j_z is allowed to vary in x and z directions, where $\boldsymbol{e_z}$ is along the background magnetic field $\boldsymbol{B}_0$, the only nonvanishing perturbations will be B_y, E_x and E_z.

3.1 Model equations

If the terms of the order of electron to ion mass ratio are neglected, the electrons move along the magnetic field lines, while the ions move in the transverse direction. The propagation of Alfvén wave is governed by the set of Maxwell's equations for nonvanishing components of E and B fields, and by the equations of motion for ion and electron fluids. In

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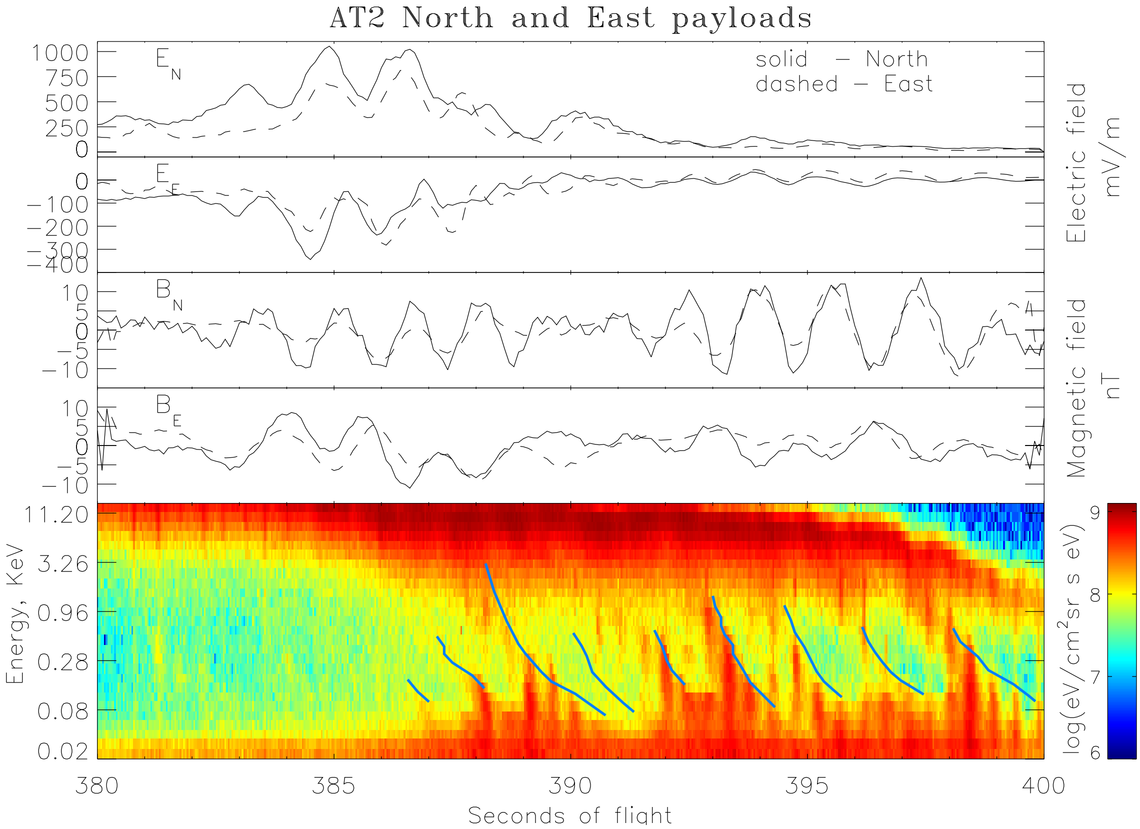

Fig. 1. Electric and magnetic field fluctuations and electron precipitation observed at the edge of an inverted-V structure by the Auroral Turbulence 2 sounding rocket (Ivchenko et al. (1999)).

the dimensionless variables these equations read:

$$\frac{\partial B_y}{\partial t} = -\frac{\partial E_x}{\partial z} + \frac{\partial E_z}{\partial x}, \tag{1}$$

$$\frac{\partial E_x}{\partial t} = -\frac{1}{n}\frac{\partial B_y}{\partial z}(1 - \alpha\frac{\partial E_x}{\partial x}), \tag{2}$$

$$\frac{\partial n}{\partial t} = \frac{\partial j_z}{\partial z}, \tag{3}$$

$$j_z = \alpha\frac{\partial B_y}{\partial x}, \tag{4}$$

$$E_z = \frac{1}{\alpha n}(\frac{\partial j_z}{\partial t} + \frac{j_z^2}{n^2}\frac{\partial n}{\partial z} - \frac{2j_z}{n}\frac{\partial j_z}{\partial z}). \tag{5}$$

The normalizations were chosen to be

$$B_y = \tilde{B}_y/B_0,\ E_x = \tilde{E}_x\frac{c}{V_{A0}B_0},\ n = \tilde{n}/n_0,\ j_z = \frac{\tilde{j}_z}{n_0 e V_{A0}},$$
$$E_z = \tilde{E}_z\frac{\omega_{P0}\tau}{B_0}, \qquad t = \frac{\tilde{t}}{\tau}, \qquad z = \frac{\tilde{z}}{V_{A0}\tau}, \qquad x = \frac{\tilde{x}\omega_{P0}}{c},$$

where tilde refers to variables in dimensional units. Here B_0 is the background magnetic field, n_0 is the background plasma density at the ionosphere level, $V_{A0} = B_0/\sqrt{4\pi n_0 M_i}$ is the Alfvén velocity and ω_{p0} is the plasma frequency at the ionosphere level, and $\alpha = \sqrt{M_i/m_e}$. Normalization in time is somewhat arbitrary, but it is convenient to take $\tau = 1\ s$.

3.2 Boundary conditions

At the magnetospheric end of the system the open boundary condition was implemented by setting the ratio of E/B to the local Alfvén speed. At the ionosphere the electric and magnetic fields were related by the Pedersen conductivity: $B = \Sigma_P E$.

Electric currents, flowing towards and out from the ionosphere modify the ionospheric conductivity. This happens due to the convective transfer of charge carriers and by the additional ionization caused by energetic electrons precipitating in the region of upward current. A general assumption is that the Pedersen conductivity Σ_P is proportional to the number of charge carriers in the conductive layer:

$$\Sigma_P \sim N \sim n_0 \Delta z,$$

where Δz is the thickness of the conductive layer. Thus,

$$\frac{1}{\Sigma_P}\frac{\partial \Sigma_P}{\partial t} = \frac{1}{N}\frac{\partial N}{\partial t} = \frac{j_z}{e\, n_0\, \Delta z}, \tag{6}$$

where e is the charge of the electron. Equation (6) describes only the convective transfer of charge carriers and additional ionization may be included in the right hand side by a factor $(1+\gamma)$, where γ is the number of electron-ion pairs per incident electron. For electron energies between 100 eV and

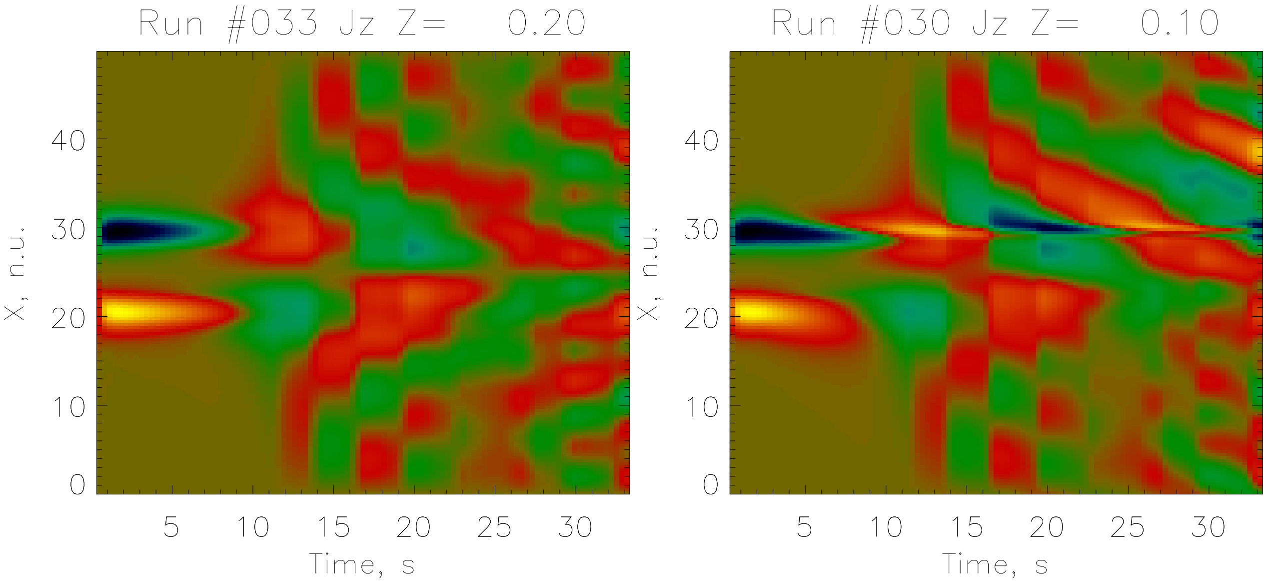

Fig. 2. Field-aligned current as a function of x vs time for the runs with and without feedback. The value of field aligned current is monitored at the cut parallel to the X axis at a normalized value of $z = 0.2$.

10 KeV, γ is between 5 and 100. In the normalized units equation (6) reads:

$$\frac{\partial \Sigma_P}{\partial t} = Q \frac{\partial B_y}{\partial x},$$

where

$$Q = (1+\gamma)\Sigma_P \left(\frac{c\tau_B}{\Delta z}\right) \frac{\omega_{Be}}{\omega_{Pe}}.$$

Here ω_{Pe} and ω_{Be} are the electron plasma and cyclotron frequencies respectively, and Σ_P is normalized to $1/\mu_0 V_{A0}$. For realistic ionospheric parameters Q lies between 10^3 and $2 \cdot 10^4$.

4 Numerical results

Results from two runs are presented here, with and without the feedback interaction. In both runs the conductivity was gradually enhanced from $\Sigma_P = 10$ to $\Sigma_P = 22$ in the middle of the grid, and the evolution of fields and currents was monitored. The density profile was chosen as $n(z) = \exp(-z \ln(225)/L_z)$, so that V_A changed by a factor of 15 on the grid. A large scale electric field in x direction was imposed on the system. The difference between the runs is in that the feedback interaction is present in Run30 ($Q = 5 \cdot 10^4$) and turned off in Run33. Figure 2 shows the development of the field aligned currents at $z = 0.2$ for both runs. As the conductivity enhancement is growing, a field-aligned pair is formed on the both sides of it (at $x = 20$ and $x = 30$), with the polarity determined by the sign of $E_x \frac{\partial \Sigma_P}{\partial x}$. After some time the currents reflected from the density gradient return and partially cancel the initial current pulse, until they change its polarity starting with $t = 9$. Later a number of reflections is observed. Due to the dispersion of Alfvén

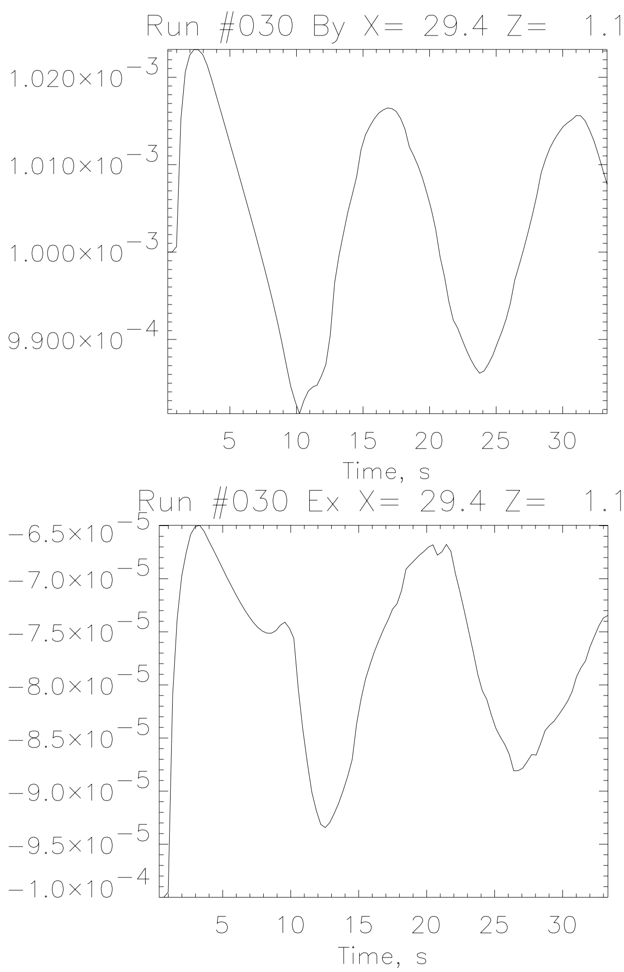

Fig. 3. Time variation of B_y and E_x in a point near the edge of the conductivity enhancement.

waves and periodic boundary conditions in x the different spatial harmonics in x separate with time.

The feedback interaction in Run30 leads to the increase in the conductivity in the region of upward current (at $x = 20$), producing an initial motion of the conductivity enhancement in the negative x direction (seen until the current reversal). On the other edge of the conductivity enhancement the same motion is observed in the beginning. The picture is changed when the reflected current reaches the ionosphere. The current around $x = 30$ arrives at the low conductivity ionosphere, producing a larger relative conductivity change than the one coming at the high conductivity ionosphere at $x = 20$. A localized pulsation region is thus formed at $x = 30$. Figure 3 presents the magnetic and electric field variations seen in the region.

5 Conclusions

The fast dynamics of the Alfvén waves produced at the conductivity enhancements related to auroral structures in the presence of a large scale electric field is considered, including reflections off the vertical density gradient and feedback interaction. The feedback interaction sets the conductivity enhancement into motion, and the reflected currents return to regions other than ones they originated from. As the electric field is larger in the low conductivity region, the current returning to the trailing edge is more effective in producing feedback. The ionospheric Alfvén resonator is thus excited at the trailing edge of the conductivity enhancement.

The spatial-temporal behavior of E and B variations is qualitatively consistent with observations. A similar picture is expected if the motion of the conductivity enhancement is due to any other mechanism than the feedback interaction (e.g. a component of large scale electric field in y direction).

The scenario operates for sharp (when compared to the electron skin depth) conductivity gradients, and thus it is favored at the night side.

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