Electron Energization by Alfvén Waves: Freja and Sounding Rocket Observations

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Recent sounding rockets observations highlight some space-time ambiguities in phenomena taking place in the auroral ionosphere, previously observed by the Freja spacecraft. Field aligned electron populations with energies from a few tens of eV to a few keV streaming through cold background plasma are usually observed in the auroral zone in association with strongly nonlinear electromagnetic perturbations. Simultaneous observations of bursty Langmuir emissions indicate the unstable character of these plasma distributions. A detailed analysis shows that the electromagnetic perturbations take the form of quasi-stationary nonlinear spatial structures related to inertial Alfvén waves. We suggest that inhomogeneous altitude distribution of the parallel electric field of these structures due to ionospheric density gradient is responsible for the observed electron distributions.

I. INTRODUCTION

The auroral zone is characterized by a number of different particle populations. In the upward current region downgoing accelerated hot electrons of plasmasheet origin [1] and upflowing ionospheric ions are often observed. It has been found recently [2] that in the downward current regions ionospheric electrons are accelerated upwards, carrying the return current of the auroral current circuit. Beside those major populations, downward accelerated essentially field aligned electrons are often observed throughout the auroral region, both within auroral arcs [3,4] and outside them [5].

The pitch-angle distribution of this population is clearly different from the one of plasmasheet electrons. The electrons have energies in the range of 50 eV to several hundreds of eV, with transverse energy of just several eV. This is a strong indication of their ionospheric origin and suggests a local acceleration of background electrons. Sounding rocket observations of similar field-aligned electron bursts typically show a time-of-flight type dispersion [6], which is less pronounced at Freja altitudes (1500 km) and rarely observed at FAST altitudes [7].

On the other hand quasiperiodic electromagnetic structures in the ULF-frequency range are often observed together with these field aligned electrons. It has been suggested that dispersive Alfvén waves (DAW) may be responsible for the electron acceleration. DAW is described by dispersion relation [8]

$$\omega = k_{\|} v_A \sqrt{\frac{1 + k_\perp^2 \rho_i^2}{1 + k_\perp^2 \lambda_e^2}}, \qquad (1)$$

where $\lambda_e = c/\omega_p$ is the electron inertial length, ρ_i the ion Larmor radius, and v_A the Alfvén velocity. Dispersive Alfvén waves propagate almost normal to the ambient magnetic field with $k_{\|} \ll k_\perp$ and have a very small transverse velocity $v_\perp = \omega/k_\perp$.

Several different configurations of the wave field in space and time were proposed to explain this turbulence. This includes solitary waves propagating from the magnetosphere [9], quasi-stationary structures [10], and waves in the ionospheric Alfvén resonator [11]. Single satellite observations cannot resolve the space-time ambiguity of the observations and it is difficult to distinguish these different mechanisms.

II. SATELLITE OBSERVATIONS (FREJA)

The Freja satellite was launched to an orbit with perigee 600 km, apogee 1750 km, and inclination 63^0 in 1992. Here we present data from Freja orbit 7279, April 10, 1994. The satellite was at 1380 km altitude, 20.9 hours MLT, 66^0 magnetic latitude. A comprehensive description of the Freja scientific payload can be found in a special issue of *Space Science Reviews (70, 405-602, 1994)*.

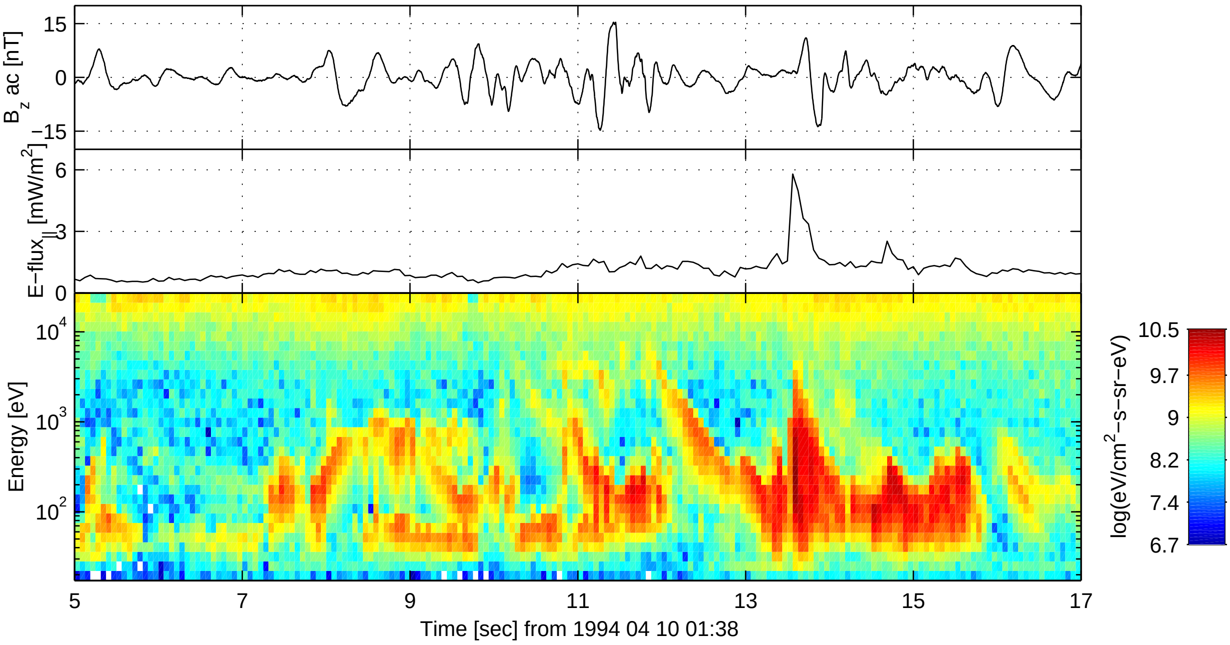

FIG. 1. Electron energization and Alfvénic turbulence event observed on Freja orbit 7279, April 10, 1994. Upper panel - F7 TESP electron time-energy spectrogram for pitch-angles $< 20^0$, middle panel - parallel energy flux calculated for energies < 5 keV, lower panel - magnetic field component ac $f > 1$Hz measured along the satellite spin axis.

One of the typical electron energization events observed by Freja is presented on the upper panel of Figure 1. We can identify two main electron populations. One is an inverted-V population with energies above 1 keV. It is seen in a broad pitch-angle range ($\alpha < 90^0$) and clearly has a magnetospheric origin. The second population forms the Dispersive Electron Burst (DEB) with an energy falling from few keV down to a few tens of eV. This dispersion in energy is mainly due to a "time of flight" effect: if acceleration occurs somewhere above the satellite, the more energetic electrons will first hit the spacecraft and the less energetic will follow later. An estimation of the distance between the satellite and the acceleration source gives values in the range of 1,000 to 10,000 km. The observed distribution functions (Figure 2) are almost field aligned ($\alpha < 20^0$) in pitch-angle and are close to a plateau or a weak "bump in tail" distribution. Through a beam-plasma instability they may excite Langmuir waves which would quasilinearly thermalize the beam [12]. On the other hand the perpendicular temperature of this population is about several eV and remains constant. This suggests the ionospheric origin of the accelerated electrons which are accelerated either above the spacecraft or locally when there is no dispersion in energy.

DEBs carry relatively strong currents of several tens of μA/m^2. The associated paralell energy flux (Figure 1, middle panel) is usually about several mW/m^2 and sometimes reaches up to 20 mW/m^2. This is above the threshold of 1 mW/m^2 at which visible auroral arcs could be produced.

Simultaneously with DEBs an electromagnetic turbulence is observed with δE up to 500 mV/m , δB up to 50 nT and density variations about several tens of percent. By study the ratio $\delta E/\delta B$, which for DAW have following form

$$\left|\frac{\delta E_\perp}{\delta B_\perp}\right| = v_A\sqrt{(1+k_\perp^2\lambda_e^2)(1+k_\perp^2\rho_i^2)}, \tag{2}$$

it has been possible to identify low frequency electromagnetic turbulence as a spatial turbulence of DAWs [13] which is Doppler-shifted by the fast motion of the spacecraft (7 km/sec) across the magnetic field lines.

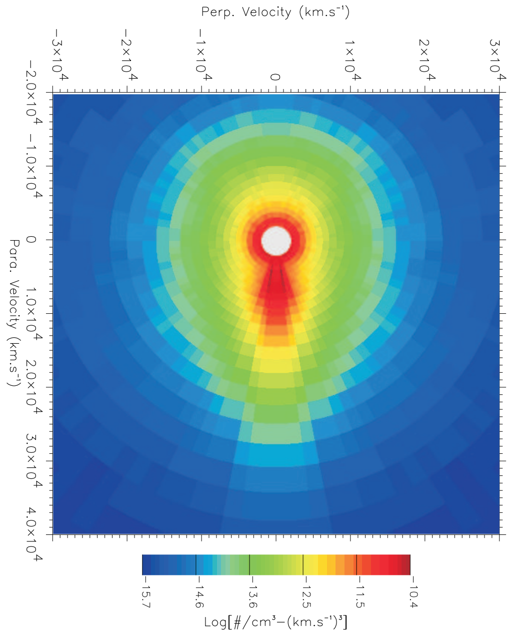

FIG. 2. Electron distribution function observed by Freja orbit 7279 on April 10, 1994 01:38:13 - 01:38:14.5.

III. ROCKET OBSERVATIONS (AT2)

The Auroral Turbulence 2 (AT2) rocked was launched on February 11, 1997 from Poker Flat, Alaska. The rocket had three separated payloads (Main, North and East). Each payload was carrying a fluxgate magnetometer, a double probe electric field instrument and a particle detector. The AT2 reached an apogee of about 500 km. Just before apogee, AT2 crossed an intense auroral arc with a small relative velocity of 0.3 km/sec transverse to the arc.

An electron acceleration event similar to the one described in the previous section was observed by AT2 at the edge of the arc (see Figure 1 in [14,15]). Payloads separated by 3 km observe an Alfvénic activity at 0.5 Hz with electric and magnetic field oscillations almost in phase. On the other hand the detection of the envelope of these oscillations was clearly shifted in time between the payloads. This means the payloads were crossing a spatially localized region of temporal oscillations. The estimated width of the region was about 4 km which is much larger than the electron inertial length $\lambda_e \approx 160$ m. Field aligned dispersive electron precipitations were observed simultaneously on all payloads and appear to be in phase with Alfvénic fluctuations.

IV. SUMMARY AND DISCUSSION

We presented two complementary data sets from two different altitudes. Freja observations show that the main part of the turbulence seen in the range 1-500 Hz is due to a Doppler-shifted Alfvénic turbulence of spatial character (large Δk). Dispersive electron bursts are observed simultaneously with this turbulence and have a quasiperiodical character. Multipoint measurements of AT2 provide a complementary view of the same phenomenon without the strong Doppler-shift effect. Spatially separated slowly moving payloads directly identify spatially localized Alfvénic oscillations and simultaneous dispersive electron precipitations on scales similar to those seen on Freja. The time of existence of these structures is much larger than the wave period of 2 sec.

Both satellite and rocket observations show temporal variations of electron fluxes and spatial localization of Alfvénic structures. It means that purely temporal or spatial models should be disregarded and therefore a spatio-temporal model should be suggested. Alfvén waves form almost field aligned structures which are localized in the perpendicular direction and carry oscillating paralell electric fields. Homogeneous in the paralell direction, Alfvén waves may accelerate electrons through Landau resonance. But this will accelerate particles with a velocity close to the phase velocity of the wave and therefore cannot account for the observed acceleration of cold background electrons. The acceleration of these electrons might be explained if one considers the inhomogeneity of the ionospheric density distribution. From the polarisation relation for inertial Alfvén waves

$$\left|E_{\parallel}\right| = \mu_0 \omega \lambda_e^2 \left|J_{\parallel}\right| \tag{3}$$

one can see that if λ_e decreases (when the density increases) with constant $J_{\parallel}$ then $E_{\parallel}$ will also decrease. As the density of the ionospheric plasma dramatically increases below 4,000-2,000 km of altitude, Alfvénic structures at low altitudes will have significantly smaller $E_{\parallel}$ than at high altitudes. Thus the sharp density gradient will introduce a boundary for the acceleration region of these electrons. Depending on the distance to this boundary one might observe two different electron distibution signatures. One like the burst appearing at 9-10 sec on Figure 1 when all the energies from 1 keV down to 50 eV are present simultaneously. This represents a measurement very close to or inside the acceleration region. The second type of signatures appears at 5-8 sec on Figure 1 or on Figure 1 of Ref. [14]. It exhibits a "time of flight" energy dispersion, indicating a measurement which is done below the alcceleration region. This interpretation is supported by the fact that "time of flight" dispersive signatures are almost always seen by rockets (below 1000 km), only occasionnaly by Freja (between 1300 and 1800 km) and almost never at higher altitudes by FAST.

In conclusion the observed ULF waves are interpreted as an oscillating Alfvénic turbulence which is confined into a quasistationary spatial region localized in the direction normal to the magnetic field. Region of parallel elecric field of Alfvénic structures responsible for elecron acceleration is limited by the ionospheric density gradient. Multiple point observations of dispersive electron bursts show their clear relation to this Alfvénic turbulence. The quasiperiodical nature of these dispersive electron precipitations is related to the temporal oscillation of the parallel electric field of the dispersive Alfvén wave. The existence of the field itself is closely connected to the spatial localization of the Alfvénic structures and to the presence of a sharp density gradient in the ionospheric plasma.

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