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ULF ACTIVITY IN THE AURORAL OVAL AS OBSERVED BY THE MICROSATELLITE ASTRID-2 AND THE GREENLAND CHAIN

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Abstract. Composition of ULF observations along the Greenland magnetometer chain and measurements of electromagnetic fields in the upper ionosphere on-board microsatellite Astrid-2 gives possibility to study the coupling between auroral arc, auroral electrojet and electromagnetic disturbances of different spatio-temporal scales. Spectral analysis of electromagnetic bursts with the MEM technique reveals the spectral power enhancements at frequencies ~few Hz, corresponding to spatial scales ~few km. The possible mechanism of the frequency-dependent enhancement of electromagnetic noise may arise during the resonant conversion of ULF disturbances into dispersive Alfven waves.

Introduction

The localized electromagnetic bursts observed by low-orbiting satellites at auroral latitudes could be used as simple indicators of field-aligned currents (FAC) [*Gary et al.,* 1998]. However, the physical nature of these bursts must be clearly identified for a reliable application. So far, most studies were devoted to the analysis of intense events detected by satellites, especially in the cusp and night auroral region [*Chaston et al.,* 1999]. Here we consider typical features of electromagnetic bursts observed during the satellite pass through FAC systems with moderate intensity in the morning/dusk sector. In this study we use the high sensitivity measurements of electric and magnetic fields made with the EMMA instrument onboard the Astrid-2 micro-satellite [*Marklund et al.,* 2001].

Auroral Electrojet and Pc5 waves: image on ground and in space

In virtually every pass of Astrid-2 through the auroral oval in dawn and dusk hours, even with weak auroral and magnetic signatures, bursts of wide-band noise are observed in both electric and magnetic components. We have analyzed more than 20 events during February-March 1999, when moderate magnetic activity is observed at the Greenland array. As a typical example, we consider the ascending orbit of Astrid-2 for Feb. 14, 1999 (DOY=045). Its geomagnetic projection on the ionosphere passes over Greenland west coast array around 1115 UT.

At Greenland magnetometer array the intensification of westward auroral electrojet (AEJ) is observed, producing maximal H-component disturbance ~300 nT around 10 UT at station SKT (geomagnetic latitude 72.0^0). The intensification of westward AEJ is accompanied by an enhancement of ULF activity in the Pc5 band (central frequency ~ 3 mHz) with amplitudes up to few tens of nT. The localization and dynamics of AEJ and Pc5 ULF activity are both displayed in Fig. 1. The distribution of the ionospheric east-west current, reconstructed from ground H and Z magnetic data using the technique [*Popov et al.,* 2001], shows that in the interval 0930-1130 UT the westward AEJ is centered at CGM latitude ~ 72^0. On the same plot in Fig. 1 the spatial-temporal distribution of ULF total power in the band 2-8 mHz is shown by contour lines. As can be seen from this plot, ULF intensity is closely coupled with the AEJ: the ULF spectral power reaches maximum at the same latitude and evolves in time in a similar way as the AEJ.

When Astrid-2 crosses at ~1114 UT the probable latitude of AEJ an electromagnetic burst is detected by onboard magnetometer and electric sensor. Most evidently the burst can be seen in electric (E1) component. Variations of the magnetic field (B1 component) have been spline-interpolated and then differentiated to derive an estimate of FAC. The resultant FAC and high-pass filtered (cut-off frequency 0.1 Hz) components are shown in Fig. 2. The burst occurrence coincides spatially with the peak of FAC intensity, ~ 2μA/m^2, at ~11:13:50 UT.

Even visual inspection of detrended data reveals quasi-periodic variations of electric (especially evident in E1, ~30 mV/m) and magnetic (B2, ~15 nT) components. However, with common spectral analysis it is hard to identify the actual frequencies of a burst, because the data are contaminated with the despun interference in the same frequency band. Using the dynamic spectrogram based on the maximum entropy method (MEM), which provides a better resolution for short impulsive signals as compared with standard FFT, it was possible to differentiate spectral peaks caused by spin-related interference and burst. The MEM spectrogram reveals the presence of quasi-periodic component with f ~3.5 Hz immersed into the electromagnetic burst. The assumption that the response at this frequency corresponds to spatial variations of electromagnetic field gives the relevant scale ~2 km.

For the identification of the physical nature of electromagnetic burst the method of an apparent impedance has been used. For orthogonal components, E2 and B1, the relevant impedance *U(f)* is shown in Fig. 3. The obtained *U*(*f*) turns out to be frequency-dependent, increasing from ~1580 km/s at *f*~ 0.1 Hz to ~3160 km/s at *f* ~5 Hz.

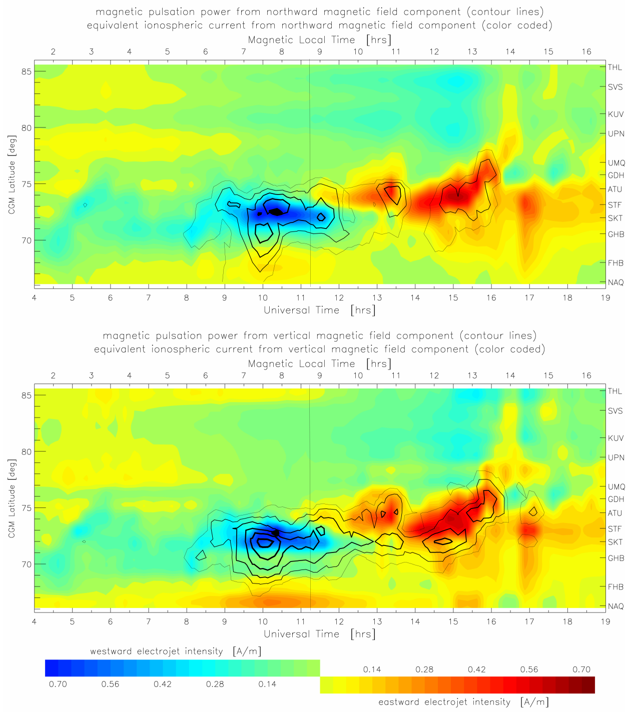

Fig.1. The distribution of the ionospheric east-west current, reconstructed from the ground H (upper panel) and Z (middle panel) magnetic data and the spatial-temporal distribution of ULF total power in the band 1-10 mHz (contour lines). The moment of the Astrid-2 crossing the magnetometer network is shown with thin vertical lines.

Small-scale Periodic Structure of Electromagnetic Bursts: Possible Physical Mechanism

Localized electromagnetic disturbances in the upper ionosphere can be manifestations of small-scale Alfvenic structures. In non-ideal MHD there are two competing effects leading to transverse dispersion of small-scale ($k_\perp^2 \gg k_{||}^2$) dispersive Alfven wave (DAW) [*Lysak*, 1998; *Strelsov and Lotko,* 1999]: (a) electron inertia, characterized by the electron plasma skin length λ_e, and (b) finite Larmor radius of ions ρ_S. In summary, the significance of dispersive effects may be characterized by the characteristic dispersive radius ρ_d [*Leonovich and Mazur*, 1989], $\rho_d^2 = \lambda_e^2 + \rho_S^2$, comprising both effects.

Transverse scales detected by Astrid-2, ~few km, are an order of magnitude larger than typical dispersive radius. Al low altitudes $\rho_d \sim \lambda_e$ is very small, less 100 m, and it will produce during observations at satellite moving across the spatial structure with velocity V_0 a response at $f \sim \lambda_e/V_o > 70$ Hz!? However, even the seemingly discrepancy between this estimate and Astrid-2 observations does not exclude DAW from possible mechanisms.

Ground-based observations evidence that the AEJ, being the ionospheric projection of the auroral region, at the same time, is the region with a highest Pc5 wave activity. Thus, the MHD wave energy, pumped from remote parts of the magnetosphere, is accumulated and eventually absorbed in a magnetic shell at auroral latitude. The absorption may be accompanied by a partial conversion of large-scale MHD disturbances into small-scale DAWs. It is essential, that the actual transverse scale of these "secondary" DAWs is to be determined not by ρ_d, but by other parameter.

The typical spatial transverse scale δ of the ULF wave structure in a resonant region is controlled by a dominant dissipation mechanism of Alfven wave in the magnetospheric Alfven resonator (MAR). A pumping of wave energy into the resonant region causes the growth of amplitude and narrowing of δ. In the steady state this growth is terminated at some level, determined by the quality factor Q_A of MAR. Parameters of MAR can be estimated via the damping rate γ, as $Q_A \sim (2\gamma/\omega)^{-1}$ and $\delta \sim (\gamma/\omega)L$, where *L* is the typical scale of Alfven frequency spatial variations. Diminishing of the transverse scale and the amplitude growth in the Alfven resonance region may be saturated either due to the ionospheric dissipation or to the energy leakage from the resonant region caused by the transverse dispersion. The ionospheric Joule dissipation is essential for the fundamental field-aligned Pc5 mode, but for harmonics dispersive mechanisms may come into play.

Transverse Spatial Structure of Localized DAW

We consider DAW, described by the wave equation for the potential $A=A_z$ [*Hasegawa and Chen*, 1976]

$$\frac{\partial^2 A}{V_A^2 \partial t^2} - \frac{\partial^2 A}{\partial z^2} + \rho_d^2 \nabla_\perp^2 \frac{\partial^2 A}{\partial z^2} = 0$$

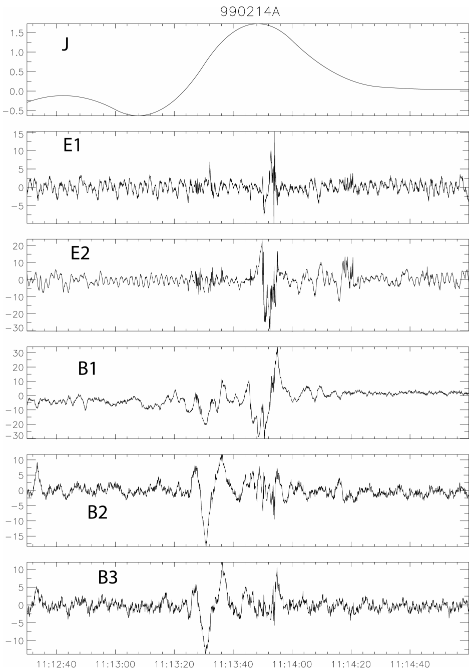

Fig.2. The estimated FAC and high-pass filtered (cut-off frequency 0.1 Hz) components of electromagnetic burst in GEI coordinate system recorded by Astrid-2 on 14.02.99, 11:13:40-11:14:18 UT. 2-rd and 3-rd panels are electric components (E1, E2), three lower panels - magnetic components (B1, B2, B3).

During its derivation it was assumed that the transverse gradient of the wave field is large, $\nabla_\perp \gg \partial_z$.When $\rho_d \to 0$ this equation reduces to local dispersion relation for Alfven wave $\omega_A = k_\| V_A$. In the vicinity of resonant point *x=0* the radial profile of Alfven velocity can be approximated as a linear function with the typical scale *L*:

$$V_A^{-2}(x) \simeq V_A^{-2}(0)\left(1 + x/L\right)$$

Then, this equation transforms into the following

$$\rho_d^2\left(\frac{\partial^2}{\partial x^2} - \frac{x}{L}\right)A = 0$$

Exact solution of this equation can be obtained via Airy functions [*Chen and Hasegawa,* 1974]. However, an estimate of typical scale of the solution behavior near the resonant point can be obtained even with a simple scaling, as follows $\Delta \simeq \left(\rho_d^2 L\right)^{1/3} = \rho_d \left(L/\rho_d\right)^{1/3}$. Thus, the actual scale of the quasi-periodic KAW resonantly excited in MAR is determined not by ρ_d, as often assumed, but by a larger value, Δ. Thus, in a dispersive MAR the typical scale of resonant oscillations in saturation state and quality factor are

$$\Delta = \left(L\rho_d^2\right)^{1/3} \qquad Q_A = \left(L/\rho_d\right)^{2/3}$$

Actual influence of dispersive effects is determined by the integrated over the field-aligned wave structure parameter $<\rho_d>$. At small altitudes, R<2 R_E, its reasonable estimate is $<\rho_d> \sim <\lambda e> \sim 0.5$ km. Assuming that *L*~10-400 km, we obtain that the expected scales of DAW are Δ~1.4-5.8 km, which are to be detected by a low-orbiting satellite with $V_0 \sim 7$ km/s as a burst at frequency *f* ~1.2-5.0 Hz.

Identification of Disturbance Physical Nature from Multi-Component in-situ Observations

The modified apparent impedance, or impedance velocity (ratio between orthogonal electric $E_\perp$ and magnetic $B_\perp$ components) can be used to identify the physical nature of disturbances:

$$U = \frac{Z}{\mu_o} = \frac{E_\perp}{B_\perp}$$

For quasi-steady 1-dim FAC sheet the amplitude part of impedance is $U(\omega,k) = V_P = \left(\mu_o \Sigma_P\right)^{-1}$ is ionospheric Pedersen velocity. For travelling shear Alfven wave with $E_\| = 0$ the apparent impedance is $U(\omega,k) = V_A$. For standing shear Alfven wave in the MAR *U* depends on altitude z, and varies in the range $V_P \le |U| \le V_A(V_A/V_P)$. The characteristic feature of impedance is that it does not depend on spatial scale of disturbance. Hence, during satellite observations the experimentally observed values *U*(*f*) should be frequency independent. In DAW the electron inertia and FLR dispersion increase the value of an apparent impedance making the waves more "electrostatic" as compared with shear Alfven wave [*Stasiewicz and Potemra,* 1998]

$$U(\omega,k)=V_A\sqrt{(1+k_\perp^2\lambda_e^2)(1+k_\perp^2\rho_s^2)}$$

The U must grow beginning from scales $k_\perp\rho_d\sim o(1)$. Parameter $k_\perp\rho_d$ for DAW generated by a conversion process can be estimated as $k_\perp\rho_d\sim 2\pi(L/\rho_d)^{-1/3}\sim 2\pi/(2.7-9.3)\sim 0.7-2.3$. Therefore, $U(f)$ should be frequency-dependent, that is grows with f starting from critical $f^*\sim kV_O/2\pi=\frac{V_O}{2\pi\rho_d}(k_\perp\rho_d)$. As has been observed by Astrid-2 (Fig.3), beginning from $f>f^*$ ~few Hz, the impedance $U(f)$ indeed becomes frequency-dependent and grows with frequency. The observed $U(f)$ growing dependence is in accordance with the suggestion of *Stasiewicz & Potemra* [1998] that DAWs determine the spatial structure of electromagnetic turbulence down to scales ~30 m.

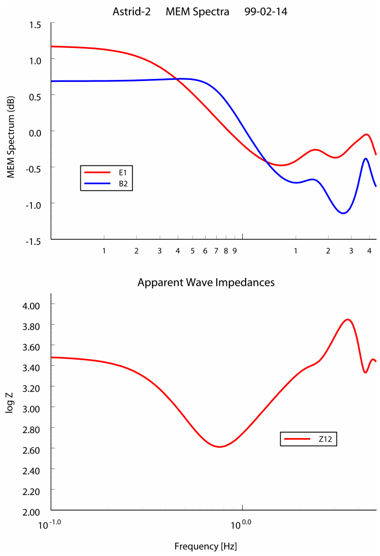

Fig.3. MEM spectra of two electric and magnetic components (upper plot) and the apparent impedance, derived from two orthogonal components, E2 and B1).

Conclusions

We analyzed electromagnetic observations made onboard Astrid-2 over the Greenland array during periods of intense westward AEJ and ULF activity in the morning sector. Modeling of the ionospheric east-west currents from the ground magnetometer data shows that Pc5 activity tends to be localized in the same latitudinal range as AEJ. In virtually every pass of Astrid-2 through a gradient of geomagnetic field, indicating FAC occurrence, burst of wide-band noise is observed in both electric and magnetic components. These FAC and AEJ are parts of global magnetosphere-ionosphere current system. In the range 0.01-5 Hz power spectra of bursts have "colored-noise" form, corresponding to fractal hierarchy of spatial scales from few 100 km to few km. MEM spectral analysis of bursts reveals the spectral power enhancements at f~1-4 Hz, which correspond to spatial scales ~ few km.

Apparent wave impedance exhibits a growing frequency dependence, indicating a presence of DAW. The observed electromagnetic pattern can be explained as a result of resonant conversion of MHD disturbances into DAWs at a magnetic shell conjugate to AEJ. Small-scale DAWs are totally screened from the ground by the ionosphere and could be detected on satellite only. The wave activity observed at the ground is a large-scale part of Alfven disturbances driven by an external broad-band source. The whole process may be visualized as a breaking of large-scale MHD wave approaching magnetic "shore" into small-scale electromagnetic "splashes".

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