

# Electromagnetic waves and bursty electron acceleration: Implications from Freja

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**Abstract.** Dispersive Alfvén wave activity is identified in four dayside auroral oval events measured by the Freja satellite. The events are characterised by ion injection, bursty electron precipitation below about 1 keV, transverse ion heating and broadband extremely low frequency (ELF) emissions below the lower hybrid cutoff frequency (a few kHz). The broadband emissions are observed to become more electrostatic towards higher frequencies. Large-scale density depletions/cavities, as determined by the Langmuir probe measurements, and strong electrostatic emissions are often observed simultaneously. A correlation study has been carried out between the E- and B-field fluctuations below 64 Hz (the dc instrument's upper threshold) and the characteristics of the precipitating electrons. This study revealed that the energisation of electrons is indeed related to the broadband ELF emissions and that the electrostatic component plays a predominant role during very active magnetospheric conditions. Furthermore, the effect of the ELF electromagnetic emissions on the larger scale field-aligned current systems has been investigated, and it is found that such an effect cannot be detected. Instead, the Alfvénic activity creates a local region of field-aligned currents. It is suggested that dispersive Alfvén waves set up these local field-aligned current regions and in turn trigger more electrostatic emissions during certain conditions. In these regions ions are transversely heated, and large-scale density depletions/cavities may be created during especially active periods.

## 1 Introduction

An Alfvén wave propagating from the magnetosphere towards the ionosphere will encounter a denser plasma and as a result may change its characteristics. For instance, the Alfvén wave may be reflected (e.g. Haerendel, 1983; Knudsen et al., 1990, 1992), dissipated (e.g. Clark and Seyler, 1999; Goertz, 1984), or broken down into other wave modes

(e.g. Seyler et al., 1998). A dispersive Alfvén wave (DAW) (e.g. Lysak and Lotko, 1996; Stasiewicz et al., 2000, and references therein) may therefore enhance both its inertial and kinetic characteristics, and develop a field-aligned electric field in the wave front when it propagates at a small angle to the Earth's magnetic field. These Alfvén waves are therefore often suggested as candidates for auroral zone field-aligned electron acceleration process.

The low frequency part of the broadband extremely low frequency (ELF) emissions observed by spacecraft in the auroral zone is often considered to be Alfvénic in nature, with perpendicular wavelengths of the order of the electron inertial length ( $\lambda_e$ ) (e.g. Chmyrev et al., 1989; Louarn et al., 1994; Wahlund et al., 1994; Seyler et al., 1995), and to be associated with field-aligned electron bursts at suprathermal energies (Boehm et al., 1990; Knudsen and Wahlund, 1998; Wahlund et al., 1998; Chaston et al., 1999). This wave activity is also connected with transverse heating of ions (Knudsen and Wahlund, 1998; Knudsen et al., 1998) and might cause large-scale density depletions.

The field-aligned currents into and out from the ionosphere are often described as being closed within the ionosphere. The conductivity in the ionosphere is in this scenario connected to the strength of the field-aligned current and hence the particle acceleration. When a widespread region of DAW activity exists, this scenario will change to a local region of very strongly fluctuating field-aligned currents of several 100  $\mu\text{A}/\text{m}^2$  with a rather weak contribution to the overall large-scale current systems.

The Freja mission is dedicated to observe the space plasma environment in polar regions with an orbit altitude of 900-1700 km. In this paper we apply the formalism of the concept of DAW (e.g. Lysak and Lotko, 1996) to the ELF electric and magnetic field emissions measured by the Freja spacecraft in order to show that these measurements are consistent with such a model. Other observed parameters, such as those associated with field-aligned electron bursts, transverse ion heating, field-aligned current systems and the appearance of large-scale plasma density depletions/cavities, are discussed

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in terms of a DAW model. In sections one and two the characteristics of four Freja passages through the dayside auroral region are presented and discussed. In section three a detailed study of the ELF emissions below 64 Hz is presented and discussed in terms of a DAW model. In section four the expected field-aligned electric fields and propagation angles are derived from the electric and magnetic field measurements under the assumption that they are produced by dispersive Alfvén waves. In addition, the DAW associated field-aligned currents are investigated with regard to the effect on field-aligned current systems. A correlation study between the electric and magnetic ELF fields and field-aligned electron burst characteristics is described, and finally we make some concluding remarks regarding the overall interpretation of the observed processes in terms of wave-particle interactions caused by dispersive Alfvén waves.

## 2 The Freja instrumentation and orbit characteristics

The Swedish/German satellite Freja passes the northern auroral region at an altitude of about 1700 km and at an inclination of 63°. It is a sun-pointing spacecraft with a spin period of 6 seconds. Detailed information about the Freja experiments can be found in a special Freja issue of *Space Science Reviews* (see Boehm et al., 1994; Eliasson et al., 1994; Holback et al., 1994; Marklund et al., 1994). Relevant experimental information for this study is discussed where necessary.

## 3 General characteristics of the four Freja auroral oval crossings

Data are presented from four Freja satellite passages through the dayside auroral region during ion injection events. For convenience these orbits are referred to as *I*, *II*, *III*, and *IV*, respectively, corresponding to actual orbits 5200 (November 3, 1993), 5265 (November 8, 1993), 5292 (November 10, 1993), and 6653 (February 21, 1994). A short description of the general observational characteristics is given here, and more detailed information regarding these particular data can be found in (Andersson et al., 2000).

Figure 1 displays the overview of particle and wave data from all four orbits, and Figure 2 shows the corresponding energy densities as well as the dc electric and magnetic field waveforms. The three first orbits occurred during moderately active conditions ( $K_p \sim 2-3$ ), while orbit *IV* occurred during very active conditions ( $K_p \sim 6$ ).

### 3.1 Ion injection and heating

All four orbits are characterised by clear ion injections with energies from 500 eV up to the TICS instrument threshold of 4.3 keV (Figure 1, panel b). The downward proton energy flux (Figure 2, panel a) is calculated by integrating over all TICS energies from 50 eV to 4.3 keV and over pitch angles between 0° and 90°. The time resolution of this calculated

ion energy flux is 400 ms. Occasionally these fluxes are somewhat spin modulated due to limitations in pitch-angle coverage. Downward ion energy fluxes of 0.01–1 mW/m<sup>2</sup> exist during the observed ion injections. The ion injections are accompanied by bursty electron precipitation, transverse ion heating as well as broadband ELF emissions up to the lower hybrid cutoff frequency (Figure 1). Large-scale density depletions, as measured by the Langmuir probe, are only detected during the most active orbit, *IV* (Figure 1, panel 6). Intense transverse ion heating (mainly O<sup>+</sup>) is only encountered in orbit *IV*, for which it reaches energies of up to ~400 eV, while the ion heating during the other three orbits reaches at most ~50 eV.

### 3.2 Electron precipitation characteristics

The electron bursts have downward energy fluxes (calculated from pitch angles 0°–90°) of the order of 0.01–10 mW/m<sup>2</sup> (Figure 2, panels b and c), with the most intense events encountered in orbit *IV*. Panel b contains TESP data in the lower energy range, 12–50 eV, which corresponds roughly to energies below the local Alfvén velocity ( $v_A$ ). Panel c includes almost the full energy range of the TESP instrument (36 eV–25 keV). The time resolution of the electron measurements is 62.5 ms.

The most field-aligned electron precipitation can also be found in orbit *IV* (Figure 2, panel d; red line denotes 0° pitch angle, green 45° and black 90°). In all four orbits the flux in 45° and 90° pitch angle is equal but during the bursts of electrons the 0° pitch angle fluxes are much higher. In orbits *II* and *III* bursts appear more sporadically, while in orbit *IV* the electron bursts occur more frequently in time.

### 3.3 Cold plasma characteristics

A set of spherical Langmuir probes samples continuously the current from the plasma at a fixed positive bias voltage. This current is proportional to  $n_e/\sqrt{T_e}$ , where  $n_e$  and  $T_e$  are the electron density and temperature. Usually the variation of the electron temperature is small and slow and the Langmuir probe current variation is assumed to be due solely to plasma density variations. When possible, we have used the narrowband HF Langmuir emissions near the plasma frequency,  $\omega_{pe}$ , as well as the intermittent Langmuir probe bias voltage sweeps to confirm that the sampled probe current is mainly due to the variations in  $n_e$ , even though a variation in  $T_e$  may account for a current decrease by up to a factor of 2 during active periods.

The regularly measured probe sweeps are seen as shaded grey areas in Figure 2 (panel e). In Table 1 measurements from the analysed probe sweeps, such as the plasma temperatures ( $T_i$ ,  $T_e$ ) and the temperature ratios ( $T_i/T_e$ ), are presented together with some useful calculated plasma characteristics. As mentioned above, the ion heating is weak during orbits *II* and *III*, somewhat stronger in orbit *I* and intense in orbit *IV*. It should be noted that it is the whole bulk ion population that is heated, not just the energetic tail of the ion

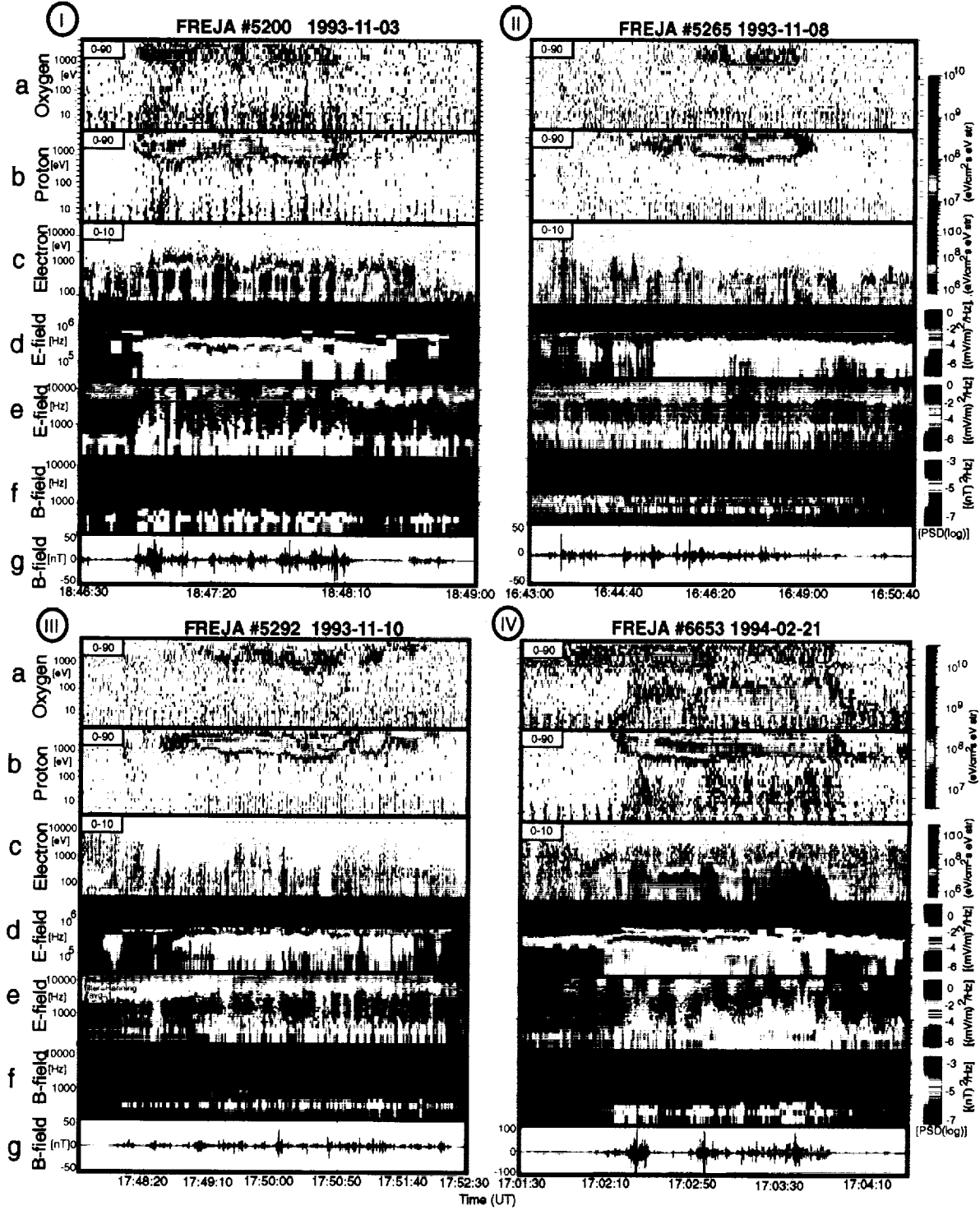


Fig. 1. Overview data from four Freja satellite passes of the northern dayside auroral region. The panels display from the top;  $O^+$  (TICS),  $H^+$  (TICS), field-aligned downgoing electrons (TESP), HF electric wave component (F4), MF electric and magnetic wave components (F4), and the ac magnetic field (F2) respectively.

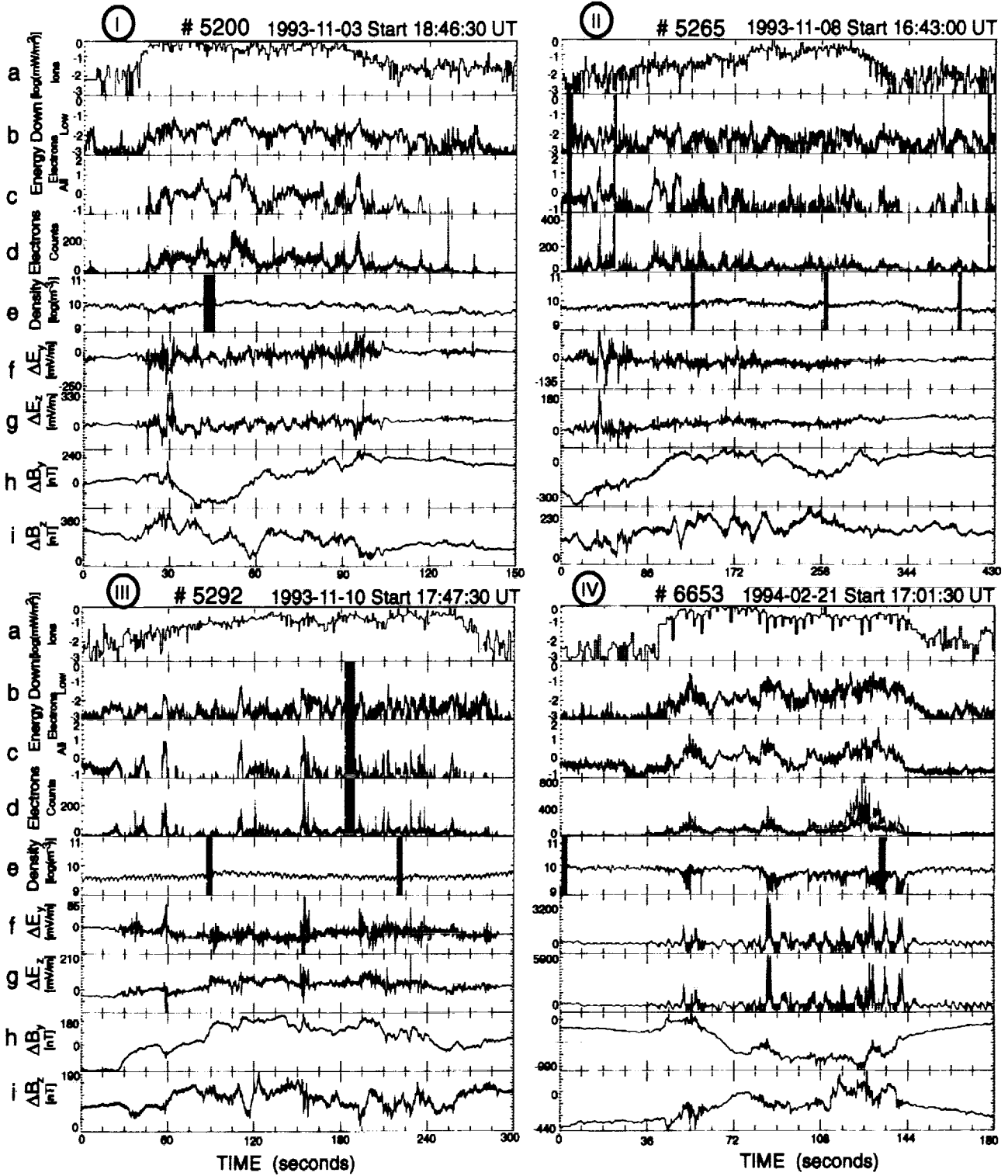


Fig. 2. Data from the same four Freja satellite passes as shown in Figure 1. The panels show from the top; proton (50 eV–4.3 keV), electron (12–50 eV) and electron (36 eV–25 keV) downward energy fluxes ( $\text{mW/m}^2$ ); the total electron counts for three different pitch angles ( $0^\circ$  red,  $45^\circ$  green and  $90^\circ$  black); the Langmuir probe measured density; the dc electric and magnetic fields perpendicular to the model magnetic field lines.

distribution.

During orbit *IV*, several density drops (Figure 2, panel e) are observed simultaneously with ion injection (panel a) and high electron count rates in the field-aligned direction as compared to count rates at other pitch angles (panel d). The three largest density drops (hereafter referred to as cavities) are centred around +55, +90 and +135 seconds into the plot. The highest electron count rates (120–130 seconds) have their main contribution from the lowest energies, below 50 eV. The electric field fluctuations (panels f and g) during orbit *IV* have extreme amplitudes ( $>3$  V/m!), especially within the cavity regions.

### 3.4 Electromagnetic fields and wave characteristics

It is clearly seen from Figure 1 (panels e and f) that the broadband ELF emissions can reach frequencies above 1 kHz and in some cases up to 6 kHz, which is close to the lower hybrid cutoff. It can also be seen that the emissions become increasingly electrostatic towards higher frequencies, while the magnetic component becomes dominant at the lowest frequencies (see panels f and g, for ac magnetic field measurements). See Wahlund et al. (1998) for further details regarding the broadband ELF emissions. This study concentrates more on the lower frequency, more electromagnetic part, of the ELF spectrum and its relationship to electron bursts, day-side ion injections and density depletions.

The dc electric and magnetic field instruments were operated somewhat differently during the four selected orbits. The dc electric field measurements normally make use of two orthogonally positioned spherical probe pairs on 10.5 m long wire booms in the spin plane (i.e. 21 m between spheres). However, during orbit *IV* one of the probe pairs was operated in a current collection mode allowing for  $\delta n/n$  interferometry measurements, and as a consequence only one probe pair measures the dc electric field on this orbit. This explains why the electric field on orbit *IV* (Figure 2, panels f and g) is spin modulated. The sampling rates for orbits *I*, *II* and *III* are 768 samples/s for the dc electric field, and 128 samples/s for the dc magnetic field. On orbit *IV* the dc electric field was sampled at 1536 samples/s and the dc magnetic field at 256 samples/s.

The dc electric and magnetic field measurements have been de-spun and are presented in a coordinate system for which the x-axis is along a model magnetic field line, positive y points towards west, and positive z points towards the equator. The Freja satellite measures the electric field in the spin plane of the spacecraft and therefore only gives a 2-dimensional estimate of the total electric field. We therefore assume that the magnetic field-aligned component ( $E_z$ ) is zero. The assumption should be good since the field-aligned electric field component of a dispersive Alfvén wave is theoretically much smaller than the perpendicular electric field component.

The field fluctuations (Figure 2, panels e to f) are of extremely large amplitude during orbit *IV*. When the downward ion energy flux is close to 1 mW/m<sup>2</sup> the magnetic field

data show a large gradient, the electron distribution is isotropic with a loss cone, there is no density gradient, and the dc electric field shows just a spin modulation about zero. On orbit *III* downward bursts of electrons are correlated with sharp changes of the magnetic field.

## 4 Detailed study of the ELF emissions below 64 Hz

The time series of the dc electric and magnetic field measurements were analysed by an overlapping sliding window Fast Fourier Transform (FFT) analysis (Figure 3, panels a–e). In order to cover all frequencies below 64 Hz, four different time windows were selected (15, 6, 1, and 0.3 s corresponding to lowest non-dc frequencies of 0.133, 0.333, 2 and 7.1 Hz respectively). Each time window was weighted with a Hamming filter. The longer time windows are then used at the lower frequencies, while the shorter time windows are used at the higher frequencies in Figure 3 (panels a–e). The wave spectrograms presented in Figure 3 have the same apparent time resolution as the electron data (TESP, 62.5 ms). This analysis corresponds very much to a wavelet analysis, although it is FFT-based.

### 4.1 Poynting flux

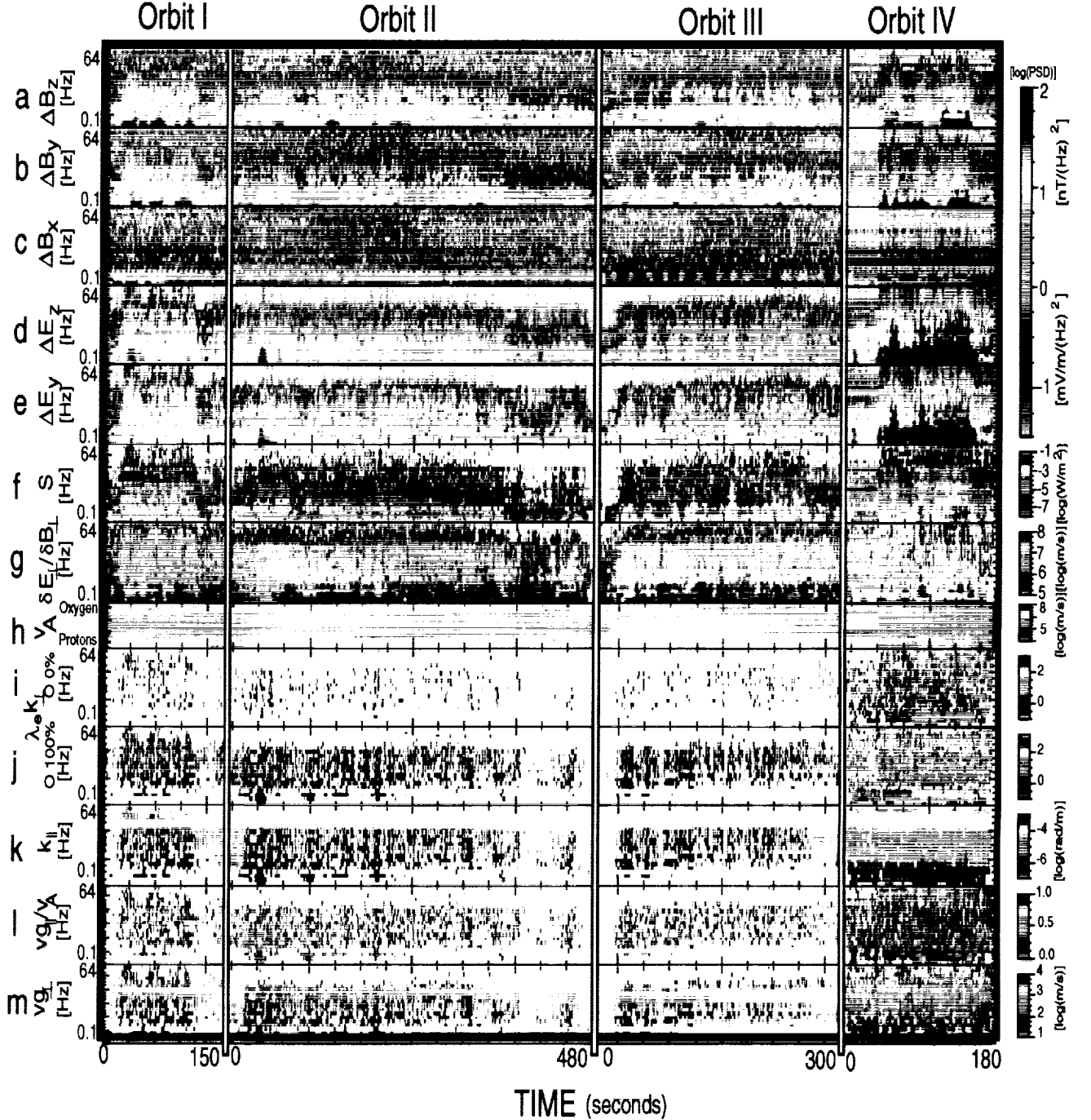
The wave energy per unit time and area is represented by the spectral Poynting flux ( $S(f) = 1/\mu_0 E(f) \times B(f)$ ) in Figure 3 (panel f). The Poynting flux along the Earth's magnetic field is calculated from the wave data represented in panels a through e by

$$S_z = \text{Re} \left[ \frac{1}{\mu_0} (E_y \cdot B_z - E_z \cdot B_y) \right] \quad (1)$$

for each frequency component. It should be noted that the direction and magnitude of the total Poynting flux when integrated over frequency will depend on the frequency window used and their significance is unclear when treating broadband plasma wave emissions with several possible non-linear wave modes involved. We do not present the direction of the spectral Poynting flux because it shows very complex small scale variations, more suitable for detailed event studies on the time scale of seconds, and is therefore left for a future paper. Here we just note that the spectral Poynting flux is highest at the lowest frequencies, and correlates well with the downward electron energy flux (Figure 2, panels b–d).

### 4.2 The Alfvén velocity and the $\delta E_{\perp}/\delta B_{\perp}$ -ratio

Panels g and h in Figure 3 display as function of time the ratio between the electric and magnetic field fluctuations ( $\delta E_{\perp}/\delta B_{\perp}$ ) and the local Alfvén velocity ( $v_A$ ). The local Alfvén velocity ( $v_A = B_0/\sqrt{\mu_0 m_i n_i}$ ) is calculated for four different ion compositions (using a H<sup>+</sup> and O<sup>+</sup> mixture with 100%, 88%, 47%, 0% H<sup>+</sup> composition) and is based on the plasma density estimated from the Langmuir probe measurements.



**Fig. 3.** More detailed ELF wave characteristics for the four orbits presented in Figure 1. Panels from the top are respectively; a–e) the power spectral densities (PSDs) for the three magnetic field components and the two perpendicular electric field components; f) the magnitude of the Poynting flux ( $S$ ); g)  $\delta E_z / \delta B_z$ ; h) the Alfvén speed ( $v_A$ ) for four different plasma compositions; i–j) the value of  $\lambda_e k_\perp$  for a pure oxygen and a pure hydrogen plasma respectively; k) the parallel wave vector ( $k_{||}$ ); l) the parallel group velocity of inertial Alfvén waves as fraction of the local Alfvén speed; m) the perpendicular group velocity of inertial Alfvén waves. See the text for more details.

Table 1. Values from the probe sweeps

ORBIT	I	II	II	II	III	III	IV	IV
$N_{O^+}/N_{i,tot}$	0.85	0.95	0.95	1.0	0.8	0.9	0.9	0.95
$T_e$ [eV]	0.8	0.7	0.7	0.6	0.5	0.6	0.5	2.5
$T_i$ [eV]	0.5	0.1	0.1	0.2	0.1	0.1	0.1	15
$N_e$ [cm <sup>-3</sup> ]	6100	5000	5000	4200	3000	2500	5000	4000
$T_i/T_e$	0.63	0.14	0.14	0.33	0.33	0.17	0.2	6
$B_0$ [nT]	29400	29900	29700	29500	29500	29400	30600	30800
$\rho_{O^+}$ [m]	9.8	4.3	4.4	6.2	4.4	4.4	4.2	51.4
$\lambda_e$ [m]	68	75	75	82	97	106	75	84
$v_A$ [10 <sup>6</sup> m/s]	2.1	2.3	2.3	2.5	2.9	3.2	2.4	2.7
CGLAT [°]	74.5	73.4	73.8	74.2	73.5	73.8	67.3	70.5
H [km]	1730	1660	1700	1720	1710	1725	1537	1570
UT	18:47:10	16:45:05	16:47:25	16:49:45	17:49:00	17:51:50	17:01:30	17:03:40

Data in the top five rows originate from evaluation of the probe sweeps. The values in the middle four rows are calculated using the assumption of a 100% oxygen plasma. The last three rows show the locations and times of the spacecraft during the probe sweeps.

At the lowest displayed frequencies the ratio  $\delta E_{\perp}/\delta B_{\perp}$  is lower than  $v_A$  during the three first moderately active orbits (I, II and III). This suggests that dc-like field-aligned current systems dominate the magnetic field fluctuations below about 0.5 Hz. Between 0.5–7 Hz the  $\delta E_{\perp}/\delta B_{\perp}$ -ratio increases to a more stable plateau value somewhat above the local Alfvén velocity for a pure oxygen plasma. The drop at the highest displayed frequencies is probably an instrumental artifact; it might be that the magnetic emissions reach the noise level of the fluxgate magnetometer.

During orbit IV the whole displayed frequency interval attains  $\delta E_{\perp}/\delta B_{\perp}$ -ratios in excess of the local Alfvén velocity for all possible H<sup>+</sup>–O<sup>+</sup> compositions. The ELF emissions are therefore more electrostatic than expected for a classical Alfvén wave, and inertial and/or kinetic effects are probably important. The large values at the lowest frequencies below 0.5 Hz may just be an effect of that only one probe pair was used for electric field measurements.

#### 4.3 Dispersive Alfvén Waves (DAW)

The term DAW is a general description covering inertial Alfvén waves (IAW, Goertz and Boswell (1979)) applicable in a plasma with  $v_{th,e}(=\sqrt{k_B T_e/m_e}) < v_A$  and  $\beta(=2\mu_0 n_e k_B T_e/B_0^2) < m_e/m_i$ , and kinetic Alfvén waves (KAW, Stefant (1970); Hasegawa (1976)), applicable in a plasma with  $v_{th,e} > v_A$  and  $\beta > m_e/m_i$ . The concept originates from a development by Lysak and Lotko (1996), and is described in more detail in a review article by Stasiewicz et al. (2000). The dispersive properties of DAWs become important when the perpendicular wavelength becomes comparable to the ion gyroradius ( $\rho_i$ ) or the electron skin depth ( $\lambda_e$ ), i.e. when the quantities  $k_{\perp}\rho_i$  and/or  $k_{\perp}\lambda_e$  become comparable to or larger than 1. When this happens parallel electric fields develop, which in turn can accelerate electrons.

The dispersion relation for a low frequency DAW ( $\omega < \omega_{ci}$ ) propagating in a cold electron ( $v_{th,e} < v_A$ ) low  $\beta$  plasma

can be described

$$\omega^2 = k_{\parallel}^2 v_A^2 \frac{(1 + k_{\perp}^2 \rho_i^2)}{(1 + k_{\perp}^2 \lambda_e^2)} \quad (2)$$

and the group velocity becomes

$$\frac{\partial \omega}{\partial \mathbf{k}} = \hat{\mathbf{x}} \frac{v_A}{(1 + k_{\perp}^2 \lambda_e^2)^{1/2}} - \hat{\mathbf{y}} \omega \lambda_e \frac{k_{\perp} \lambda_e}{1 + k_{\perp}^2 \lambda_e^2} \quad (3)$$

Solving the dispersion relation in this cold electron limit gives a ratio of

$$\left| \frac{E_{\perp}}{B_{\perp}} \right| = v_A \sqrt{(1 + k_{\perp}^2 \lambda_e^2)(1 + k_{\perp}^2 \rho_i^2)} \quad (4)$$

and the relationship between the field-aligned and the perpendicular electric field becomes

$$\frac{E_{\parallel}}{E_{\perp}} = \frac{k_{\parallel} k_{\perp} \lambda_e^2}{1 + k_{\perp}^2 \lambda_e^2} \quad (5)$$

These relationships do not take into account several possible non-linear effects that can for example, steepen the wave-front of a DAW, breaking the wave into higher frequency components, and enhancing the parallel electric field further (e.g. Seyler et al., 1995; Seyler and Wahlund, 1996).

#### 4.4 Inertial term and $k_{\perp}$

The perpendicular wave vector ( $k_{\perp}$ ) can be estimated from the Alfvén speed ( $v_A$ ) and the ratio  $\delta E_{\perp}/\delta B_{\perp}$  (equation 4). From Table 1,  $\rho_i^2 \ll \lambda_e^2$ , which is a good approximation except possibly during the active periods on orbit IV. The value of  $k_{\perp}\lambda_e$  is presented in Figure 3 (panels i and j) for pure hydrogen and oxygen plasmas respectively. It should be noted that only points which satisfy  $\delta E_{\perp}/\delta B_{\perp} > v_A$  for a pure oxygen plasma are kept in panels i through m, and values below  $v_A$  are white in those graphs (equation 4).

The value of  $k_{\perp}\lambda_e$  increases significantly above zero when enhanced broadband electric field emissions appear (panels d and e), and values up to  $k_{\perp}\lambda_e \sim 1$ –2 can be detected during

orbit *IV*. This correspond to perpendicular wavelengths of around 250–500 m in the case of orbit *IV* and values in excess of that for the other three orbits.

The maximum possible Doppler shift (broadening) of the perpendicular wave vector (wave fields) due to the motion of the satellite is estimated to be  $k_{\perp} v_{sc} \sim 10\text{--}20$  Hz for orbits *I*, *II* and *III* and 100–200 Hz for orbit *IV*. Thus the enhanced ELF wave emissions which occur during orbit *IV* may be heavily Doppler broadened (shifted) depending on the exact  $k$ -vector distribution.

#### 4.5 Group velocity and $k_{\parallel}$

From knowledge of  $k_{\perp}$ , several other characteristics can be estimated; among them the perpendicular and the parallel group velocities (panels l and m) as well as the parallel wave vector (panel k). These parameters are estimated assuming a pure oxygen plasma and by using  $k_{\perp}$  calculated from panel j. While  $k_{\perp}$  is independent of frequency, except for frequencies above about 40 Hz during active parts of orbit *IV*,  $k_{\parallel}$  will depend on frequency throughout the DAW dispersion relation. The parallel wavelengths as estimated in this way are in the range of 100–1000 km.

The parallel group velocity is close to the Alfvén speed during orbits *I*, *II* and *III*, while during orbit *IV* the parallel group velocity becomes a fraction of the Alfvén speed, which is simply a consequence of the dispersion relation and the larger inertial terms. The perpendicular group velocity remains mostly below 1 km/s, at least at the lower frequencies.

### 5 Parallel electric fields

The parallel electric field associated with a DAW can be calculated in various ways. We shall adopt three methods and compare the results; one method makes use of the magnetic field measurements, the other two are calculated based on the perpendicular electric field and the above estimated wave vectors.

The first method (Figure 4, panel a) is based on the estimated field-aligned current from the magnetic field measurements ( $\delta B_{\perp}$ ) along the satellite path ( $\delta x = v_{sc} \delta t$ ) through the approximate relationship

$$\delta j_{\parallel} = \frac{\delta B_{\perp}}{\mu_0 \lambda_{\perp}} \approx \frac{\delta B_{\perp}}{\mu_0 \delta x} \quad (6)$$

The total field-aligned current fluctuations for orbit *IV* are displayed in Figure 5 (panel c). However, for the calculation at hand,  $\delta j_{\parallel}$  will be treated as frequency dependent through the magnetic field fluctuations. Subsequently the parallel electric field is calculated from the polarisation relation for inertial Alfvén waves (DAW with cold electrons) as

$$|\delta E_{\parallel}(f)| = \mu_0 2\pi f \lambda_e^2 |\delta j_{\parallel}(f)| \quad (7)$$

The second method (Figure 4, panel b) is calculated from

the estimated perpendicular electric field ( $\delta E_{\perp}$ ) and the propagation angle of the DAW through

$$|\delta E_{\parallel}(f)| = \theta \epsilon |\delta E_{\perp}(f)| \quad (8)$$

The propagation angle of the DAW can be found from  $\tan \theta = k_{\parallel}/k_{\perp}$ , and is usually very small ( $\theta < \epsilon = \sqrt{m_e/m_i}$ ). When a DAW propagates at larger angles,  $\theta > \epsilon$ , it is known as a slow ion-acoustic (SIA) wave (Seyler and Wahlund, 1996; Seyler et al., 1998; Wahlund et al., 1998; Stasiewicz et al., 2000). The angle of propagation (Figure 4, panel d) is small for low frequencies. Above the local gyrofrequency for  $O^+$  (near 30 Hz on orbit *IV*) the propagation angle reaches  $\epsilon$ , consistent with the proposition that SIA emissions start to dominate the ELF emission characteristics (Wahlund et al., 1998). The  $\delta E_{\perp}/\delta B_{\perp}$  ratio for a SIA wave should approach  $10^8 - 10^9$  m/s, which is also consistent with the observed values presented here (Figure 3, panel g).

The third method (Figure 4, panel c) of estimating  $\delta E_{\parallel}$  is based on equation (5) above. Parallel electric field strengths of up to 0.1–1 mV/m are inferred from methods 2 and 3 (panels b and c) during active times, while significantly lower values are obtained from method 1. This discrepancy is ascribed to the difficulties in estimating a frequency dependent field-aligned current from the magnetic field measurements, i.e. method 1 is considered to be the most unreliable. Also, the increase at the upper frequencies in panel a is just the result of the fact that the fluxgate magnetometer reaches the noise level. In any case, the field-aligned electric field strengths are correlated rather well with the Poynting flux (Figure 3, panel f).

#### 5.1 Effect on DAW induced field-aligned current systems

The total field-aligned current variation is calculated from the fluxgate magnetometer data according to equation 6 and displayed for orbit *IV* in Figure 5 (panel c). Values up to 200  $\mu A/m^2$  are reached. The largest current fluctuations, which are mainly due to the ELF electromagnetic emissions, are detected when the Langmuir probe (panel a) detects plasma density depletions/cavities together with enhanced Poynting fluxes (Figure 3, panel f).

The net integrated current along the satellite path ( $J_{\parallel}$ ) is displayed in panel b. This current gives information on where the large scale current systems are situated. The net integrated current over a cavity is small, as can be most clearly seen near +55 s, +90 s, +135 s, and +155 s; i.e., the effect of DAW activity is small on the overall field-aligned current system. Instead, the Alfvénic activity creates a local region of field-aligned currents through the acceleration of the low energy plasma. Field-aligned electrons move downwards by the parallel electric field and transverse ion heating occurs possibly through intermediate more electrostatic ELF waves. As a result the plasma density drops, which causes the increased perpendicular wave vectors and the inertial and kinetic dissipative effects enhancements. A small net field-aligned current will remain due to the accelerated plasma.



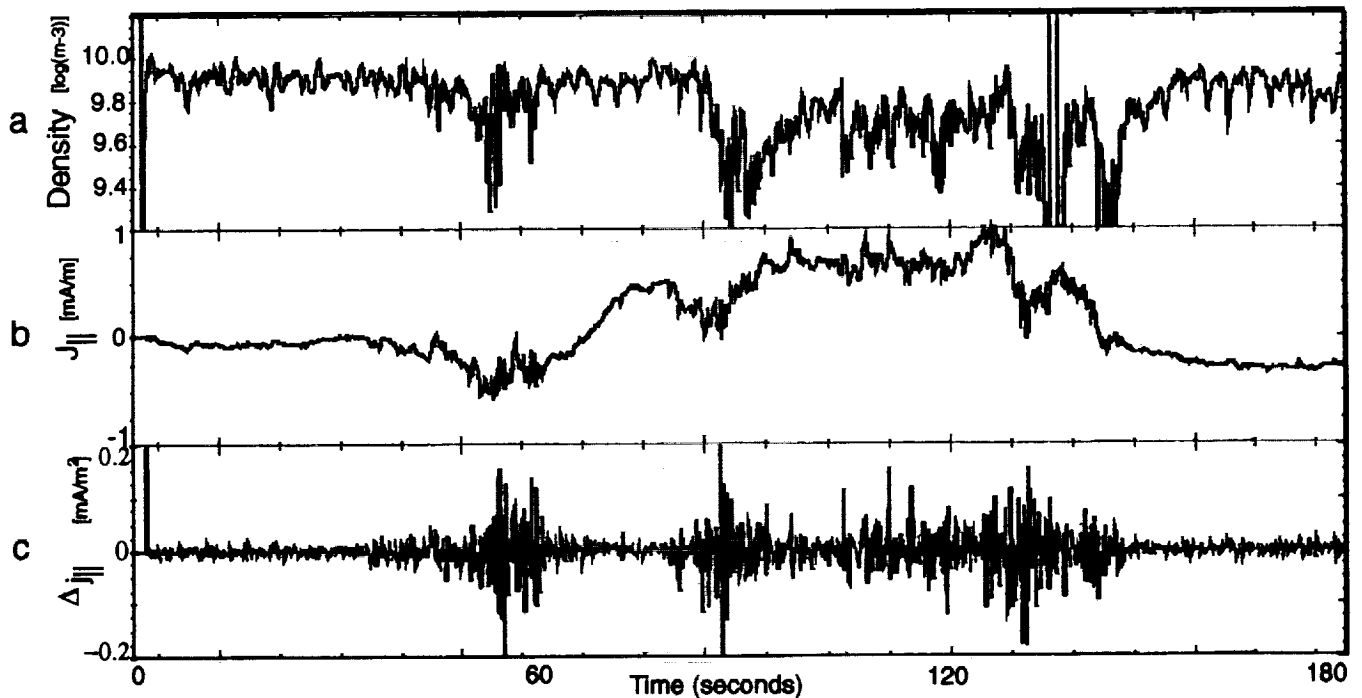


Fig. 4. The field-aligned electric field as calculated by three different methods are presented in the three top panels (see text for further details), together with the estimated propagation angle of a dispersive Alfvén wave (last panel). Parallel electric fields of the order of 0.1–1 mV/m are inferred, which can readily accelerate thermal electrons to energies of several 100 eV within fractions of a second.

A larger integrated current can be found in the time interval 62–82 s (17:02:20 UT–17:02:50 UT), for which only low levels of DAW activity are found, the downward proton energy flux rises to 1 W/m<sup>2</sup> (Figure 1, panel b; Figure 2, panel a) and the precipitating electrons are characterised by an isotropic, smooth, inverted-V-like population (compare with Figure 1, panel c, and Figure 2, panel d). Two DAW active regions are situated at the edges of this region where the precipitating electrons probably give rise to the large integrated current by the constant flux of isotropic electrons. Since the associated field-aligned electric fields in this middle region are probably very small according to commonly used current–voltage relationships (e.g. Knight, 1973), this current, compared to that during strong Alfvén activity, is not easily cancelled out by the cold dense background plasma.

During periods when the ELF wave activity is enhanced without Langmuir probe detection of plasma density cavities, e.g. during the proton injections on orbits *I*, *II*, and *III* (not shown) and during the time period 120–130 seconds on orbit *IV*, there is also almost no net integrated current. This can be interpreted as follows. The Alfvén waves accelerate particles due to the large inertial and kinetic components and by so doing try to create a small current. However, since this occurs in a dense background plasma the current carried by the energetic electrons will quickly be cancelled out.

## 6 Correlation study

The electromagnetic ELF wave characteristics (wave amplitudes and  $\delta E_{\perp}/\delta B_{\perp}$ ) have been correlated with various electron characteristics (energy, spectral shape, downward energy flux) as well as the plasma density for five selected spectral wave emission frequencies between 1–46 Hz. The correlations are based on 16,600 points, i.e. the data presented in Figure 3.

### 6.1 Particle spectral fits

The electron spectral shape is approximated by an exponential fit to the TESP data and characterised by the two parameters  $\gamma$  and  $\beta$  according to

$$f_0(E, \phi) = \gamma(E) \cdot e^{\beta(E)\alpha} \quad (9)$$

where  $\alpha$  represents the pitch angle and  $f_0$  is the measured count rate. The electron spectral fits were carried out for pitch angles 0°, 45° and 90° for which  $\alpha$  was set to 0, 0.1 and 0.2, respectively, for simplicity. The parameter  $\beta$  represents the degree to which the electron population was isotropic,  $\beta \sim 0$ , or field-aligned,  $\beta < 0$  (i.e. spectral shape), and parameter  $\gamma$  is the magnitude of the flux in the field-aligned direction. It is not possible to perform a lag correlation (shift in time) between the field fluctuations and various characteristics of the detected particles due to the fact that low frequen-

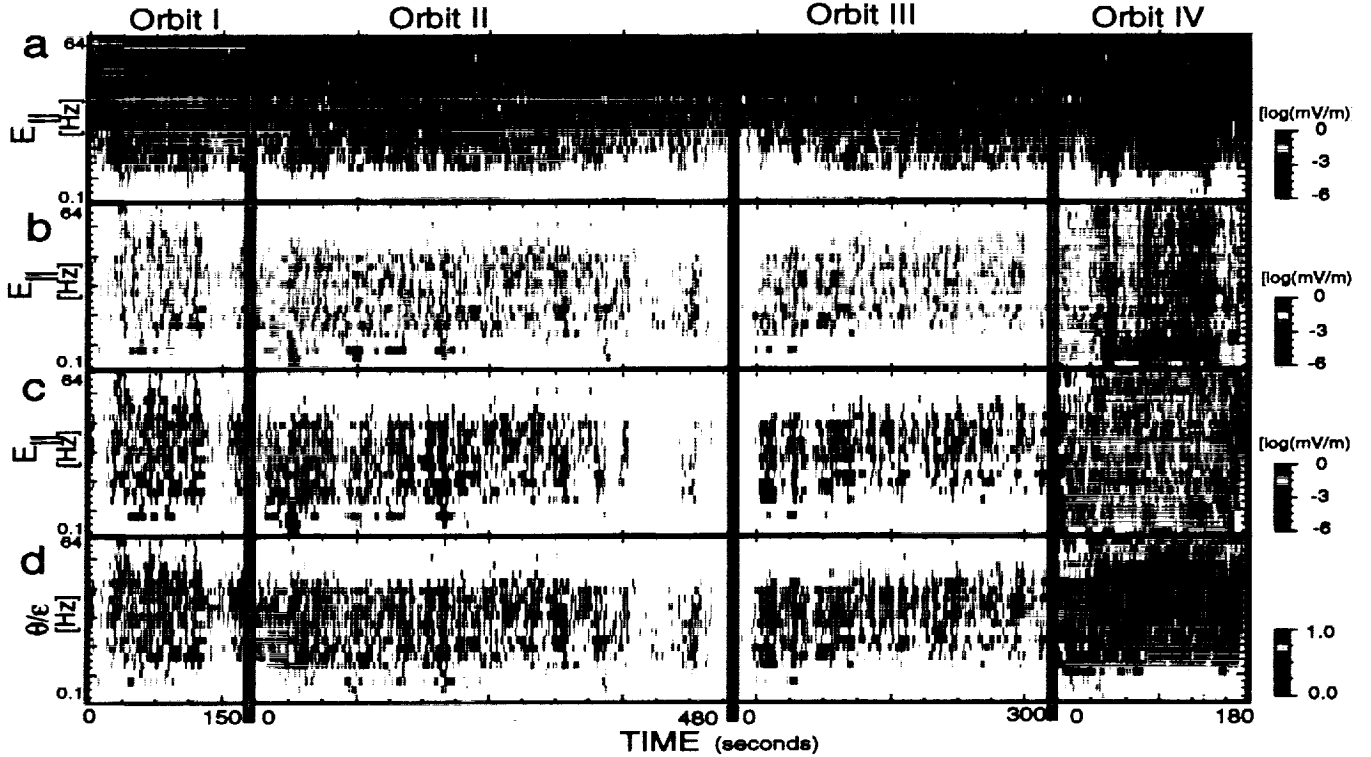


Fig. 5. The plasma density estimated from the Langmuir probe measurements (panel a) together with the estimated field-aligned current density assuming the Freja spacecraft encounters spatial structures (panel c), and the corresponding integrated net current (panel b). Alfvén wave activity results in localised regions with rather small net integrated currents on top larger scale current systems.

cies correspond to large times while the bursts occur during much shorter times.

## 6.2 Panel set A: field-aligned count dependence

The results of the parameter fits for an electron energy of 55 eV are compared with the electromagnetic field parameters (Figure 6, panel set A). Contour lines of constant density of points are drawn in the figure in order to resolve better the statistical shape of the correlation.

Both the electric and magnetic field amplitudes, and consequently the  $\delta E_{\perp}/\delta B_{\perp}$ -ratio, correlate positively with the electron flux counts (parameter  $\gamma$ ), except for the higher frequency channels of the magnetic field fluctuations. From this it follows that the Poynting flux is also correlated with the electron flux (not shown). The decrease in correlation between the field fluctuations at higher frequencies is due to the fact that the fluxgate magnetometer reaches its noise detection level, and the result is thus an artifact.

## 6.3 Panel set B: electron spectral shape dependence

Electron spectral shape values ( $|\beta|$ ) of less than 6 should be regarded as representing isotropic electron spectra, while  $|\beta| > 6$  indicate more field-aligned populations. The more negative the value; the more field-aligned the spectral shape, Figure 6. The more field-aligned electron populations appear

when the electric and magnetic field amplitudes increase. The result is valid for all displayed frequencies.

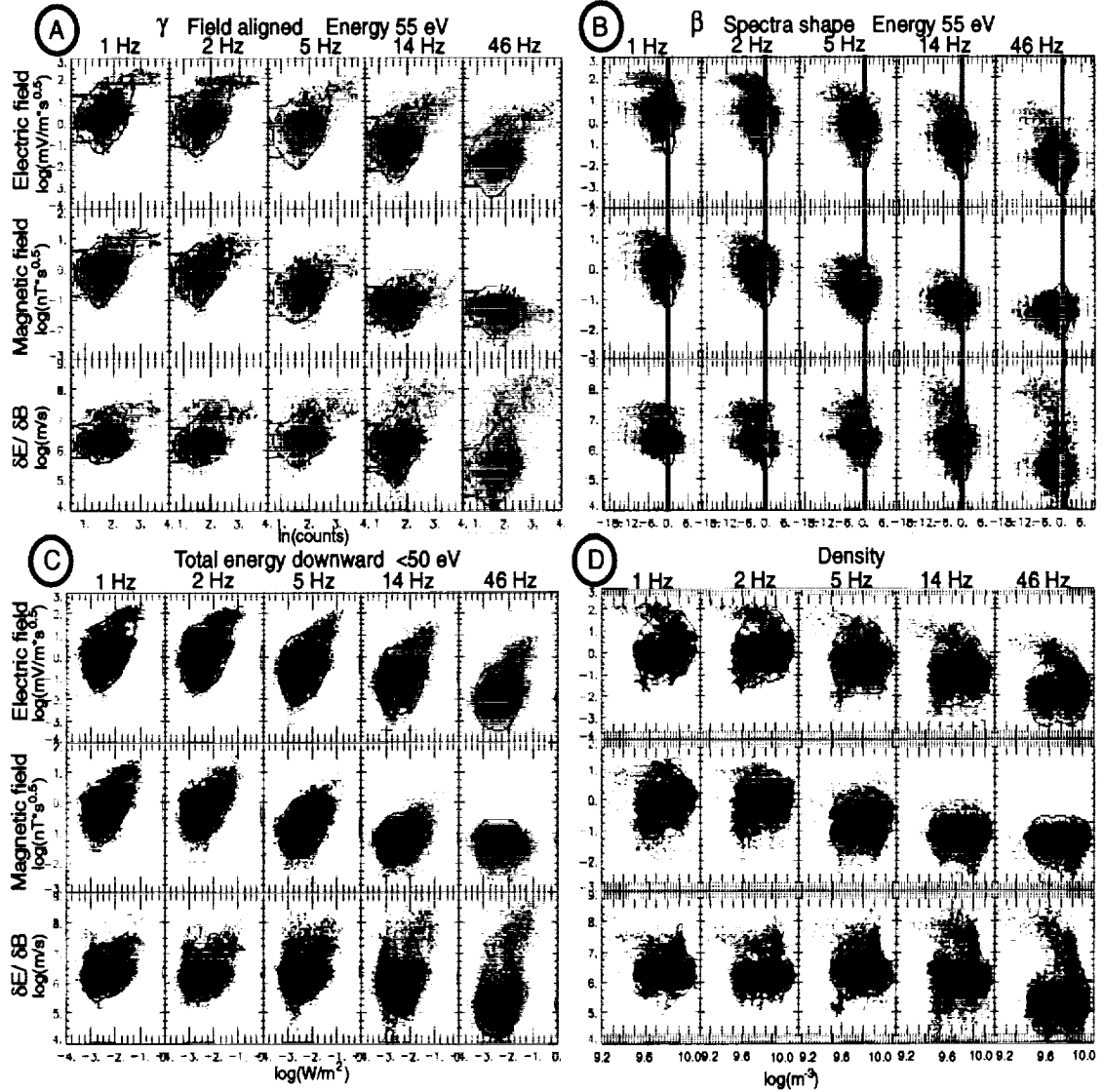
The electron spectra at the low energy of 55 eV show a better correlation with the amplitude of the waves compared to a higher electron energy (not shown). This is not so surprising since the low energy field-aligned electrons are suggested to be accelerated more easily by the Alfvén waves than higher energy electrons (Andersson et al., 2000). Also, the high energy electrons, which are observed with a broad pitch angle distribution (low value of  $\beta$ ), are suggested to arrive before the Alfvén waves themselves.

## 6.4 Panel set C: Electron energy flux dependence

The total downward energy flux within the energy range between  $\sim 20$ –50 eV is correlated with the field characteristics. The result from this correlation follows in much the same way as the correlation with the field-aligned electron count rate at 55 eV, but is better. The contour curves indicate a good correlation between both the electric and magnetic field amplitudes with increased downward energy flux.

## 6.5 Panel set D: Plasma density dependence

The correlations of the plasma density with the field amplitudes show that high plasma densities (i.e. outside cavities) are not well correlated with the electromagnetic wave fields. Within plasma cavities, on the other hand, the electric field



**Fig. 6.** Correlations between various characteristics of the electrons and electromagnetic field fluctuations. Four types of correlations are presented; A-B correlate the field-aligned electron count rate at 55 eV and the electron spectral shape; C correlate the total downward electron energy flux below 50 eV; D correlates the plasma density with the field fluctuations. The field characteristics are represented by the electric, magnetic and  $\delta E_{\perp}/\delta B_{\perp}$  ratio at 5 selected frequencies (1, 2, 5, 14, and 46 Hz).

amplitudes become large. The magnetic field strength hardly correlates with the plasma density at all, indicating that the magnetic fluctuations are not important for the formation of plasma cavities and that it is the more electrostatic component of the ELF wave activity that is related to the cavity formation. Again, since the magnetic fluctuations are below the detection level of the fluxgate magnetometer at the highest frequency channel, the correlation loses its physical meaning at that frequency.

The good correlation between wave activity and low energy field-aligned electron precipitation, and the anti-correlation between wave activity and plasma density, has previously also been reported by Chaston et al. (1999).

## 7 Summary and conclusions

In the four analysed events, wave-particle interactions occurred together with intense downward proton injection. The ion injection can therefore be assumed to be produced by a common process which also creates the Alfvén wave activity, which in turn interacts with electrons through its dispersive induced field-aligned electric field in its wave front. Alternatively an ion injection gives rise to the Alfvén wave activity which can accelerate electrons. A scenario can be visualised in which the ratio  $T_i/T_e$  plays an important role by becoming large so that the Alfvén wave approaches the electrostatic limit and begins to accelerate more and more electrons and at the same time transversely heats the bulk ion population and raises the  $T_i/T_e$  ratio further (Clark and Seyler, 1999). This positive feedback process then increases the effect of the inertial and kinetic terms further, and more energy dissipation can occur and so on.

The Freja mission was in operation during declining solar activity condition. The presence of Alfvén waves is identified when the  $\delta E_{\perp}/\delta B_{\perp}$  ratio becomes equal to or exceeds the local Alfvén velocity. The variations of the plasma density, the Earth's magnetic field strength and the ion composition with geocentric distance cause the Alfvén speed to have a maximum below  $2 R_E$  geocentric distance.

During orbit IV (6653), which is an extreme dayside event recorded by the Freja satellite, the largest plasma temperatures were encountered and density depletions/cavities were found. Also during this orbit, the  $\delta E_{\perp}/\delta B_{\perp}$ -ratio became significantly larger than the local Alfvén speed ( $v_A$ ) at frequencies above the local oxygen gyro frequency (about 30 Hz). Furthermore, the largest perpendicular wave vector was found at these larger frequencies, and the wave characteristics became more electrostatic with increasing frequency. The data were therefore consistent with an interpretation in terms of dispersive Alfvén waves Lysak and Lotko (1996), which attain slow ion acoustic characteristics at larger frequencies (e.g. Seyler et al., 1995; Wahlund et al., 1998).

The data presented in this paper support an earlier analysis (Chaston et al., 1999) that strong ELF wave activity, especially in the electrostatic limit, is associated with larger scale plasma density depletions/cavities and at the same time

enhances the low-energy electron fluxes along the geomagnetic field lines. The correlation study presented also gives a good correlation between electromagnetic field fluctuations and the presence of accelerated electrons with energies corresponding to values below the local Alfvén velocity. Intense electrostatic ELF emissions were found to correlate well with the occurrence of density cavities.

During periods of large plasma densities, broadband ELF wave activity and bursty electrons, the integrated field-aligned net currents were zero or very small. When larger scale density depletions/cavities were detected from the Langmuir probe measurements, the integrated field-aligned net currents became more significant although remained rather small. The fluctuating field-aligned current densities, however, are large, reaching several  $100 \mu\text{V/m}$ . The largest integrated field-aligned net currents were detected in association with periods of low or zero ELF wave activity. At those times the fluctuations in the field-aligned current densities were on the contrary very low. A possible explanation of this behaviour is that the more isotropic electron energy distribution occurring during those times carries the current, not really affecting the local plasma, while the large parallel electric fields associated with dispersive Alfvén wave activity interact heavily with the local plasma, which in turn compensates for the fluctuating field-aligned currents induced by the impulsive Alfvén waves. The flux tube associated with a large net current might be closed in the ionosphere, while the dispersive Alfvén induced currents may have a more complex fate.

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