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Poloidal ULF oscillations in the dayside magnetosphere: a Cluster study

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Abstract. Three ULF wave events, all occurring in the dayside magnetopshere during magnetically quiet times, are studied using the Cluster satellites. The multi-point measurements obtained from Cluster are used to determine the azimuthal wave number for the events by means of the phase shift and the azimuthal separation between the satellites. Also, the polarisation of the electric and magnetic fields is examined in a field-aligned coordinate system, which, in turn, gives the mode of the oscillations. The large-inclination orbits of Cluster allow us to examine the phase relationship between the electric and magnetic fields along the field lines. The events studied have large azimuthal wave numbers ($m\sim100$), two of them have eastward propagation and all are in the poloidal mode, consistent with the large wave numbers. We also use particle data from geosynchronous satellites to look for signatures of proton injections, but none of the events show any sign of enhanced proton flux. Thus, the drift-bounce resonance instability seems unlikely to have played any part in the excitation of these pulsations. As for the drift-mirror instability we conclude that it would require an unreasonably high plasma pressure for the instability criterion to be satisfied.

Keywords. Ionosphere (Wave propagation) – Magnetospheric physics (Plasma waves and instabilities; Instruments and techniques)

1 Introduction

Although waves with small azimuthal length scale in the Pc5 frequency range have been studied since the 1930s (Rolf, 1931) there are still open questions regarding their generation mechanism, largely due to insufficient data for a complete picture of both the waves and the particles. ULF waves in the Pc5 frequency range are seldomly observed close to noon MLT in the magnetosphere (Hudson et al., 2004), however, when they appear it is usually during magnetically quiet times.

The usual angle of attack on geomagnetic ULF waves is to solve the MHD equations for a magnetised plasma in a dipole field geometry (e.g. Radoski, 1967). For small azimuthal wavelengths the solution to these equations for the magnetic field is predominantly in the meridional and parallel directions. In the limit when the azimuthal wavelength goes to zero, the eastward magnetic field component also becomes zero. This is usually termed the poloidal mode. The proposed excitation mechanisms for this mode are internal to the magnetosphere and involve unstable particle distributions. Sources external to the magnetosphere (such as solar wind waves) are ruled out because of heavy damping. The reason for this is that transmission between the magnetopause and the resonance position is by means of the fast wave. Consider a box model with the x-axis along the Sun-Earth line (positive earthward); the magnetic field lines are parallel to the z-axis and the y-axis completes the coordinate system. In a small β plasma the local dispersion relation is (Walker 2004):

$$\frac{\omega^2}{V_A^2} - k_x^2 - k_y^2 - k_z^2 = 0, \qquad (1)$$

where ω is the angular frequency of the wave, $k_{x,y,z}$ is the x, y, z component of the wave vector, V_A is the Alfvén speed. We can assume $m=k_y r$, where r is the radial distance and m is the azimuthal wave number. It follows then that if k_y^2 dominates the leading term of Eq. (1), k_x becomes imaginary. The wave is then evanescent everywhere between the magnetopause and the resonance position. Its decay is of the order of $\exp(-\int|k_x|dx)$ with distance from the magnetopause. When k_y is large, no significant energy can reach the resonance position.

During magnetically active times, substorm injection of energetic particles can produce an unstable plasma distribution that via drift-bounce resonance interaction can couple to

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ULF waves. The drift-bounce resonance criterion between the wave and the particles is normally written as

$$\omega - m\Omega_D = N\Omega_B, \quad (2)$$

where Ω_D is the particles' bounce-averaged drift frequency, Ω_B is the bounce frequency of the particles and N is an integer (Southwood et al. 1969). Recently, Glassmeier et al. (1999) generalised Eq. (2) by allowing an asymmetric ionospheric conductivity. In doing so they came to the conclusion that N could take any real value, determined by the physical properties of the system. Oscillations that occur during active times are normally observed in the dusk sector and are termed storm-time pulsations.

Another proposed excitation mechanism is the drift-mirror instability (Chen and Hasegawa, 1991; Walker et al., 1982). It can develop in finite beta plasmas when there is a significant pressure anisotropy, with the instability criterion

$$\frac{P_\perp}{P_\parallel} > 1 + \frac{1}{\beta_\perp}, \quad (3)$$

where $P = Nk_bT$ and $\beta_\perp = 2\mu_0 P_\perp / B^2$ (that is, the perpendicular pressure is larger than the parallel pressure, so particles are "squeezed" from regions of higher magnetic field into regions of lower). In the rest frame of the plasma the mirror instability grows without oscillations (zero real frequency). This instability is a viable excitation mechanism at $L > 8$, where the magnetic field becomes weak enough to allow β to exceed unity during normal conditions.

There are a number of spacecraft observations of large-m ULF pulsations and two reviews of these are given by Anderson (1994) and Takahashi (1988). The majority of these studies were with satellites near the equatorial plane and some utilised multi-spacecraft configurations. One such study was conducted by Takahashi et al. (1985), who investigated the azimuthal wave number of several compressional Pc5 waves. They found m in the range of -40 to -140 by observing the phase difference between two azimuthally spaced satellites. We shall adopt a similar approach in this paper.

2 Instrumentation

Our study uses the EFW (Gustafsson et al., 1997) and the FGM (Balogh et al., 1997) instruments on board the four Cluster spacecraft (e.g. Escoubet et al., 2001). The Cluster spacecraft have an orbital period of 57 h and the nearly polar orbits have a perigee of 4 R_E and an apogee of 19.6 R_E. The orbital planes are fixed in inertial space, so as the Earth progresses around the Sun, apogee will change from local noon in midwinter to midnight in midsummer. The spacecraft constellation forms a tetrahedron, which, in general, is non-regular (i.e. the separation between each pair of satellites is not equal). The EFW (Electric Field and Waves) instrument measures the electric field components in the spin plane of each spacecraft. This plane is close to the ecliptic plane and the two components measured (duskward and sunward) are thus very close to the x and y components in GSE-coordinates. The FGM instrument (Fluxgate Magnetometer) measures the three components of the magnetic field. The Cluster data used have a time resolution corresponding to one spacecraft spin period (4 s). Data from the LANL geosynchronous satellites have been used to monitor possible particle injections. The CPA and SOPA instruments carried on board the satellites measure electron and proton fluxes. The satellites used to monitor injections are (with their longitudinal position in geographical coordinates), 1990−095 (38° W) 1991−080 (166° W) 1994−084 (145° E) LANL−01A (7.9° E) LANL−02A (69° E) LANL−97A (102° E), all of which are in geostationary orbit.

3 Observations and data analysis

This paper focuses on three ULF wave events occurring in the dayside (MLT ∼10–15) magnetosphere in the vicinity of the plasmasphere ($4 \le L \le 6$). This region of space is crossed by Cluster in the period May-September when the spacecraft are close to perigee. For this time period ULF oscillation events have been identified by inspection of the duskward electric field.

A field-aligned coordinate system is needed to determine the relevant polarisation of the oscillations. This system is defined as follows: a 20-min running average is applied to the measured magnetic field. This average is then taken as the background magnetic field and its direction defines the parallel component, $\hat{\boldsymbol{p}}$, in the coordinate system. The other components are then chosen to be $\hat{\boldsymbol{e}} = (\hat{\boldsymbol{p}} \times \boldsymbol{R}) / |\hat{\boldsymbol{p}} \times \boldsymbol{R}|$, where $\boldsymbol{R}$ is the radius vector of the satellite and $\hat{\boldsymbol{r}} = \hat{\boldsymbol{e}} \times \hat{\boldsymbol{p}}$; $\hat{\boldsymbol{e}}$ thus defines the eastward direction and $\hat{\boldsymbol{r}}$ is meridional (radially outward at the magnetic equator). The coordinate system is illustrated in Fig. 1. By plotting the electric and magnetic fields in this coordinate system, the polarisation can be found. This then tells us whether the oscillations are in the toroidal or poloidal mode. For this study, only events which are found to be in the poloidal mode are selected.

The large-inclination orbits of Cluster make it a good platform for studying the physics along the field lines for a ULF pulsation event. In addition, the azimuthal separation of the spacecraft allows us to determine the propagation characteristics of the wave in the azimuthal direction (i.e., the azimuthal wave number, m). This is done by calculating the phase difference between the satellites. A detailed description of the calculations of the azimuthal wave number is given in Eriksson et al. (2005). Figure 2 shows the duskward electric field for s/c 1 and s/c 2 (top panel) and the phase difference between the two (bottom panel). The phase difference at the time when both spacecraft are on the same L-shell is selected and divided by the azimuthal angle separation of the spacecraft in SM-coordinates. This is performed on as many combinations of satellite pairs as possible, to obtain multiple estimates of m. An interesting aspect is how much the frequency of the oscillations is Doppler-shifted due to the motion of the spacecraft. If we assume wave propagation of the form $e^{im\phi - i\omega t}$, the Doppler-shift can be estimated

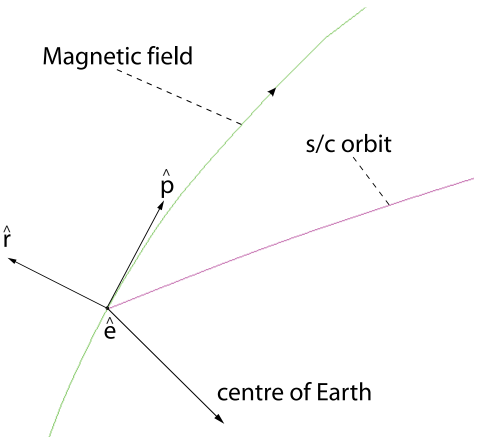

Fig. 1. Schematic illustration of the field-aligned coordinate system used in this study. The green line represents a magnetic field line and the purple line represents the spacecraft orbit. See text for the definition of the coordinate axis.

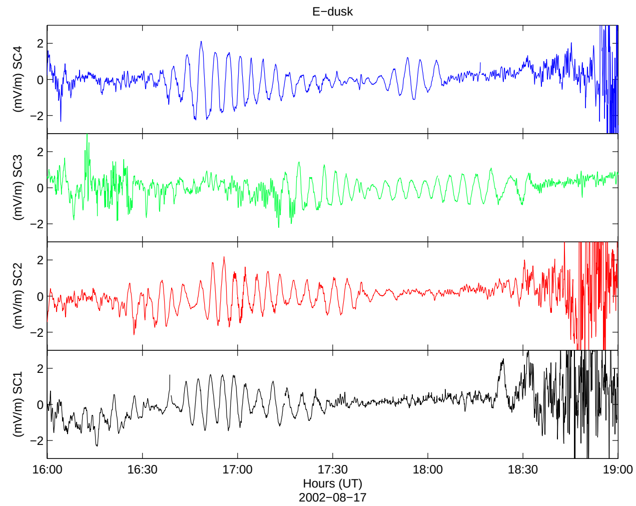

Fig. 3. The duskward electric field for the 17 August 2002 event. The bottom panel is s/c 1 (black), followed by s/c 2 (red), s/c 3 (green) and s/c 4 (blue) at the top.

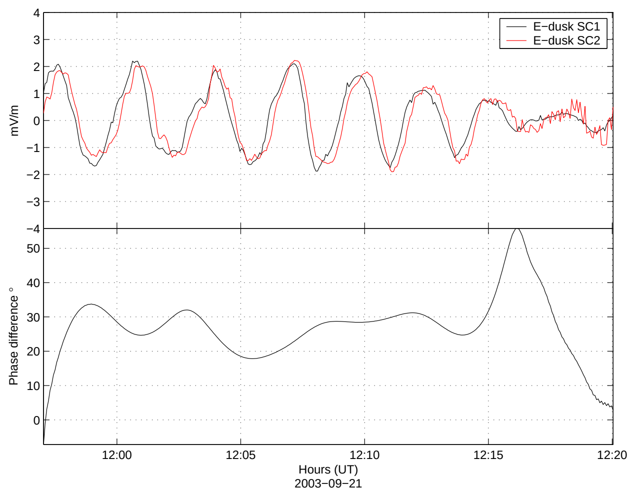

Fig. 2. The top panel shows the duskward electric field for s/c 1 (black line) and s/c 2 (red line), and the bottom panel shows the phase difference between s/c 1 and s/c 2 for the 21 September 2003 event.

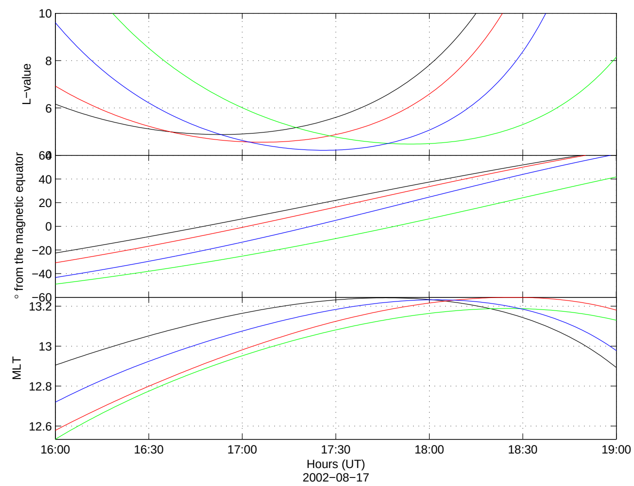

Fig. 4. L-value, polar angle in SM-coordinates and MLT for s/c 1 (black), s/c 2 (red), s/c 3 (green) and s/c 4 (blue) for the 17 August 2002 event.

by $mf_{\rm sat}$ where $f_{\rm sat}$, is the azimuthal orbital frequency of the satellite in SM-coordinates. Of interest is also the phase relationship between the electric and magnetic fields. In this study the phase difference between the $\hat{\boldsymbol{r}}$ component of the magnetic field oscillations and the $\hat{\boldsymbol{e}}$ component of the electric field oscillations has been examined. From this we can deduce if the standing wave is in an asymmetric or a symmetric mode with respect to the wave magnetic field, or if the wave has developed into a quarter wavelength mode due to large asymmetry in ionospheric conductivity.

3.1 17 August 2002

Figure 3 shows the duskward electric field measured by the four spacecraft. The oscillations appear in the data at about 16:40 UT for s/c 1, 2 and 4. For s/c 3 they appear at 17:15 UT, consistent with the fact that s/c 3 is trailing the rest of the satellites, as seen in panel 1 of Fig. 4. This event occurs at about noon MLT. The abrupt onset and end of the oscillations might be related to an abrupt change in plasma density, like a crossing of the plasmapause. As the spacecraft move to smaller L, the amplitude of the oscillations decreases (i.e., the spacecraft are moving away from the resonant L-shell), so that the extent of this event is about 1 R_E in the equatorial plane. Figure 5 shows the fields plotted in our field-aligned coordinate system . The polarisation of the magnetic field in the field-aligned coordinate system shows clear oscillations in the $\hat{\boldsymbol{r}}$ and $\hat{\boldsymbol{p}}$ directions but none in the $\hat{\boldsymbol{e}}$ direction. This indicates that the wave is in the poloidal mode. The estimate of the azimuthal wave number yields m=130±30, so the sense

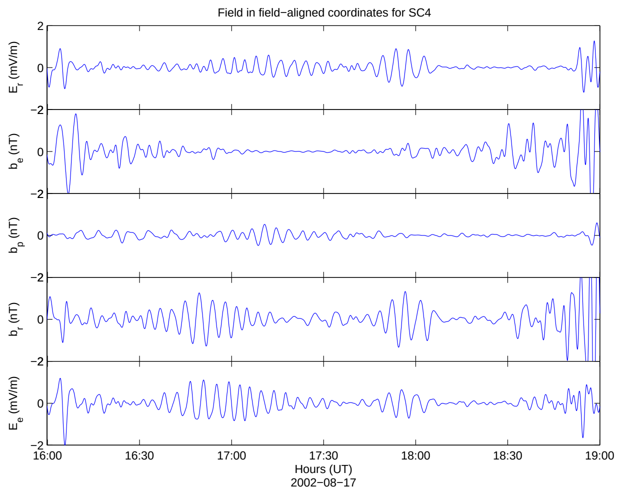

Fig. 5. The electric and magnetic fields in a field-aligned coordinate system for the 17 August 2002 event. The subscript r indicates the meridional, e the eastward and p the field-aligned (parallel) direction.

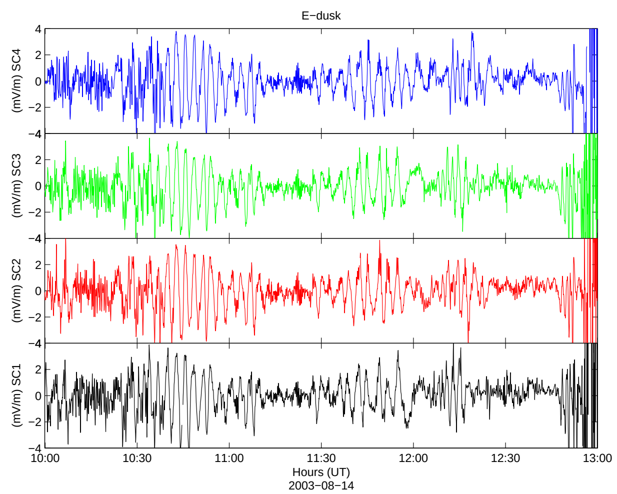

Fig. 6. The duskward electric field for the 14 August 2003 event.

of propagation is eastward for this wave. By inspecting the phase difference between b_r and E_e we find that it is approximately 100° south of the equator and approximately −80° north of it, meaning that there is a 180° phase shift across the equator. So this is an asymmetric (odd) mode with respect to the b_r-component of the wave magnetic field. This event is monochromatic in time and space, with the wave oscillating at 4.2 mHz measured in the satellite frame. Regarding the Doppler-shift, s/c 2 moves about 2.5° from 16:30 UT to 17:00 UT, which means $f_{sat} \approx 4.0 \cdot 10^{-3}$ mHz. For an azimuthal wave number of 100 this would give us a Doppler-shift of 0.4 mHz, an order of magnitude less than the observed frequency for this event. The geomagnetic K_p index is 1+ from 15:00 to 18:00 UT and the interplanetary magnetic field (IMF) B_z has mainly a weak negative component from 15:00 UT to 20:00 UT.

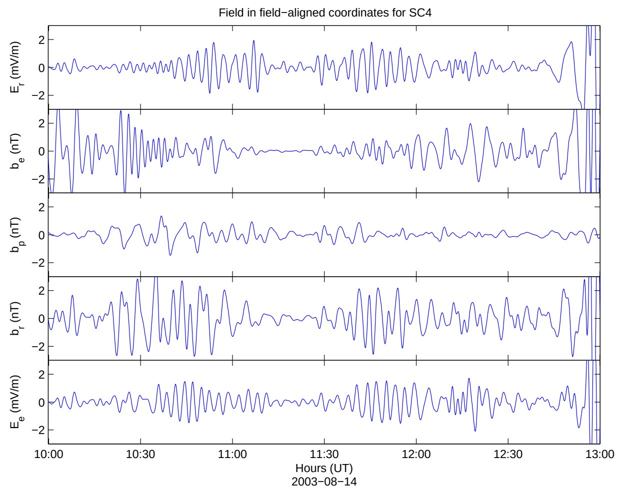

Fig. 7. As Fig. 5 but for the 14 August 2003 event.

3.2 14 August 2003

This event occurs at about 13:30 MLT, when the spacecraft are relatively close to each other, ≤0.1 R_E in L and ≤0.5° in azimuthal separation. Accordingly, the commencements of the oscillations in the duskward electric field are within mins between the satellites, as seen in Fig. 6. For this event the phase difference between the satellites range from 5° to 30°, with fluctuations in the same range. So we cannot make a precise determination of the m-number other than that it is large (∼100). The observed frequency is about 5.8 mHz when the spacecraft are south of the magnetic equator and then decreases to about 5.4 mHz north of it. Since we do not know the azimuthal wave number, this change might be caused by a Doppler-shift in frequency, but it is unlikely since f_{sat} changes approximately from $4.5 \cdot 10^{-3}$ mHz south of the magnetic equator to $6.3 \cdot 10^{-3}$ mHz north of it, meaning that m has to be about 220 to accommodate this change. The magnetic field exhibits the poloidal mode polarisation (i.e. oscillations are in the radial and field-aligned components), as shown in Fig. 7. K_p is 2o from 09:00 UT to 12:00 UT and the IMF B_z is mostly positive from 08:00 UT to about 15:00 UT.

3.3 21 September 2003

The ULF oscillations in the duskward electric field component start at about 11:55 UT on all four satellites (Fig. 8), due to their relative proximity (≤0.1 in L during the event, Fig. 9). At about 12:30 UT, coinciding with the minimum in amplitude in the electric field oscillations, the satellites pass perigee. Pc 3 pulsations are also visible, especially from about 12:50 UT to 13:30 UT. The Pc 5 wave event of interest here occurs at about 11:00 MLT. From the phase difference of the duskward electric field between the satellites, the azimuthal wave number is estimated to be about 90±30, meaning that this is a high m event, with the wave propagating eastward. By inspection of the polarisation of the magnetic

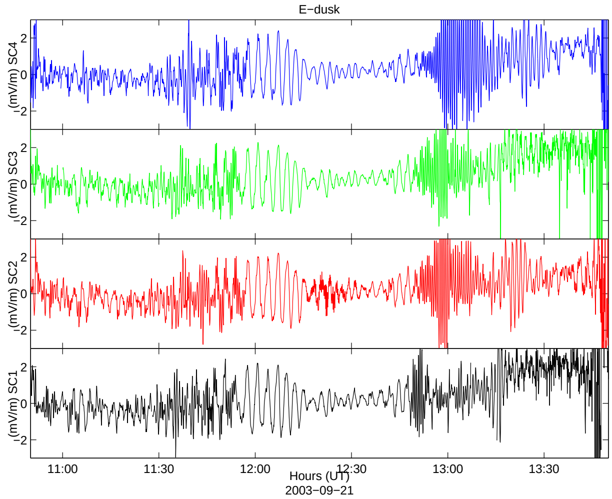

Fig. 8. The duskward electric field for the 21 September 2003 event.

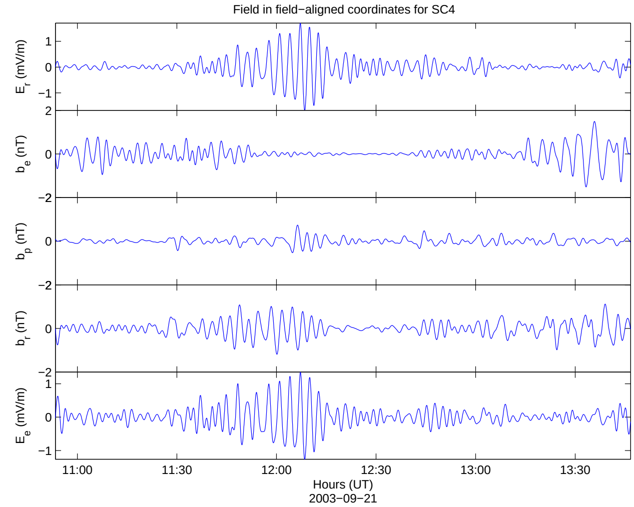

Fig. 10. As Fig. 5 but for the 21 August 2003 event.

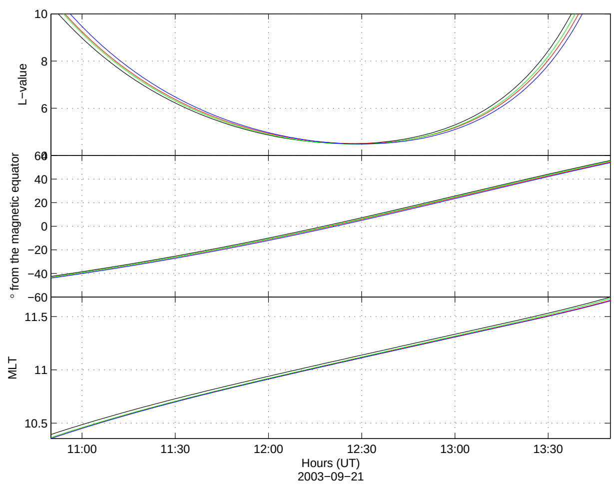

Fig. 9. L-value, polar angle in SM-coordinates and MLT for s/c 1, s/c 2, s/c 3 and s/c 4 for the 21 September 2003 event.

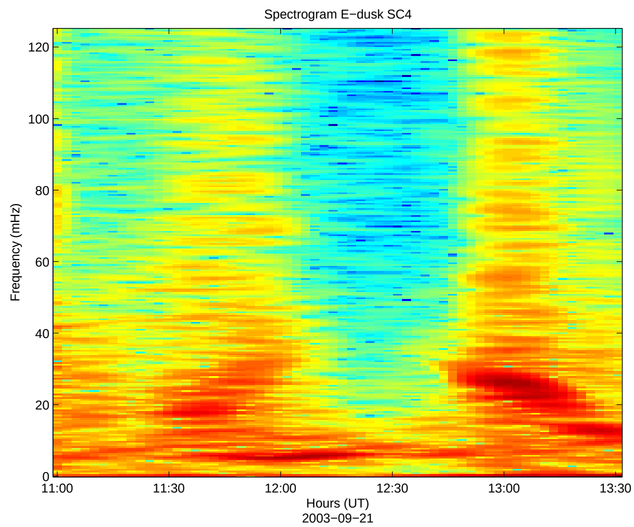

Fig. 11. Spectrogram for the duskward electric field measured by s/c 4 on the 21 September 2003 event.

field in the field-aligned coordinate system, we see that the field is oscillating in the $\hat{\boldsymbol{r}}$ and $\hat{\boldsymbol{p}}$ directions (Fig. 10), whereas no oscillations are found in the $\hat{\boldsymbol{e}}$ direction, indicating that it is the poloidal mode that is excited. Looking at the phase difference between b_r and E_e, we find that its about −90° south of the equator and about 100° north of it, with variations of the order of ±15°. Figure 11 shows a spectrogram for the duskward electric field on s/c 2. Apparent is the increase in frequency from about 4.6 mHz at 11:50 UT to about 6.6 mHz at 12:20 UT. This increase cannot be accounted for by an increase in Doppler-shift, since the angular frequency f_{sat} is more or less constant through the event. The K_p index is 3+ from 09:00 to 12:00 UT and 4o from 12:00 UT to 15:00 UT; the IMF is northward from about 10:00 UT to 12:00 UT when it rapidly changes sign and stays southward for a couple of hours.

4 Results

The high values (∼100) of the azimuthal wave number found in all three events are consistent with the poloidal mode type polarisation of the wave magnetic field. All of the studied events are located within ($4 \leq L \leq 6$). Many authors have studied the eigenfrequencies for geomagnetic ULF pulsations (e.g. Cummings et al., 1969; Schulz, 1996; Takahashi et al., 2004). These studies adopted a power law for the plasma density along a field line:

$$\rho = \rho_{eq} \left(\frac{L R_E}{r} \right)^{\alpha}, \tag{4}$$

where ρ_{eq} is the density at the equator, L is the McIlwain parameter, R_E is the radius of the Earth, r the geocentric distance to a point on the field line and α is the scaling index.

From this model of the density the Wentzel-Kramer-Brillouin (WKB) approximation can be used to calculate the eigenfrequencies. In this approximation the harmonics are multiples of the fundamental frequency which is inversely proportional to $\int \frac{ds}{v_A}$, where s is the coordinate along the field line and v_A is the Alfvén speed. However, the WKB approximation is, in general, only true for α=6. So, in reality, the frequency ratios of the different harmonics are dependent on the variations of the plasma density. This effect can be incorporated by solving the governing wave equations numerically, yielding a numerical approximation for the eigenfrequencies. This was done by Takahashi et al. (2004) for the toroidal mode. Their Table 1 shows the obtained ratio for f_{T2}/f_{T1} and f_{T3}/f_{T1} for integer values of α in the range $-6 \leq \alpha \leq 6$ at L=6.6. They also find that $\alpha \sim 0.5$ at $4 \leq L \leq 6$. The events studied here also occur within $L \leq 6$, so we can use α=1 as an estimate of the distribution of plasma along a field line. For α=1 Takahashi et al. (2004) obtained f_{T3}/f_{T1}=4.09 for the toroidal mode. Cummings et al. (1969) showed that the frequency of the fundamental poloidal mode is lower than for the frequency of the fundamental toroidal mode. Schulz (1996) derived an empirical relation factor between the two fundamental frequencies, given by:

$$\frac{f_{P1}}{f_{T1}} \equiv F_{P1}=0.690 + \left(\frac{0.246}{L}\right). \quad (5)$$

So at L=4 the fundamental poloidal frequency is about 25% lower than the corresponding toroidal frequency (and about 27% at L=6). Furthermore, we assume that the frequency ratio of the higher order harmonics is one. So we obtain f_{P3}/f_{P1}=5.44 as an estimate for the ratio for the poloidal mode (where we have assumed $f_{P3}=f_{T3}$). Although this ratio is L dependent, it does not vary strongly for $L \geq 4$ (Schulz, 1996, Table 2). If we assume that the observed oscillations in the 17 August 2002 event were the third harmonic, we obtain the estimate of 0.7 mHz (with the calculated Doppler shift taken into account) for the fundamental mode. Although low, this value is not unreasonable. If we instead assume that the observed frequency is the fundamental mode, we obtain 21 mHz for the third harmonic. By following the same reasoning for the 4.6−6.6 mHz wave of the 21 September 2003 event (which also had an approximately 180° phase jump across the equator, and accordingly, occurred in the asymmetric (odd) mode), we obtain 0.9−1.2/25−36 mHz as an estimate for the fundamental/third harmonic.

Most of the studied poloidal wave events with high azimuthal wave number have displayed westward propagation (consistent with the predominant drift motion of ions). In this study at least two of the three events exhibit eastward propagation (positive wave number). Events with eastward propagation have been studied with radar by Walker and Nielsen (1984) and with satellite by Takahashi et al. (1987); however their events occurred in the post-midnight sector, in contrast to the dayside events observed here.

The existence of pressure anisotropy can render the plasma unstable to the mirror instability. Takahashi et al. (1987) observed an anisotropy of 14% and $\beta_\perp \sim 9$ at geostationary orbit. Thus, they found the instability criterion (Eq. (3)) to be satisfied. Woch et al. (1988) found an anisotropy of 60% for a Pc5 pulsation event observed by GEOS-2 on 14 November 1979. As the magnetic field increases as L decreases, larger anisotropy is needed for an instability to develop. We can make an estimate of the plasma density required for Eq. (3) to be satisfied based on the observed magnetic field. The absolute value of the magnetic field is 220–380 nT for the 17 August 2002 event, 300−480 nT for the 14 August 2003 event and 250−400 nT for the 21 September 2003 event. If we assume a temperature anisotropy of 60% and $T_\perp$=1 MK (∼86 eV), the particle density has to be between 1.1×10^3 cm^{-3} and 2.3×10^3 cm^{-3} for Eq. (3) to be satisfied. This is a very high value for $L \sim 5$. Farrugia et al. (1989) found the ion temperature in the quiet plasmasphere to range from 4×10^3 K to 1.5×10^4 K and the proton density to vary smoothly between $\sim 10^2$ cm^{-3} ($L \approx 6$) and 2×10^3 cm^{-3} ($L \approx 3$). Thus, it seems unlikely that the drift-mirror instability is the driver for any of these three events.

SOPA and CPA data from the LANL satellites have been studied for signs of proton injections prior to, or during, the observed ULF events. An observed enhancement of the proton flux in conjunction with the waves would give a strong case for the drift-resonance instability as a driving mechanism. However, none of the satellites show enhancements in proton flux for any of the events, several hours prior to, as well as during the events themselves. For the 17 August 2002 event three LANL satellites had data available (LANL−01A, LANL−97A and 1991−080). This event was particularly quiet, with no signs of injections observed in the data eight hours prior to the observation of the ULF oscillations. For the 14 August 2003 event, data from all six LANL satellites were available and none of them show any sign of proton injections three hours before, or during, the ULF event. LANL data from 21 September 2003 does not show any injection two and one half hours before, as well as during the event, although 1991–080, 1994–084 and LANL−97A show a depression in the proton flux during the ULF wave event. The satellites LANL−01A and LANL−02A show no significant alterations in the flux. 1990–085 had no data available for this event.

5 Discussion and conclusions

The drift-mirror instability caused by an anisotropy in the plasma pressure has been considered by several authors to be a driving mechanism of high-m ULF pulsations. However, for the events studied here unusually high values would be needed for either the pressure anisotropy, the density or the temperature, for the instability criterion to be satisfied. The drift-resonance instability is also unlikely since the events occur during magnetically quiet times and no proton injections are visible from geostationary satellites. A Kelvin-Helmholtz instability at the magnetopause, or other driving mechanisms outside the magnetosphere, are also ruled out, due to the very large azimuthal wave numbers observed. Thus, it seems likely that the 17 August 2002 and 14 August 2003 events were driven by some other plasma instability. The drift-wave instability associated with a gradient in the cold plasma population, discussed by Hasegawa (1971), or a modification of the drift-mirror instability such as the one studied by Pokhotelov et al. (2001), would be two candidates. As for the drift-wave instability Hasegawa (1971) assumed the following plasma parameters at the plasmapause: the ion and electron temperature $T_i = T_e = 1\,\mathrm{eV}$, the plasma density $n_0 = 10^2\,\mathrm{cm}^{-3}$, the ambient magnetic field $B_0 = 5\times10^{-7}\,\mathrm{T}$ and the density gradient length scale $1/\kappa = 0.1\,R_E$, where $\kappa = -\nabla \ln n_0$. From this he obtained a growth rate $\gamma \approx 7\times10^{-4}\,\mathrm{s}^{-1}$, but since $\gamma \sim T_e^2$ the growth rate becomes significant for higher electron temperatures. Pokhotelov et al. (2001) studied the effects of plasma inhomogeneities on the drift-mirror instability and showed that this substantially modifies the instability threshold, requiring a smaller anisotropy for the instability to develop. The modulation of the observed frequency for the 21 September 2003 event might be related to changes in the density and thus the Alfvén velocity. This would correspond to a local maximum in density at approximately 12:00 UT, where there is a minimum in the observed frequency. Measurements of the plasma density and temperatures would have been a valuable asset in this study. Unfortunately, the ion density instrument on Cluster is crippled by energetic particles when inside the radiation belts.

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