OBSERVATIONS OF PC5 PULSATIONS NEAR FIELD-ALIGNED CURRENT REGIONS

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ABSTRACT

Examples of long period Pc5 magnetic field pulsations near field-aligned current (FAC) regions in the high-latitude magnetosphere, observed by INTERBALL-Auroral satellite during January 11, April 11 and June 28, 1997 are shown. Identification of corresponding magnetosphere regions and subregions is provided by electrons and protons in the energy-range of 0.01–100 keV measured simultaneously onboard the spacecraft. The examined Pc5 pulsations reveal a compressional character. A fairly good correlation is demonstrated between these ULF Pc5 waves and the consecutive injection of magnetosheath low energy protons. The ULF Pc5 wave occurrence is observed in both upward and downward FACs.

Key words: field-aligned currents, ULF wave, INTERBALL spacecraft

1. INTRODUCTION

A solar activity event like ejecta or coronal mass ejection (CME) propagates away from the Sun in form of interplanetary coronal mass ejection (ICME). As a result of encounter of ICME with the Earth' magnetosphere, the geomagnetic activity increases to a large extent and geomagnetic storms and substorms could be initiated (*Burlaga et al., 1998*).

In the process of ICME - terrestrial interactions, field-aligned currents (FACs) and ultra-low frequency (ULF) waves transmit the stress on the outer magnetosphere towards the ionosphere. In particular, the interaction of the ICME high density material with the magnetospheric boundaries can initiate ULF waves. Geomagnetic pulsations in the Pc5 band (1.5–7 mHz) - long period part of ULF waves, are probably the most easily observed ULF waves. The experimental evidence of appearance of geomagnetic field oscillations in the FACs regions during ten consecutive orbits (an extraordinary long period of duration of these events) of VIKING satellite is well known (*Potemra et al., 1988, 1989*). The latter authors have concentrated on appearance of 3 mHz variations being seen only on the transverse magnetic field components. They have believed that their study gives for the first time experimental evidence for appearance of resonant geomagnetic oscillations, so called Field Line Resonances (FLR), investigated theoretically in the 70-ies (*Southwood, 1974*; *Hasegawa and Chen, 1974*) on the same field lines which guided the region 2 Birkeland currents. Evidence has been provided on existence of discrete spectral peaks with frequencies 1.3, 1.9, 2.6, 3.4 mHz at high latitudes (*Ruohoniemi et al., 1991*; *Samson et al., 1991, 1992*). Discrete spectral peaks with frequencies of 1.8 mHz, a broad region of enhanced spectral power at 2.4–2.8 mHz and a peak of 3.2 mHz have been observed independently at mid latitudes (*Provan and Yeoman, 1997*). The existence of discrete spectrum, the frequency dependence of Pc5 pulsations, the relationship between auroral electrojet and Pc5 ULF waves are still considered to be timely and important (*Fedorov et al., 2001*; *Pilipenko et al., 2001*; *Baker et. al., 2003*; *Martines-Bedenko et al., 2003*; *Volwerk et al., 2005*; *Sinha et al., 2005*; *Nenovski et al., 2007*; *Sarris et al., 2007* and references there in).

January 11, 1997 was a famous ICME event which largely affected both the magnetosphere and ionosphere. Coordinated WIND, INTERBALL-Tail and ground observations of ULF waves and particles are well known (*Farrugia et al., 2000*). An analysis of geomagnetic field variations observed at very high and low latitude ground-based observatories in opposite hemispheres has shown that the major solar wind variations are followed by intense geomagnetic disturbances or hydromagnetic waves (*Villante et al., 1998*). The authors have suggested a tentative interpretation in terms of compressional oscillations of the whole magnetosphere by strong solar wind pressure pulse. Both POLAR and INTERBALL spacecraft have indicated the presence of periodic magnetic variations in the Pc5 frequency range in the FAC region 1 in the mid- and high-altitude magnetosphere during a rare case of conjunction (*Bochev et al., 2006a*; *Bochev and Nenovski, 2002*).

The multiple ejecta of halo type which left the Sun surface on April 7, 1997 at about 14 UT, was composed by two ejecta (*Berdichevsky et al., 1998*). The second one (slow ejecta), accompanied by an extended period of northward magnetic field, was detected at the Earth on April 11, 1997. The ground based Terra Nova Bay (TNB), L'Aquila (AQ), and geosynchronous observations (GOES-8, -9) on April 11 indicated that the observed ULF intensifications (at 3.6 mHz) well correspond to the solar wind density enhancements (*Lepidi et al., 1999*). They demonstrated a perfect coincidence of the pressure drop with the initiation of ULF activity. By using POLAR observations in the polar cusp and surrounding regions, ground-based and low-altitude spacecraft polar cap observations, a global MHD simulations of the solar wind interaction with the magnetosphere on April 11, 1997 were performed (*Le et al., 2001*).

A strong pressure change in the solar wind during ICME may not be the only agent for an ULF wave activity to be provoked. During low geomagnetic activity on June 28, 1997 interesting results on appearance of periodic dispersive structures in the high-energy ions and electron spectra were observed in the dawn plasma sheet by the INTERBALL-Au mission (*Lutsenko et al., 2002b*).

The present work is an attempt to show and analyze ULF wave signatures and field-aligned currents (FAC)s in the mid-altitude polar magnetosphere by using INTERBALL-Auroral (INTERBALL-Au) spacecraft magnetic field and particle flux experiments. Some results from a joint analysis with POLAR (apogee $9R_E$, period 17.5 h), geosynchronous and ground-based observations can be found elsewhere (*Bochev and Nenovski, 2002*; *Bochev and Kudela, 2005*; *Bochev et al., 2006a,b*).

2. SATELLITE MEASUREMENTS

The INTERBALL-Au spacecraft (6 h orbital period), apogee $4R_E$ (R_E being Earth's radius), provides long time detailed measurements over the north polar regions (*Galeev et al., 1995*). The spacecraft is stabilized by rotation. The spin axis *X* is directed to the Sun. One spin rotation takes 120 s. The orbital period is about 1 h more and its apogee is $1R_E$ higher as compared with VIKING. The duration of each interval at the apogee of a given orbit used in our analysis is about 4 hours.

The three component flux-gate magnetometer IMAP-3 aboard the INTERBALL-Au spacecraft measures the field (from 0 to 4 Hz) along the whole orbit. The sampling rate is 8 vectors per second but in the present study the digital channel data, transmitted via telemetry system, have data rate 1 vector per 3 seconds. So IMAP-3 magnetometer has a unique chance to sense a variety of ULF Pc5 perturbations and FACs in the high latitude magnetosphere regions. Details about the Bulgarian magnetometer IMAP-3 are given elsewhere (*Arshinkov et al., 1995*).

The observations of ion and electron fluxes are made by the PROMICS-3 instrument onboard of the INTERBALL-Au. It performs three dimensional measurements of ions and electrons (*Sandahl et al., 1997*). The PROMICS-3 standard energy-time spectrograms used in our analysis contain graphs from 8 detectors: low energy $E = 0.004–1.5$ keV ions (D1, D3, and D5 detectors) and high energy $E = 1–35$ keV ions (D6, D8, and D10 detectors). They characterize the ion fluxes coming from different directions: sunward (D1, D6); anti-sunward (D5, D10); sideward or spin plane (D3, D8) and all directions (D11). A high energy electron detector (D15), lying in the spin-plane, is used also. The full unit sphere is covered during one spin of the spacecraft (120 s). Fortunately, during the considered events the PROMICS-3 operated in fast regime (12 proton spectra and 36 electron spectra per one spin).

The energetic particle experiment DOK-2 on board of the same spacecraft uses two pairs of energetic particle telescopes. Each telescope has a single, passively cooled, totally depleted, surface-barrier silicon detector. In each pair, in front of the first detector (1e, 2e) a thin foil with a thickness of 0.3 mm absorbs protons with energies $E < 400$ keV, so this detector measures electron spectrum in 20–420 keV range. The second detector (1p, 2p) is supplied with a thin (0.15 mm) broom magnet, deflecting electrons up to 1500 keV. It measures spectrum of ions (protons) in 20–850 keV range. Full aperture angles and geometric factors of electron telescopes are of 27° and 0.066 $cm^2 \times sr$. For proton telescopes these values are 12.7° and 0.015 $cm^2 \times sr$ (*Lutsenko et al., 1998*).

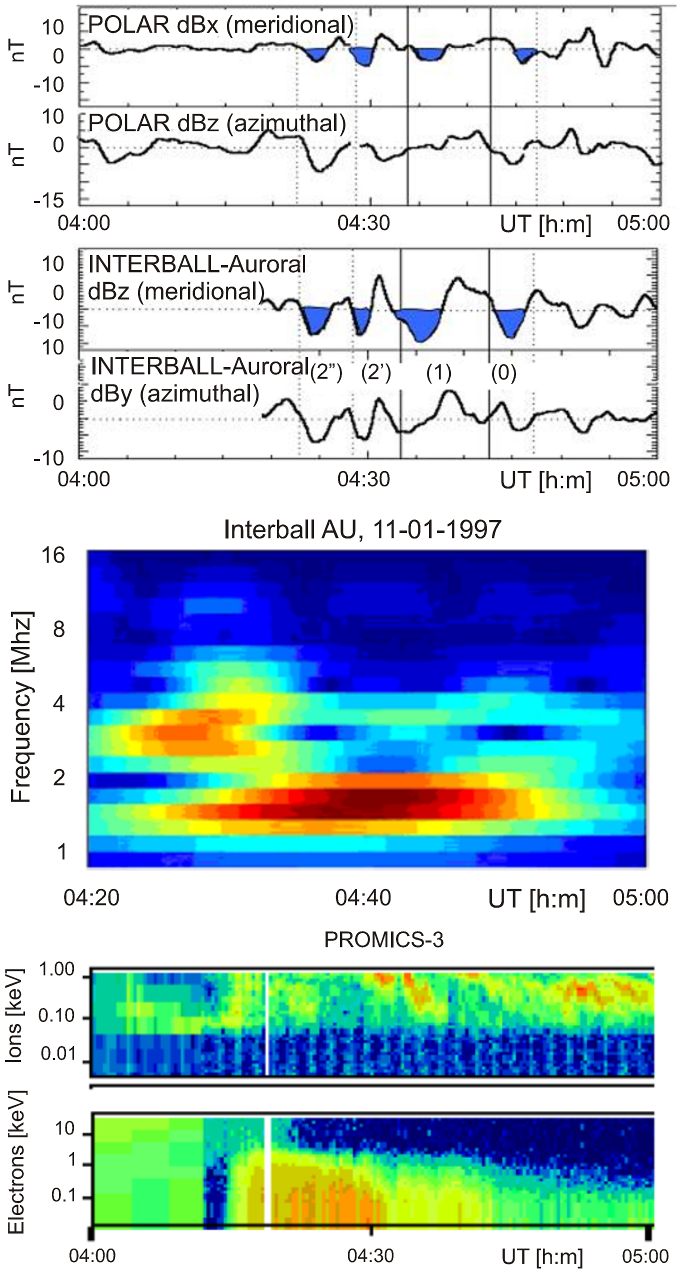


Fig. 1. The long-period magnetic disturbances aboard POLAR and INTERBALL-Au (panels 1–4) for January 11, 1997, the meridional component dynamic spectra (panel 5), and the PROMICS-3 energy-time spectrograms for ions and electrons from detectors D3 (panel 6) and D15 (panel 7), respectively (see also PROMICS graphs in Fig. 4).

2.1. January 11, 1997, 04:00–05:00 UT

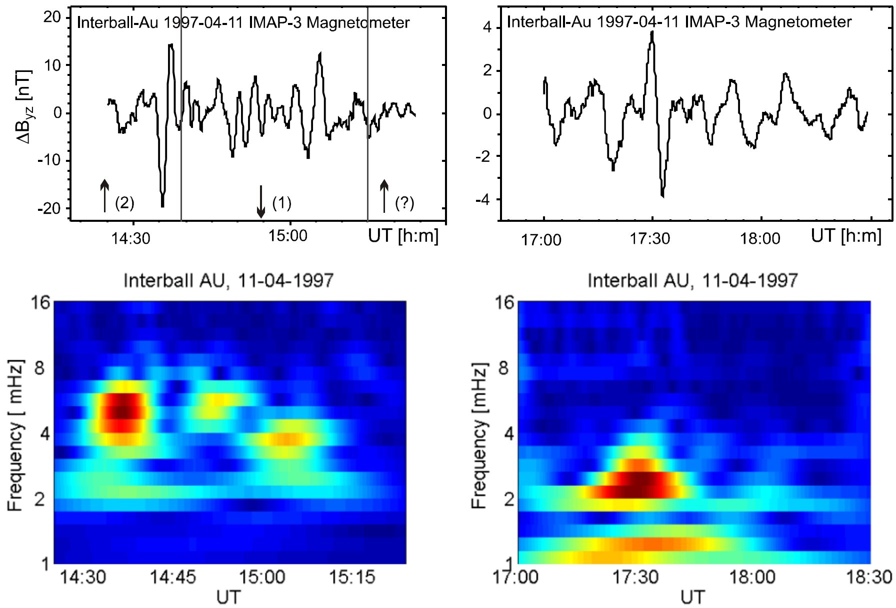
The observations on January 11, 1997, from 04:00 to 05:00 UT, one hour after the passage of the dense part (trailing edge) of the famous magnetic cloud (ICME), covered a period of strongly northward *IMF*. During the event *Dst* and *AE* were low. For the above mentioned time interval, the *IMF By*, *IMF Bz*, clock angle and plasma density can be found in Fig. 6 (Appendix). A number of interplanetary parameters (graphs) is given in other publications too (*Sandahl et al., 1998*; *Villante et al., 1998*; *Fenrich et al., 1998*; *Farrugia et al., 2000*; *Bochev et al., 2006a*; *Nenovski et al., 2007*).

In Fig. 1, panels 1–2 (3–4) transverse components of long-period variations aboard POLAR (INTERBALL) in field-aligned coordinates are represented. The INTERBALL magnetic field data are plotted from 04:17 to 05:00 UT (there is a gap from 04:00 to 04:16 UT). In Fig. 1 four cycles of ULF waves denoted as (2''), (2'), (1) and (0) can be identified. Cycles (2'') and (2') are located in FAC region 2 (downward current) and in the interface between region 2 and region 1 respectively as demarcated by vertical lines: from 04:23 to 04:29 UT and from 04:29 to 04:34 UT (FAC direction is indicated in Appendix, Fig. 6). Cycles (1) and (0) are located in the FAC region 1 (upward) and region 0 (downward) respectively as indicated from 04:34 to 04:42 UT and from 04:43 to 04:47 UT. Note that a significant portion of ULF wave activity is concentrated in region 1 (upward FAC). Details on calculation of differences “measured - IGRF model field” and detection of ULF waves are also given in the Appendix.

In Fig. 1, panel 6 represents the PROMICS-3 low energy ions measured by the D3 detector. Surprisingly four dispersion ramps can be identified. The first one commencing at 04:29 UT is characterized by intense particle flux with mean energy $E \approx 1$ keV. The dispersion of this proton event is the steepest one and the whole duration 4.5 min. Note an appearance of oxygen ions simultaneously with protons which indicates that the event probably occurs on closed field lines (*Sandahl et al., 1998*). The second event begins at 04:34 UT forming a dispersion slope with the lower cut-off energy decreased from 1 keV to 100–200 eV in 8–10 min. The availability of intense low-energetic protons encountered by the spacecraft characterizes the event as accelerated magnetosheath ion injections. The third injection begins at about 04:40 UT, its dispersion slope is small and we observe that its low energetic proton part appears simultaneously with the most energetic protons of the forth injection starting at 04:46 UT, so an overlapping between two consecutive events is demonstrated. It can be seen that cycle (2”) occurs where no intense injection is available, i.e. probably between the inner and outer boundary plasma sheet (BPS). The cylce (2') covers approximately the period of the first intense injection in the outer BPS. The cycle (1) is related to the second injection in the same domain; Further in the BPS the cycle (0) is within the third dispersion ramp.

Similar relationship between Pc5 cycles and magnetospheric regions might be found by examining higher energetic electron fluxes measured by the detector D15 (Fig. 1, panel 7). That is why magnetic field cycle intervals are designated as subregions as well.

From INTERBALL-Au navigation information (Fig. 2 - bottom panel), it is seen that the satellite footprints cross high latitudes over the Western hemisphere (Alaska and Canada). At 04:20 UT the INTERBALL-Au footprint is at 72 MLAT (corrected geomagnetic latitude) and 16.5 MLT (corrected geomagnetic local time). At 05:00 UT it



UT [h:m]	14:30	15:00	15:30	17:00	17:30	18:00	18:30
Reg.	RBT	POC	POC	AUR	AUR	RBT	RBT
R_E	2.79	3.38	3.77	3.84	3.50	2.96	2.20
MLAT	73.92	79.99	80.19	70.57	65.24	57.78	47.23
MLT	8.26	10.74	13.27	16.37	16.88	17.35	17.92
L	13.04	33.10	34.44	9.03	5.70	3.52	2.17

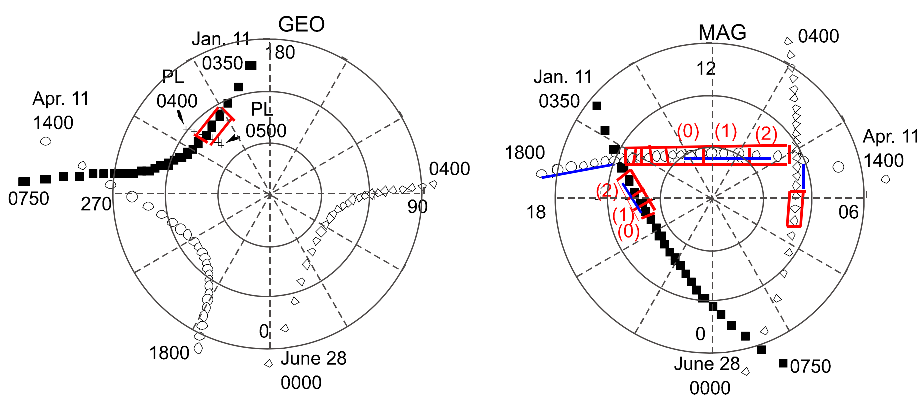


Fig. 2. Continuation of Fig. 1 for 11 April 1997 at 14:30–15:30 UT (left) and at 17:00–18:30 UT (right), (panel 1–2). Geographical (GEO) and geomagnetic (MAG) corrected coordinates of INTERBALL-Au footprints, step 10 min, for 11 January, 11 April, and 28 June, (bottom panels), (input data provided by Prokhorenko, 1995). The UT interval of each transit is fixed by thick numbers [hm]. The same for POLAR (PL) footprints in GEO on 11 April. The field-aligned current regions 0, 1, and 2 are indicated by rectangulars, and the ULF waves by bold lines.

is at 77 MLAT and 19 MLT. The satellite encounters the dispersive ions at high corrected geomagnetic latitudes (74°–78°) in the dusk sector (16–21 MLT). The POLAR footprints in geographical coordinates (crosses) are given also and it is seen that they are nearly perpendicular to INTERBALL-Au. At 04:30 UT both spacecrafts are near to conjunction in the dusk side of the magnetosphere (approximately 18 MLT, $L = 14$). At that time POLAR (INTERBALL-Au) radial positions are $6R_E$ ($3.4R_E$), respectively, so the altitude difference between both spacecrafts is about 16 000 km.

Note also that the POLAR and INTERBALL-Au meridional disturbances are similar in most of subregions (Fig. 1, panels 1 and 3). This comparison indicates that the meridional component of observed long period disturbances seems more synchronized in the mid-high altitude range. It is suggested that the wave process is initiated by a solar wind density increase and by the clock angle variations (Fig. 6, panel 2–3, Appendix).

In Fig. 1, panel 5, a dynamic spectrogram for INTERBALL-Au meridional component is displayed. Subregions (2”) and (2’) are characterized by an appearance of an intense wave packet (from 2.6 to 3.6 mHz). It occupies a comparatively short interval (11 min) at 72–75 MLAT. After 04:20 UT the INTERBALL-Au data reveal a strong signal in the band from 1.5 to 1.8 mHz with a comparatively long duration (30 min) which corresponds to FAC region 1 (upward current) and region 0 (downward).

At the same time (around 04:30 UT) at CANOPUS stations, magnetic field oscillations with amplitude up to 50 nT appear (*Farrugia et al., 2000*). Simultaneous observations at low latitudes near Rome (L’Aquila, AQ, 36°N, MLT = UT + 1:40) and Antarctica (Terra Nova Bay, TNB, 80°S, MLT = UT – 08:00) show oscillations despite the wide latitudinal and longitudinal separation (*Villante et al., 1998*). Major peaks clearly emerge on H and D approximately at the same frequencies, namely 1, 1.4, 1.8 and 2.2 (TNB) – 2.4 (AQ) mHz (*Villante et al., 1998*). Generally, all data reveal an existence of global (1.8 mHz) mode simultaneously observed at a large MLT sector: 16–21 MLT (TNB), 1.4–6.4 MLT (AQ) and around 18 MLT (POLAR and INTERBALL) in the early hours on January 11 at 00:00–05:00 UT. Therefore, there is a strong support (from ground based measurements) in favor of wave interpretation of the detected oscillations aboard INTERBALL-Au and POLAR.

Could the 1.8 mHz mode, observed simultaneously at high and mid latitudes, be interpreted as a global mode? For this purpose we refer to the POLAR data from an earlier period (at 03:00–04:20 UT, during the same ICME), which is characterized however by a strong density increase from 20 cm^{-3} up to 170 cm^{-3} of the solar wind while the solar wind velocity remained nearly constant, about 420–450 km/s (*Nenovski et al., 2007*). Following the solar wind pressure changes that follows the solar wind density changes (5–6 times), the magnetopause approaches and even crosses the geosynchronous orbit ($L = 6.6R_E$). Such a dynamic pressure change suggests that the global mode frequency will change its value in considerable way. It is worth noting that despite this strong solar wind pressure change, the frequency of the observed global 1.8 mHz mode remains practically unchanged. Hence, this fact can not be reconciled by the global mode interpretation. Instead, we can interpret the observed 1.8 mHz mode in terms of surface wave compressional mode. For this purpose we need to use the spectrum the surface wave modes examined recently (*Nenovski et al., 2007*). It has been shown that the surface wave mode frequency is proportional to the solar wind velocity and in the same time remains practically unchanged when the solar wind density changes. Under constant solar wind velocity conditions the surface mode frequency changes are less than 5–10% in magnitude. One concludes that the observed non-variability of the frequency peak at 1.8 mHz during solar wind pressure changes between 20–170 cm^{-3} could be reconciled with the surface mode model (*Nenovski et al., 2007*).

Inversely, the 3.3 mHz peak location area (about 3° in latitude), observed also by INTERBALL and POLAR (Fig. 1, panel 1 and 3) probably resembles a field-line resonance (FLR) structure.

2.2. April 11, 1997 Dynamics Pressure Sharp Changes, 14:10–18:30 UT

On April 11, 1997 at 05:00–15:00 UT an ICME structure, named "ejecta itself" was identified by the WIND (*Berdichevsky et al., 1998*). A moderate geomagnetic storm was detected by ground based magnetometers at 05:00 UT ($Dst = -80$ and $Kp = 6$). Its recovery phase ($Dst = -15$, $Kp = 3$) occurred at 14:00–18:30 UT; both *IMF By* and *IMF Bz* were positive (*IMF By* = 6 nT and *IMF Bz* = 12 nT); the solar wind speed was quite steady ≈ 470 km/s while the plasma density showed several variations (*Lepidi et al., 1999*; *Bochev et al., 2006b*). As comparing with the Earth's magnetosphere response it takes ≈ 55 min of the IMF to pass from WIND location to the Earth.

In Fig. 2 - bottom panel, the INTERBALL-Au footprints at 14:00–18:00 UT (step 10 min) are displayed. The INTERBALL-Au crosses the cusp sector from dawn to dusk close to MLAT = 82°. For such a segment, directed perpendicular to the Sun in the cusp sector, the transverse (Eest-West) disturbance could be approximately presented by the $Byz = (By^2 + Bz^2)^{1/2}$ component where By and Bz are measured spin-plane components. The IMAP-3 magnetometer detects an unusually strong perturbation $dByz = 150$ nT, corresponding to a quite intense FAC systems; The appearance of ULF waves on the large-scale FAC disturbance is evident on *dByz* graph (*Bochev et al., 2006b*, Fig. 3). To separate the ULF waves we have used similar technique to January 11 case (Appendix). To have a full correspondence with the respective intervals of intensification of ULF waves, known from ground-based observations (*Lepidi et al., 1999*), we divide the whole interval (14:30–18:30 UT) into two intervals.

In Fig. 2, left side - panel 1, ULF wave activity is displayed for the first interval (14:30–15:30 UT). Several groups of intense oscillations can be seen. The respective sonogram is shown in the same Fig. 2 (left side - panel 2). It reveals clearly a number of distinctive wave packets: the first one is centered approximately at 5.6 mHz, corresponds to FAC region 2 (upward); the second one of about the same frequency is near to the boundary between FAC region 2 and region 1 (downward) and a third one of 4.2 mHz appears in FAC region 1. Surprisingly at 14:30 UT a lower frequency of approximately 2.4 mHz, although weak, appears in FAC region 2 in the dawn flank of the cusp sector and continues till 15:15 UT covering FAC region 1 too. Note that at 14:30 UT the hourly averaged low frequency fluctuation power has a maximum at LQ and TNB although the two stations are at a very different magnetic local time (*Lepidi et al., 1999*). Satellite and ground-based results suggests that in particular the fluctuation at 2.4 mHz is not a local phenomenon; it rather reflects global magnetospheric disturbances driven by the solar wind.

The second part (from 17:00 UT to 18:30 UT) extends deep into the ring current towards the plasmapause (see the navigation information at the bottom the same Fig. 2). The respective ULF signals are shown in Fig. 2, right side - panel 1. In contrast with the first groups they are comparatively weak (the mean peak to peak variation is ≈ 4 nT). Two groups of wave appear in the respective sonogram (Fig. 2, right side - panel 2). It is interesting to note that the first group is similar to the 2.4 mHz from panel 2 - left, which shows that this packet persists throughout the two intervals. In contrast with the first sub interval localized waves at higher frequencies are not observed. Unexpectedly, a second packet at 1.3 mHz appears only in this interval. Note that wave activity refers to the dusk part of the orbit where intense large-scale FACs have not been detected. Similar to the first interval, hourly averaged low frequency fluctuation power has a maximum at LQ and TNB (*Lepidi et al., 1999*) and the power spectra at LQ reveals a peak at 2.2–2.3 mHz. This characterizes the 2.4 mode as a rather global magnetospheric disturbance. Unfortunately we can not do a similar conclusion about existence of 1.3 mHz in the ground-based observations; the AQ and TNB power spectra analysis (conducted by *Lepidi et al., 1999*) is constrained in the range of 1.6–5.0 mHz.

We examine in details the appearance of compressional component in the magnetic field disturbances. The modulus of the field is calculated as $Bt = (Bx^2 + By^2 + Bz^2)^{1/2}$

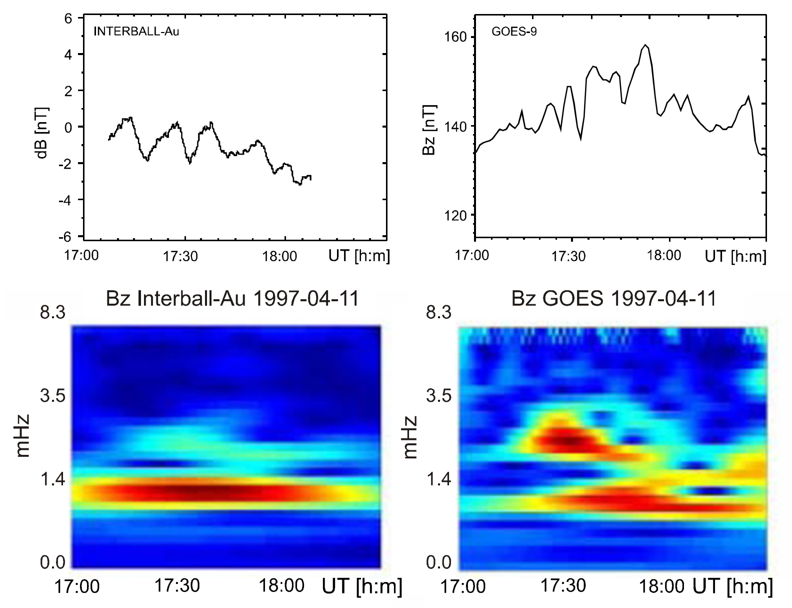


Fig. 3. Continuation of Figs. 1 and 2 for 11 April at 17:00–18:30 UT. Simultaneous detection of compressional oscillations by the INTERBALL-Au (left) and GOES-9 (right). The fundamental and the harmonics can be identified at frequencies 1.3 mHz and 2.6 mHz.

where *Bx*, *By* and *Bz* are components measured by the IMAP-3 magnetometer. In Fig. 3, left side - panel 1, the obtained graph is presented. The peak to peak value is ≈ 2.4 nT which is comparable with the transverse variation (4 nT). The dynamic spectra analysis showed a quite intriguing dependence. In panel 2-left, it could be seen that two groups of wave appear: apart from 2.6 mHz, a strong 1.3 mHz signal co-exists with the transverse ones (Fig. 2, right side - panel 2). This analysis indicates that the observed waves have compressional character. This is another example showing a global character of such oscillations.

To support our finding related to the compressional component frequency features we have analyzed simultaneous magnetic data (the *Bz* component - along the main magnetic field) from the geosynchronous GOES-9 satellite operated at 225°E longitude (Fig. 3, right side - panel 1). The longitudinal lag of GOES-9 with respect to INTERBALL is 110°. For the interval 17:00–18:30 UT we get a sonogram similar to INTERBALL: the picture is dominated by two frequency groups centered at 1.3 mHz and 2.6 mHz respectively (panel 2 - right). So the dynamics spectra of the magnetic field modulus measured aboard GOES-9 reveals the same frequencies appearance. This fair coincidence makes the INTERBALL finding of discrete spectra more confident.

2.3. June 28, 1997, 00:00–04:00 UT

The period under study at 00:00–04:00 UT on June 28 occurred during recovery phase of a weak magnetic storm started one day earlier. On June 27, from 06:00 to 12:00 UT, the WIND registered a dense structure, proton number density n_p = 30 cm^{-3}, accompanied by strong magnetic field, directed southward *IMF Bz* = −10 nT. The trailing edge of the dense structure was dominated by a large solar wind velocity increase (350–550 km/s). A weak geomagnetic storm started at 10:30 UT on June 27, 1997 (*Dst* = −25 and *Kp* = 2+). During the recovery phase, the solar wind density was fluctuating with peak to peak variations ≈ 0.5 cm^{-3} and a jump of *IMF Bz* from −2 to 0 nT occurred at 00:40 UT on June 28, 1997. For comparison of solar wind changes with the Earth's magnetosphere response note that it takes ≈ 16 min of the IMF to pass from WIND to the Earth.

For such an orbit (the considered segment is approximately Sun aligned) the transverse magnetic field component has a significant projection in sunward direction. Note that in the polar region the spacecraft is close to 73 MLAT (Fig. 2). In the middle of Fig. 4, the *Bx* magnetogram is represented. The IMAP-3 magnetometer reveals a presence of intense ULF wave event around 01:30 UT. Four cycles of oscillations are clearly seen. The process starts at about 01:17 UT with a large amplitude, peak to peak variation ≈ 70 nT. These oscillations continue until ≈ 01:35 UT, their mean period being approximately 4.5 min which corresponds to ≈ 3.7 mHz. In a case of a skimming orbit it is difficult to determine the boundary between region 1 and region 2 in particular when FACs are masked by a strong wave activity.

In Fig. 4, panels 1–8, standard energy-time spectrograms from PROMICS-3 are displayed. All low energy ion detectors (D1, D3 and D5) demonstrate an unusual appearance of dispersive ramps. In particular four consecutive dispersive ramps of magnetosheath ions are clearly seen on the D1 graph (panel 7). An almost fair correlation is demonstrated between these dispersive ramps and the ULF waves detected by the

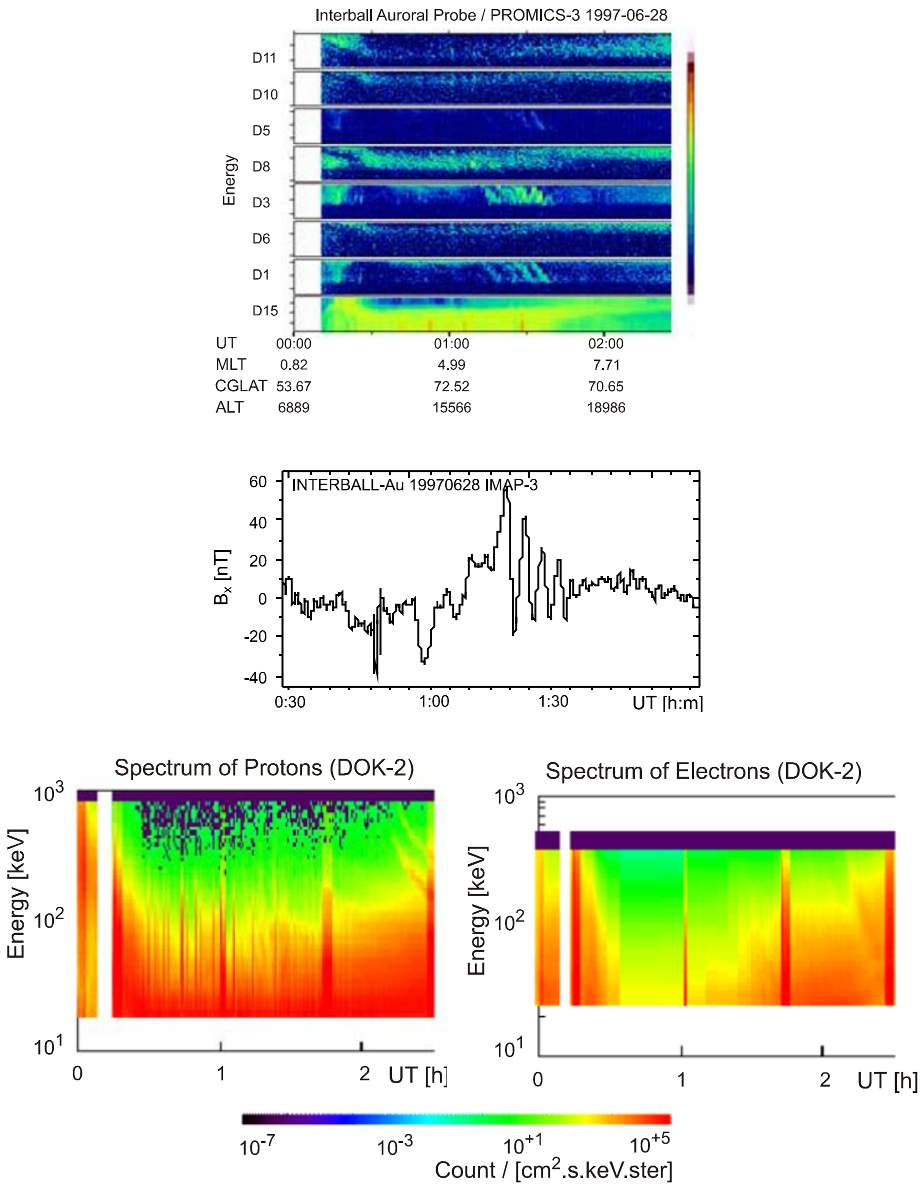


Fig. 4. Continuation of Figs. 1–2 for 28 June, 1997. The PROMICS-3 energy-time spectrograms (panels 1–8), (vertical scales: D1, D3, and D5 detectors - the same as Fig. 1, panel 6; D6, D8 and D10 thick labels are 1 and 10 keV. Color bar: D1, D3, D5 and D15 from 1 to 10^4 counts; D6, D8, D10, and D11 from 1 to 10^3 counts). The IMAP-3 magnetic field (panel 9). The DOK-2 energy-time spectrograms for high energy protons and electrons (panel 10 and 11, respectively).

magnetometer. High energy ion detectors (D6, D8, D10 and D11) do not indicate similar structures. The D8 graph (panel 4) indicates that the whole ULF waves interval corresponds to an overlapping of two ion distributions with different energies: several keV and tens of keV which probably correspond to the boundary plasma sheet (BPS) and the central plasma sheet (CPS) respectively. An accompanying interesting event can be seen on D15 graph which indicates several intense spike-like structures of low energy electrons (a few hundreds eV). Similar structured in space and energy spectra probably correspond to the BPS. In the dawn magnetosphere usually the downward FAC region 1 (upward FAC region 2) is connected predominantly to the BPS (CPS).

In Fig. 4, panels 10–11, the DOK-2 high energy protons and electrons are represented respectively. The DOK-2 proton spectra demonstrate a penetration of high energy ($E \approx 40$ keV) structures (although weak) in the whole interval of magnetic field disturbances (00:50–01:20 UT), including ULF waves segment. That is why we might suppose that the ULF waves may be related to a part of a more complicated process in which energetic protons play some role. The DOK-2 electron spectra indicate significant persistence of high energy electrons from 01:30 UT on - suggestive for the CPS.

We mention that the detected ULF event differs from what is known from a former study (*Lutsenko, 2002b*) of the same orbit. The high energy dispersion events, described by Lutsenko (and partially seen in our graph - upper right corner, in form of two “horns”), occur one hour later when the magnetic field oscillations go out slowly. Of course, time variations of the ion peak energies can be accompanied by Pc5 waves in a local magnetic field with the same period however these are other type ULF waves explained in a frame of gradient-curvature drift model (*Lutsenko, 2002a*).

We again focus on the appearance of the compressional component in the magnetic field disturbances. Similar to previous case, we examine the modulus of the field subjected to identical treatment as above. In Fig. 5, left side - panel 1, the obtained graph is presented. Evidently the maximum wave peak to peak variation is comparatively weak about 4.5 nT. The dynamic spectra of the INTERBALL-Au data indicate frequency ~ 3.5 mHz (Fig. 5, left side - panel 2). We visited the simultaneous magnetometer data for total field variation (sampling interval 6 s) from POLAR spacecraft. We identified the same pulsations frequency ~ 3.5 mHz - similar to INTERBALL-Au. The oscillations were short-lived similar to INTERBALL-Au. As these satellites were far apart in terms of L-value (though in terms of local time they fall in similar sectors), it may be safely concluded that these waves are global in nature characterized as magnetospheric compressional waves. As compared to the perpendicular variation (peak to peak variation 70 nT) the compressional oscillations are weak (peak to peak ~ 5 nT). Simultaneous presence of compressional oscillations along with transverse oscillation of enhanced amplitude suggests the resonant coupling between the two components (*Chen and Hasegawa, 1974*; *Southwood, 1974*; *Kivelson and Southwood, 1986*).

As it can be seen (see Figs. 4–5) the ratio between both the wave amplitudes b_x (transverse) and $b_{||}$ (compressional) amounts to ~ 16. The duration of this resonance event is approximately 13–16 min. The resonance frequency ω_R is 3.7 mHz and we need to evaluate the damping rate ω_i. The damping rate of Alfven waves is given by

$$\omega_i/\omega_R = -(1/n\pi)\ln\left|(\mu_0\Sigma_P v_A - 1)/(\mu_0\Sigma_P v_A + 1)\right|, \qquad (1)$$

where Σ_P is the Pedersen conductance, μ_0 is the magnetic permittivity, v_A is the Alfven velocity, n is a number (e.g. for the fundamental mode $n = 1$). From our June 28 observations, the oscillations were located in the morning sector (~ 06 LT) and at radial distance $r \cong 4R_E$. The INTEBALL position is mapped to magnetic latitudes between 72° and 75° (around $L \approx 11$). As it is expected at auroral latitudes and in the morning hours the Pedersen conductance Σ_P is high enough compared with the effective wave conductance $\Sigma_A = (\mu_0 v_A)^{-1}$. Under such conditions Σ_P is 5–10 S, while the wave conductance Σ_A is around 1 S (*Pilipenko et al., 2001*). This means that the reflection of the Alfven mode is strong and the estimated damping will not prevent the excitation of magnetospheric Alfven resonances.

Having in mind this the amplitude ratio at the resonance field line v_0 (at the maximum) can be estimated. According to the *Chen and Hasegawa (1974)* the wave amplitude ratio $b_x/b_{\|}$ amounts to

$$b_x/b_{\|} \cong 1/m\eta \ln \eta ,$$

where m is the azimuthal number of the wave mode and

$$\eta = -2\frac{\omega_i}{\omega_R}\left(\frac{v_0 d \ln v_A^2}{dv}\right)^{-1} . \qquad (2)$$

Here the dipole coordinate v is related to the spherical coordinate by the relation $v = \sin^2\theta/r$ (θ is co-latitude). The latter factor $d(\ln v_A)/dv$ specifies the spatial gradient scale λ_A of the Alfven velocity v_A. This scale depends on the plasma density and Earth's magnetic field gradients. Under magnetospheric conditions the magnetospheric plasma density distribution follows the power law dependence on the radial distance r: $r^{-\alpha}$, where index α varies. For an estimate of this factor the equatorial plane is used: $v \equiv 1/r$. Assuming $\alpha = 4$, $m = 1$ and combining Eqs.(1) and (2) the following estimate of ω_i/ω_R, η and $b_x/b_{\|}$ are found:

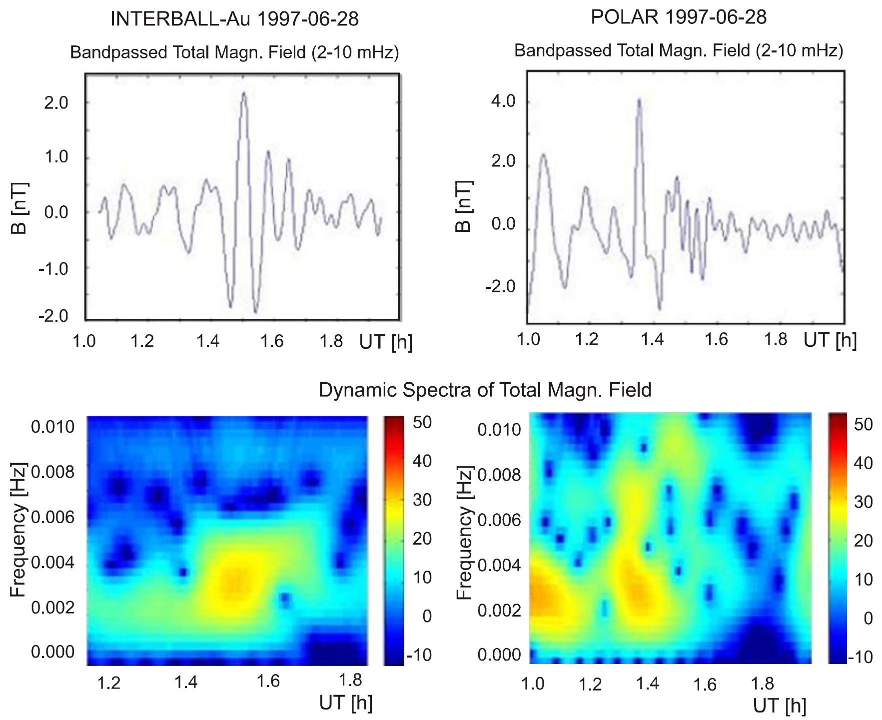
$$\eta \cong \omega_i/\omega_R \text{ and } \omega_i/\omega_R = \Sigma_A/n\pi\Sigma_P = (5n\pi \div 10n\pi)^{-1} .$$

Depending on harmonic number n, the calculated amplitude ratio amounts to:

$$b_x/b_{\|} \approx (5.7 \div 9.1)/m \quad \text{for } n = 1,$$

$$b_x/b_{\|} \approx (9.1 \div 15)/m \quad \text{for } n = 2,$$

$$b_x/b_{\|} \approx (12.2 \div 20.7)/m \quad \text{for } n = 3.$$



UT [h:m]	01:00	01:30	02:00	01:00	01:30	02:00
Reg.	AUR	AUR	AUR			
R_e	3.44	3.80	3.98	8.66	8.79	8.93
MLAT	76.62	72.50	70.75	83.25	83.77	84.22
MLT	5.00	6.59	7.71	8.32	9.02	9.32
L	11.20	11.06	9.20	1000	1000	1000

Fig. 5. The same as in Fig. 3 for 28 June, 1997, for the INTERBALL-Au (left) and POLAR (right).

For this estimate the Pedersen conductance Σ_P was chosen equal to 5–10 S and the wave conductance Σ_A is 1 S. Using the observed wave amplitude ratio of 16, a better coincidence is obtained either for $n = 2$ and value of $\Sigma_P \approx 10$ S, or for $n = 3$ and Σ_P value lying in the interval 5–10 S. Assuming the wave-wave coupling mechanism as a possible source of the observed oscillations on board the INTERBALL satellite on June 28, 1997, this estimate suggests that the azimuthal number (m) of the compressional mode and the harmonic of the resonance (n) should be 1 and 2 (3), respectively. Unfortunately, the azimuthal number m can not be testified. Resonance wavenumber k_n is expressed through the length l of the field line: $k_n/2\pi = n/2l$ ($l \cong 2.7\,L$). This allows us to evaluate the wave conductance $\Sigma_A = 1/\mu_0 v_A$. Using relation $\omega_R = k_n v_A$ and that the resonance is observed at around $L = 11$, wave conductance $\Sigma_A \cong k_n/\mu_0 \omega_R$ amounts to ~ 0.8 (1.2) S. Thus, the calculated wave conductance Σ_A proves to be close to the assumed value of 1 S. Further on, if the observation suggests an excitation of second (third) harmonics, the frequency of the fundamental mode (n = 1) should be ~ 1.8 (1.2) mHz, respectively.

To conclude, the observed wave amplitude ratio $b_x/b_{||}$ of ~ 16 appears to be quite reasonable for a coupling mechanism occurred in morning sectors on the same field lines that guide FAC region 2 (flowing away from the ionosphere) and at radial distances of ~ 4 times Earth's radii.

The INTERBALL satellite measurements of the wave amplitude distribution provide us a possibility to quantify the dominant dissipation mechanism of the observed oscillations. As we pointed out above simultaneous particle observations suggest that ULF waves may be a part of more complicated process in which more energetic particles play some role.

3. CONCLUSIONS

Cases of ULF waves (Pc5 pulsations) during ICMEs (under condition that the solar wind pressure change is significant) are documented by the IMAP-3 magnetometer and particle experiments aboard INTERBALL-Au over the North polar region, supported by geostationary GOES-9, POLAR, and some ground-based measurements.

On January 11, 1997 at 04:00–05:00 UT ULF waves in form of four cycles, denoted as (2”), (2’), (1) and (0), have been identified in the dusk FAC regions: cycles (2”) and (2’) located in region 2 (downward current) and in the interface between region 2 and region 1 (upward current) respectively; cycles (1) and (0) - in region 1 (upward) and in region 0 (downward). All cycles (with the exception of region 2 cycle) are closely related to consecutive injections of accelerated low energy magnetosheath plasma. The dynamic spectra analysis has revealed mainly two frequency packets: cycles (2”) and (2’) are characterized by an appearance of an intense wave packet from 2.6 to 3.6 mHz which occupies comparatively short interval; a strong signal from 1.5 to 1.8 mHz with a comparatively long duration characterizes cycles (1) and (0). Simultaneous observations at low latitudes near Rome (LQ, L'Aquila), Antarctica (Terra Nova Bay) and at geostationary orbit (GOES-9) show that the observed 1.8 mHz mode sequence is practically not influenced by the solar wind pressure changes and persist without frequency changes at high and mid latitudes.

On April 11, 1997 at 14.4–15.4 UT a lower frequency of ~ 2.4 mHz in the transverse component, although weak, persisted throughout the cusp sector in region 2 (upward) and region 1 (downward) for a longer time as compared to waves at greater frequencies localized in region 2. Further in the same orbit (17.00–18.20 UT) waves at ~ 2.4 mHz with the emergence of subharmonic at ~ 1.3 mHz have been observed equatorward from FAC regions. The same frequencies exist in the parallel component too. The power spectra at LQ reveals a peak at 2.2–2.3 mHz which is similar to our finding. We focus that in the interval 17:00–18:20 UT the wave ~ 1.3 mHz and its harmonic 2.6 mHz were also simultaneously documented on remarkable total field sonograms of INTERBALL and

GOES-9 spacecraft being on completely different magnetic tubes (MLT), thereby suggesting that these are global compressional oscillations.

On June 28, 1997 at 01:00–02:00 UT an intense ULF waves event with peak to peak variation maximum 70 nT and frequency about 3.7 mHz was detected in the dawn sector of the magnetosphere. A fairly good correlation is demonstrated between these ULF Pc5 waves and the consecutive injection of magnetosheath low energy protons. The whole ULF waves interval corresponds to an overlapping of two ion distributions with different energies: several keV and tens of keV which probably correspond to the boundary plasma sheet (BPS) and the central plasma sheet (CPS) respectively. The event was also simultaneously detected in the total magnetic field of INTERBALL and POLAR. As these satellites are far apart in terms of *L*-value (though in terms of local time they fall in similar sectors), it may be safely concluded that these waves are global in nature characterized as magnetospheric compressional waves.

Finally, generalizing our results it is concluded:

- The ULF Pc5 wave occurrence is observed in both upward and downward FACs. In our analysis the cases when upward FAC direction is preferred for ULF wave occurrence have a small prevalence.
- As far as we know such a coincidence of Pc5 pulsations in FAC regions has been reported for the first time in the framework of INTERBALL-Au Project.
- There is a strong support from ground based measurements in favor of wave interpretation of the detected oscillations in FAC regions.
- A fairly good correlation is demonstrated between these ULF Pc5 waves and the consecutive injections of magnetosheath low energy protons.
- We argue that the examined Pc5 pulsations have a compressional character when amplitude ratio between transverse and compressional component is large ($b_x/b_{||} \sim 16$ for June 28). This result is consistent with theoretical models namely that a compressional oscillation of small amplitude can result into field line large oscillations via resonant coupling.
- The constancy of 1.8 mHz mode when the solar wind pressure changes considerably agrees with an interpretation in terms of surface wave mode model (*Nenovski et al., 2007*). In accordance with this theory the surface wave mode frequency is proportional to the solar wind velocity and in the same time weakly depending on the solar wind density. Under such solar wind velocity conditions the surface mode frequency changes are less than 5−10% in magnitude.

APPENDIX

Here we describe the method used to identify FAC regions.

In our former work (Fig. 2, *Bochev and Nenovski, 2002*) we begin with POLAR components in GSM coordinate system. To help data interpretation, we transform POLAR measurements from GSM to field-aligned coordinates; then we calculate the differences “measured-model (IGRF)”values for both components - meridional and azimuthal (Fig. 6, panels 4–5).

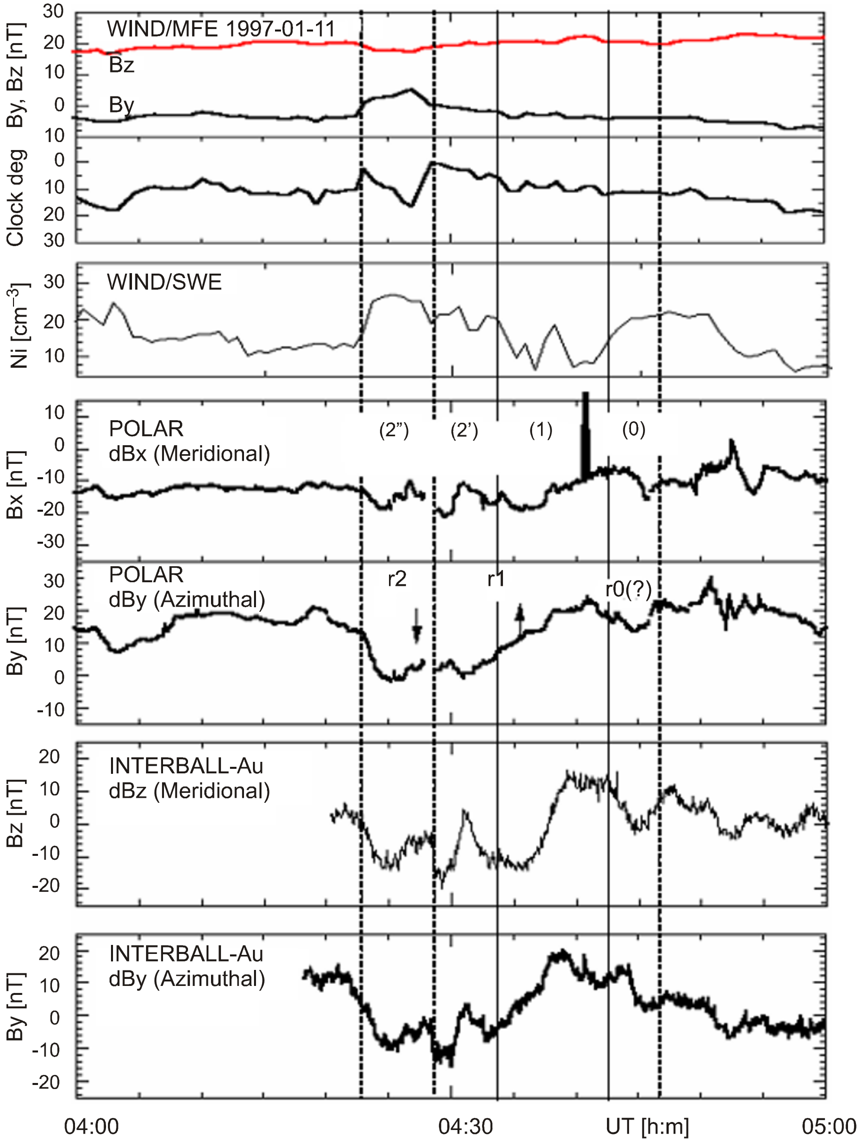


Fig. 6. The ULF waves in the large-scale field-aligned current (FAC) regions: r1 (region 1), r2 (region 2), and r0 (region 0). Panel 1 is the IMF By and IMF *Bz* components. Panel 2 - IMF clock angle (positive bottomward). Panel 3 - solar wind ion density. Panels 4–7 - measured minus IGRF model azimuthal and meridional components in field-aligned coordinates for POLAR and INTERBALL (the POLAR dBy is plotted with negative sign); Arrows indicate FAC direction; vertical lines demarcate four subregions: (2"), (2'), (1), and (0) investigated for ULF waves; interval (1) designated by solid lines corresponds to conjunction.

In Fig. 6 it is clearly seen that in the new coordinates, the large-scale disturbances appear predominantly in the azimuthal (West-East) component in the interval 04:20–04:40 UT. In particular POLAR graph *By* (azimuthal) is dominated by this anomaly. So the large-scale magnetic field disturbances have a pronounced appearance in West-East direction which is in favor of their traditional interpretation in term of FAC sheets, namely FAC region 2 (downward current) and FAC region 1 (upward current) as indicated by arrows. In contrast, small-scale disturbances persist in both components, in particular they are intense in the meridional direction too, so they can not be interpreted as fine FACs sheets elongated along the large-scale FACs. In region (2) and in the interface between region (2) and region (1), two subintervals (2”) and (2’) could be distinguished, indicated by vertical lines from 04:23 to 04:29 UT and from 04:29 to 04:34 UT, respectively. Without applying any filtration we could say that the first two cycles (2”) and (2’) have roughly a similar period of 5.5 min which corresponds to frequency 3 mHz. That is why we suggest that in this case an existence of ULF waves superposed on region 2 and region 1 could have place.

The same procedure has been applied to identify large-scale FACs on INTERBALL magnetograms (Fig. 6, panels 6–7).

We compare ULF wave signals as seen aboard both POLAR and INTERBALL spacecraft. In both subinterval (2”) and (2’) a correlation is evident. The cycles are very important for comparison of POLAR and INTERBALL because of the conjunction situation at that moment (spacecraft location is shown in Fig. 2, bottom panel). To extract these variations needed for a further analysis, we approximate the graphs by averaging. The averaging is performed by submitting 45 (90) for “number of pts in either side to be averaged” for POLAR (INTERBALL) respectively. For POLAR (INTERBALL) the time interval between two consecutive measurements is 6 (3) seconds; so the averaging window is 9 min which is about 2 times larger than the cycle period in subinterval (2”). Then the averaged curve is subtracted. The obtained differences demonstrate the extracted ULF waves (Fig. 1, panel 1-4) which have been used as input data for dynamic power spectra analysis.

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