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Dayside geomagnetic Pc5 pulsations in the conditions of a strongly disturbed solar wind during the magnetic storm of 21 February 1994

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Abstract. Specific features of excitation of dayside long-period geomagnetic pulsations during the magnetic storm of 21 February 1994, under extremely high interplanetary magnetic field (IMF) and solar wind parameters and their large variations are discussed. Two intervals have been analyzed. The first is 1300–1400 UT under a very high (up to ~100 nPa) dynamic solar wind pressure, and the second is 1500–1600 UT under a high magnetic pressure and lower (to ~10 nPa) dynamic solar wind pressure. Two bands, a low-frequency band at $f < 2$ mHz and a high-frequency band at 3–5 mHz, were chosen according to the geomagnetic pulsation spectrum. During the first and second intervals, maximum amplitudes of low-frequency oscillations were observed at the dayside polar cusp latitudes and in the closed magnetosphere, respectively. The morphological characteristics of the high-frequency pulsations (3–5 mHz) were similar during both intervals and were consistent with the resonance nature of their generation. However, contrary to the "classical" Pc5, the highest pulsation intensity was observed in the afternoon sector rather than in the morning one. Simultaneously, similar variations of the IMF parameters were observed. For the conditions of a high dynamic solar wind pressure (1300–1400 UT) the dynamic pulsation spectra proved to be similar in the interplanetary space and at the Earth's surface at the dayside cusp latitudes. Variations in the solar wind density and magnetic field were found to be in antiphase, which can be the evidence of the compressional wave approach to the Earth.

1. Introduction

During strong geomagnetic disturbances, typical auroral zone phenomena are detected at middle and even equatorial latitudes. For instance, during strong magnetic storms long-period geomagnetic Pc5 pulsations (1.5–6.0 mHz), whose maximum amplitudes under moderately disturbed conditions are observed at $\Phi \sim 68^\circ - 72^\circ$, occur at much lower latitudes. *Bol'shakova et al.* [1994] showed that a drastic compression of the magnetosphere by the solar wind during the great magnetic storm of 13 March 1989, resulted in the

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excitation of Pc5 at the latitudes $\sim 53^\circ - 57^\circ$ which are not typical for this class of pulsations. The maximum frequency in the pulsation spectra increased with decreasing latitude from $f = 3.6$ mHz at $\Phi \sim 57^\circ$ to $f = 4.9$ mHz at $\Phi \sim 53^\circ$, which is consistent with the hypothesis of the resonance nature of oscillations [*Samson et al.,* 1992; *Walker et al.,* 1992].

Schott et al. [1998] and *Kleimenova et al.* [1998] analyzed geomagnetic Pc5 pulsations during another, also very strong, magnetic storm of 24 March 1991. In the daytime, two types of long-period geomagnetic pulsations were detected at middle latitudes. They were (1) quasimonochromatic ~1.5–2.0 mHz oscillations with a very low azimuthal wave number ($m \sim 1$) and synchronous wave packets on the global scale and (2) broadband oscillations in the frequency band ~2.5–3.5 mHz with $m \sim 3 - 5$ and wave packets incoherent in space.

During the great magnetic storm of 5 August 1972, intense geomagnetic Pc5 pulsations in the magnetosphere were observed at $L \sim 4.5$ [*Engebretson et al.,* 1983]. During the magnetic storm of 10–11 January 1997, *Villante et al.* [1998] observed a simultaneous occurrence of the 0.8–5.0 mHz ULF pulsations at low latitudes in Europe (observatory L'Aquila, $\Phi = 36.2^\circ$N) and at the antipodal meridian in the southern polar cusp (observatory Terra Nova Bay, $\Phi = 80.5^\circ$S). The authors interpreted the observed effect as a generation of global magnetospheric compressional waves due to a strong solar wind pressure pulse.

The 21 February 1994 magnetic storm (with SC at 0901 UT) was caused by the interplanetary magnetic cloud approaching the Earth [*Araki et al.,* 1995; *Petrinec et al.,* 1995]. The storm expansion phase began at ~1300 UT. It was characterized by strong geomagnetic disturbances with Kp up to 7+ and AL up to ~1400 nT, the ring current intensity being relatively low ($Dst \sim (-145)$ nT).

During the expansion phase of this storm the IMP 8 and Geotail satellites were in the radial direction at a distance of $\sim 55\, R_E$ from each other (IMP 8 at $+25\, R_E$ and Geotail at $-30\, R_E$). In spite of this, both satellites detected similar, unusually large, variations in the IMF and solar wind parameters [*Yamauchi et al.,* 1996], which means that a large-scale solar wind structure (an interplanetary magnetic cloud caused by coronal mass ejection (CME)) approached the Earth. In the conditions of a sufficiently high and slightly varying solar wind velocity both satellites detected very high solar wind densities, almost up to 80 cm^{-3}. The dynamic solar wind pressure was as high as ~100 nPa. The strongest variations in the IMF parameters were observed at 1300–1700 UT. At 1330–1400 UT the IMF B_z sharply changed from −35 nT to +55 nT, and B_y varied from +44 nT to −65 nT. Figure 1 shows the IMF and solar wind data (B, B_x, B_y, B_z, n, and v) obtained by Geotail on 21 February 1994. Note that Geotail was at $X \sim -30\, R_E$, $Y \sim +60\, R_E$, and $Z \sim 2\, R_E$, which means that the time delay of several minutes (~7–9) should be taken into account when the satellite and ground-based data are compared.

The magnetic storm of 21 February 1994 was of particular interest for the analysis because during this period not only very high values of all solar wind parameters but also their unusually strong variations took place near the Earth's orbit. During the interval ~1300–1340 UT the IMF variations were observed on the background of a very high dynamic solar wind pressure ($P \sim 100$ nPa), and at ~1500–1600 UT, they were detected under a considerably lower pressure ($P \sim 10$ nPa). *Yamauchi et al.* [1996] showed that during this storm the first situation (a high dynamic pressure) resulted in the expansion of the dayside polar cusp, and the second situation (a high magnetic pressure) led to its narrowing. Since the intervals mentioned above were characterized by a high (up to ~750 km s^{-1}) and relatively stable solar wind velocity, variations in the dynamic pressure actually manifested variations in the solar wind density.

The goal of this work was to analyze in detail the ground-based long-period geomagnetic Pc5 pulsations (1–6 mHz) in the dayside magnetosphere during the periods of a high dynamic solar wind pressure and large variations in all IMF components (1300–1400 UT) and relatively lower dynamic pressure (1500–1600 UT) which was also accompanied by high values of the IMF parameters and their variations.

2. Data

For the analysis we used the 1-min sampling data obtained from the global network of ground-based stations in the Northern Hemisphere (INTERMAGNET) and from three French observatories in the Southern Hemisphere (AMS, CZT, PAF), as well as 10-s sampling data of the Scandinavian network of stations (IMAGE). Figure 2 shows schematically the location of the main observatories used, and Table 1 lists in alphabetical order their corrected geomagnetic coordinates and codes.

Owing to the longitudinal arrangement of the selected observatories, characteristics of the geomagnetic pulsations could be studied simultaneously in the morning, afternoon, and evening sectors of the Earth. For instance, during the interval 1300–1400 UT observatories NAQ ($\Phi = 68.1^\circ$) and STJ ($\Phi = 55.5^\circ$) were near the geomagnetic noon; observatories PBQ ($\Phi = 66.2^\circ$) and OTT ($\Phi = 59.3^\circ$) were in the morning sector, 0800–0900 LT; observatories FCC ($\Phi = 69.8^\circ$) and GLN ($\Phi = 60.4^\circ$) were also in the morning sector, but in the earlier one (0600–0700 LT); and the European and Scandinavian stations were in the evening sector. The geomagnetic latitudes of these observatories allowed us to study the geomagnetic pulsations in both the closed magnetosphere and the dayside polar cusp.

To analyze morphological characteristics of the long-period geomagnetic pulsations, the initial data were preliminary, digitally filtered in the 0.6–10 mHz band (Pc5), and then amplitude and dynamic spectra of the oscillations were calculated for the chosen time intervals. After this the waves were analyzed in a narrower frequency band corresponding to the maxima in the pulsation spectra.

3. Analysis of Observations

Let us consider the morphological features of the dayside geomagnetic pulsations detected at the Earth's surface dur-

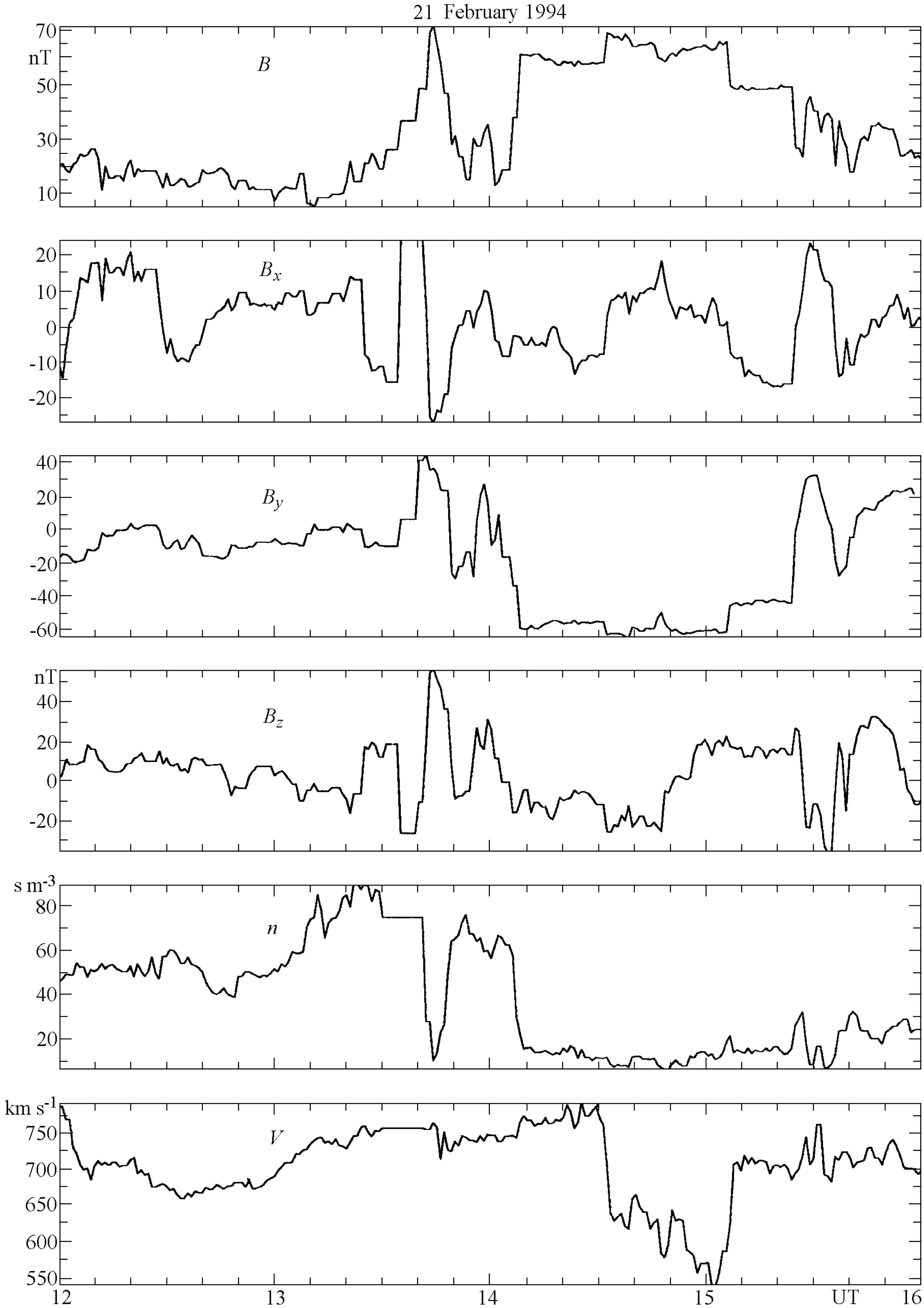

Figure 1. Variations in the IMF parameters during the time interval studied on 21 February 1994.

Table 1. List of Observatories

Observatory		Geographic Coordinates		Corrected Geomagnetic Coordinates (Tsyganenko model, 1995)	
Name	Code	Latitude	Longitude	Latitude	Longitude
Martin de Vivis	AMS	−37.83	77.57	−49.2	137.7
Bear Island	BJN	74.50	19.20	71.3	108.7
Chambon-la-Foret	CLF	48.08	02.26	43.8	80.2
Port Alfred	CZT	−46.43	51.87	−51.7	110.5
Eskdalemur	ESK	55.32	356.8	53.1	78.6
Fort Churchill	FCC	58.77	265.9	69.8	329.0
Godhavn	GDH	10.43	34.62	77.3	41.4
Glenlea	GLN	49.60	262.9	60.4	327.0
Hankasalmi	HAN	62.30	26.65	58.6	105.0
Hartland	HAD	35.68	80.15	48.1	75.9
Hermanus	HER	−34.43	19.24	−42.1	80.9
Horsund	HOR	77.00	15.60	74.0	110.5
Lerwik	LER	60.13	358.82	58.2	82.5
Longyearbyen	LYR	78.20	15.82	75.1	113.0
Masi	MAS	69.46	23.70	66.1	106.9
Moscow	MOS	55.48	37.31	51.0	112.0
New Aalesund	NAL	78.92	11.93	76.1	112.2
Narssarssuaq	NAQ	61.10	314.8	68.1	44.0
Nurmijarvi	NUR	60.51	73.00	56.6	103.0
Ottava	OTT	45.40	284.45	59.3	359.1
Oulujarvi	OUJ	64.52	27.23	60.9	106.5
Port-aux-Français	PAF	−49.35	70.20	−57.9	128.0
Poste-de-la-Baleine	PBQ	55.30	282.25	66.2	358.1
Pello	PEL	66.90	60.89	63.5	105.4
Sodankyla	SOD	67.37	26.63	63.8	107.7
Soroya	SOR	70.54	22.22	67.2	106.7
St. Jons	STJ	47.60	307.32	55.5	31.1
Wingst	WNG	53.74	09.07	51.1	87.8

ing two chosen time intervals: (a) 1300–1400 UT under a very high dynamic solar wind pressure and (b) 1500–1600 UT under strong IMF variations on the background of a lower dynamic solar wind pressure.

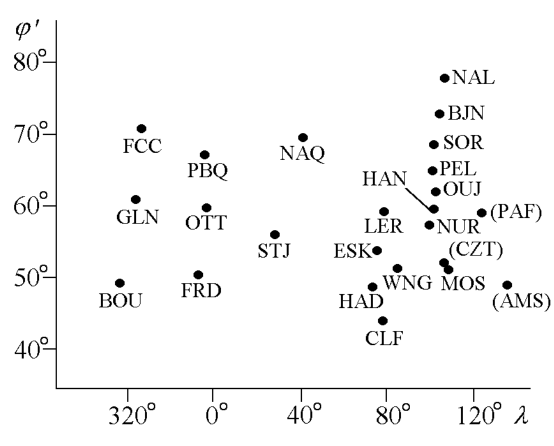

Figure 2. Location of observatories.

3.1. Interval 1300–1400 UT

A spectral analysis of the dayside geomagnetic pulsations has revealed an increased oscillation intensity in the closed magnetosphere in two frequency ranges: low frequencies, $f < 2$ mHz, and high frequencies, $f \sim 3-5$ mHz. Figure 3a demonstrates, as an example, the amplitude pulsation spectra for several observatories at 1300–1400 UT. It can be seen from Figure 3a that the spectral distributions of the pulsation intensity in the morning (GLN, FRD) and evening (NUR, PAF) sectors are similar, the pulsation amplitude in the afternoon hours being nearly twice as high as in the forenoon hours. Note the presence of well-defined discrete peaks in the oscillation spectra at similar frequencies in the morning and evening sectors.

The growth of the Pc5 pulsation amplitudes to the East and West from the noon meridian is also clearly seen in Figure 4, which shows oscillations filtered in the 3–5 mHz band for four meridians: dawn (FCC and GLN), morning (PBQ and OTT), near noon (NAQ and STJ), and evening (SOD, OUJ, and NUR). It is obvious from Figure 4 that at higher latitudes, at observatories FCC, PBQ, and NAQ, oscillations had a continuous quasi-noise character, while at the remaining observatories, the pulsations were in the form of individual wave packets coinciding in time. It can be supposed that FCC, PBQ, and NAQ were in the region of the footprint of the dayside polar cusp and entry layers, and the other stations were in the closed magnetosphere.

The geomagnetic pulsation amplitudes at similar latitudes near noon were much smaller than in the morning and evening sectors, the amplitude in the evening sector being larger than in the morning (Figure 4). For instance, at 1300–1400 UT the 3–5 mHz subauroral pulsation amplitude at observatory NUR (1700 LT) was nearly 4 times as large as that at observatory STJ (1200 LT) located at the same latitude. At the European middle-latitude observatories the Pc5 pulsation amplitudes increased from the western to the eastern observatories. For instance, in the longitudinal interval ~80°–115°, at a latitude of ~50°, the pulsation amplitude at MOS was nearly twice as high as at ESK, though ESK is located at a somewhat higher latitude.

Wave packets on the morning and evening sides were similar, with opposite directions of the wave polarization vector rotation. At ~1330 UT the polarization vector of the 3–5 mHz pulsations rotated counterclockwise in the morning (OTT) and clockwise in the afternoon sector (for instance, NUR, ESK, CLF, and others). These facts indicate that waves propagated westward and eastward from the noon meridian. The phase (φ_1) of the X component oscillations at STJ ($\lambda = 31°$) was ahead of the wave phase (φ_2) at NUR ($\lambda = 103°$) by ~2 min, which corresponds to very low azimuthal wave numbers [$m = (\varphi_2 - \varphi_1)/\Delta\lambda$] $m \sim 1$–2. The same values of m were obtained from comparison of phase differences at observatories HAD (~1300 LT) and AMS (~1800 LT) at $\Phi \sim 50°$. Note that 1-min sampling data were used in the analysis, which means that the time of the phase lag could be determined with an accuracy not better than 1 min.

The reversal of the polarization vector rotation sense took place not only in the longitudinal but also in the latitudinal direction. At the Scandinavian chain of stations the maximum amplitudes of the 3–5-mHz pulsations at 1330–1400 UT were observed at $\Phi \sim 62°$ (OUJ). On both sides of the amplitude maximum the polarization vector rotation directions were opposite (counterclockwise poleward and clockwise equatorward), which agrees with the theory of field line resonances (FLR).

Comparison of observations at the quasi-conjugate observatories CLF and HER at $\Phi \sim 43°$ has shown that oscillations in the X component occur in phase and oscillations in the Y component are in antiphase. The same picture was obtained for observatories MOS–CZT at $\Phi \sim 51°$ and for NUR–PAF at $\Phi \sim 57°$. This means that the motion of field lines at their north and south ends was symmetric with respect to the equatorial plane, which corresponds to the first (odd) harmonic of the standing wave. The polarization vector rotated in the Northern and Southern Hemispheres (CLF and HER) in opposite directions, as at MOS–CZT and NUR–PAF.

Figure 5 shows dynamic spectra of geomagnetic pulsations at three meridional profiles: morning (PBQ, OTT, FRD),

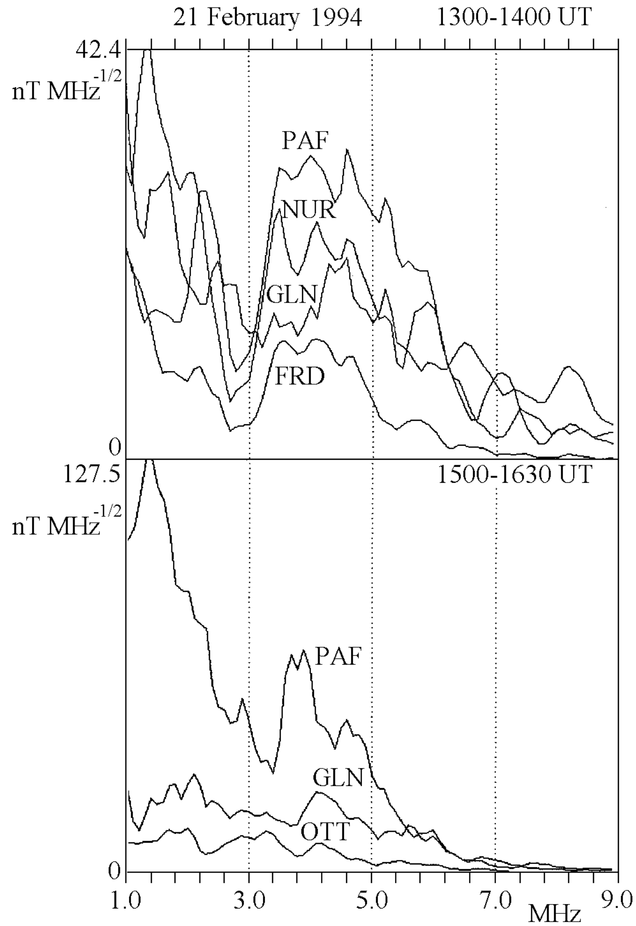

Figure 3. Examples of amplitude spectra of pulsations: (a) 1300–1400 UT and (b) 1500–1600 UT.

noon (NAQ, STJ), and afternoon (Figure 5b). Figure 6 presents dynamic spectra of oscillations for the meridional Scandinavian profile of stations (IMAGE) at the latitudes from $\Phi \sim 56°$ to $\Phi \sim 76°$. Figures 5a and 6a demonstrate that at dayside polar cusp latitudes (observatories PBQ, NAQ, NAL–BJN), at 1330–1405 UT, the amplitude maximum in the pulsation spectrum was observed at lower frequencies (0.8–1.7 mHz). The largest amplitude was observed at $\Phi \sim 74°$ (HOR), the amplitude increasing eastward.

It is evident from comparison of the spectral distributions of pulsations at observatory BJN ($\Phi \sim 72°$) and observatory SOR ($\Phi \sim 67.5°$) that the oscillation spectra extended to higher frequencies with increasing latitude. Below $\Phi \sim 62°$ the pulsation amplitudes at $f < 2$ mHz became comparable with the wave amplitudes in the 3–5 mHz range (Figure 5b).

Two well-defined temporal wave packets, at 1320–1345 UT and 1355–1410 UT (Figures 4–6), were observed at all observatories located inside the closed magnetosphere. The first wave packet contained only low-frequency pulsations with $f < 2$ mHz, and the second packet contained high-frequency pulsations with $f > 3$ mHz. This picture was especially pronounced in the morning sector at observatories OTT and FRD (Figure 5a), and also in the afternoon

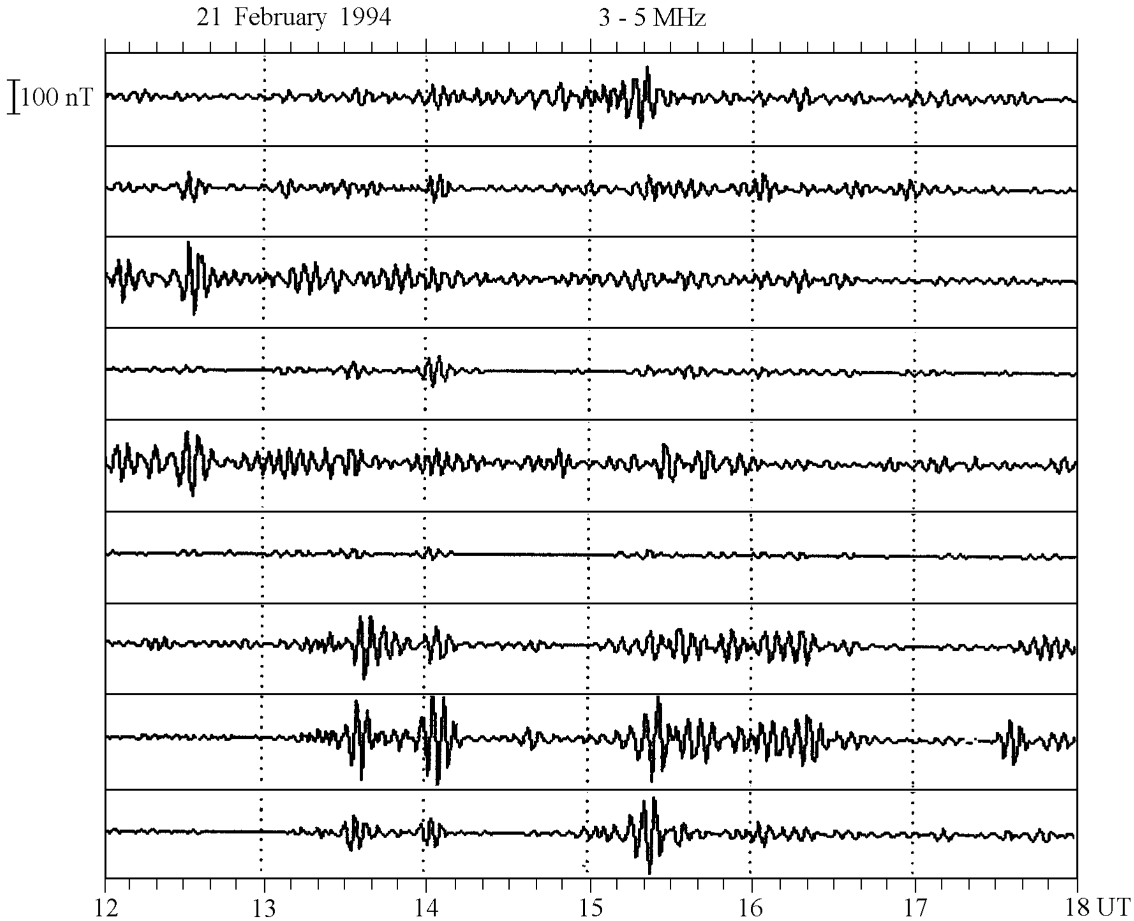

Figure 4. Geomagnetic pulsations filtered in the 3–5 mHz band for three local time sectors: (a) morning, (b) near noon, and (c) afternoon.

time at observatories HAN and NUR (Figure 6b) where pulsation amplitudes were nearly an order of magnitude larger (see the scale of the graphs). In the noon time (observatory STJ in Figure 5a) the low-frequency oscillations had a much greater intensity than the high-frequency oscillations.

At the Scandinavian meridian (Figure 6b), at 1320–1410 UT, two wave packets are also clearly seen. The first was characterized by a strong burst of low-frequency pulsations at polar latitudes (Figure 6a, NAL–BJN). Their amplitudes decreased rapidly with decreasing latitude. Note that the bursts of the 3–5-mHz oscillations were observed in these two wave packets both at the latitudes of the dayside polar cusp (NAL, LYR, HOR) and in the closed magnetosphere (Figure 6b). At lower latitudes (HAN, NUR) the amplitudes of the 3–5 mHz oscillations were larger in the second burst than in the first burst. A similar picture was observed in the morning sector (FRD, OTT). The SOR and MAS stations were probably located near the boundary between the closed and the open magnetosphere.

An abrupt suppression of the 3–5 mHz oscillations (Figures 4–6) occurred at 1404 UT and coincided with the occurrence of a negative magnetic impulse which was most pronounced at the magnetograms of the European observatories (Figure 7) and also with a sharp decrease in the dynamic solar wind pressure from $P \sim 70$ nPa to $P \sim 10$ nPa [*Yamauchi et al.,* 1996]. According to the Geotail data, the solar wind density decreased at this moment from $n \sim 66$ cm^{-3} to $n \sim 12$ cm^{-3}, the solar wind velocity remaining nearly stable ($V \sim 750$ km s^{-1}). The amplitude dynamic pulsation spectra show that a drastic suppression of oscillations at ~1400 UT is more typical of the Pc5 pulsations (3–6 mHz). At the polar cusp latitudes, at observatories NAL–HOR (Figure 6a), intense ($f < 2$ mHz) pulsations also disappeared at ~1400 UT; and less intense oscillations ($f \sim 3-5$ mHz) also sharply decayed at ~1415 UT. Similar to lower latitudes (observatories HAN–NUR), weak waves with $f < 2$ mHz were then observed at higher latitudes during the entire period studied (till ~1440 UT).

At observatories NAQ (noon) and PBQ (morning), which is located at a close latitude but $\sim 40^\circ$ to the West, the low-frequency 0.6–2.0-mHz wave packets did not coincide, though the spectra exhibited a broad maximum in this frequency range. The pulsation amplitude at NAQ was as high as 100 nT, and at STJ (the same meridian but 12° lower in the latitude), it was only ~20 nT. This means that the low-frequency oscillation amplitude decreased sharply with latitude, as at the Scandinavian meridian. The dynamic spectra shown in Figure 5a suggest that PBQ and NAQ were located near the projection of the equatorial boundary of the dayside polar cusp where intense pulsations at $f < 2$ mHz, typical of these latitudes, were excited. At lower latitudes (OTT and STJ), in the closed magnetosphere, the amplitudes of these pulsations were 4–5 times smaller.

The differences between the morphological characteristics and the dynamics of the pulsations at the frequencies above and below 3 mHz suggest that these pulsations have different origins.

3.2. Interval 1500–1600 UT

The beginning of this interval was characterized by a decrease in the dynamic solar wind pressure to $P \sim 10$ nPa on the background of a very high magnetic pressure. The IMF B was greater than 60 nT under large positive B_z (to +20 nT) and very large negative B_y (to −60 nT); the solar wind velocity was about 600 km s^{-1} (Figure 1).

At ∼1500 UT a small jump in the dynamic pressure of the solar wind from ∼4.5 nPa to ∼11 nPa due to a sharp increase in its velocity from ∼550 to ∼700 km s^{-1} was observed. It was accompanied by a new burst of long-period geomagnetic pulsations with the highest intensity in the afternoon sector, as during the interval discussed earlier. Compared to 1300–1400 UT, only a slight enhancement of the $f < 2$ mHz pulsations and weak higher-frequency oscillations were observed at the polar cusp latitudes (Figures 5a and 6a).

At the Scandinavian meridian, i.e., at ∼1700 LT (Figure 6a), two bands in the wave spectrum, at $f < 2$ mHz and $f > 2$ mHz, were well pronounced at the latitudes lower than ∼65°, similar to 1300–1400 UT. The low-frequency maximum had a much higher intensity than the high-frequency one. The Pc5 pulsations had the largest amplitudes at $f \sim 3 - 4$ mHz. The wave intensity maximum was observed at $\Phi \sim 60^\circ - 62^\circ$ (OUJ, HAN) at 1520–1530 UT, i.e., somewhat later than the low-frequency maximum. At the midlatitude European observatories (Figure 5b) the main maximum in the oscillation spectrum was observed at low frequencies, $f < 2$ mHz.

The onset of the burst of the 3–4-mHz oscillations coincided with the sign reversal of the B_z component, from +25 nT to −24 nT (Figure 1). At that time the change of the B_y from −44 nT to +30 nT and B_x from −17 nT to +23 nT also occurred. In the dayside sector of the magnetosphere (Figure 5a), observatories NAQ and STJ detected only low-frequency ($f < 2$ mHz) oscillations with much smaller amplitudes than at 1300–1400 UT. In before noon hours (1000 LT), the pulsation spectra at FRD ($\Phi \sim 50^\circ$) had two pronounced frequency bands (Figure 5a), similar to the pre-evening post-noon sector (the Scandinavian meridian), but the oscillation amplitude was much smaller than in the evening. Figure 3b shows the amplitude pulsation spectra at observatories GLN (0800 LT), OTT (1000 LT), and PAF (2000 LT). It is obvious that oscillations are considerably enhanced in the evening sector.

Thus a sudden southward reversal of the B_z direction led to the excitation of the 3–5 mHz geomagnetic Pc5 pulsations with the maximum amplitude in the afternoon hours, both at 1300–1400 UT, under the conditions of a high dynamic solar wind pressure ($P > 70$ nPa), and at 1500–1600 UT, under a lower pressure ($P \sim 5 - 10$ nPa). A sharp large decrease in the solar wind density resulted in an abrupt suppression of the Pc5 generation. In the low-frequency range ($f < 2$ mHz), bursts of oscillations occurred during both intervals. The highest pulsation amplitudes were observed at the dayside polar cusp latitudes during the first interval and in the evening sector inside the closed magnetosphere during the second interval.

4. Discussion

Thus on 21 February 1994, at 1300–1600 UT, a passage of a large-scale solar wind irregularity with very strong variations in the interplanetary magnetic field and solar wind (Figure 1) happened in the near-Earth space. It was accompanied by bursts of long-period geomagnetic Pc5 pulsations with maximum amplitudes in the afternoon sector.

Many authors attribute the generation of Pc5 pulsations to development of the Kelvin-Helmholtz instability at the magnetopause or flanks of the entry layers of the magnetosphere flowed by the solar wind. Generally, symmetric flowing around the Earth must give rise to surface waves symmetric in space with respect to noon. However, the majority of researchers [e.g., *Chisham and Orr*, 1997; *Kokubun et al.,* 1989; *Nosé et al.,* 1995; *Ol',* 1963; *Pilipenko et al.,* 1997; *Yumoto et al.,* 1983] convincingly showed the asymmetry of pulsations on the morning and evening sides of the Earth. It is probably the result of a spiral structure of the solar wind when the IMF direction is closer to the normal to the magnetopause boundary in the morning hours than in the afternoon. Hence the criteria for excitation of the Kelvin-Helmholtz instability on the morning side are satisfied more easily than on the afternoon side [*Lee and Olson*, 1980].

Comparison of the ground-based and satellite observations has shown [*Kokubun et al.,* 1989; *Yumoto et al.,* 1983] that in the morning magnetosphere, transverse azimuthally polarized waves well correlating with the oscillations at the Earth's surface are mostly detected, while in the afternoon sector, radially polarized compressional waves poorly correlating with the ground-based observations dominate.

In the case we discuss here the largest amplitudes of the Pc5 pulsations (3–5 mHz) were observed in the afternoon sector rather than in the morning sector. Hence it is unlikely that their source is the Kelvin-Helmholtz instability.

The morphological characteristics of the 3–5-mHz geomagnetic pulsations observed on 21 February 1994, such as opposite polarizations in the morning and afternoon sectors, polarization reversal along latitude near the wave amplitude maximum, a discrete spectrum, the phase relations between oscillations, opposite directions of the polarization vector rotation in conjugate regions, low azimuthal wave numbers ($m \sim 1 - 2$), and the temporal structure of the pulsations in the form of individual wave packets. These characteristics suggest that the pulsations have a resonance nature.

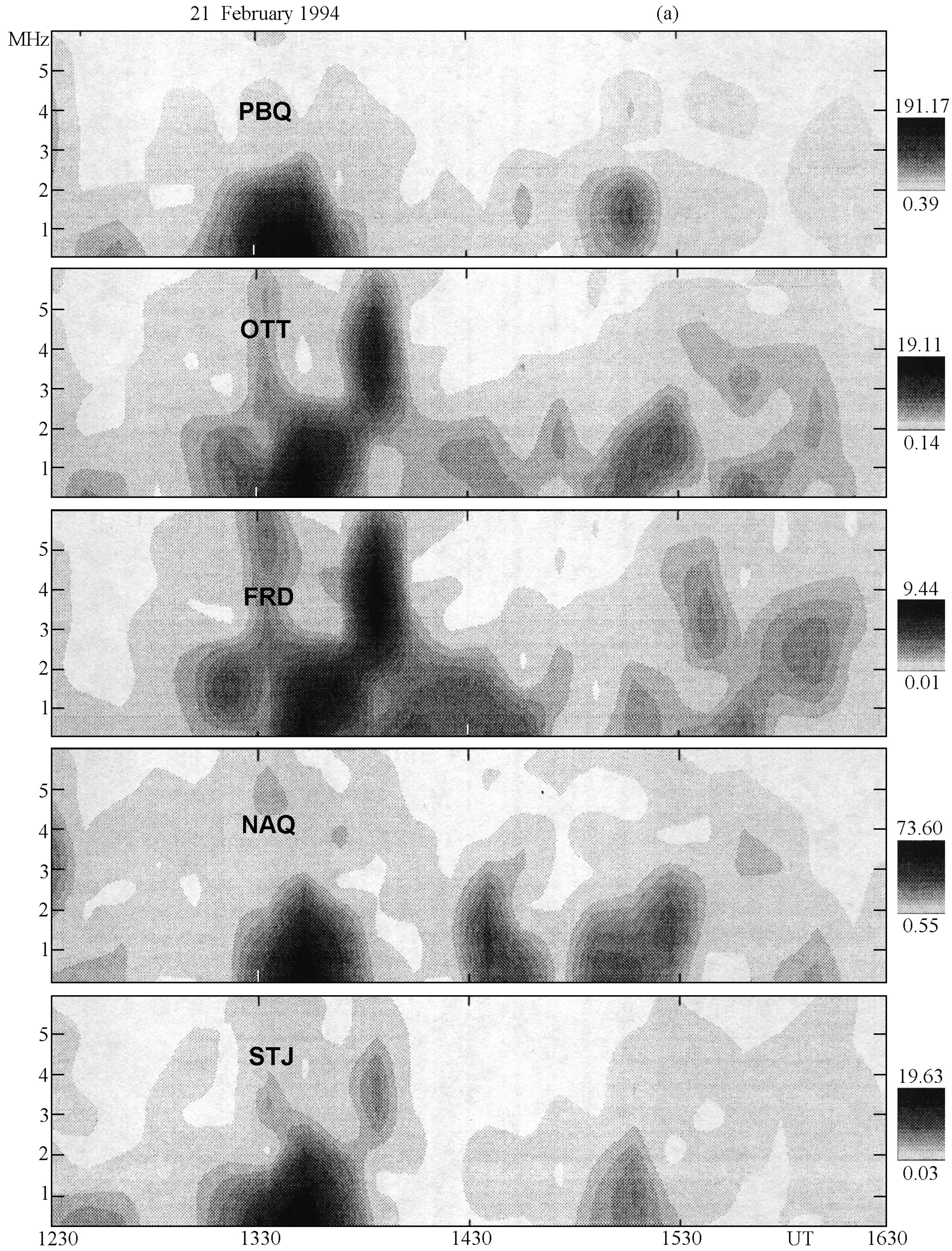

Figure 5. Dynamic spectra of pulsations in three local time sectors: (a) morning and near noon and (b) afternoon.

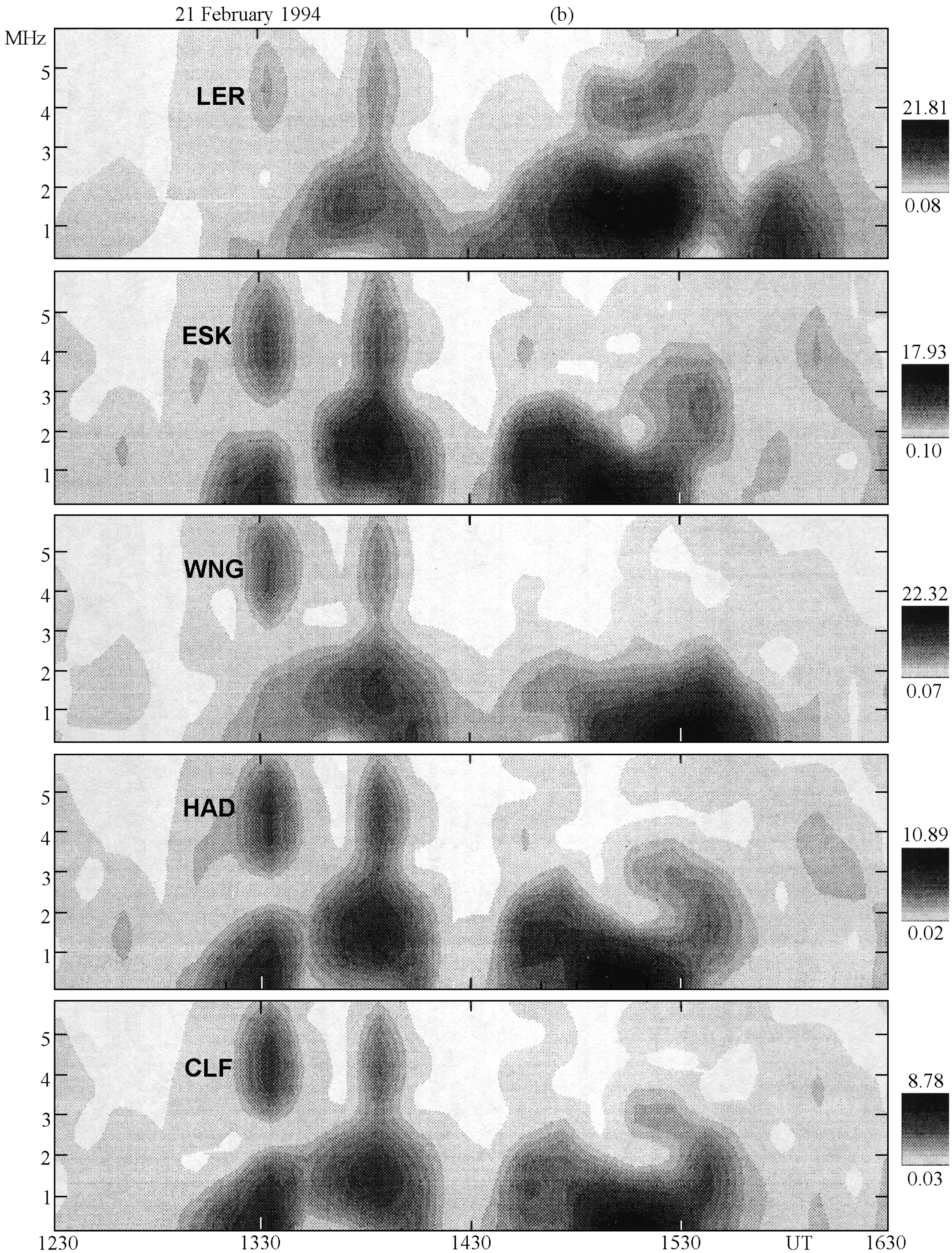

Figure 5. (continued).

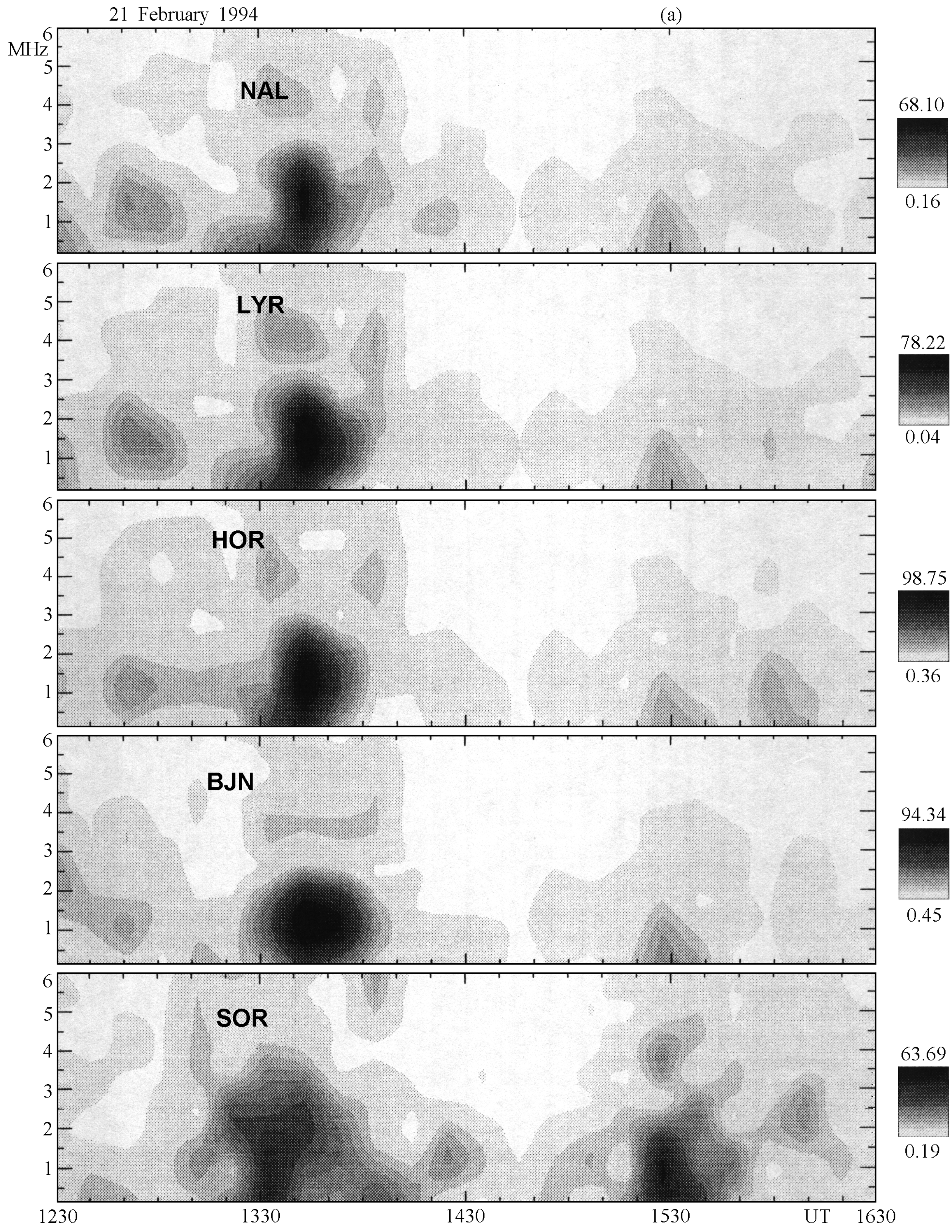

Figure 6. Dynamic spectra of geomagnetic pulsations at the Scandinavian meridian.

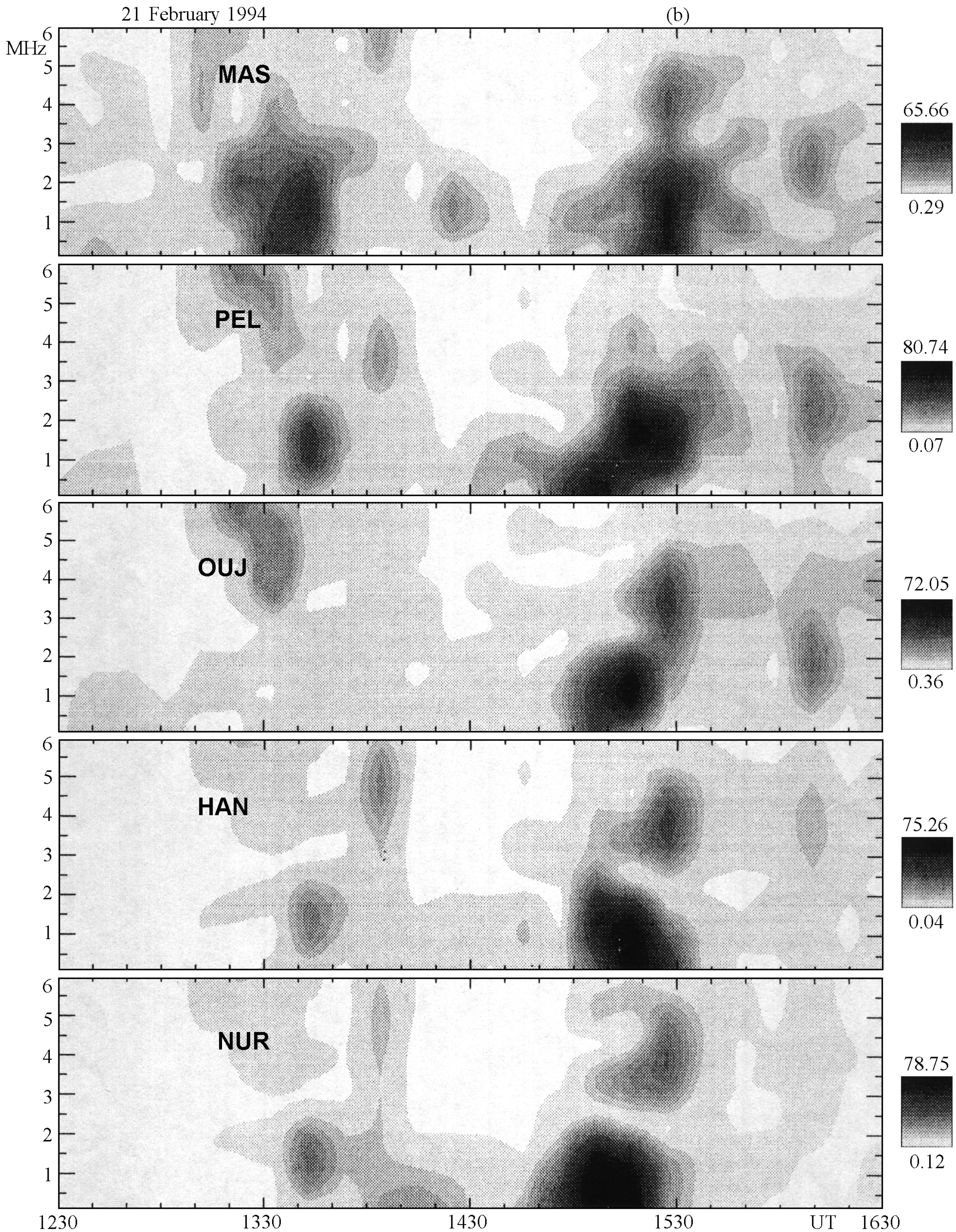

Figure 6. (continued).

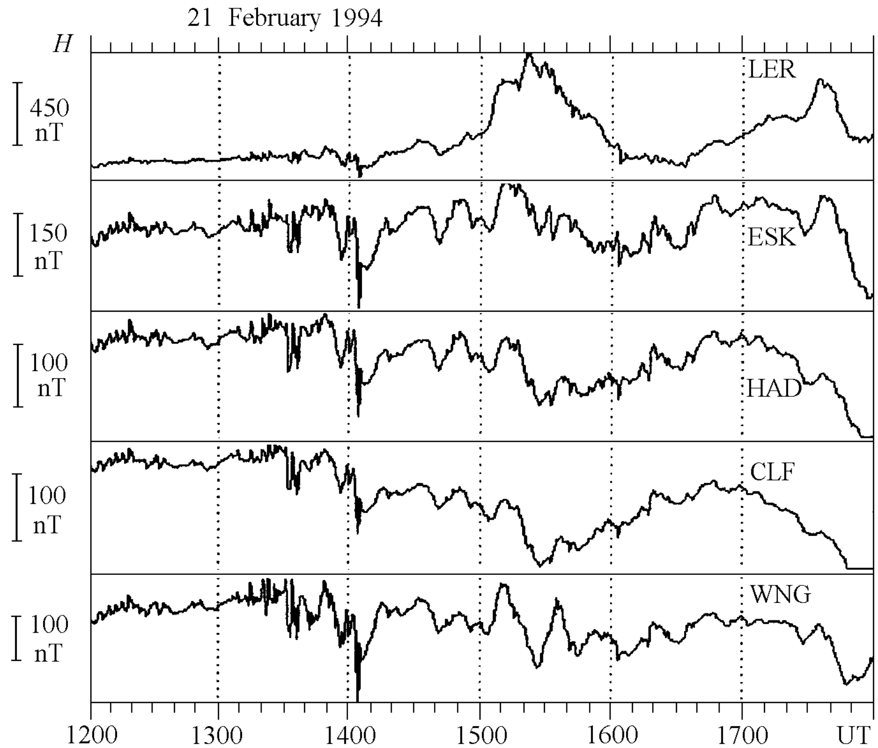

Figure 7. Magnetograms of midlatitude European observatories illustrating a sharp suppression of geomagnetic pulsations after a sudden negative impulse Si.

Besides the Kelvin-Helmholtz instability, the Alfvén resonance of field lines (FLR) can also be caused, for instance, by a magnetic impulse in the IMF. As a rule, FLRs are observed mainly in the morning sector of the magnetosphere. However, some authors reported on the cases of simultaneous occurrence of the geomagnetic Pc5 pulsations on the morning and afternoon sides of the Earth. For instance, in the initial phase of the great magnetic storm of 24 March 1991, quasi-sinusoidal oscillations with a period of 8–10 min, synchronous wave packets, and maximum amplitude in the afternoon sector were observed on the dayside of the magnetosphere [*Araki et al.,* 1995; *Kleimenova et al.,* 1998; *Schott et al.,* 1998].

Shimazu et al. [1995] also described the events of simultaneous occurrence of the geomagnetic Pc5 pulsations with similar waveforms in the morning (0400 LT, observatory College) and evening (1800 LT, observatory Kiruna) sectors. The *H*-component variations at observatories Kiruna and College were in antiphase and corresponded to opposite directions of the polarization vector rotation in the morning and evening times, as in our case. The intensification of pulsations was observed under a high (~620 km s^{-1}) solar wind velocity and increased dynamic solar wind pressure. *Shimazu et al.* [1995] concluded that the source of global Pc5 is associated with the magnetosphere cavity resonance excited by the passage of a high-pressure front of the solar wind irregularity in the interplanetary space.

The global geomagnetic 3–5-mHz pulsations that we observed are likely to have the same origin, namely, a global compressional wave in the magnetosphere. This frequency range agrees with the numerical calculations of *Kivelson et al.* [1984]. The oscillations are enhanced at the frequencies at which the wave cavity mode matches local FLRs [*Kivelson and Southwood*, 1986]. *Yeoman et al.* [1990] showed that the closest interaction between the compressional mode and Alfvén FLR is observed for the waves with low wave numbers ($m \sim 1-3$). We observed the same values of m for the 3–5 mHz range on 21 February 1994.

Potemra et al. [1989] showed that periodical variations in the solar wind density lead to excitation of waves propagating from the dayside toward the magnetotail. In turn, these waves give rise to local Alfvén field line resonances. Figure 8 presents the amplitude dynamic spectra of variations in the IMF B and solar wind density observed by Geotail. Note that in order to refer the satellite observations to the Earth's orbit, it is necessary to take into account the ~7–8 min lag for 1300–1400 UT and a somewhat smaller lag (~4–6 min) for 1500–1600 UT because of the satellite position during the time interval analyzed [*Yamauchi et al.,* 1996].

Comparison of Figure 8 with Figures 5 and 6 reveals that the burst of geomagnetic pulsations at 1300–1400 UT coincides with a similar burst of the interplanetary magnetic field and solar wind density variations. As at the ground-based observatories, the main maximum in the spectrum of variations in the solar wind parameters is observed at $f < 2$ mHz. Hence it allows us to propose hypotheses that the geomag-

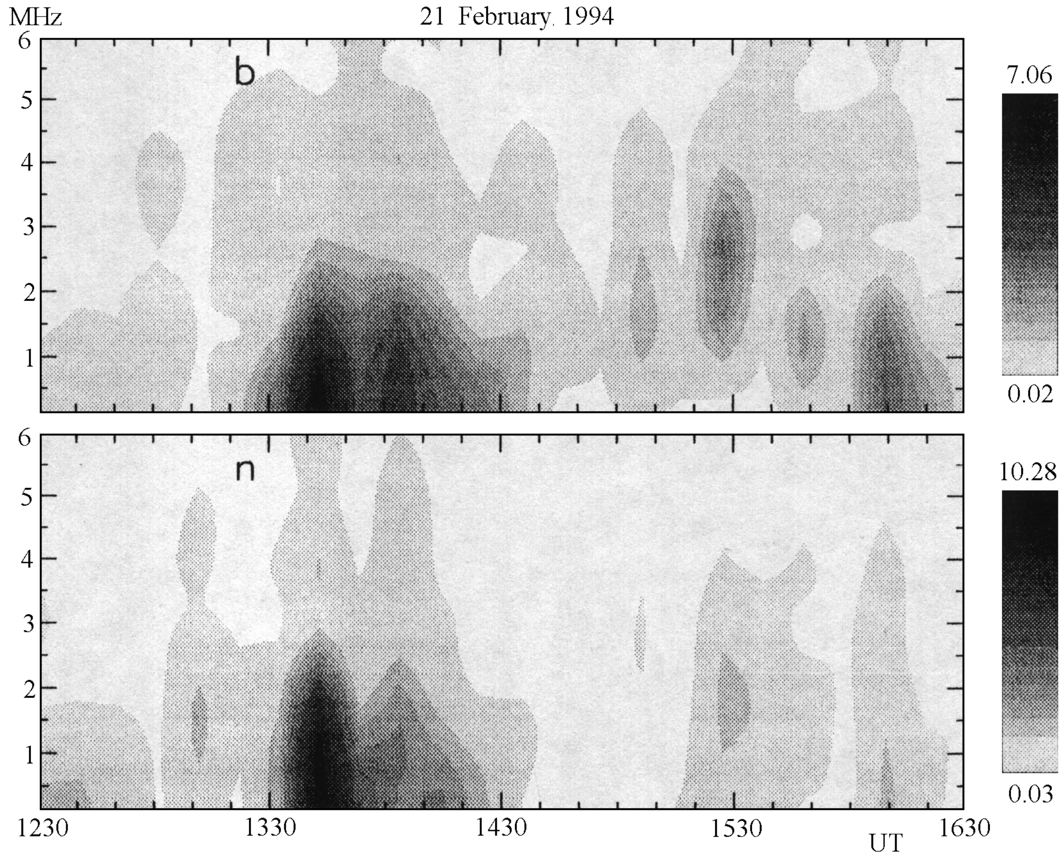

Figure 8. Dynamic spectra of density and IMF $|B|$ variations according to the Geotail data for the intervals studied on 21 February 1994.

netic pulsations can be caused by corresponding oscillations in the IMF which penetrate immediately into the dayside polar cusp region.

The Pc5 generation was abruptly suppressed when a sudden impulse *Si* occurred (Figure 7). Such a sudden disappearance of Pc5 pulsation was also observed during the magnetic storm of 24 March 1991 [*Kleimenova et al.,* 1998]. The effect of an abrupt suppression of the Pc2–4 pulsations on the global scale (observatory Petropavlovsk, Kamchatka, observatory Borok, Europe, and observatory Soroa, Cuba) after *Si* was also noted by *Troitskaya et al.* [1969] who attributed it to a sudden expansion of the magnetosphere. However, in our case a sharp decay of Pc5 after ~1405 UT can be caused by changes in the conditions in the IMF, or namely, a sudden sharp decrease of the cone angle, because the B_x/B ratio suddenly decreased from ~0.45 to ~0.003 under very high values of the IMF B-component. This confirms our hypothesis that the source of Pc5 at 1300–1400 UT is the IMF variations.

Note that during the interval 1500–1600 UT, contrary to 1300–1400 UT, the geomagnetic pulsation spectra on the ground did not coincide with the spectra of variations in the IMF parameters. At ~1530 UT the intensity of low-frequency pulsations in the solar wind was much lower than at ~1330 UT. However, the afternoon and evening $f < 2$ mHz pulsations on the ground were much stronger at ~1530 UT than at ~1330 UT (Figures 5 and 6). They were not observed at the polar cusp latitudes (Figure 6a). Therefore it can be supposed that under a high dynamic solar wind pressure the magnetic pulsations at the Earth's surface at 1300–1400 UT had an external origin, while under the conditions of a high magnetic pressure at 1500–1600 UT, the source of oscillations was located inside the magnetosphere.

The 3–5-mHz pulsations were observed not only on the ground but also in the interplanetary space. Figure 9 shows variations in B, B_x, B_y, B_z, and solar wind density (n) filtered in this band. It is seen that variations in the density and magnetic field (IMF B_x) are in antiphase, which corresponds to the compressional wave in the solar wind.

For the interval 1330–1340 UT the Geotail measurements were not available, and it was impossible to define whether the burst of the ground (3–5 mHz) Pc5 at that time coincided with the onset of pulsations in the solar wind density in the same frequency range. A sudden suppression of the middle-latitude Pc5 coincided with a sharp decrease in the solar wind density and disappearance of pulsations of the same periods in the density as well as in IMF B_z and B_y. It is interesting to note that during the period when the first wave packet of Pc5 (1325–1350 UT) was detected, the

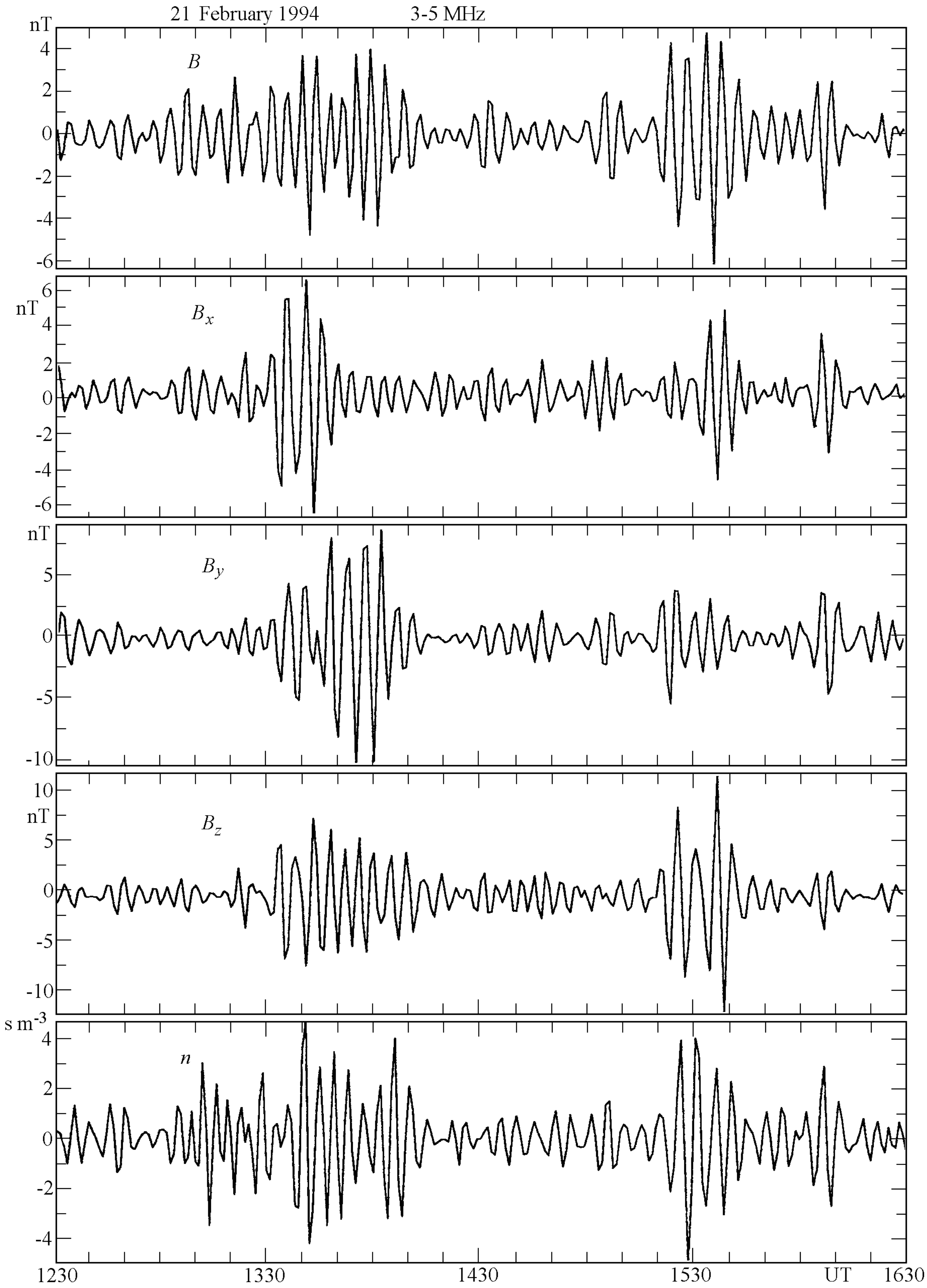

Figure 9. Variations in the IMF parameters and solar wind density filtered in the 3–5 mHz band.

strongest variations occurred in the IMF B_x (the data on density variations were not available), which means that the waves had a compressional structure. During the second Pc5 wave packet (1355–1406 UT) the strongest variations were detected in the IMF B_y, though pulsations of the IMF B_z were also observed. Therefore the wave in the solar wind had both the transverse and the compressional field components, and source of ground Pc5 could be associated with compressional waves of the same periods in the solar wind. A similar excitation of FLR due to quasi-periodical oscillations in the solar wind parameters was reported by *Prikryl et al.* [1998].

The regression analysis of the relationship between the Pc5 amplitude on the ground and the IMF parameters has shown that during the first interval, under the strong solar wind dynamic pressure and $B_z > 0$, $B_x < 0$, and $B_y > 0$, the dayside pulsation amplitude was mostly controlled by the IMF B_y (with the regression coefficients up to 0.93), as well as it is typical for field-aligned currents. During the second interval, under the strong IMF magnetic pressure and $B_z < 0$, $B_x > 0$, and $B_y > 0$, the most effective IMF component was B_x (with the regression coefficients up to 0.89). During both intervals, the strongest bursts of pulsation were observed under $B_y > 0$.

5. Conclusions

Thus under the extreme conditions of the magnetic storm of 21 February 1994, characterized by very high values of the interplanetary magnetic field and solar wind parameters and their strong variations (Figure 1), the dayside geomagnetic pulsation spectra showed two well-defined bands of enhanced oscillations (low frequency, $f < 2$ mHz, and high frequency, 3–5 mHz).

During the first interval (1300–1400 UT), variations in the IMF occurred on the background of a very high solar wind dynamic pressure (to ∼100 nPa). According to the Geotail data, oscillations of the interplanetary magnetic field and density were in antiphase, which can be the evidence of the approach to the Earth of an interplanetary compressional wave causing generation of geomagnetic pulsations at $f <$ 2 mHz with the largest amplitudes near the dayside polar cusp (Figures 5a, 6a, and 8).

During the second interval (1500–1600 UT) the solar wind dynamic pressure decreased to ∼10 nPa, and no intense pulsations at $f < 2$ mHz were observed either in the solar wind or in the polar cusp. However, a more intense burst of oscillations at $f < 1.5$ mHz than at 1300–1400 UT was observed in the afternoon closed magnetosphere. The onset of these oscillations coincided with the approach of a sharp gradient of the dynamic solar wind pressure to the Earth. It can be supposed that in the first case the low-frequency oscillations had the external origin, and in the second case, the source of waves was located inside the magnetosphere.

The high-frequency Pc5 (3–5 mHz) geomagnetic pulsations in the dayside magnetosphere were observed during both intervals. Their morphological characteristics corresponded to FLR (polarization reversal near the noon longitude and in the latitude region of the wave amplitude maximum, a discrete spectrum with coinciding maxima in the morning and evening hours, the antiphase H components in conjugate regions, very low azimuthal wave numbers, the temporal structure of the pulsations in the form of individual wave packets). However, contrary to typical Pc5, these pulsations were more intense on the evening side than on the morning side (Figure 4); the onset of their generation coincided with a sudden change of the IMF B_z from positive to negative; the abrupt suppression of pulsations coincided with a sharp drop in the solar wind density. The observation of simultaneous similar pulsations in the IMF (Figure 9) suggests that a possible source of FLR are IMF oscillations in the solar wind.

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References

Araki, T., H. Luehr, D. Orr, and D. K. Milling, Geomagnetic sudden commencement on February 21, 1994, part II, *STEP GBRSC News, 5*(1), 13, 1995.

Bol'shakova, O. V., O. K. Borovkova, N. G. Kleimenova, Yu. E. Borovkov, and J. Bitterly, Magnetic storm of March 13, 1989: The structure of the extremely disturbed magnetosphere from geomagnetic Pc5 pulsations, *Geomagn. Aeron. (in Russian), 34*(4), 73, 1994.

Chisham, G., and D. Orr, A statistical study of the local time asymmetry of Pc5 ULF wave characteristics observed at midlatitudes by SAMMET, *J. Geophys. Res., 102*, 24,339, 1997.

Engebretson, M. J., I. J. Cahill, and D. J. Williams, Pulsations in magnetic field and ion flux observed at $L = 4.5$ on August 5, 1972, *J. Geophys. Res., 88*, 161, 1983.

Kivelson, M. G., and D. J. Southwood, Coupling of global magnetospheric MHD eigenmodes in the field-aligned resonances, *J. Geophys. Res., 91*, 4345, 1986.

Kivelson, M. G., J. Etcheto, and J. G. Trotignon, Global compressional oscillations of the terrestrial magnetosphere: The evidence and a model, *J. Geophys. Res., 89*, 9851, 1984.

Kleimenova, N. G., O. V. Kozyreva, M. Bitterly, J. J. Schott, U. Villante, P. Francia, and A. Best, Two types of dayside long-period geomagnetic Pc5 pulsations at middle latitudes during a strong storm, *Geomagn. Aeron. (Engl. Transl.), 38*(1), 45, 1998.

Kokubun, S., K. N. Erickson, T. A. Fritz, and R. L. McPherron, Local time asymmetry of Pc4–5 pulsations and associated particle modulations at synchronous orbit, *J. Geophys. Res., 94*, 6607, 1989.

Lee, L. C., and J. I. Olson, Kelvin-Helmholtz instability and the variation of geomagnetic pulsation activity, *Geophys. Res. Lett., 7*, 777, 1980.

Nosé, M., T. Iyemori, M. Sugiura, and J. A. Slavin, A strong dawn/dusk asymmetry in Pc5 pulsation occurrence observed by the DE-1 satellite, *Geophys. Res. Lett., 22*(15), 2053, 1995.

Ol', A. N., Long period gigantic geomagnetic pulsations, *Geomagn. Aeron. (in Russian), 3*, 90, 1963.

Petrinec, S. M., K. Yumoto, K. Shiokawa, and S. Kokubun, Geomagnetic sudden commencement on February 21, 1994, part 1, *STEP GBRSC News, 5*(1), 11, 1995.

Pilipenko, V. A., N. G. Kleimenova, O. V. Kozyreva, K. Yumoto, and J. Bitterly, Longitudinal features of Pc5 geomagnetic pulsations in the morning and evening sectors, *Geomagn. Aeron. (Engl. Transl.), 37,*(3), 307, 1997.

Potemra, T. A., H. Luhr, L. J. Zanetti, K. Takahashi, R. E. Erlandson, G. T. Marklund, L. P. Block, L. G. Blomberg, and R. P. Lepping, Multisatellite and ground-based observations of transient ULF waves. *J. Geophys. Res., 94*, 2543, 1989.

Prikryl, P., R. A. Greenwald, G. J. Sofko, J. P. Villain, C. W. S. Ziesolleck, and E. Friis-Christensen, Solar-wind-driven pulsed magnetic reconnection at the dayside magnetopause, Pc5 compressional oscillations, and field-aligned resonances, *J. Geophys. Res., 103*, 17,307, 1998.

Samson, J. S., B. G. Harrold, J. M. Ruohoniemi, and A. D. M. Walker, Field line resonances associated with MHD waveguides in the magnetosphere, *Geophys. Res. Lett., 19*, 441, 1992.

Schott, J. J., N. G. Kleimenova, J. Bitterly, and O. V. Kozyreva, The strong Pc5 geomagnetic pulsations in the initial phase of the great magnetic storm of March 24, 1991, *Earth Planets Space, 50,* 101, 1998.

Shimazu, H., T. Araki, T. Kamei, and H. Honado, A symmetric appearance of Pc5 on dawn and dusk sides associated with solar wind pressure enhancement, *J. Geomagn. Geoelectr., 47*, 177, 1995.

Troitskaya, V. A., R. V. Shchepetnov, and A. V. Gul'el'mi, The effect of sudden suppression of geomagnetic Pc2–4 pulsations, *Geomagn. Aeron. (in Russian), 9*, 363, 1969.

Villante, U., P. Francia, S. Lepidi, M. De Lauretis, E. Pietropaolo, L. Cafarella, A. Meloni, A. J. Lazarus, R. P. Lepping, and F. Marimi, Geomagnetic field variations at low and high latitude during the January 10–11, 1997 magnetic cloud, *Geophys. Res. Lett., 25*(14), 2593, 1998.

Walker, A. D. M., J. M. Ruohoniemi, K. B. Baker, R. A. Greenwald, and J. C. Samson, Spatial and temporal behavior of ULF pulsations observed by the Goose Bay HF radar, *J. Geophys. Res., 97*, 12,187, 1992.

Yamauchi, M., et al., Dynamic response of the cusp morphology to the solar wind: A case study of passage of the solar wind plasma cloud on February 21, 1994, *J. Geophys. Res., 101,* 24,674, 1996.

Yeoman, T. K., M. Lester, D. Orr, and H. Luhr, Ionospheric boundary conditions of hydromagnetic waves: The dependence on azimuthal wave number and a case study, *Planet. Space Sci., 38*, 1315, 1990.

Yumoto, K., T. Saito, and T. Sakurai, Local time asymmetry in the characteristics of Pc5 magnetic pulsations, *Planet. Space Sci., 31,* 431, 1983.

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