"Physics of Auroral Phenomena", Proc. XXXII Annual Seminar, Apatity, pp. 85 - 88, 2009

Polar Geophysical Institute

GENERATION OF MAGNETIC AND PARTICLE *PC5* PULSATIONS AT THE RECOVERY PHASE OF STRONG MAGNETIC STORM

V.B. Belakhovsky [1], V.A. Pilipenko [2], T. Ulich [3]

[1]*Polar Geophysical Institute, Apatity*
[2]*Institute of the Earth Physics, Moscow*
[3]*Sodankyla Geophysical Observatory, Finland*

Abstract. The intense *Pc5* pulsations at the recovery phase of strong magnetic storm 21 November 2003 are considered in detail. A global structure of disturbance is studied using data from a world-wide array of magnetometers and riometers augmented with data from particle detectors and magnetometers on board the geosynchronous *GOES* and *LANL* satellites. The local spatial structure is examined using the Finnish riometer array and *IMAGE* magnetometers. Though a general similarity between the quasi-periodic magnetic and riometer variations is observed, their local propagation patterns turn out to be different. To interpret the observations, we suggest a hypothesis of coupling between two oscillatory systems: magnetospheric MHD waveguide and the system turbulence + electrons. The observed *Pc5* oscillations are supposed to be a result of the MHD waveguide excitation at both flanks of the magnetosphere. The magnetospheric MHD waveguide turns out to be in a meta-stable state under high solar wind velocities. A comparison of electron fluxes at *LANL* and ground ULF observations shows that the magnetospheric waveguide is excited by particle injection into the morning side of the magnetosphere.

Introduction

The dynamics of waves during magnetic storms is observed to be closely related to that of particles, and various kinds of interrelationships can occur: resonant or non-resonant, excitation of MHD waves by instabilities of energetic particles, modulation of ionospheric fields and currents by quasi-periodic particle precipitation, modulation of the ring current particles by magnetospheric MHD waves, and energization of the equatorial and auroral electrons by ULF turbulence. To reveal the wave-particle interaction effects from ground-based observations the magnetometer data should be supplemented with ionospheric riometer observations, indicating the level of energetic particle precipitation into the ionosphere.

The ULF modulation effects for precipitating electrons were revealed by simultaneous magnetic and riometer observations of the cosmic noise absorption (CNA) [Olson et al., 1980; Posch et al., 1999]. Conjugate observations reveal a variety of temporal associations between CNA disturbances appearing in opposite hemispheres [Posch et al., 1999]. CNA is caused by the precipitation of magnetospheric electrons or flare-associated solar energetic protons. The increased CNA may be related to increased intensity of precipitating electrons or to the increase of the rigidity of their spectrum. However, ULF waves detected by ground magnetometers, however, are not always accompanied by riometric pulsations. Inverse situations, when ionospheric ULF modulation is not accompanied by ground geomagnetic pulsations, are more rare.

Most currently understood mechanisms for the modulation of electron precipitation by ULF waves are based on the mechanism suggested by Coroniti and Kennel [1970], in which a compressional wave component $b_{\|}$ modulates the growth rate of the electron-cyclotron VLF instability. However, quite often investigations of electron precipitation associated with Pc5 pulsations did not reveal either $b_{\|}$ [Nose et al., 1998] or background VLF turbulence [Paquette et al., 1994]. Therefore other mechanisms should be invoked. In this paper we consider example of global *Pc5* pulsations of geomagnetic field and riometric absorption during the recovery phases of the strong magnetic storms on 21.11.2003, and examine their spatial structure and their relation to variations of energetic particle fluxes at geosynchronous orbit and interplanetary parameters. These observation results raise, in our opinion, several important questions about the possible excitation mechanisms of *Pc5* magnetic and CNA pulsations.

Observational facilities

The interplanetary parameters are characterized by 1-min magnetic and plasma data from *OMNI* database. We use *LANL* and *GOES* geostationary satellites to observe particle flux and magnetic field in the magnetosphere. The local structure of magnetic and precipitation disturbances are examined using 10-s data from magnetic and riometer stations in Finland. These stations may be grouped in the following gradient pairs to reveal propagation effects in the latitudinal and longitudinal directions:

Meridional (along geomagnetic longitude ~107°) high-latitude (*IVA-SOD*) and low-latitude (*OUL-HAN*/*JYV*) pairs; An azimuthal pair of stations *ABK-IVA* at geomagnetic latitude Φ~65°, separated by $\Delta\lambda$=6.8° in longitude (350 km).

The event of November 21, 2003

The global spatial-temporal structure of these Pc5 pulsations was examined in detail by Kleimenova et al. [2005]. The severe magnetic storm on November 20, 2003 (*Dst* ~ -400 nT) was caused by a rapid increase of the solar wind velocity *V* from 450 up to 700 km/s and density *N* up to 20 cm^{-3}, accompanied by an *IMF* orientation change to southward *Bz*~ -40 nT. During the recovery phase November, 21 2003 (day 325) a substorm occurred at ~0540 UT, with maximal intensity (~1600 nT) in the dusk sector at rather high latitude (*BRW*) (**Fig. 1**.). The velocity *V* at this time dropped down to ~540 km/s.

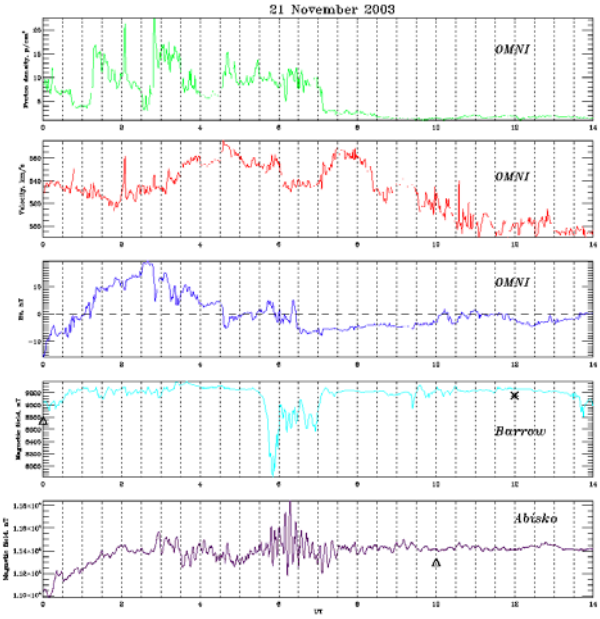

Fig.1. Interplanetary parameters from *OMNI*, magnetic field from *Barrow* and *Abisko* stations.

Temporal structure of magnetic and CNA variations. The overlaid magnetic and *CNA* variations at *ABK* (**Fig. 2a**) and *LOZ* (**Fig. 2b**) show that synchronization of both variations occurs only for a very short time interval near ~0615 *UT*, of about 1-2 periods. Beyond this moment though magnetic and *CNA* variations demonstrate oscillatory behavior, there is practically no coherence between them.

Local meridian structure. The latitudinal profile of magnetic pulsations (*H*-component) at stations *IVA-SOD-OUL-HAN* (**Fig. 3**) is similar at near-by stations, e.g. *IVA-SOD* and *OUL-HAN*, but becomes noticeably different at stations separated by more than ~5°. The central frequency of the main spectral peak gradually grows upon decrease of latitude (not shown). In the interval 05.30-08.00 *UT* at *IVA-SOD* the frequency ~1.9 mHz dominates the spectra, while at *OUL-HAN* the main spectral energy leaks into the peak at *f*~2.9 mHz.

The occurrence of time shifts between stations separated in latitude, *IVA-SOD* and *OUL-HAN*, indicates the apparent signal propagation northward (**Fig. 3.**). The amplitude and phase features of the localized spatial structure of *Pc5* pulsations are typical for resonant structures, which is formed upon the transformation of compressional disturbances into the field line Alfven oscillations in the magnetosphere.

Riometer variations (**Fig. 3**) are much less monochromatic than magnetic pulsations, and their wave forms vary noticeably along the meridian (**Fig.3.**). No consistent dependence of central frequency on latitude and latitudinal propagation pattern can be seen.

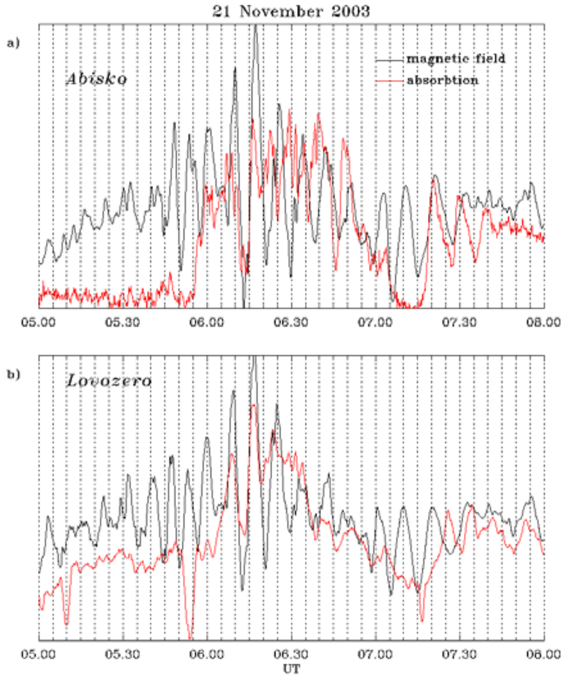

Fig.2. Magnetic and riometer absorption *Pc5* pulsations at *ABK* (a) and *LOZ* stations (b).

Azimuthal propagation. The azimuthal wave number *m* is determined as the ratio between the phase difference $\Delta\varphi$ and the longitude separation between stations Λ (in degrees) as follows: $m=\Delta\varphi/\Delta\Lambda$ (positive *m* corresponds to eastward propagation direction). The phase shifts make sense only when the signal's coherence is high enough, so they are not determined for weak amplitude wave trains.

The propagation in azimuthal direction at the morning flank is validated by the data from *ABK* and *IVA*. Time shifts and cross-spectral phase estimates provide the values of *m* and V_{ph}. Magnetic records have small regular time shifts Δt ~ 10-20 s, which correspond to small azimuthal wave numbers: for *Pc5* m ~ - 4, and for $P_{SC}5$ *m* ~ - 2; and westward (anti-Sunward) phase velocities: for *Pc5* V_{ph}~30 km/s, and for $P_{SC}5$ V_{ph}~60 km/s. The phase velocity we determine from the formula (1).

$$V_{ph} = \frac{\Delta\Lambda R\cos\Phi}{\Delta t} = \frac{2\pi f R}{m}\cos\Phi, \qquad (1)$$

R – radius of the Earth, *Φ* – geomagnetic latitude, *f* – frequency.

Estimates of *m* for riometer data had a much larger dispersion than that for magnetometers. For the event on Nov. 21, 2003 the riometer signals have rather irregular time shifts, and a correspondingly large dispersion of *m* numbers from -7 to +7. On average, both magnetic and *CNA* pulsations propagate in the same anti-Sunward direction, though with different apparent velocities. The cross-correlation coefficient between *ABK* and *IVA* for riometer variations reaches a peak value R~0.39 at lag Δt~25 s, whereas for magnetic pulsations R~0.48 and Δt~10 c.

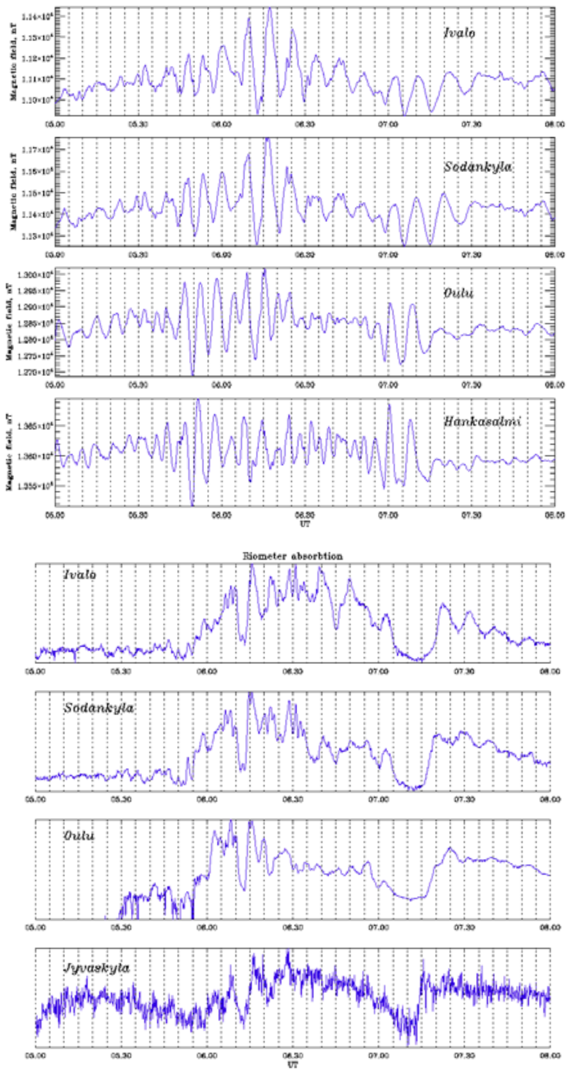

Fig.3. Magnetic (top panel) and riometer absorption (low panel) *Pc5* pulsations at meridian profile *IVA-SOD-OUL-HAN (JYV*).

Thus, *CNA Pc5* pulsations are not simply a replica of magnetic *Pc5* pulsations; their spatial structures both in latitudinal and longitudinal directions are not identical. Only for relatively short periods do their wave forms become synchronized.

Comparison with energetic particle dynamics

On the **Fig.4** proton number density and solar wind velocity from *OMNI* database, electron fluxes with energies 50-75 keV, magnetic field variations and riometer variations at *ABK* station are shown. Triangles show local magnetic noon, asterisk show local magnetic night.

The coordinated analysis of the solar wind variations, particle fluxes in the magnetosphere, and magnetic field and *CNA* pulsations on the ground shows that *Pc5* waves on the morning flank occur simultaneously with the injection of the electron and proton clouds. The solar wind velocity during this *Pc5* event was rather high and nearly steady at V ~540 km/s, and the density was also nearly constant at N ~ 10 cm^{-3}. However, the excitation of *Pc5* pulsations occurred not permanently, but only during a specific time interval, whereas V during this interval was even reduced. Therefore, the *Pc5* pulsations observed on the ground are expected to be stimulated by the electron injection at ~06 *UT*.

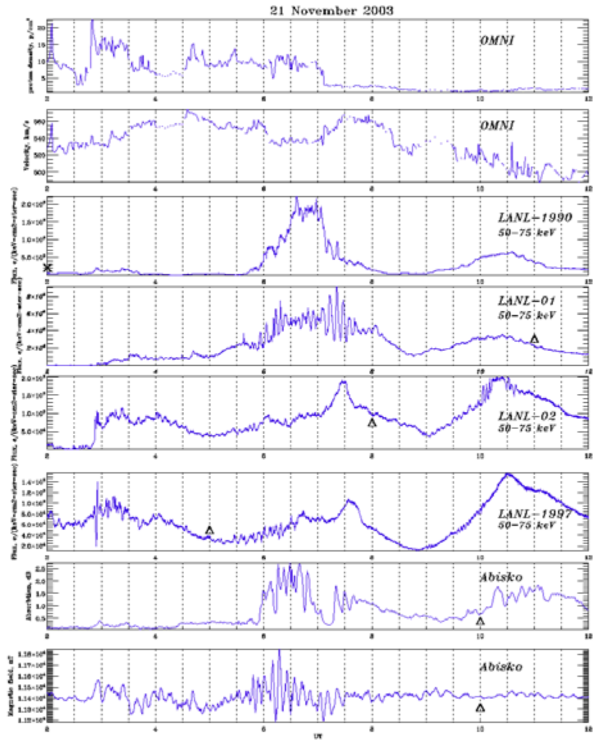

Fig.4. Proton number density (*OMNI*), solar wind velocity (*OMNI*), electron fluxes (*LANL*), riometer absorption (*ABK*), magnetic field (*ABK*).

Discussion

The event presented here show that traditional notions that periodic variations of particle fluxes in the magnetosphere and *CNA* in the ionosphere are due to entirely passive ULF wave modulation are insufficient. Examination of the local spatial structure of geomagnetic *Pc5* pulsations has shown the presence of specific resonant distortions: the latitudinal variation of the spectral power content and poleward phase propagation. However, no resonant structure is observed in the local spatial structure of *CNA Pc5* pulsations. Even the comparison of magnetograms and riograms demonstrates that a synchronization between magnetic and CNA pulsations occurs only for a limited time period. This situation resembles a synchronization of two weakly-coupled oscillator systems. In magnetospheric situations these systems may be an MHD waveguide/resonator and the system cyclotron turbulence + electrons. The latter system is described by equations from quasi-linear theory, which have the form of balance equations with their own quasi-periodic solutions.

In collisionless near-Earth plasma, pitch-angle diffusion of electrons occurs due to their interaction with electron-cyclotron waves. In the approximation of weak pitch-angle diffusion at time scales larger than the electron bounce period, the quasi-linear theory equations are reduced to the equations of balance between the number of electrons *Ne* in a flux tube, and turbulent noise energy *W*. Analysis of these equations showed that relaxation oscillations can take place in the system cyclotron turbulence + electrons [Bespalov, 1981]. The eigenfrequency of these oscillations Ω is determined by the particle source power F and the averaged turbulence growth rate $\gamma=\gamma_o N/2$, namely $\Omega^2=\gamma_o F$. In a steady state $F=2S$, where *S* is the flux density of electrons precipitating into the ionosphere, hence $\Omega^2=2\gamma_o S$. The quality factor of relaxation oscillations is determined by the turbulence decay rate υ: $Q=\Omega/2\upsilon$. The occurrence of an eigenfrequency makes the electron fluxes sensitive to external periodic disturbances with frequencies close to Ω.

Thus, in the region of energetic electron injection two coupled resonant contours occur: the MHD waveguide/resonator with characteristic frequency Ω_A and the system electrons + electron-cyclotron turbulence with eigenfrequency Ω. During the moments when these frequencies match, $\Omega \sim \Omega_A$, the synchronization of these two resonant systems can occur. Probably, this possibility has been realized in the event presented here. The short duration of synchronization is due to the frequency mismatch because of temporal variations of Ω.

In our opinion, the possibility of triggered *Pc5* wave excitation is related to the qualitative distinction in regimes of the solar wind plasma flow around the magnetosphere boundary under moderate and high solar wind velocities. Under moderate *V* unstable oscillations are localized at the magnetosphere – magnetosheath interface, and decay exponentially inside the magnetosphere. These oscillations do not grow to large amplitudes because they are convected rapidly by the solar wind flow into the magnetotail region. Under high *V* conditions the magnetosphere – magnetosheath boundary becomes over-reflecting, that is, magnetospheric MHD modes are amplified upon reflection from this moving boundary [Mann et al., 1999]. In this case, growing disturbances are not oscillations localized at the boundary, but oscillations of the entire MHD waveguide, formed between the magnetopause and a reflection point deep in the magnetosphere. In a realistic magnetosphere, probably, the rigid regime of the waveguide excitation is realized, for which finite-amplitude initial disturbances are necessary. The necessary disturbances are produced by particle injection. The hypothesis of triggered *Pc5* excitation may explain in a natural way the coincidence of a substorm onset at evening hours (that is the moment of particle injection into the magnetosphere) with enhancement of *Pc5* pulsations in the morning sector, noticed by Samson and Rostoker [1981] and Kleimenova et al. [2005].

Conclusion

We suggest that the high-speed solar wind flow around the morning flank of the magnetosphere results in the formation of a meta-stable system: a MHD wave guide with a super-reflecting boundary. Spontaneous growth of thermal fluctuations (soft excitation) in such a system cannot be realized, because long-growing disturbances are convected into the magnetotail. For the rigid excitation of the system an initial disturbance of a finite magnitude is necessary, which then stimulates growth of magnetospheric waveguide modes. Such a disturbance was produced by an injected energetic electron cloud.

In the region of electron injection, an interaction occurs between the MHD wave guide modes and relaxation oscillation of electron fluxes. However, this interaction cannot be visualized as a mere modulation of electron fluxes by MHD wave, but is revealed as a short-term synchronization between geomagnetic waves and riometric absorption pulsations.

Acknowledgements. This study is supported by the grants 07-05-00185, 09-05-00818 from the Russian Fund for Basic Research and by Presidium of the Russian Academy of Science (program 16).

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