Spectral Structure of Pc1 Geomagnetic Pulsations under Magnetically Quiet and Disturbed Conditions

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Abstract. The analysis of geomagnetic *Pc1* pulsations recorded in 2006-2010 at the Scandinavian network of the induction magnetometers has been performed. It was found that the spectral structure of Pc1 pulsations was different under the quiet and disturbed magnetic conditions. Analysis of these data showed that in magnetically quiet conditions (*Kp* ~0-1), in more than 90% of cases, *Pc1* pulsations were observed in a narrow frequency band of around 0.2-0.4 Hz with the central oscillation frequency in the series (wave packets) of ~ 0.5-0.7 Hz. Under the disturbed conditions (*Kp* ~ 2-3), the central frequency of *Pc1* waves became almost twice greater (~ 1.0-1.2 Hz) and the spectral width increased up to ~ 0.5-0.7 Hz. The relation of the frequency spectrum width of *Pc1* pulsations with magnetospheric parameters was theoretically studied. An analytical expression was obtained and the numerical calculations have been performed. The performed theoretical calculations showed that the evolution of the frequency width of the dynamic spectrum of the *Pc1* wave packets depends on the magnetosphere plasma parameters. It was found that the *Pc1* spectral width increases with decreasing of the proton thermal anisotropy. We suppose that under quiet conditions, the *Pc1* generation can take place inside the plasmasphere but near the plasmapause located at higher L there were small V_A values. During the disturbed periods, the *Pc1* generation can take place outside the plasmasphere at lower *L* there were high V_A values.

Keywords: magnetosphere, geomagnetic activity, geomagnetic pulsations, Alfven waves

Introduction

Geomagnetic pulsations play very important role in the solar-terrestrial interactions as the main agent of the solar wind energy transfer into the Earth magnetosphere. There are several types of geomagnetic pulsations differing in the frequency spectrum and generating mechanisms. The pulsations are divided into two classes: irregular (Pi) and continues (Pc). The first class is observed mainly during the nighttime and the second one is typical for the daytime. According to the wave periods ranging from few to thousands seconds, the pulsations are classified from *Pc1* to *Pc6*. The shortest period pulsations (*Pc1*) which periods are in a range of the human cardiac rhythms could be an important factor of hazard. Some authors (e.g., Kleimenova and Troitskaya, 1992; Kleimenova et al., 2007) supported that geomagnetic Pc1 pulsations could be one of central biotropic "agents" of magnetic storms. Thus, the *Pc1* pulsation behavior study becomes important for the heliobiology as well.

Geomagnetic *Pc1* pulsations represent quasi-sinusoidal packets of the Alfven waves in the frequency range of ~0.2–5.0 Hz travelling between the conjugated hemispheres. The waves characterize by the amplitude modulation in the form of repeated single wave packets with the 1–4 min duration. This pulsation type known as "pearls" has been the subject of extensive study since many years ago (Troitskaya, 1964; Jacobs and Watanabe, 1964; Obayashi, 1965; Troitskaya and Guglielmi, 1967; Jacobs, 1970). Their theory of generation and the morphological properties are widely discussed in the literature last time in several books and revues (e.g., Bespalov and Trakhtengerts, 1986; Guglielmi and Pokhotelov, 1994; Kangas et al., 1998; Demekhov, 2007; Trakhtengerts and Rycroft, 2008). The results of the last 10-years satellites (THEMIS, CHAMP, Cluster) measurements were presented in some papers, (e.g., Min et al., 2012; Park et al., 2013; Lin et al., 2014). It is no doubt that *Pc1* pulsations ("pearls") are generated via the cyclotron instability of radiation belt protons with anisotropic velocity distribution as it has been early established by (Cornwall, 1965; Kennel and Petchek, 1966; Feygin and Yakimenko, 1971; and many others).

The aim of this paper is to study the Pc1 spectral behavior depending on the geomagnetic activity level based on the data obtained from the ground-based induction magnetometer network at Scandinavia. In this study we continue our investigation published recently by Feygin et al., (2015) and discuss the relationship of the spectral feature of the Pc1 pulsations with the possible location of the plasmapause .

Observations

The analysis of geomagnetic *Pc1* pulsations has been performed using the data recorded at the Scandinavian network of the induction magnetometers whose spectrograms are stored in (http://sgo.fi/Data/Pulsation/pulArchive.php). There were 6 ground-based stations located at geomagnetic latitudes between 57° and 66° along the geomagnetic meridian 105–109°. They are: NUR (57°), OUL (61°), ROV (63°), SOD (64°), IVA (65°), and KIL (66°). Only long-lasting (more 2 hours) *Pc1* pulsation series have been analyzed. The same data base as that in the paper (Feygin at al., 2015) has been used, namely, 178 selected pulsation events under quiet geomagnetic conditions with *Kp* < 2 and 193 events under disturbed periods with *Kp* > 2.

We found that the spectral structure of the *Pc1* pulsations was different in quiet and disturbed magnetic conditions (Feygin at al., 2015). As a rule, under the low geomagnetic activity with *Kp* ~ 1, in more than 90% of cases, the shape of the frequency-temporal *Pc1* wave spectra look like a very monochromatic emission with a narrow width of the dynamic spectra and the duration less than 3–5 hours. The central frequency of the *Pc1* emissions was ~ 0.5–0.7 Hz and the spectral width was in the order of 0.2–0.3 Hz. An example of such event is presented in the right panel of Fig. 1. It is seen the wave intensity increased with latitude and the pulsations are observed only at geomagnetic latitudes higher 61˚. Such *Pc1* pulsations are typically observed in the beginning of the minor geomagnetic activity enhancement after long-lasting quiet periods.

It is well known (e.g. Moldwin et al., 2002; Liu et al., 2015, and very many others) that under such quiet conditions the day side plasmapause is located at L > 5.5-6.0. One *Pc1* event observed on July 24, 2009, when, according to the model (www.spaceweather.eu), the estimated plasmapause could be located at *L* ~ 5.5, is shown in Fig. 2 where the *Pc1* data at SOD (*L* ~ 5.3) are compared with the *Pc1* pulsations at NUR (*L* ~ 3.6). It is seen the *Pc1* pulsations were stronger at SOD (inside of the plasmasphere, but not very far from the plasmapause) than at NUR (deep into the plasmasphere). We may suppose that the plausible Pc1 generation region could be located in the vicinity of the plasmapause as that was previously discussed by some authors (e.g., Mazur and Potapov, 1983; Dmitrienko and Mazur, 1985).

During the declining (2006) and increasing (2010) phases of the solar activity, *Pc1* pulsations were typically observed under the moderate disturbed geomagnetic conditions with (*Kp* ~ 2÷3) after magnetic storms. The spectral structure of *Pc1* pulsations became more complicated and the duration of the *Pc1* series increased up to 10–12 hours. The central frequency of *Pc1* waves significantly increased and became almost twice greater (~ 1.0÷1.2 Hz), the spectral width increased up to ~ 0.5÷0.7 Hz. Sometimes the wave packet consisted of several varying frequency bands as it was demonstrated in the left panel of Fig. 1. Under such condition, the day side plasmapause is typically located at *L* < 4.0÷4.5 (www.spaceweather.eu). It means that the station recorded the *Pc1* waves (left panel of Fig. 1) were mapped outside of the plasmasphere.

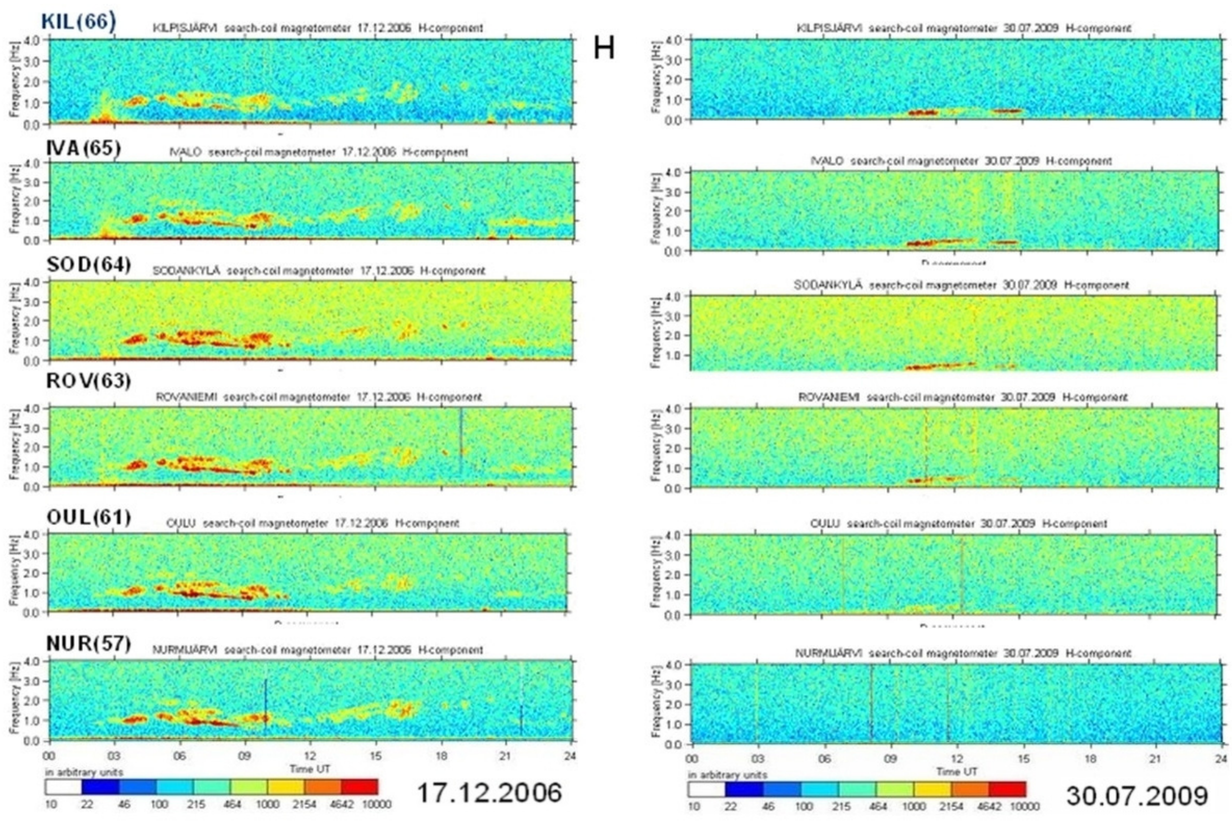

Fig. 1 The spectral structure of *Pc1* pulsations under magnetically disturbed period (left panel) and under very quiet conditions (right panel). The geomagnetic latitude of the stations is shown behind the station cod.

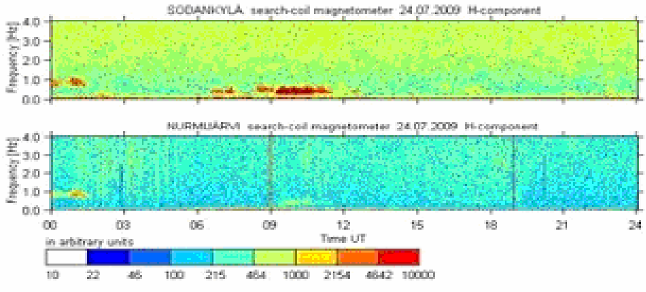

Fig.2 The example of Pc1 spectrogram at SOD (*L* ~ 5.3) and NUR (*L* ~ 3.6) on July 24, 2009 when, according to the model (www.spaceweather.eu), the estimated plasmapause could be located at *L* ~ 5.5

Discussion: Theoretical consideration

We consider electromagnetic wave, with electric and magnetic components $\boldsymbol{E}_1$, $\boldsymbol{B}_1$ perpendicular to the constant magnetic field $\boldsymbol{B}_0$. The wave vector $\boldsymbol{k}$ is assumed parallel to the $\boldsymbol{z}$ axis, which is directed along $\boldsymbol{B}_0$. The wave amplification is due to a cyclotron interaction between the wave and hot particles. The amplification coefficient (growth rate) γ is a function of the wave number k. It reaches its maximum at value of k, namely k_0, which corresponds to a pulsation frequency ω_0 (central frequency of the wave packet). The frequency of the pulsations ω and k for the EMIC waves, as it is well known, is

$$\omega^2 = k^2 V_A^2 (1 - \omega / \Omega_i) \qquad (1)$$

If the concentration of the hot protons in the plasma n_1 is low as compared with the cold plasma number density N ($n_1 << N$), the distribution function of the hot protons is presented by the be-maxwellian function with different temperatures $T_\perp$ and $T_{||}$ relative to the magnetic field $\boldsymbol{B}_0$, then the growth rate of the EMIC waves, with the wave vector $\mathbf{k} \parallel \boldsymbol{B}_0$ is given by the formula (Feygin, Yakimenko, 1969, 1970; Gendrin at al., 1971)

$$\gamma = \frac{\pi^{1/2}(n_1/N)(1-x)[A-(A+1)x]}{x(2-x)}\sqrt{y}\exp(-y) \qquad (2)$$

$$y = \frac{V_A^2}{U_\parallel^2}\frac{(1-x)^3}{x^2} \qquad (3)$$

where $\Omega_i = eB_0/m_i c$ is ion gyrofrequency, $x = \omega/\Omega_i$, $U_\parallel = (2T_\parallel/m_i)^{1/2}$ is the mean parallel velocity of the particles, $V_A = B_0(4\pi N m_i)^{1/2}$ is the Alfven velocity, and $A = (T_\perp/T_\parallel - 1)$.

The growth rate $\gamma = \gamma_{max}$ for the wave with frequency $\omega = \omega_{opt} = (V_A/U_\parallel)\,\Omega_i << \Omega_i$. Over time, the form of the wave packet is determined predominantly by the Fourier components with frequencies close to ω_{opt}. If the initial disturbance, for example, a magnetic field at time $t = 0$ has the form of $B_1(z,0) = B_1^0 exp(-z^2/b^2)$, then the value $B_1(z,t)$ in the presence of the cyclotron instability during the time defined by the formula (Feygin, Yakimenko, 1969, 1970; Gendrin et al., 1971)

$$B_1(z,t) = exp[(\gamma_0 - \gamma_{eff})t]\times$$
$$\times exp\left\{ i\left[k_0 z - \omega_{opt}(t_n+\tau) + \frac{\beta V_{g0}^2\tau^2 + \alpha k_0 b^2 V_{g0}\tau}{2(\alpha^2+\beta^2)t} - \frac{\beta k_0^2 b^4}{8(\alpha^2+\beta^2)t}\right]\right\}\times \qquad (4)$$
$$\times exp\left\{\frac{-\alpha V_{g0}^2\tau^2 + k_0\beta b^2 V_{g0}\tau}{2(\alpha^2+\beta^2)t}\right\}\times exp\left(-\frac{k_0^2 b^2}{4}\right)(pt)^{\frac{1}{2}}$$

where $t_n = z_n/V_{g0}$, $\tau = t - t_n$, $\alpha = -d^2\gamma/dk^2\big|_{k=k_0}$, $\beta = d^2\omega/dk^2\big|_{k=k_0}$, and $V_{g0} = \partial\omega/\partial k\big|_{k=k_0}$ are terms of the expansion of the growth rate γ and frequency ω on the wave number k (γ_{max} corresponds $k = k_0$), γ_{eff} is the effective decrement, taking into account the attenuation in the ionosphere, $p = 2(\alpha + i\beta)\,b^{-2}$. We assume that the wave packet is reflected from both ends of the field line, and it comes back to the equator, where it is amplified, after distance z_n and travel time t_n (corresponding to the central frequency of the wave packet ω_{opt}), n being the number of passes through the amplifying region, τ describes the time inside the wave packet. Wave packet propagates with the group velocity V_{g0}, and the rate of the amplification is determined by γ_0. The specific form of the initial disturbance $B_1(z,0)$ is not crucial. Terms in the exponents of the formula (4), proportional to b^2 and b^4, give only some additions to the oscillation phase, frequency ω_{opt} and position of the signal maximum. These modifications do not change a lot over time of the signal passes through a given point (assuming that this time is $t^* \sim [(\alpha^2+\beta^2)t\alpha^{-1}]V_{g0} << t$ and $\tau << t_n$). During a wave packet duration (τ), the width of the frequency spectrum can be found from the expression (4) as

$$\Delta\omega \propto 2\beta\, V_{g0}\, \alpha^{-1/2}(\alpha^2+\beta^2)^{-1/2}\, t_n^{-1/2} \qquad (5)$$

Using expressions (1) and (2), we obtain the formula for evaluating α, β and V_{g0}:

(6)

$$\beta = -\frac{V_A^2}{\Omega_i}\frac{(1-x)^2(1-x/4)}{(1-x/2)^3} \qquad (7)$$

$$V_{g0} = V_A(1-x)^{3/2}(1-x)^{-1} \qquad (8)$$

$$\Psi = 1 + \frac{x(1-7x^2/16)}{(1+x/2)(1-x/2)^2} + \frac{3x(1+x/3+x^2/6)}{4(1+x/2)[A-(A+1)x]} + \frac{Ax^2(1-x)}{4[A-(A+1)x]^2} \qquad (9)$$

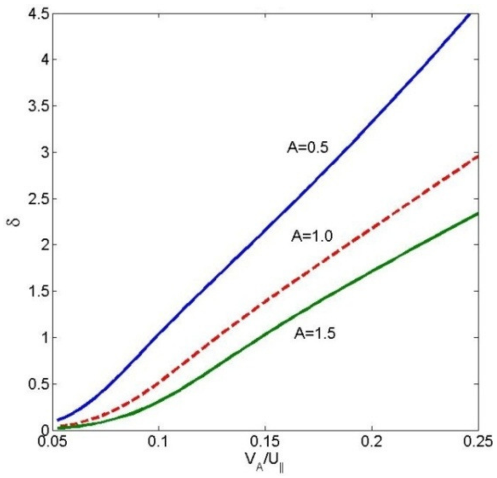

Fig. 3 The dependence of the normalized width of the frequency spectrum $\delta = [\Delta\omega/(\Omega_i/t_n)^{1/2}]$ on the parameter ($V_A/U_{\|}$) for different values of anisotropy A. (from [Feygin et al., 2015])

The formula for the growth rate (2, 3) includes an important magnetospheric parameter $V_A/V_{\|}$. Numerical calculations (Fig. 3) show that for small value of this parameter the amplification of *Pc1* wave packets with narrow frequency spectrum is possible. When the parameter $V_A/V_{\|}$ increases, *Pc1* wavepackets with wider frequency spectra could be generated.

The optimal frequency of the signal ω_{opt} (corresponding to the central frequency of the wave packet) connected with this parameter as $\omega = \omega_{opt} = (V_A/U_{\|})\Omega_i << \Omega_i$. Fig. 3 shows that with increasing of the anisotropy coefficient *A*, the frequency spectrum width is reduced. Furthermore, according to the relation $\omega_{opt} = (V_A/U_{\|})\Omega_i$, the decrease of the normalized frequency also leads to the decrease of the width of the frequency spectrum.

Under magnetically disturbed periods, the central frequency of *Pc1* waves and the spectral width become almost twice greater. That could a result of the shift of the wave generation region to the lower *L*. But, in such condition, the plasmapause shifts to the lower *L* too. The optimal cold plasma density corresponded to the growth rate of the EMIC wave maximum can be calculated according to (2, 3):

$$N_0 = 2B_0^2(1-x)^3 / 3U_{||}^2\ x^2 4\pi m_i \qquad (10)$$

During the moderate magnetic activity, the estimated values of the optimal cold density in the vicinity of the *Pc1* generation region are in the order of few tens cm^{-3} that corresponds to the typical cold density outside the plasmasphere. However, under the low magnetic activity these estimated values were in the order of several hundred cm^{-3} that corresponds to the density inside the plasmasphere.

Numerical results show that the frequency width of the spectrum (at *L*≈5) is associated with a minimum density of the background plasma 50–300 cm^{-3}. Moreover, at the same frequency widths smaller density values correspond to higher values of the anisotropy coefficient. The anisotropy coefficient after the magnetic storm decreases to some value, which changes very little during several days (Feygin and Yakimenko, 1970).

The *Pc1* wave packet frequency band $\Delta\omega$ is determined by the expression (5). The growth rate γ given by the expression (2) depends on the parameter $V_A/U_{||}$, where V_A is the Alfven speed at the equatorial section of the magnetic field line, and $U_{||}$ is the average parallel velocity of the anisotropic protons. For the numeric calculations, we suppose that in the generation area, $U_{\|}$ changes very little and the major role in the wave generation plays the magnetic field strength B_0 and the optimal cold plasma density N_0. The numeric calculations showed that at the small values of $V_A / U_{\|}$, the frequency *Pc1* band could be small as well as the width of the wave spectra. However, when values of this parameter are large, the *Pc1* pulsation frequency band becomes wide.

Thus, the performed theoretical calculations showed that the evolution of the frequency width of the dynamic spectrum of the *Pc1* wave packets depends on the magnetosphere plasma parameters. It was found that the *Pc1* spectral width increases with decreasing of the proton thermal anisotropy.

We assume that under quiet conditions, the generation of *Pc1* pulsations with a narrow frequency band can take place inside the plasmasphere but near the plasmapause located at higher *L*, there were small V_A values. During the disturbed periods, the generation of *Pc1* pulsation with a broadband wave structure can take place outside the plasmasphere, also in the vicinity of the plasmapause which is located now at lower *L*, there were high V_A values. The similar dependence of the frequency structure on the magnetic activity, for the much longer period Pc5 geomagnetic pulsations recorded by ATS 1 geostationary spacecraft, has been published early by Cumminings and O'Sullivan (1969).

Summary

The analysis of the ground-based Scandinavian data showed:

1. The spectral structure of the ground-based Pc1 pulsations (pearls) is controlled by the geomagnetic activity level. Under the magnetically quiet conditions (Kp ~1), *Pc1* pulsations were observed in a narrow frequency band of around 0.2–0.4 Hz with the central oscillation frequency in the series (wave packets) of ~0.5÷0.7 Hz. Under the moderate disturbed conditions (Kp ~ 2–3), the central frequency of Pc1 waves became almost twice higher (~ 1.0÷1.2 Hz) and the spectral width was ~ 0.5÷0.7 Hz.
2. The developed theory and numerical calculations show that spectral structure of the Pc1 is controlled by the parameter $V_A / U_{\|}$, (where V_A is the Alfven velocity in the equatorial plane of the magnetic field line, and $U_{\|}$ is the average parallel velocity of the anisotropic protons) in the vicinity of the *Pc1* generation region and by the magnetosphere cold plasma density.

3. We suppose that under quiet conditions, the *Pc1* generation can take place inside the plasmasphere but near the plasmapause located at higher *L* there were small V_A values. During the disturbed periods, the *Pc1* generation can take place outside the plasmasphere at lower *L* there were high V_A values.

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