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Pc 1-2 and Pc 4-5 pulsations observed at a network of high-latitude stations

T. A. Plyasova-Bakounina,[1,2] J. Kangas, [3] K. Mursula,[3] O. A. Molchanov,[1]
and A. W. Green [4]

Abstract. Analysis of magnetospheric Pc 1 and Pc 2 (in brief Pc 1-2) pulsations at a network of six northern hemisphere stations at latitudes 65°-76° CGM shows that their average frequency decreases with increasing latitude of the station. Their maximum occurrence is at L=6-9 and 1200-1600 LT. The ionospheric ducting is weak for $f < 0.3$ Hz. Occasionally the Pc 1 intensity at a station is modulated by a simultaneously arriving quasi-periodic Pc 4-5 signal. A mechanism for generating micropulsations which is common to both high-frequency and low-frequency waves is presented and discussed, the proposed mechansim being that a broadband signal from the solar wind is amplified in the magnetosphere in the frequency bands of the field line resonance (Pc 4-5) and in the He^+ cyclotron frequency (Pc 1-2) range.

Introduction

Regular geomagnetic pulsations in the period range from 0.2 to 10 s have been subdivided into Pc 1 (0.2 to 5 s) and Pc 2 (5 to 10 s) by an international agreement [see *Jacobs et al.*, 1964]. Pulsations in this period range have also been classified into two main categories according to whether they exhibit structures with frequency rising with time (structured) or not (unstructured) [*Heacock and Akasofu*, 1973]. Investigations have shown that structured Pc1 pulsations are typical at low and middle latitudes [*Webster and Fraser*, 1985], while unstructured Pc 1 pulsations occur mostly at high latitudes [*Heacock*, 1974; *Arnoldy et al.*, 1988]. Considering the close similarity that often prevails between Pc 1 and Pc 2 pulsations, it is questionable whether the separation into these two classes with a transition at a period of 5 s has any physical significance. This is especially true for unstructured Pc 1-2.

Pc 1-2 pulsations are thought to be due to wave-particle interactions in the magnetosphere [*Kennel and Petschek*, 1966]. Propagation of these waves between hemispheres [*Jacobs and Watanabe*, 1964; *Obayashi*, 1965; *Gendrin et al.*, 1971] explains the multiple wave packets seen at conjugate sites as a single wave packet traveling back and forth along a field line between conjugate points. Reflection losses are compensated by amplification in the equatorial plane due to the interaction between the energetic protons, moving along drift orbits, and Alfvén waves propagating along field lines. Growth rate calculations [*Mauk and McPherron*, 1980; *Roux et al.*, 1982; *Kozyra et al.*, 1984] indicate that the proton cyclotron instability can account for wave generation.

Observational evidence supports the assumption that ducting of Pc 1 and Pc 2 waves in the ionosphere is important [*Fraser*, 1976]. Such ducting was found to exist for Pc 1 pulsations with period less than 2 sec [*Troitskaya et al.*, 1975]. Therefore the station at which the Pc 1-2 is observed may not be near the footprint of the field line on which the waves were generated in the magnetosphere. For a chain of midlatitude stations, *Baransky et al.* [1981] showed that the Pc 1 period depends on the latitude of observation point. *Gendrin* [1963], *Matveeva* [1970] and *Sastry et al.* [1978] revealed an empirical relationship between Pc 1 frequency (f) observed at midlatitudes and its repetition period (τ), that is, the period of modulation of structured Pc 1. *Gendrin* [1963] found $f \cdot \tau \approx 120$ and *Sastry et al.* [1978] obtained $f \cdot \tau \approx 80$, while *Matveeva* [1970] obtained $f \cdot \tau \approx 100$.

The occurrence of Pc 1 on magnetically quiet days following magnetic storms was demonstrated for the midlatitude stations by *Wentworth* [1964] and *Plyasova-Bakounina and Matveeva* [1968]. A correlation between sudden impulses (SI) and associated ground Pc 1 events has been demonstrated [*Troitskaya et al.*, 1968; *Olson and Lee*, 1983; *Kangas et al.*, 1986]. Comparing Pc 1 at low- and high-latitude stations reveals a difference in diurnal and seasonal occurrence, in mean and repetition periods, and in dependence on Dst and Kp indices [*Toya et al.*, 1979].

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[1] Institute of Physics of the Earth, Moscow, Russia.
[2] Now at U.S. Geological Survey, Denver, Colorado.
[3] University of Oulu, Dept. of Physical Sciences, Oulu, Finland.
[4] U.S. Geological Survey, Denver, Colorado.

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An apparently confusing variety of Pc 1-2 types have been found at high latitudes. This confusion can be explained by the fact that most experimental studies have been based on data collected at a single station. Observations at several high-latitude stations [*Hansen et al.*, 1992; *Menk et al.*, 1993] have shown that the so-called Pc 1-2 band may be associated with the cusp-cleft regions. It is useful to compare this result with the finding [*Plyasova-Bakounina et al.*, 1986] that the cusp region corresponds to the maximum of intensity of Pc $2\text{-}4_{sw}$, that is, the solar wind-controlled pulsations. As Pc 1-2 and Pc $2\text{-}4_{sw}$ have partly overlapping frequency ranges, one should proceed with caution when investigating the high-latitude distribution of Pc 2 pulsations. One should avoid mixing magnetospheric Pc 2 and solar wind-controlled Pc 2_{sw}. In the present paper, we restrict ourselves to events which correspond to low values (< 10 nT) of the magnitude of the interplanetary magnetic field (IMF). At high probability [*Plyasova-Bakounina and Münch*, 1991] such low IMF values lead to the generation of lower-frequency Pc $3\text{-}4_{sw}$ waves only.

Studies of the occurrence of Pc 1-2 waves in the magnetosphere, first in the geostationary orbit and recently in the outer equatorial magnetosphere, have revealed the following:

1. The maximum generation region of Pc 1-2 is located at $L = 7\text{-}9$ [*Ludlow et al.*, 1991; *Anderson et al.*, 1990, 1992a, b].
2. Pc 1-2 pulsations are generated mainly in the afternoon at 1200-1500 MLT [*Anderson et al.*, 1990; *Ludlow et al.*, 1991; *Anderson et al.*, 1992a, b].
3. Pc 1-2 pulsations are sometimes found to be accompanied and modulated by Pc 4-5 waves [*Barfield and McPherron*, 1972; *McPherron*, 1981; *Fraser et al.*, 1992; *Rasinkangas et al.*, 1994].
4. Analyzing the simultaneous observations of Pc 1 by an equatorial satellite (at the top of field line) and on the ground (at the field line footprint), *Glangeaud* [1980] found that the satellite "saw" the Pc 1 wave packet only once not twice as should be expected according to the theory. We believe that Glangeaud's observations give strong evidence that there is no back-and-forth propagation of Pc 1 along a field line from one conjugate point to another.

The significant role of low-frequency Pc 4-5 oscillations in amplification of Pc 1 waves is discussed by *Lyatsky and Plyasova-Bakounina* [1986]. Supposing that the cyclotron instability of protons accounts for generation of the Pc 1 waves, the authors suggest that waves are amplified because of displacement of the field line into the region of high-temperature anisotropy. Pc 4-5 oscillations can lead to such displacements. In this case, the Pc 1 "wave packet" does not bounce along a field line. Its alternating appearance in conjugate points is related to the modulation by an antisymmetric mode of low-frequency oscillations (second harmonic), which causes an increase of the Pc 1 growth rate alternately in the northern and southern hemispheres. This mechanism can readily account for Glangeaud's observation and the modulation of Pc 1 by Pc 4-5 oscillations. Although simultaneous Pc 1-2 and Pc 4-5 waves have been observed in the magnetosphere, such a correlation has not so far been found on the ground.

In this paper, we present first results of our observations on two meridional networks of stations from subauroral to polar cap latitudes. We show that auroral and subauroral Pc 1-2 pulsations have many similar morphological characteristics, indicating similar generation mechanisms. We show that the Pc 1-2 period depends on latitude. We investigate the relationship between the Pc 1-2 frequency (f) and the period of repetition of Pc 1 wave packets (τ) as well as the dependence of Pc 1-2 occurrence on Kp and latitude of the station. We study the structure of Pc 1-2 as a function of latitude and verify that unstructured Pc 1-2 are common for high latitudes. We propose that the ionospheric duct propagation is weak for Pc 1-2 waves with periods of more than 3 s. We demonstrate events where the high-latitude Pc 1-2 is modulated by simultaneous low-frequency Pc 4-5 oscillations. We invoke a new concept about the common source for low-frequency Pc 4-5 and high-frequency Pc 1-2 micropulsations.

Data and Analysis

A network of six equally equipped stations set up at northern latitudes recorded the H and D components of magnetic pulsations during the time period from June to October 1978. Simultaneous recordings at all six stations were obtained for approximately 4 months of operation. The geomagnetic coordinates of the stations are shown in Figure 1. The stations at Ny Alesund (NYA), Bear Island (BI), and Andenes (AND) formed the eastern north-south profile, while the ones at Angmassalik (ANG), Thingeyri (THI), and Fagurholsnyng (FAG) constituted the western north-south profile. The two profiles are separated by approximately 3.4 hours in MLT. The equipment consisted of pulsation magnetometers and digital recording devices for data storage on magnetic tapes. The magnetometers measured periods in the range 500 - 0.6 s had dynamic range of 4096, a sampling interval of 0.3 s, and a timing accuracy of 0.1 s.

Additionally, we used pulsation data during March 1986 from two Scandinavian stations of Alta (ALT) and Muonio (MUO) and one Russian station, Borok (BOR), which are also shown in Figure 1. ALT and MUO are equipped with instruments identical to those described above, while BOR is equipped with an induction magnetometer with flat frequency response at the Pc 1-5 frequency band. BOR data are registered on a chart record. All three stations recorded the H and D components of magnetic pulsations.

Change of Pc 1-2 Period With Latitude

Figure 2 (August 20, 1978, 1430 - 1436 UT, Kp = 1_-) depicts a typical picture of Pc 1-2 activity at three

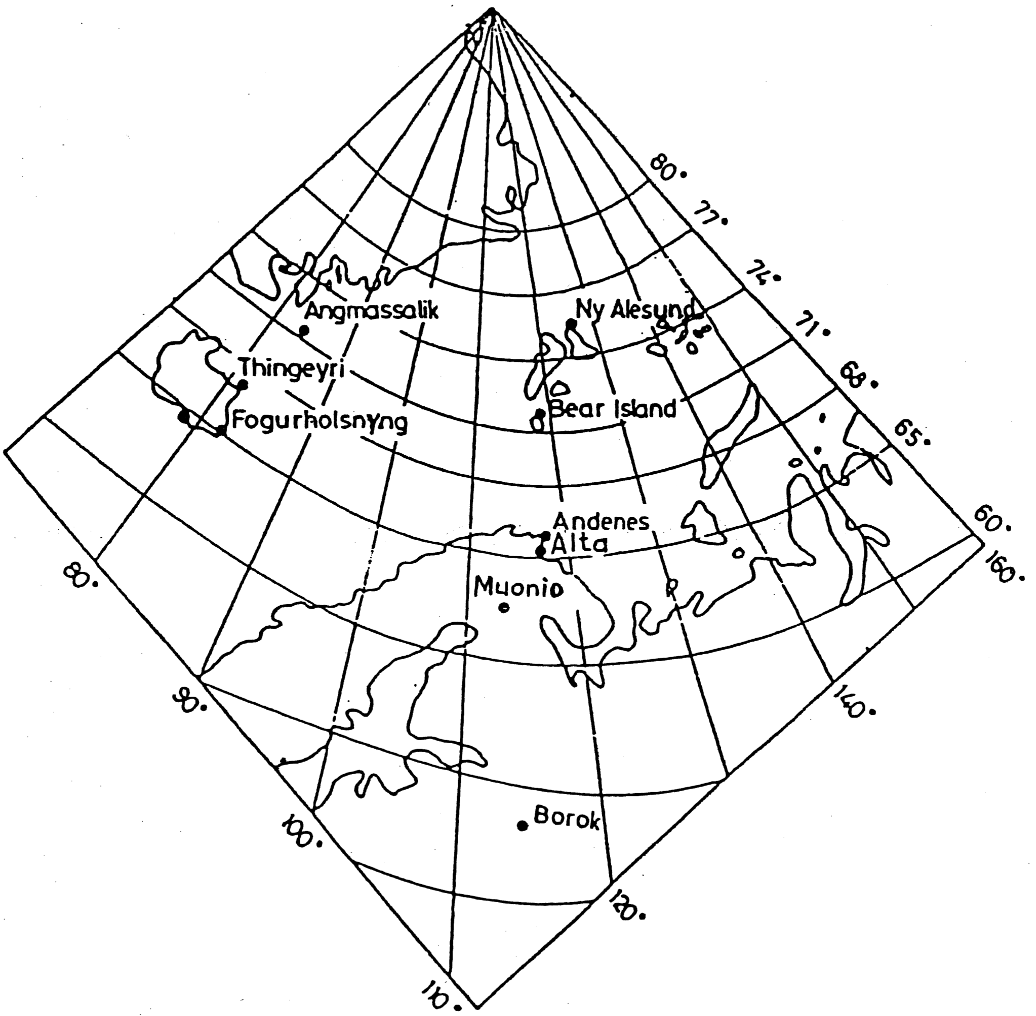

Figure 1. Location of the nine geomagnetic stations: six (Ny Alesund, Bear Island, Andenes, Angmassalik, Thingeyri, and Fogurholsnyng) operated by Siegen University, two (Alta and Muonio) by Göttingen University, and one (Borok) operated by Institute of Physics of the Earth, Moscow.

stations of the western profile. The period of the pulsations was 5.6 s at ANG and 3.2 s at THI and FAG. BOR station showed no Pc 1 activity. The more southerly stations normally have shorter periods. Simultaneous Pc 1 at the northernmost stations of each profile are shown in Figure 3 (August 26, 1978, 1124-1130 UT, Kp = 1_-). The common observed period at NYA and ANG was 4.6 s. All other stations, including BOR, measured only background noise. The event displayed in Figure 4 (August 24, 1978, 0854-0900 UT, Kp = 1_0) occurred at the southernmost stations of both profiles. The period of pulsations observed at FAG was 2.1 s. Pc 1 at AND started shortly before 0857 and showed the same frequency. The period of Pc 1 at Borok was also 2.1 s. In this case we observed the same frequency band of Pc 1 at three stations, two located at approximately the same L-shell but with a time difference of 3.5 hours and one at midlatitudes.

A total of 48 days of observation time were investigated by dividing each hour into ten 6-minute intervals. Pc 1 or Pc 2 within such an interval was counted as an event, whenever we observed four or more sinusoidal oscillations. We restricted the wave sample to those corresponding to low values of magnitude of B (IMF), mainly less than 10 nT. Such low values correspond to generation of the solar-wind windcontrolled pulsations with periods bigger than 16 s, that is, Pc 3-4_{sw}. Using this restriction, the solar wind could be excluded as a source of Pc 1-2 waves with high probability. Figure 5 shows the distribution of Pc 1-2 events in the D component as a function of period for all the stations. We obtained similar results for the H component. The lowest periods are observed at the lowest L shells, and the average period of Pc 1-2 increases with increasing L shell from FAG to BI. (The highest-latitude station NYA deviates from this pattern but includes too few points to make a definitive statement.)

Dependence of Pc 1-2 Occurrence on LT, L shell, and Kp

Figure 6 presents the number of Pc 1-2 events (in D component) per 1 hour of local time (LT) for each station. We obtained a similar result for the H component. In constructing Figure 6, we used Pc 1-2 events identified by the procedure described above. The maximum number of events is found in the early afternoon sec-

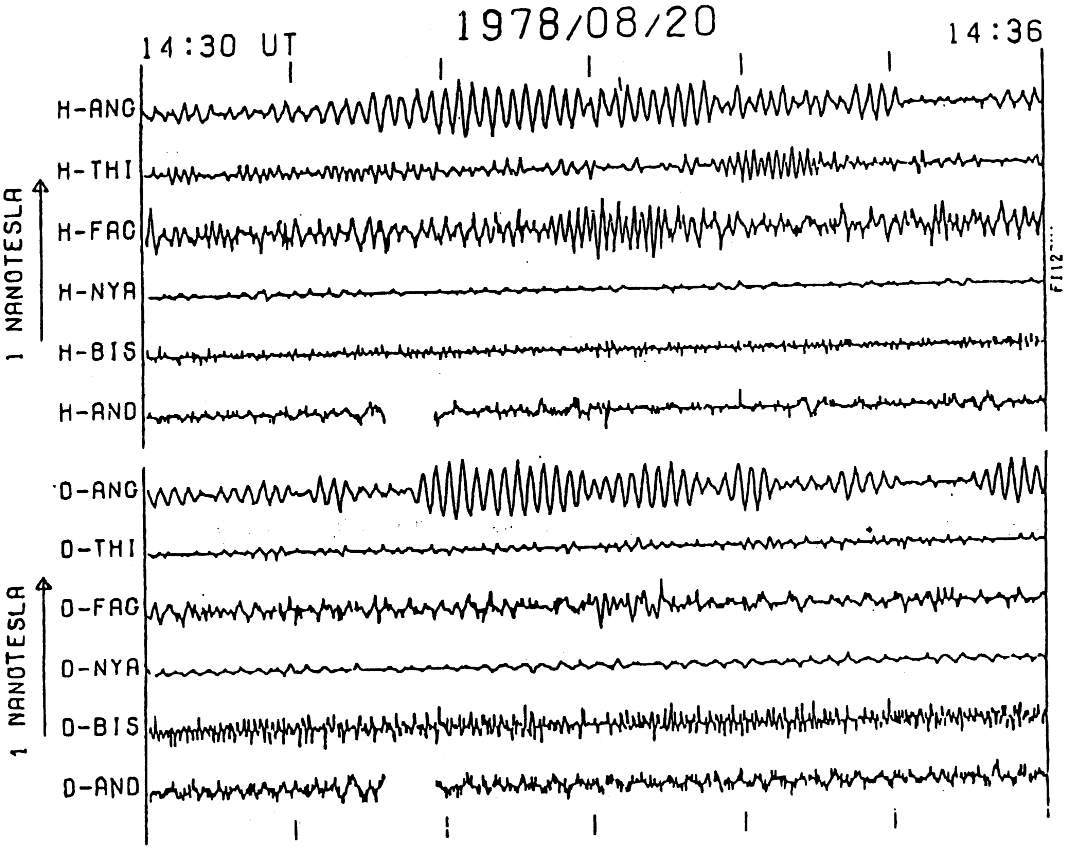

Figure 2. Simultaneous Pc 1-2 activity at the three stations of the western profile (August 20 1978; 1430 - 1436, UT; Kp = 1₋). Pulsation period is 5.6 s at ANG and 3.2 s at THI and FAG.

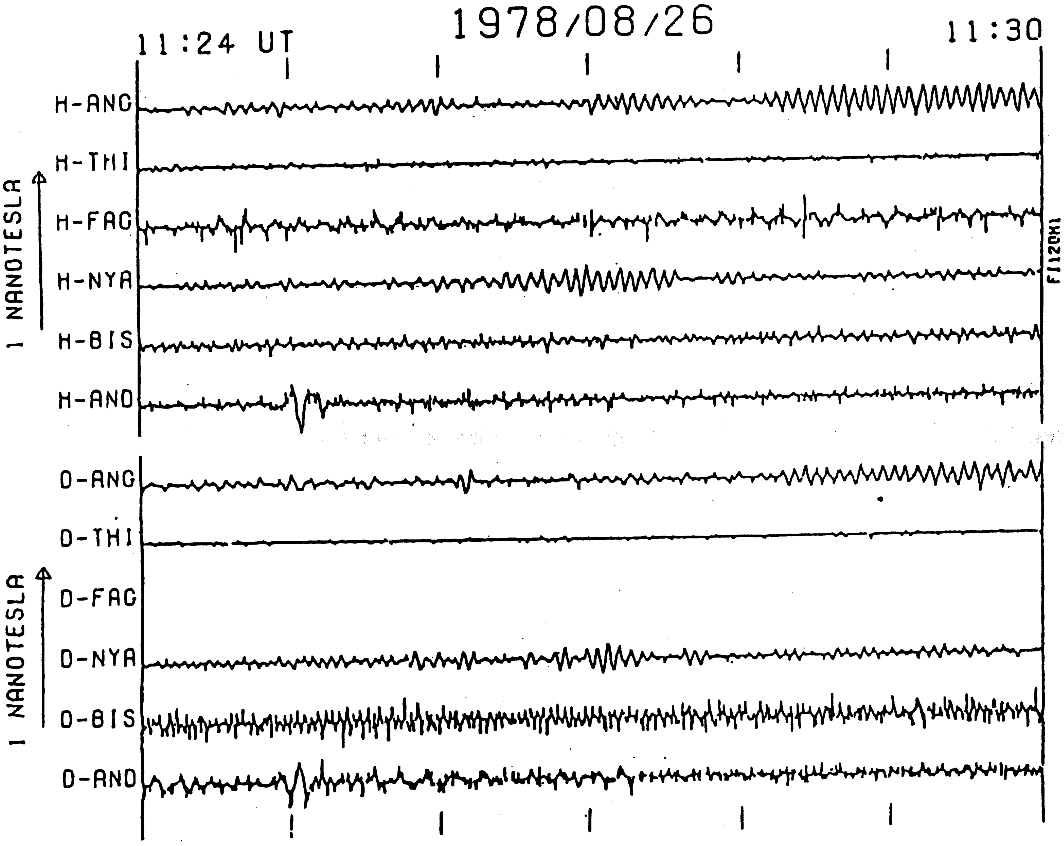

Figure 3. Simultaneous Pc 1-2 activity at the northernmost stations of the two networks (August 26 1978; 1124 - 1130 UT; Kp = 1₋). The common period at NYA and ANG is 4.6 s.

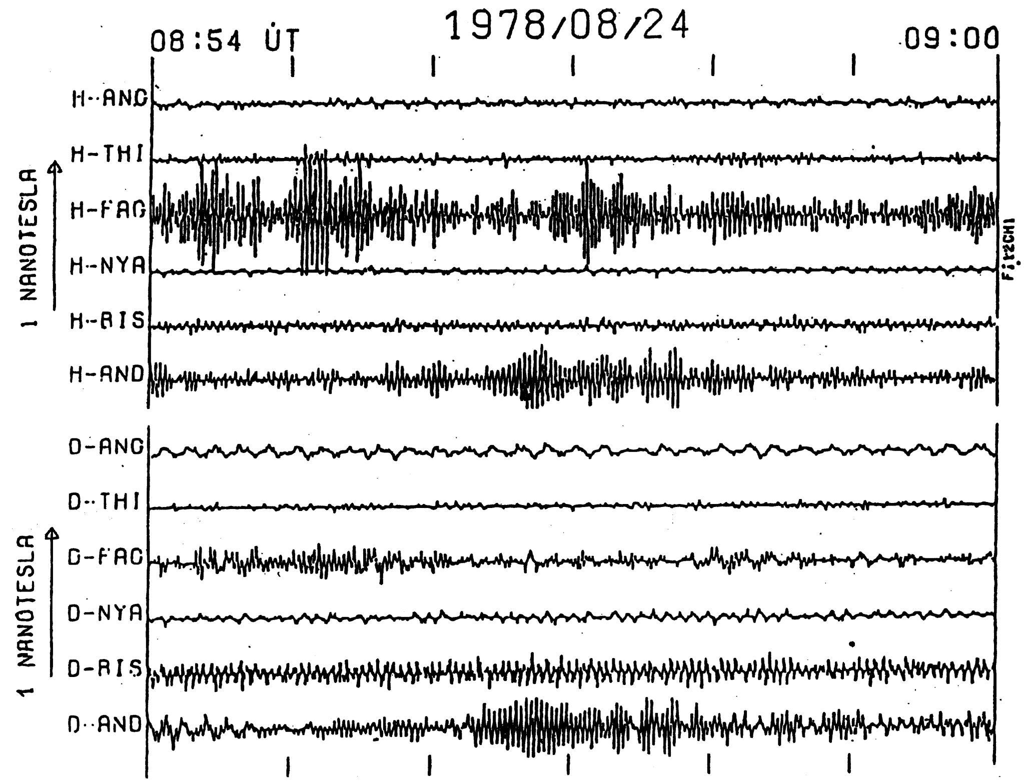

Figure 4. Simultaneous Pc 1-2 activity at the southernmost stations of both profiles (24 August 1978; 08:54 - 09:00, Kp = 1_0). Period at FAG and AND is 2.1 s.

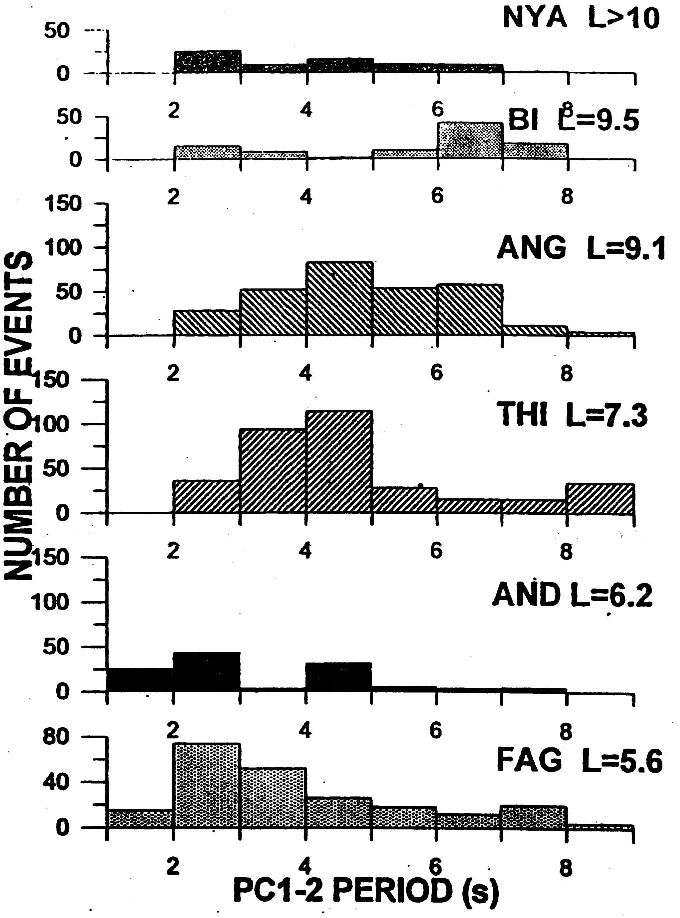

Figure 5. Spectral composition of Pc 1-2 events (in D component) for the six stations.

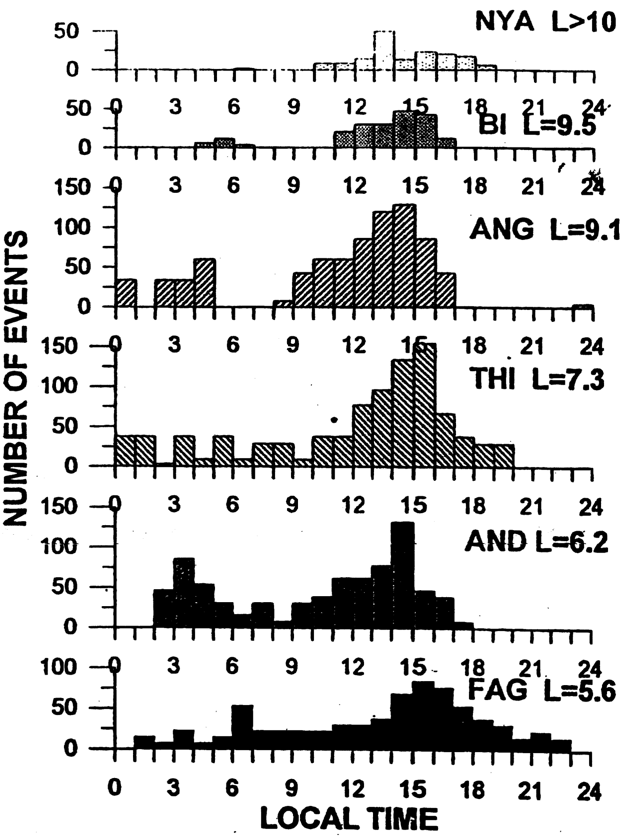

Figure 6. Number of Pc 1-2 events (in D component) at each station versus local time.

Table 1. Percentage of Simultaneous Pc 1-Pc 2 Events

Component	ANG/THI[a]	THI/FAG	ANG/FAG	NYA/BI	BI/AND	NYA/AND
D	23	21	4	1	14	4
H	30	38	12	9	22	10

[a] The ratio (in percentage) of the number of pulsation events common and simultaneous to the two stations mentioned in the heading (e.g., ANG and THI), to the number of all events observed at the first station (e.g., ANG).

tor (1200-1600 LT) at each station of the two chains. If we take the absolute number of events found at 15 LT, the maximum value 154 is found at THI at $L = 7.3$. The maximum number of events corresponds to $L = 6\text{-}9$. All observed events correspond to low magnetic activity with $Kp = 0\text{-}2_+$. Most of the Pc 1 we observed occurred during $Kp = 2_0$.

Number of Pc 1-2 Occurring Simultaneously at Two Stations

Table 1 presents the relative occurrence frequencies of simultaneous events at two stations. Simultaneous events at neighboring stations are much more frequent than those covering the whole profile. For the H component, 38% of the events at THI also occurred at FAG, but only 12% of the events at ANG were observed simultaneously at FAG. The same relations are also true for the eastern profile. (We can see only small NYA - BI correlation, which verifies that the NYA station is different from all others.)

We observed more unstructured than structured Pc 1-2, the latter occurring mostly at the southern end of our networks. Actually, events often consist of a superposition of signals and complex structures are seen, as noted also by other authors [*Kemp*, 1983; *Webster and Fraser*, 1985]. Our results support the findings of *Heacock* [1974] and *Arnoldy et al.* [1988] that unstructured Pc 1-2 occur mostly at high latitudes. Many events we observed had a pearl necklace-like amplitude modulation, although it was not as pronounced as with midlatitude Pc 1. In fact, this effect is revealed in an empirical relation between the Pc 1 frequency and its repetition period. Our result, for frequencies 5 to 10 times lower that those in the midlatitude studies, is that $f \cdot \tau$ varies from 4 to 80.

Modulation of Pc 1-2 Intensity

The two subauroral stations ALT and MUO recorded the H and D components of magnetic pulsations in March 1986. We have observed eight events when Pc 1 and low-frequency oscillations with periods of 100-300 s were occurring simultaneously at the two stations.

One typical event occurred on March 9 1986, 0100-0130 UT. Figure 7a presents a dynamic spectrum of H component data from MUO showing a narrow band Pc 1 event with a period of 3.4 s. The raw data were band pass filtered between 2 and 54 s. We get similar figures for D component of MUO and H and D components of ALT. Figure 7b presents the wave form of the H component of MUO data, showing a Pc 5 wave with average period of about 300 s coexisting with Pc 1. The Pc 1 intensity maxima occur roughly at the same frequency as Pc 5 waves. Although the relation is not fully consistent, most Pc 1 maxima are found close to Pc 5 amplitude maxima. We get similar results for D component of MUO and both components of ALT. BOR station exhibits Pc 5 of the same period with small intensity, but no Pc 1 activity.

Discussion and Conclusions

Now let us consider some central results of our investigation.

1. A pearl necklace-like amplitude modulation which is common for midlatitude Pc 1 is also observed for high-latitude Pc 1-2, but modulation is not as pronounced as with midlatitude Pc 1. The empirical relation between

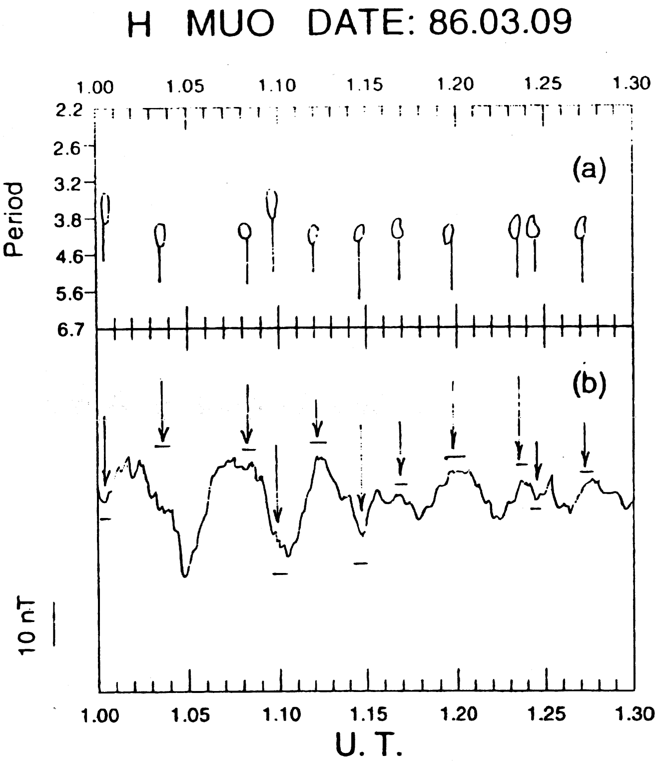

Figure 7. (a) Intensity maxima of Pc 1 dynamic spectrum and (b) simultaneous wave form of a Pc5 event (H component; March 9 1986, at MUO).

the Pc 1-2 frequency (f) and the repetition period (τ) is $f \cdot \tau = 4$ to 80. This relationship is much more constrained for midlatitudes (where $f \cdot \tau = 80$-100), but for high latitudes it attains a larger range of values.

2. We did not observe pulsations with the same period at all stations simultaneously for periods larger than 3 s. This suggests that the ionospheric ducting of high-latitude Pc 1-2 pulsations with periods larger than 3 s is fairly weak. An ionospheric duct cutoff period of about 2-3 s has been calculated [*Duong and Fraser*, 1977].

Figure 6 demonstrates that the occurrence of Pc 1-2 at subauroral to superauroral latitudes has a similar maximum during the early afternoon hours. This implies a common source of Pc 1-2 at these latitudes. The increasing amount of pulsations in the morning at the lowest stations corresponds to the morning maximum of Pc 1 pulsations at low latitude and midlatitude and is most probably explained by the low damping of the Pc 1 signal in the duct at these hours.

3. The pulsation period was found to increase with latitude, in agreement with results of *Baransky et al.* [1981] for lower latitudes. The most significant amplification of the waves is expected below the helium gyrofrequency. This is confirmed both by satellite observations [*Ludlow et al.*, 1991] and by theoretical calculations [*Kozyra et al.*, 1984]. Therefore we can estimate the expected change of pulsation period with L:

$$T > (\omega_{B,He^+})^{-1} = (135/L^3)^{-1}s.$$

This dependence is shown in Figure 8. Some experimental values of periods taken from Figures 2-4 and the event of 10.08.78 (1200-1600 UT) are also shown on Figure 8 with the corresponding L of the station of observation. In spite of the fact that the above estimate was made using a dipole approximation, the agreement of the theoretical curve and the experimental data is fairly good.

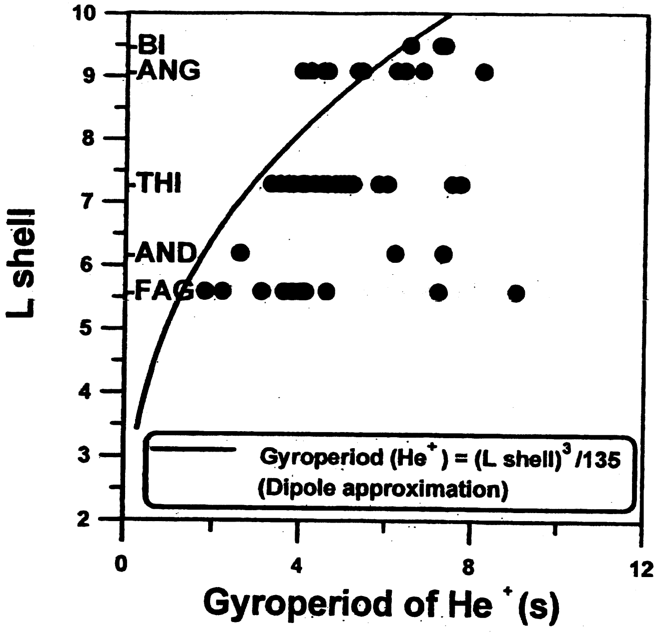

Figure 8. The line depicts the He$^+$ gyroperiod versus L value for a dipolar magnetic field. Points show some Pc 1-2 events observed at the respective stations.

4. Maximum Pc 1-2 occurrence was found for L shells 6-9. In contrast to *Hansen et al.* [1992] and *Menk et al.* [1993] we find that this maximum is located at latitudes lower than the cusp-cleft region, definitely on closed field lines inside the magnetosphere. Probably the cusp-cleft maximum reported in the above mentioned papers resulted from the inclusion Pc 2_{sw} in their data. Pc 2_{sw} pulsations have their maximum intensity in the cusp [*Plyasova-Bakounina et al.*,1986; *Engebretson et al.* 1989]. It is worth noting here that our results coincide very well with the latitude and MLT distribution of Pc 1-2 in the outer magnetosphere [*Anderson et al.*, 1992a, b]. Furthermore, on a given day, we often see the Pc 1-2 waves first on the eastern profile and 2 or 3 hours later on the western profile. Hence the Pc 1-2 source seems to be fairly stationary with respect to MLT.

5. Figure 7 depicted an event where Pc 1-2 are accompanied and modulated by long-period Pc 4-5. A similar phenomenon is observed and reported by Y. A. Kopytenko using data from Spitzbergen [personal communication, 1994]. Let us first compare some morphological characteristics of Pc 1-2 and Pc 4-5 pulsations: (1) Both have their maximum occurrence in the early afternoon (for Pc 4-5 data see *Bolshakova* [1965, 1966]); (2) The periods of Pc 4-5 and Pc 1-2 pulsations increase with increasing latitude; (3) The Pc 1-2 repetition period roughly coincides in value with the resonance period of Pc 4-5 at the same station; (4) Both Pc 4-5 and Pc 1-2 are strongly connected with SI; (5) In the magnetosphere, satellite observations often show simultaneous Pc 4-5 and Pc 1-2 waves, the latter being modulated by Pc 4-5 in 80% of observed events [*Barfield and McPherron*, 1972].

These similarities give strong evidence for a common source for Pc 1-2 and Pc 4-5 at high latitudes. We suggest that this common energy source is formed by the upstream waves, located in the solar wind near the bow shock in the noon sector. There are different types of upstream waves (see review by *Russell and Hoppe* [1983]). Monochromatic Alfvén waves are driven by a reflected proton beam and are responsible for solar wind-controlled Pc 2-4_{sw} pulsations [*Plyasova-Bakounina*, 1993]. Another wave type is the highly compressional broadband wave driven by "diffuse" protons. We believe that these are responsible for the excitation of resonance ULF oscillations because they can easily propagate through the magnetopause tangential discontinuity and, as a broadband signal, they can excite a broad-band Alfvén resonance in the magnetosphere.

When penetrating into the magnetosphere, the low-frequency part of these compressional MHD-waves can couple to the resonance oscillations of field lines, thus generating Pc 4-5 pulsations. This process is widely discussed in the literature. The high-frequency part of MHD waves can be amplified due to the resonance interaction of the waves with energetic ions near the helium gyrofrequency and be focussed at L= 6-9 when propagating from the equatorial magnetosphere to the ground. In this process, energy of the resonance low-frequency oscillations may be transferred into the high-frequency waves as explained by the following facts:

1. The mean power of the long period pulsations is orders of magnitude greater than the typical power included in Pc 1-2 pulsations.

2. The frequency response of the magnetospheric resonator has to have a multiharmonic structure [*Dungey*, 1954; *Southwood*, 1974], which is confirmed by experimental observations on the satellites [*Takahashi and McPherron*, 1982; *Tonegava et al.*, 1983]. Hence it is natural to suppose that some of the higher harmonics of this structure occur at the frequency range of Pc 1-2 pulsations.

3. One or several high harmonics of long-period pulsations may be selected as a result of the resonance amplification with the energetic ions. The increase of the amplitude of Pc 4-5 oscillations can lead to simultaneous increase of intensity of high harmonics, which leads to the modulation of Pc 1-2 intensity by long-period Pc 4-5 oscillations.

The periodicity of Pc 1 wave ackets is determined in the model by the period of low-frequency oscillations (antisymmetric mode), not by bouncing of the wave packet between conjugate points. Since the wave packet does not bounce between conjugate points, a sharp gradient of the cold plasma density is not required for wave ducting and, consequently, the mechanism can operate on any field lines of the magnetospheric resonator, that is, can operate also in the outer magnetosphere.

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A. W. Green and T. A. Plyasova-Bakounina, U. S. Geological Survey (M/S 968), POB 25046, Denver Federal Center, Denver CO 80225, USA; e-mail awgreen@gldfs.cr.usgs.gov

J. Kangas and K. Mursula, Department of Physical Sciences, University of Oulu, FIN-90570, Oulu, Finland; e-mail Kalevi.Mursula@oulu.fi

O. A. Molchanov, Institute of Physics of the Earth, 10, B. Grusinskaya str., 123242, Moscow, Russia: e-mail oleg@aurora.ee.uec.ac.jp

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