"Physics of Auroral Phenomena", Proc. XXX Annual Seminar, Apatity, pp. 119 - 122, 2007

Polar Geophysical Institute

STORM-TIME Pc1-2 WAVE EVOLUTION: A CASE STUDY

N.A. Zolotukhina[1], V.A. Pilipenko[2], M.J. Engebretson[3], A. Roger[4]

[1]*Institute of Solar-Terrestrial Physics, Irkutsk, Russia*
[2]*Institute of the Physics of the Earth, Moscow, Russia*
[3]*Augsburg College, Minneapolis, USA*
[4]*British Antarctic Survey, Cambridge, UK*

Abstract. We have analyzed 0.1-5 Hz geomagnetic pulsations recorded by an array of Northern mid-latitude and Southern high-latitude stations during the maximum and early recovery phase of the great magnetic storm on April 6-7, 2000. These pulsations started at the storm maximum as IPDP-like phenomenon observed in the morning sector at mid-latitudes, and then transformed into superposition of the hydromagnetic (HM) whistlers and structured HM emissions observed both at middle and high latitudes. Intensity of structured HM emissions matched the solar wind dynamic pressure pulses very well, while intensity of HM whistlers was not related to them clearly. The structured HM emissions ended as HM whistlers, which had the same frequency as the preceding emission did and appeared out of phase between the Northern and Southern hemispheres. The transformation of structured emissions into whistlers took place during reductions of the solar wind pressure and IMF pulses.

Introduction

Geomagnetic pulsations analyzed in this paper belong to Pc1,2 hydromagnetic emissions (frequencies f =0.1-5 Hz) which, as it follows from the satellite and ground-based observations, are generated by energetic ions (10-100 keV) in the equatorial region of the magnetosphere. Emitted waves propagate along the geomagnetic field lines, penetrate into the ionosphere, and spread along the F2 ionospheric wave guide over the Earth [Kangas et al., 1998, Loto'aniu et al., 2005]. Under favorable conditions, Pc1,2 can be observed globally as it is in the case under study.

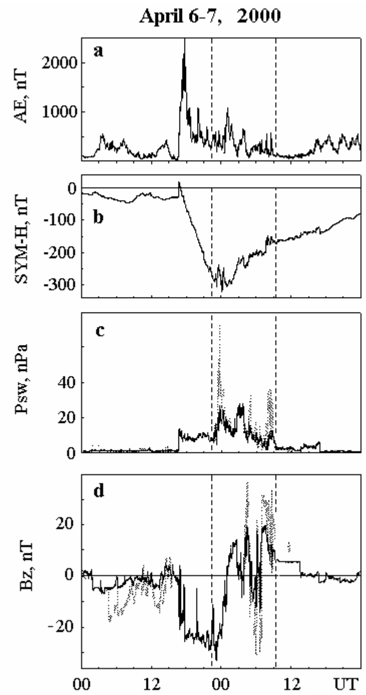

Fig. 1

2. External and internal conditions

The sketch of geomagnetic and interplanetary conditions on April 6-7, 2000 is given in Fig. 1. The interval of Pc1,2 succession (from 2220 UT on April 6 to 0920 UT on April 7) is marked by vertical dotted lines. To determine this interval we used the search-coil magnetometer data from two mid-latitude and four high- latitude stations listed in Table. Pc1,2 waves were registered during the maximum and early recovery phase of the great magnetic storm (minimum Dst =-288 nT). AE (UT) and SYM-H (UT) dependencies were taken from http://swdcwww.kugi.kyoto-u.ac.jp/wdc/. The dynamic pressure (P_{sw}) and interplanetary magnetic field (IMF) B_z-component, measured by Wind in the solar wind, are shown by solid lines. The same parameters measured by IMP 8 in the magnetosheath are indicated by dotted lines. The satellite data are available at http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/. A time of a space plasma propagation Δt from the satellite to the sub-solar magnetosphere is taken into account. A similarity between the dynamic pressure/magnetic field variations from the Wind and those from the IMP 8 points to the fact that on April 6-7, 2000 the solar wind inhomogeneities penetrated into the magnetosheath, hit the magnetopause, and compressed/decompressed the magnetosphere. One can see that the Pc1,2 waves accompanied the decrease of: **a)** auroral activity (AE index), **b)** ring current intensity (SYM-H index), and **c)** P_{sw}; and the rise of B_z from –26 to 18 nT **(d)**. It is significant that Pc1,2 sequence started to develop after 5.7 hours of the strong magnetospheric convection associated with the almost stable negative IMF B_z =-22±5.5 nT.

3. Analyzed ULF phenomena

Dynamic spectra of the 0.1-5 Hz pulsations calculated from POL, BOR, and MON data (0.1 s sampling period) are given in Fig. 2. The pulsations spectra from A80, A81, and A84 (0.5 s sampling period) are similar to those from POL in the 0.1-1 Hz frequency range and aren't presented. For the sake of convenience, the P_{sw} (UT) and B_z (UT) dependencies are indicated respectively by a line and shadow areas at the top of Fig. 2. It can be seen that the Pc 1,2 succession began as a mid-latitude IPDP event that was registered at morning (MON, 2220-0020 UT, 0520-0720 MLT), and, partially, at post-midnight (BOR, 2350-0020 UT, 0250-0320 MLT) hours. There are no Pc1,2 structures at the high-latitude Antarctic stations during mid-latitude IPDP registration.

Table. List of search-coil magnetometer stations

Station	Code	Geomagnetic		*L*	sampling period, s	April 6-7, 2000 daylight (UT)
		Lat., degree	Lon., degree			
South Pole	POL	-74.02	18.35	13.2	0.1	-
A80	A80	-66.30	28.70	6.2	0.5	10:30-16:30
A81	A81	-68.60	36.50	7.5	0.5	09:05-14:30
A84	A84	-69.10	25.60	7.9	0.5	-
Borok	BOR	53.95	113.98	2.9	0.1	02:40-16:05
Mondy	MON	46.74	173.44	2.1	0.1	22:45-11:50

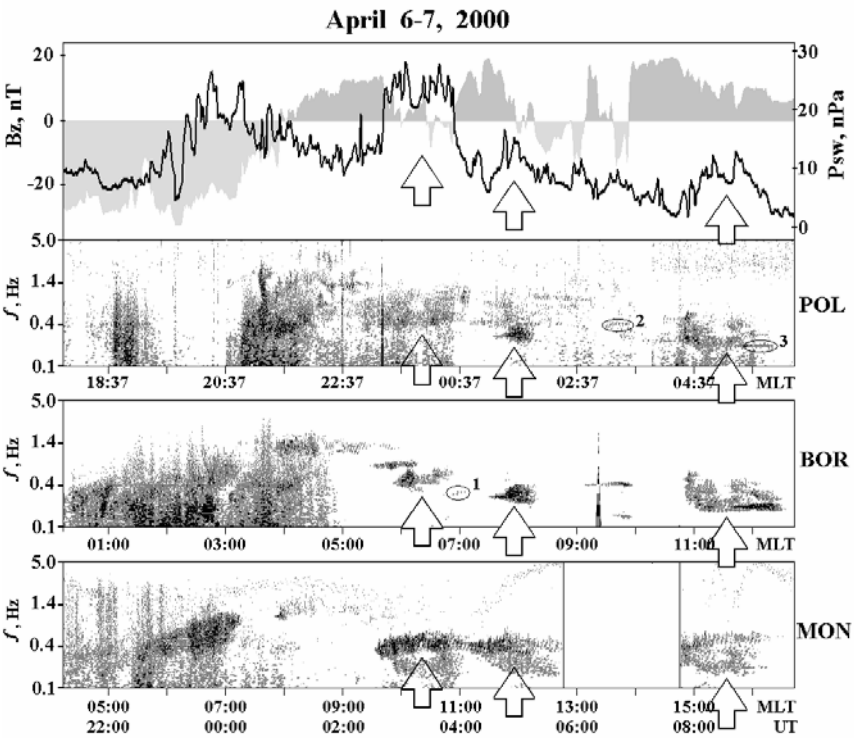

Fig. 2. Dynamic spectra of pulsations from POL, BOR and MON. Variations in Psw (line) and Bz (shadow areas) from Wind are shown at the top. Some of the structured HM emissions are marked by arrows, some of the HM whistlers - by ellipses.

The dynamic spectra of Antarctic stations became similar to those of the mid-latitude stations after 0050 UT when IMF B_z became positive. The spectra consist of broad-band ($\Delta f / f \geq 0.5$) structured HM emissions, and whistlers [Fukunishi et al., 1981]. Each wave structure appears concurrently at all stations. As an example, 3 broad-band mixed emissions, marked by arrows, were observed at all stations. They coincided with 3 strongest P_{sw} enhancements observed after 0050 UT. In contrast, the whistlers accompanied both the increase (event 2 in Fig. 2) and decrease (events 1,3) of P_{sw}; but they were also seen concurrently in the spaced station spectra.

Fig. 3 shows the variations of amplitude Ae (polarization ellipse major axis) spectra of the H and D components in a running 5-min window from BOR (top panel) and A81 (bottom panel) calculated using the Rankin and Kurtz [1970] technique. The rectangles give the limits of Ae variations in frequency band marked in each panel. Grey line indicates the P_{sw} variations. A close association can be observed between 3 strongest P_{sw} enhancements and 3 broad-band Pc1,2 activations that has been mentioned above while studying the dynamic spectra. An amplitude of the waves, accompanied the P_{sw} enhancements, is maximal at A80, A81, and A84 (~10-20 nT/s). Concurrent amplitude from mid-latitude/polar stations is almost two/three order lower (MON and BOR, Ae ~ 0.07-0.5 nT/s; POL, Ae≤0.02 nT/s) than that from Antarctic auroral stations. Close to these amplitude relations were obtained from comparison between whistler spectra.

4. Discussion

Let us to point and discuss the most significant peculiarities of the investigated wave phenomena:

- Decrease of the Pc1,2 frequency on the P_{sw} reduction background;

- Quasi-periodicity of the strongest wave amplifications;

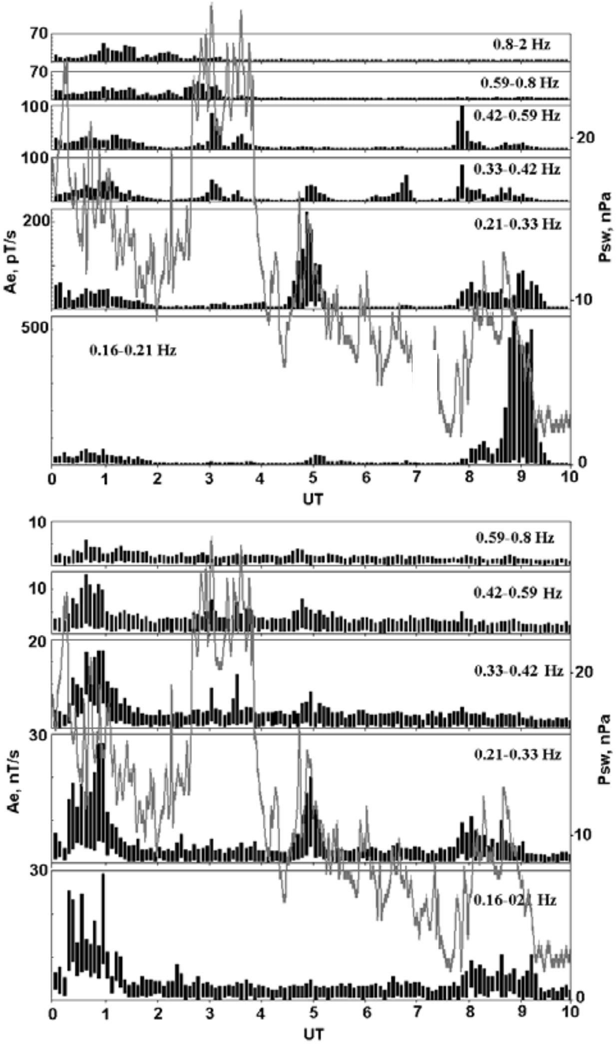

Fig. 3. Time variations of the wave amplitude (A_e) at BOR (top) and A81 (bottom) in the chosen frequency bands. The Psw variations are shown by a grey line.

Multi-component and unsteady frequency content of Pc1,2 pulsations. HM emissions of different types persist concurrently in several frequencies, and at the same time a type of Pc1,2 emissions changes during almost each individual wave activation.

Gradual decrease in the wave central frequency is the most notable peculiarity of studying Pc1,2 succession. From Figs. 2,3, one can see that this process accompanies the non-monotonic decrease in P_{sw}. Thus $f_1 \approx 0.5$ Hz with $P_{sw1} \approx 25$ nPa at 03 UT, and $f_2 \approx 0.2$ Hz with $P_{sw2} \approx 5$ nPa at 09 UT. Linear estimate made under assumptions that f ~H [Kangas et al., 1998], and the geomagnetic field H ~ $P_{sw}^{1/2}$ [Spreiter et al., 1966] gives the ratio $f_2/f_1 = (P_{sw2}/P_{sw1})^{1/2} = 0.45$, that is almost equal to $f_2/f_1 \approx 0.4$ calculated from search-coil magnetomer data. Hence the lowering of Pc 1,2 wave frequency might have resulted from the magnetosphere extension leading to a reduction of the geomagnetic field.

Judging from the compound multi-band structure of spectra, there were several sources of Pc1,2 waves at the early recovery phase of the storm. Based on the model estimates and wave spectra properties we believe that the most powerful wave source was formed from the energetic plasma sheet ions at the end of the storm main phase. In section 2, it has been pointed out that the storm main phase developed under $B_z = -22 \pm 5.5$ nT, thus the electric field of the magnetospheric convection $E_c \sim 1.8 \pm 0.4$ mV/m [Gonzalez et al., 1994]. Under these circumstances, the ions of the plasma sheet inner edge progressed from L ~ 5.7 at 16 UT to L = 2.7 at 19 UT on April 6 [Kamide and Winningham, 1977] and formed a non-monotonic ("nose-shaped" or "wedge-shaped") energy spectrum [Burke et al., 1998; Ganushkina et al., 2000]. This spatial structure is metastable in respect to the Pc1,2 wave generation [Engebretson et al., 2002]. Hence the probable Pc1,2 source was created in the inner magnetosphere 3 hours before the start of Pc1,2 waves, and manifested itself through the morning IPDP [Zolotukhina, 2005].

After the convection decay at ~ 0050 UT (when IMF B_z became positive), the new inner plasma sheet boundary formed at L ~ 6.8. The old plasma sheet particles, located at L = 2.7-6.8, passed from non-closed into closed trajectories and formed a "nose-shaped" wave source drifting around the Earth. The wave effects of this source are seen evidently in the top panel of Fig. 3 in the 0.33-0.42 Hz frequency range. Five wave amplifications characterized by Ae >20 pT/s and repetition period ΔT ~ 110-120 min can be seen. The first Ae enhancement was registered immediately after the IMF B_z re-orientation at ~ 01 UT. This Pc1,2 activation corresponds to a wave structure that is undoubtedly seen at f ~ 1 Hz in the MON spectrum, and less clearly - in the noisy dynamic spectra from BOR and POL (Fig. 2). The fifth structure was registered at ~ 08-09 UT. It started at 0740 UT as a mixed broadband HM emission with f ~ 0.2-04 Hz and evolved into the HM whistler with f ~ 0.2 Hz.

The drifting source had to generate waves which maximum intensity would have drifted to the west with a speed of ~ 3° per min as the emitting source did. By contrast, on April 7, 2000 a wave intensity rose almost simultaneously at different longitudes (see Figs. 2,3, and Table). To explain the longitude synchronism in the wave activation, one has to take into account that only the waves guided from the magnetosphere equator along the field – aligned ducts can be registered on the Earth's surface. One of the probable magnetospheric waveguides – the spatial structure associated with plasma density n = 10-45 cm^{-3} - was detected by the LANL satellites on April 7 at 1130-1600 MLT sector. Only two of the stations listed in Table were located for some time in this sector in the course of Pc1,2 registration. They are MON and BOR, which intersected the 1130 MLT meridian at 0430 UT and 0830 UT, respectively, because of the diurnal rotation. The analysis of wave polarization has shown that the MON/BOR

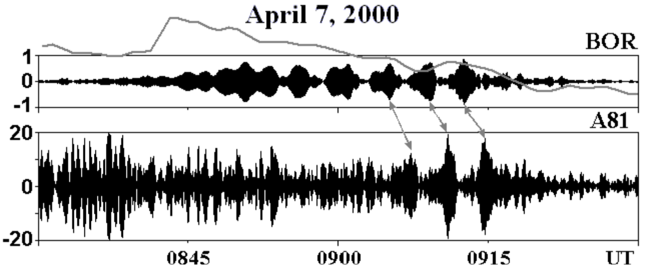

Fig. 4. Geomagnetic pulsations recorded in the 0.16-0.21 Hz frequency band at BOR and A81 during a Psw (grey line) relaxation.

registered the signals propagated only from east to west before 0430/0830 UT, but both stations also observed the waves propagated in an opposite direction after these times. Consequently, the intensive broad-band emissions observed with the ground-base magnetometers on April 7 were really generated by the drifting wave source in the detached plasma region. It would appear reasonable that the enhancements of P_{sw}, happened while the cloud of emitting particles was passing through the magnetospheric duct, strengthened the wave source power additionally. The additional Pc1,2 sources, especially the sources of HM whistlers, were likely to be produced by the interaction between drifting particles and small-scale regions of dense magnetospheric plasma [Yahnina et al., 2000]. These combined effects supplemented by propagation of the waves in the F2 ionospheric duct explain the multi-component wave spectra and the global character of Pc1,2 activations.
The Pc1,2 type transformations described above are typical for HM emissions [Kokubun, 1970]. These transformation took place many times on April 7 while Pc1,2 succession evolved. The most informative in the HM whistler nature investigation is the transformation from a broad-band structured HM emission into structured pearls happened at the end of Pc1,2 train, at 0830-0900 UT. During this time BOR/MON were located in the vicinity of the western/eastern edge of detach plasma region, whereas A80, A81 and A84 stations - in the vicinity of inner edge of the plasma sheet ionospheric projection. In Fig. 4 (BOR), five wave packets are clearly seen with f~ 1.8 Hz, repetition period τ~ 240 s, and amplitude A ~0.5 nT/s. Three wave packets with f~ 1.8 Hz, and A~ 15 nT/s are readily apparent at record from A81 station. The wave packets from Antarctica are time shifted by τ /2 relative to those from BOR, as should be in the case of "pearl" pulsations. The wave type changed under P_{sw} reduction. From Figs. 3,4, it follows that the transformation from HM structured emission into "pearls" was accompanied by a sharp increase of a wave amplitude Ae from ~0.1 to 0.5 nT/s (Fig. 3, 0.16-0.21 Hz) at BOR which developed while the station entered in the detached plasma region MLT sector. By contrast, the "pearl" amplitude from A81 is almost equal to those of the preceding noise pulsations. Hence the sharp increase in the wave amplitude at BOR is a local effect caused by progress of the station towards the ionospheric projection of the wave source. In contrast to this, the transformation of mixed structured HM emissions into "pearls" happened globally, and is indicative of the wave sources and waveguides stabilization under reduction of P_{sw} and IMF pulses (Fig. 1.2).

Conclusions

Comparative analysis of ground-based and satellite data has show that:
- The powerful source of Pc1,2 pulsations was created at the end of the main phase of the April 6-7, 2000 magnetic storm. This source drifted with azimuthal velocity ~ 3º per minute, and turned around the Earth 4 times at least;
- The power and frequency of emitted waves were modulated by the solar wind dynamic pressure variations;
- The field-aligned post-afternoon magnetospheric waveguide created the local spatial and global temporal maxima of pulsations activity;
- The final transformation of the mixed HM emission into "whistlers" developed without a significant change of the wave frequency under the wave source and wave-guide stabilization.

Acknowledgments. This study is supported by INTAS grant 03-51-5359 and Program Presidium of RAS № 16.

References

Burke W.J., et al. J. Geophys. Res., 103, 29 399, 1998.
Engebretson, M.J. et al., J. Geophys. Res., 107(A12), 1451, doi:10.1029/2001JA000198, 2002.
Fukunishi H., et al. J. Geophys. Res., 86, 9029, 1981.
Ganushkina N., et al. J. Geophys. Res., 105, 25 205, 2000.
Gonzalez W.D., et al. J. Geophys. Res., 99, 5771, 1994.
KamideY., Winningham J.D. J. Geophys. Res., 82, 5573, 1977.
Kangas J., Guglielmi A., Pokhotelov O. Space Science Reviews, 83, 435, 1998.
Kokubun S. Rep. Ionosph. Space Res. Japan, 24, 24, 1970.
Loto'aniu T.M., Fraser B.J., Waters C.L. J. Geophys. Res., 110, A07214, doi:10.1029/2004JA010816, 2005.
Rankin D., Kurtz R. J. Geophys. Res., 75, 5444, 1970.
Spreiter J.R., et al. Planetary and Space Science, 14, 223, 1966.
Yahnina T.A., et al. Geophys. Res. Lett., 27, 3575, 2000.
Zolotukhina N.A. Solar-Terrestrial Physics, 8 (121), 20, 2005.