Magnetospheric ULF Wave Phenomena Stimulated by SSC

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Several ssc were recorded simultaneously at the low-latitude longitudinal and along the 210° magnetic meridian networks. The considered ULF wave phenomena stimulated by the ssc comprise main and preliminary impulses, Psc 3 pulsations, ssc-related Pc 3 and cavity-like oscillations. The analysis of observed ssc shows that the preliminary impulse is still not able to explain invoking by the existing theory. It is also found some problems concerning the interpretation of features of other ssc-associated wave phenomena.

Further specially coordinated observations at a world-wide magnetometer network with high precision of time synchronization are required to understand these unresolved problems.

1. Introduction

Among the large variety of ULF wave phenomena in the magnetosphere a special attention has been paid to the study of ssc-related phenomena. An impulsive impact of ssc is a convenient probing signal for the experimental study of the magnetospheric response. Despite the seemingly simplicity of such impact, the complex of ULF wave phenomena stimulated by ssc turns out to be surprisingly large. A pulse of the solar wind pressure may induce in the magnetosphere a stepwise increase of the geomagnetic field—main impulse (MI), preceding it a short preliminary reverse impulse (PI), local standing field line oscillations (Psc 3-5), and global cavity-mode oscillations. There exist also other wave phenomena associated ssc, such as bursts of Pc 1 pulsations and of VLF emissions, but these high frequency phenomena are beyond the scope of the present paper.

In a particular event, an observed response on an interplanetary shock or discontinuity may be rather complicated due to the simultaneous excitation of several ULF wave processes. Despite a long history of the ssc studies, the basic physics of ssc-related wave phenomena has not been sufficiently established yet. Basing on the analysis of experimental data, Araki (1977) suggested the phenomenological model of ssc, in which the observed field is interpreted as the superposition of DL field (stepwise compression of geomagnetic field) and DP field (bi-polar impulse). The two-impulse structure, DP, is further decomposed into the parts corresponding to the PI and the following MI. The nature of a stepwise increase of the geomagnetic field is now clearly identified as a global compression of the magnetosphere. However, the appearance of PI is still an intriguing phenomena.

In this paper we shall show that none of the existing theories of PI can be considered as an adequate. Also we shall indicate some questions, concerning the physics of other ssc-associated ULF phenomena, which still should be answered. The paper is organized as follows. For each class of wave phenomena under consideration, we present some experimental examples. Then, using this experimental illustration, we attempt to examine the existing theoretical models and to show some unresolved problems of the data interpretation.
2. Experimental Database

We analyzed digital data from latitudinal and longitudinal networks of magnetic stations as shown in Fig. 1. The latitudinal network data are from the 210° magnetic meridian stations, Moshiri(MSR, \(L = 1.57\)), Kagoshima(KAG, \(L = 1.2\)), Chichijima(CBI, \(L = 1.14\)), Weipa(WEP, \(L = 1.18\)), Birdsville(BSV, \(L = 1.60\)), and Adelaide(ADL, \(L = 2.13\)) (see Yumoto et al., 1992, 1996a). All the stations are equipped with the identical fluxgate magnetometer with a flat frequency response in the range 0–1.0 Hz. The time signals from the WWVH and JJY radio systems are also recorded at these stations to correct the data with a time accuracy within 1 sec. The time channel at the CBI station was essentially influenced by a man-made interference during the period of data analysis. So, the data of this station have a greater time uncertainty of 4–5 sec.

The longitudinal network data along \(L \approx 1.6\) are from:

(a) the MSR station (geographical coordinates: 44.37°N, 142.27°E; geomagnetic: 37.7°, 213.0°; LT = UT + 9.5hr) from the 210°MM network.

(b) the meridional array of 3 stations with a small baseline, deployed along the 146° geomagnetic meridian (LT = UT + 5.5hr) in Central Asia by the US Geological Survey and the Institute of the Earth Physics (Moscow) during the period of July–August 1990 to study the spatial structure of ULF waves at low latitudes (Green et al., 1993). The geographic and geomagnetic coordinates of the central station Tash-Moynok(TM) are (42.42°N, 74.42°E) and (37.6°, 146.4°, \(L = 1.59\)), respectively. The stations Tash-Utkul(TU) and Aksai(AS) are shifted along the geomagnetic meridian by 100 km to the North, and by 250 km to the South, respectively. The measurements of ULF magnetic fields were conducted with the triaxial ring-core fluxgate magnetometers (TU, TM) and with the induction magnetometer (AS). The electronic amplifiers at all the stations show the flat frequency response in the range 0.003–0.2 Hz. The recording systems with a sampling rate of 2 sec were synchronized to within 30 milliseconds among the stations using timing radio pulses.

(c) the magnetic observatory at L'Aquila (LAQ; geographical coordinates: 42.38°N, 13.32°E, geomagnetic: 36.2°, 88.0°, \(L = 1.6\), LT = UT + 1hr), operated by the L'Aquila University (Vellante et al., 1989). An induction type magnetometer was installed to record ULF waves with a sampling rate of 1 sec.

![Fig. 1. The locations of latitudinal and longitudinal network stations.](image-url)
Using digital data from these stations, we tried to determine apparent propagation velocities of MI and PI of ssc in the meridional and in the longitudinal directions along the Earth's surface. There are two possible methods for determination of the time lag between impulsive signals detected at two separated stations. The first method is to compare moments of the signal's onsets. The second one is to estimate time delays between the relevant amplitude peaks of signals. For ssc recorded by a fluxgate magnetometer the first method usually gives a large time uncertainty. So, in this study we used the second method. For comparison of signals recorded at the longitudinally separated stations, we analyzed time-derivative data of the MSR station, which show a similar frequency response to that of the induction type magnetometer at LAQ. The data from induction-type magnetometers are denoted as $H$ and $D$. The data of MSR were also high-pass filtered with the cut-off frequency 3 mHz for the comparison of signals between MSR and stations in Central Asia. Physically reasonable results can be obtained only if a signal does not change its form essentially during the propagation, because the observed time delays are much shorter than the duration of signals.

3. MI and PI of SSC

3.1 Propagation of MI and PI along the Earth's surface

The very intense ssc occurred at 03:42 UT on 91/03/24 (day 83). Although this event was reported already by Yumoto et al. (1992), here we re-consider it in detail. This event will be considered as a reference example in the subsequent treatment of the observational data, because of its very clear and sharp temporal form. During the ssc the $H$-component magnetic variation increased sharply at all stations of the latitudinal network up to 200–250 nT within a rise-time about 30 sec as shown in Fig. 2, and then relaxed to a new disturbed level. The $D$-component magnetogram indicates a very short spike which overlays on more gradual variations. The $H$-

![Fig. 2. H-(top panel) and D-components(bottom panel) variations (in nT) of the geomagnetic field during the 91/03/24 ssc event observed at the 210°MM network stations. Abbreviated names of the stations are indicated near the ordinate axis. The reference time is marked by a dashed line.](Image)
component variations are in phase, while the short spikes in the $D$ component are roughly out-of-phase (negative in the northern hemisphere, and positive in the southern hemisphere) between the conjugated stations. We suppose that the disturbances in the $H$ and in the $D$ components are a manifestation of two different wave phenomena, overlapping each other. About 10 sec duration of the $D$-component spikes, is shorter than that of the $H$ component impulse of 20–50 sec. Then, apparent velocities of the propagation along the meridian are different in this event. The main positive peak of the $H$ component has a systematic time delay among the stations, corresponding to an apparent equatorward propagation in both the hemispheres (Fig. 2). The projection of the observed propagation pattern onto the equatorial plane in the magnetosphere gives a group velocity in the range $(3.5–18) \cdot 10^2$ km/s. On the other hand, the spikes in the $D$ component show an apparent anti-equatorward propagation in the equatorial magnetosphere with the velocity not less than $5 \cdot 10^3$ km/s. We suppose that the $D$-component spikes predominantly show the PI component, while the $H$-component positive impulse is mainly the MI component of the ssc. More clear manifestation of PI in the $D$ component can be seen in the equivalent current system of PI in the afternoon hours (Araki, 1977). The unusually short durations of PI and MI, as well as the small time lag between PI and MI, are probably caused by a very strong and rapid compression of the magnetosphere in this event.

In most other events amplitude-time variations of the geomagnetic field along the meridional network were smoother than that of the reference event of 91/03/24, but show the similar features. ssc took place at 1:07 UT on 90/07/28 (Day 209), when the 210°MM network was in the pre-noon sector ($\sim$10 LT), TM near dawn meridian ($\sim$6.5 LT), and LAQ in the post-midnight sector ($\sim$02 LT). The apparent meridional propagation of the $H$-component peak is evident towards the equator as shown in the upper panel of Fig. 3. The corresponding time delays between MSR and KAG and between KAG and CBI are about 10 sec and 30 sec, respectively. The weak PI can be seen in the $H$ component, especially at stations in the southern hemisphere. This negative peak has no time delay among the stations. The $D$ component in the reference event showed the sharp spikes, which were negative at northern stations and positive at southern stations. The amplitude maxima of these spikes have much smaller time delays between the stations: $\Delta t(ADL/WEP) = 0$ sec, $\Delta t(MSR/KAG) = 4$ sec (Fig. 3), than those of positive peaks in the $H$ component. However, the uncertainty about several sec exists in the determination of a signal's arrival time, because these spikes are not so sharp.

ssc signals at stations in Central Asia are practically identical for all the considered events. Hence, the propagation effects of MI or PI at the baseline of 100–250 km can not be identified with a sampling rate of 2 sec. Data of one station only (TM or TU) from the array in Central Asia will be presented in subsequent analysis.

The apparent propagation velocity in the azimuthal direction has been tried to estimate by the comparison of the pairs of magnetograms with similar frequency responses. However, stable and clear regularities have not been observed along the network MSR-TU(TM)-LAQ. In most cases it was hard to determine the propagation effects, because the signal waveforms at world-widely separated stations were substantially different. In some cases, when similarity of the waveforms enabled the reliable comparison between the stations, the observed time delay between positive peaks of the $H$ component was in the range 3–20 s. These delays correspond to the azimuthal propagation with velocity in the magnetosphere either about or higher than the Alfvén velocity. However, even these clear impulses did not show a regular time delay between consecutive pairs of stations. A mixture of the apparent anti-sunward and sunward propagation velocity has been observed quite often for the same event.

It's interesting that time shifts in some events could be reliable determined not only between MIs, but between PIs as well. The event 90/07/28 (day 209) is presented in Fig. 4 as an example. At the moment of the 03:31 UT, LAQ was located in the night time sector ($\sim$4.5 LT) and MSR was near the noon meridian ($\sim$12 LT). This ssc has most evident PI in the $D$ component.
Fig. 3. H-(top and middle panels) and D-components(bottom panel) variations (in nT) of the geomagnetic field along the 210° magnetic meridian during the ssc event at 03:42 UT on 90/07/28. The vertical dotted line indicates a reference time.

Comparison between the PI waveforms in the $D$ components shows that the signal at MSR leads that at TU by 11 sec as shown on the second and third plots in Fig. 4, indicating anti-sunward propagation from the noon sector to the dawnside. The time lag $\Delta t = 6$ sec can be seen also between positive PI peaks in the $\dot{D}$ ($dD/dt$) component at MSR and LAQ (two bottom plots), indicating the sunward propagation from the pre-dawn sector to the dayside.

The results of the apparent propagation effects for MI and PI can be summarized in the followings. The unambiguous propagation pattern can be seen only in the latitudinal distribution of the $H$-component MI's. This apparent propagation of the MI's is directed towards the equator in both the hemispheres. The similar effect of equatorward propagation of ssc onset at sub-auroral latitudes was reported by Wedeken et al. (1986). It should be kept in mind that the observed time delays between peaks of the $H$ components may correspond either to the equatorward propagation effect or to the increase of the rise time while approaching the equator. Most PI events of ssc were more evident in the $D$ component with opposite polarity in the northern and southern hemispheres. The PI peaks in the range of latitudes of $L \approx 1.1-1.6$ were practically simultaneous.
Fig. 4. A comparison of magnetograms at stations along the longitudinal network $L \approx 1.6$ during the ssc event at 3:28-3:35 UT on 90/07/28. The following components are shown: $H$ (in nT) at MSR (the top plot), $D$ (in nT) at MSR and TU (the second and third plots from above), $D$ (in arbitrary units) at MSR and LAQ (two lower plots).

Fig. 5. Magnetic and Electric field variations in the interval 5:36-5:46 UT during the ssc event on 90/08/26. From the top to the bottom; the $H$ and $D$ magnetic components (in nT) at MSR; the $H$ and $D$ magnetic components (in nT) at TM; the EW component of telluric electric field $E_y$ (in arbitrary units) and the vertical component of atmospheric electric field $E_z$ (in V/m) at TM.
within the timing accuracy. From the analysis of the ssc propagation along the meridian, it seems that MI and PI are just two overlapping wave processes of different physical nature.

The ground observations of ssc show rather a complicated diffraction pattern than a simple wave propagation in the azimuthal direction. In some cases the time lags indicate apparent super-Alfvénic velocities ($\approx 3 \sim 5 \cdot 10^3$ km/s) of the MI propagation in the magnetosphere. Probably, the observed time delay between $H$ component peaks does not indicate a propagation process, but reflects the difference between the rise-times of signals at different longitudes. Also, different modes might simultaneously contribute to the field of ssc, thus obscuring the propagation effects. The results concerning propagation of ssc signals between world-wide separated stations have to be considered with a great care. The small baseline between the stations does not allow to reveal a propagation effect, whilst waveforms at stations with large separation are often so distorted that it makes an estimation of group delay too ambiguous. More reliable conclusions of the ssc propagation can be observed by means of more dense longitudinal network. Nevertheless, the time delays between PI in some events were reliably detected along the longitudinal network.

### 3.2 Electromagnetic observations of ssc

The electrostatic fluxmeter ("field-mill") was installed at the station TM in Central Asia to record ULF variations of the atmospheric electric field, $E_x$. The on-line recording was made with the same acquisition system as for magnetic components. During the intervals of the $E_z$ observations ssc occurred at 05:43 UT on 90/08/26, (day 233). Figure 5 shows the magnetic field variations at MSR and TM, and the ULF electromagnetic field at TM; horizontal EW component of telluric electric field $E_y$ measured using electrode array and vertical component of the electric field in the atmosphere $E_z$. A clear PI in the $H$-component can be seen at MSR. The negative spike in the $H$-component at TM could also be attributed to the PI. The ssc is clearly evident in the data of the telluric electric field $E_y$. But, no noticeable disturbances of $E_x$ with amplitude above the natural noise level ($\approx 1$ V/m) could be detected at the moment of ssc. The significance of this observational fact will be discussed below.

### 3.3 Possible mechanisms of MI and PI

The physics of a stepwise increase of the geomagnetic field during ssc is well established by the simultaneous satellite and ground observations (Wilken et al., 1982). A rapid displacement of the magnetopause caused by an interplanetary shock induces a magnetic disturbance propagating as a fast compressional wave inward the magnetosphere. Most part of this wave energy is scattered in the magnetosphere, but some reaches the Earth. The ground signal is gradually build up with a time, governed by the propagation time of hydromagnetic disturbance from different parts of the magnetopause and the time of sweeping the dayside magnetosphere by a shock (Dessler et al., 1960). From our experimental data we can not rule out whether a decrease of $H$-component after a main peak is related to relaxation of the magnetopause or to a positive impulse of two-pulse structure (Araki, 1977; Araki et al., 1985). The apparent equatorward propagation of MI along the meridian obtained in this paper implies that a rise-time of MI becomes less with the increase of latitude. We are not aware of any calculations, which might confirm the reality of this effect.

Detailed study of sc/si asymmetries showed that the amplitudes of MI at low/middle latitudes in the summer hemisphere are larger than those in the winter hemisphere (Yumoto et al., 1996b). This observation can be interpreted by invoking an asymmetry in the northern and southern hemisphere twin-vortex-type ionosphere current driven by the DP field, i.e., by invoking enhanced ionospheric conductivities in the summer hemisphere.

Much vague is the physics of PI. As the simplest explanation of this phenomena, it might be suggested that a PI impulse is merely the result of an induction effect in the highly conductive ionosphere. The estimate of the induced electric field in the ionosphere, based on Faraday's law, gives quite reasonable value. However, this simple explanation can not be adopted by
several reasons: a) The theoretical treatment of the compressional wave incidence on the plane (Kikuchi and Araki, 1979a) and the cylindrical ionospheres (Ohnishi and Araki, 1992) show no considerable induction effect. According to these models the main result of the compressional wave transmission through the ionosphere is the smoothing of an incident stepwise impulse. b) The observation indicates that PI is not directly connected with the time derivative of $H$ component, and mostly these signals propagate independently.

In principle, a precipitation of electrons triggered by a magnetospheric compressional wave may cause the appearance of PI. Wedeken et al. (1986) really revealed that the pre-impulse in the $D$ component runs 5 sec ahead of MI, and is probably related to a burst of precipitating electrons. However, the observed pre-impulse of ssc had an amplitude much less than a typical PI. The conception of PI as a fast compressional wave has been developed by Parkhomov (1985, 1990). He assumed that PI is a manifestation of a shock, transformed in the magnetosphere into a fast compressional MHD wave, whereas MI is the result of a subsequent compression of the magnetosphere. That idea was not supported by any theoretical consideration, but a number of indirect observational evidence in favor of this picture was found. Parkhomov (1985, 1990) demonstrated the fine structure of PI, so called Pc1, which could be reasonably explained as the result of the compressional wave interaction with energetic magnetospheric particles. As an argument against the idea of PI as a magnetospheric fast compressional wave, it may be recalled that satellite measurements never revealed any disturbance preceding a stepwise increase of the geomagnetic field in the magnetosphere. The only magnetospheric detection of PI was performed by the low-orbiting (500–550 km) satellite MAGSAT (Araki et al., 1982, 1984). The observed ssc in the $D$ component consisted of PI and a following MI. The similar waveforms in the $D$ component were observed simultaneously at ground stations. The field aligned component of geomagnetic field during PI was not disturbed above the ionosphere, which excludes the mechanism of a compressional wave.

The rapid displacement of the magnetopause caused by a shock wave excites not only a fast compressional wave, but an Alfvén pulse also. Nishida (1964) and Tamao (1964) suggested independently that this pulse can be the reason of a high-latitude PI. Because an isotropic compressional disturbance propagates along the field line with a velocity slightly less than an Alfvén velocity, that may explain the emergence of a time lag between PI and MI. The rotation of an Alfvén pulse in the ionosphere causes a negative $H$-component disturbance at the ground, preceding a main compressional pulse. However, Nishida (1964) and Tamao (1964) did not consider further ways of the PI transmission from high latitudes to middle and low latitudes. In principle, there are three possible ways through the ionosphere, the magnetosphere or the atmosphere.

The first propagation along the ionospheric layers should be disregarded. The propagation zone of MHD disturbances along the ionosphere is limited by several skin-lengths determined by the Pedersen conductivity, and then the propagation distance cannot exceed several hundreds km.

Before analyzing the second possibility, it might be fruitful to try to answer a simple question. The mechanism of PI suggested by Nishida (1964) and Tamao (1964): transport of an extra-magnetospheric disturbance into the magnetosphere by a fast compressional wave, its transformation into Alfvén oscillations, and transmission through the ionosphere to the ground, is very similar to the mechanisms commonly used for the interpretation of Pc3–5 pulsations at low-latitudes (Yumoto, 1986) or of travelling convection vortices at high latitudes (Glassmeier, 1992). Then, which factor makes ssc disturbances (PI with super-Alfvénic propagation velocity) so distinct from other ULF wave phenomena? The probable answer might be related with the following points. First, a ssc is excited by a large scale disturbance, embracing the whole magnetosphere. Second, the incidence of a shock may produce a super-Alfvénic jump of the magnetopause. Third, the mentioned models of high-latitude PI actually assume a non-resonant transformation.
of a compressional wave into an Alfvén one, in contrast with the resonance theory of ULF pulsations. The process of non-resonant transformation of MHD waves in the magnetosphere was not yet theoretically treated, as far as we know.

From a general point of view, the resonant transformation should be more effective, so in a non-resonant case an observable Alfvén signal can be produced only by a rather intense compressional wave, such as ssc. Hence, the following mechanism of magnetospheric origin of PI might be possible. The front of a compressional wave during the propagation inside the magnetosphere excites an Alfvén type disturbances at each field line. An Alfvén impulses are generated away from the equatorial plane and will be barely noticeable by satellite magnetometers. Actually, this picture of the magnetospheric PI generation and its transmission to low latitudes is the extrapolation of the Nishida-Tamao mechanism to the inner magnetosphere. The comparison of ssc electric transient in the magnetosphere with conjugated ground magnetic variations demonstrated $\pi/2$ rotation of the signal in the ionosphere, typical for Alfvén mode (Nishida, 1964; Knott et al., 1985). So, the observation at the geostationary satellite and on the ground indicate the possibility of the excitation of an Alfvén pulse at the front of a compressional wave. Definitely, without model calculations of the efficiency of the non-resonant transformation the possibility of this mechanism remains under question.

Finally, let us consider the third mechanism of the atmospheric propagation suggested by Kikuchi and Araki (1979b). They were the first who noticed the possibility of the existence of TH$_0$ mode in the ionosphere-ground waveguide. This electric mode has such distinctive features as an instantaneous propagation along the Earth's surface and a weak attenuation. The theory of TH$_0$ mode was also applied to explain the simultaneous appearance of PI at high and low latitudes (Kikuchi, 1986).

Nonetheless, we have to indicate a number of serious questions related with this model. First of all, the data used in Araki (1977) and Araki et al. (1985) for the verification of the instantaneous transmission, had time accuracy not better than 10 sec. Moreover, observational data indicating an apparent super-Alfvénic propagation of ssc between widely separated points did not necessarily prove the non-hydromagnetic nature of the signals. Ray-tracing of a fast compressional wave in the magnetosphere shows a tendency of the wave front, which was plane initially, to become more circular-like in both meridional and equatorial planes while approaching the Earth (Namikawa et al., 1964; Stegeleemann and Kenschitzki, 1964). This effect is caused by the slow-down of HM wave in the magnetospheric regions with decreased Alfvén velocities, e.g. the near-equatorial region and the plasmapause. Though formally ray-tracing is not valid for the ULF disturbances in the magnetosphere, the results obtained indicate a complex diffraction pattern of a compressional MHD wave launched by ssc. As a result, a wave front may impinge the ionosphere nearly simultaneously on a global scale. The 20 s delay between ssc onset at the geostationary orbit and at the ground observed by Wedeken et al. (1986) corresponds to the apparent super-Alfvénic propagation. This fact could be interpreted as an indication on a diffractive distortion of MHD wave front in the magnetosphere.

More serious questions are related to the basic physics of TH$_0$ mode. In their treatment of TH$_0$ mode Kikuchi and Araki (1979b) did not consider the effectiveness of its excitation by a magnetospheric disturbance. This effectiveness is proportional to the part of a magnetospheric field aligned current penetrating into the atmosphere. Simple scaling shows that the atmospheric current $J_A$ resulting from a magnetospheric current $J_M$ with a transverse scale $L$ will be determined by the ratio between the resistance of the ionosphere and the resistance of the atmospheric gap

$$J_A/J_M \propto (K* L)^2.$$ \hfill (1)

In the homogeneous atmosphere the parameter $K*^2 = k_0 \kappa_A \sin^2 I/h \zeta$, where the dielectric permittivity $\kappa_A = 1 + i\sigma_A/(\varepsilon_0 \omega)$, $\sigma_A$ is the atmosphere's conductivity, $k_0 = \omega/C$ is the vacuum wave
number, h is the height of the atmosphere, \( \zeta = C/C_A + \Sigma_P/(\varepsilon_0 C \sin I) \), and \( \Sigma_P \) is the height-integrated Pedersen conductivity of the ionosphere. In the atmosphere with the height-increasing conductivity, i.e., when \( \sigma(z) = \sigma_A \exp(z/\alpha) \) (\( \sigma_A \) denotes here the atmosphere’s conductivity near the Earth’s surface) and the displacement currents can be neglected, i.e., \( \omega \ll \sigma_A/\varepsilon_0 \), the parameter \( K_\star^2 = \alpha \Sigma_P/(\alpha \Sigma_P) \). Assuming for the dayside ionosphere \( \sigma_A = 10^{-14} \) m, \( \alpha = 6 \cdot 10^3 \) m and \( \Sigma_P = 5/3 \Omega^{-1} \), we get \( K_\star = 10^{-6} \) km\(^{-1} \). Thus, the relation (1) shows that somewhat significant part of the magnetospheric current would penetrate into the atmosphere only for extremely large-scale disturbances.

This rough estimate is in accordance with the rigorous treatment of the problem on MHD wave transmission through the ionosphere by Alperovich and Fedorov (1984, 1992). Below we will extract from their mathematical formalism the results concerning the TH\(_0\) mode excitation. They considered the model consisting of two hemi-spaces: magnetosphere characterized by dielectric constant \( \kappa_M = (C/C_A)^2 \) and the atmosphere with complex dielectric permittivity \( \varepsilon_A \). These hemi-spaces are separated by a thin ionospheric film with the anisotropic height-integrated conductivities \( \Sigma_P \) and \( \Sigma_H \). The analytical properties of the transformation matrix were analyzed. This matrix describes the coupling due to the anisotropy of the ionosphere between two independent wave modes: Alfvén and magnetoacoustic in the magnetosphere, and magnetic (TE) and electric (TH) in the atmosphere.

The analysis proved that among possible electric modes the TH\(_0\) is excited by a magnetospheric HM wave most effectively. This mode is modified by the coupling with a magnetic mode due to the Hall conductivity, and has a linear polarization \( B_x/B_y = \Sigma_H/\Sigma_P \) (axis \( x \) is oriented along the horizontal wave vector). This mode has the phase velocity \( \omega/Re(K_\star) \) about the speed of light, \( C \); large wavelength, \( Re(K_\star) \ll R_e^{-1} \); and a weak attenuation. The front of TH\(_0\) mode propagates with velocity \( \leq C \), while the front of TE mode \( \sim C_A \). Below the source, i.e., at \( x \leq h \), the input of the TH\(_0\) mode to the ground magnetic field is small, \( \sim (K_\star h) \ll 1 \), as compared with that of a TE mode. At larger distances from the source the amplitude of a TE mode decreases rapidly, as \( (hL/x)^2 \), so at distances about \( 10^4 \) km the input of the TH\(_0\) mode becomes prevailing. The TH\(_0\) mode can be observed experimentally only at large distances from an auroral source.

Nonetheless, it is hard to accept the TH\(_0\) hypothesis even for the interpretation of an equatorial PI. Let us estimate the expected magnitude of vertical electric field component \( E_z \) in a wave of TH type. From the sub-system of Maxwell’s equations for an electric (TH) mode one can obtain the relationship between the wave components \( E_z \) and \( H_y \)

\[
E_z/B_y \simeq -KC/(K_\star \alpha A).
\]

On the assumption that \( K \approx R_e^{-1} \), which was justified by calculations of the TH\(_0\) mode structure in a model of spherical condenser (Alperovich and Fedorov, 1984), the equation (2) yields

\[
E_z/B_y \simeq C/(K_\star R_e \alpha A) \approx i/(\mu_0 R_e \varepsilon_0 A).
\]

From the relationship (3) it follows that, if PI would be a TH\(_0\) mode with an amplitude \( B_y \approx 1 \) nT at the ground, then it must be accompanied by a spike of the vertical component of electric filed \( E_z \) with amplitude about \( 10^2 \) V/m. Our experimental observations as shown in Fig. 5 did not reveal such large disturbances of the atmospheric electric field. Actually the PI-associated disturbance of the atmospheric electric field was less than 1 V/m. The wave electric field of this magnitude corresponds to the magnetic component \( \leq 10^{-2} \) nT. The latter value is overestimation, because we had assume that \( \sigma_A = 10^{-12} \) m. More realistic value is about \( 10^{-4} \) nT.

The accurate estimates by Alperovich and Fedorov (1984) predict that the amplitude of the \( E_z \) disturbance induced by the incident Alfvén wave with amplitude \( B_M \) above the ionosphere and scale \( L \) should be

\[
E_z/B_M \simeq CK_\star^2 L K_\star^{-1}.
\]
For $K_\ast = 10^{-6}$ km$^{-1}$ and $L = R_E \approx 6.4 \cdot 10^3$ km it follows that $E_z/B_M \approx 10^5$ T, where $T$ is the typical period of disturbance. So, Alfvén wave with $T = 10^2$ sec and amplitude $B_M \approx 100$ nT incident on the ionosphere can induce near the Earth’s surface $E_z \approx 1$ V/m only. For these magnitudes of the $E_z$ component the amplitudes of magnetic components would be experimentally negligible. Because the estimated value of the TH$_0$ signal is about the background noise level of the fair weather atmospheric electricity, special experiment is necessary to detect a TH$_0$ mode excited by ssc.

4. ULF Activity Associated with SSC

We believe that it is necessary to distinguish two classes of ULF activity stimulated by ssc. To the first class we refer the transient ULF signal, directly excited by an ssc impulse. Well-known Psc 3–5 pulsations (Saito and Matsushita, 1967) belong to this type. As the second class, we classify the long-lasting ULF activity, which starts just after a ssc. The excitation of these ULF oscillations are not caused by a ssc itself, but, probably, by the enhanced level of solar wind turbulence, following a shock wave. For these events a ssc serves as an indicator of the onset of a more intense solar wind impact on the magnetosphere. Here we present some more examples of both types of the ssc-related ULF activity.

4.1 ULF oscillations directly excited by ssc

Examples of transient Psc 3 pulsations excited by ssc are shown in Fig. 6 for two events: 90/07/28, 3:30 UT and 90/08/26, 05:43 UT. According to the visual waveforms, in the first event the Psc 3 pulsations recorded at TU have the period $T = 12.5 \pm 0.5$ sec and the Q-factor $Q = 4.8 \pm 0.3$. In the second event, the same parameters as determined at LAQ are $T = 17 \pm 0.2$ sec and $Q = 4.2 \pm 0.4$. The periods obtained well correspond to the eigenperiods of local field line oscillations. At the same time the values of Q-factor are much lower than those from the calculations of ionospheric dissipation for these latitudes (Newton et al., 1978). This fact indicates that the model of "thin ionosphere", used in the calculations of Newton et al. (1978) is not valid at the low latitudes.

Figure 7 shows the $H$-component magnetic variations in the 10-min interval, selected after the main peak of ssc at 07:42 UT on 90/08/01. The parabolic trend was eliminated. A clear damping train with period about 2 min is visible at all the stations. This transient signal can be seen in the $D$-component also (not shown), but less clearly than in $H$. The oscillations are believed to be a global event, because the same transient signal has been observed at the world-wide separated stations LAQ, TM and the 210°MM network (Fig. 7). The magnetograms show that these global oscillations are synchronous along the meridian and have noticeable phase shift along the longitudinal network. This shift is probably caused by the propagation of an excitation agent from LAQ (LT = 9hr) till TU/TM (LT = 14hr), and further till MSR (LT = 17hr).

Because the period of the signal is much larger than maximal resonant period at these latitudes, the possibility to relate this signal to local Psc-type field line oscillations should be excluded. This transient signal can not be explained also as the trace of high-latitude Psc 5 pulsation, because its amplitude decreases with increase of latitude. Probably, the observed transient ULF signal is the ground manifestation of global cavity oscillations, excited directly by the ssc impulse. However, this preliminary explanation should be verified with the more global network data.

The weak transient compressional oscillations with similar waveforms were observed also after ssc at the GEOS-2 satellite (Amata et al., 1986). Traces of transient low-frequency oscillations can be seen also after ssc on 91/03/24 (Fig. 2). The similar global transient oscillatory variations of geomagnetic field with period about 3 min after ssc were observed by Tsunomura (1990). He attributed the si-associated variations to the successive incidence of HM compressional waves,
excited by recurrent magnetospheric compressions due to pulse-like variations of the solar wind dynamic pressure. The observations show that the ssc-excited global cavity oscillations decay rapidly. The severe damping is, probably, caused by the leakage of wave energy in the azimuthal direction in the magnetosphere. So, the presented experimental examples indicate that numerous 2-D models of the cavity-like oscillations overestimate essentially the role of these oscillations in the dynamics of the MHD wave processes in the magnetosphere where the escape of wave disturbances to the night side has not been accounted for.

4.2 ULF activity associated with ssc

Figure 8 presents two examples of long-lasting continuous series of Pc 3 pulsations, excited after ssc. The upper plot shows the band-pass filtered H-component record at LAQ during the ssc at 07:42 UT on 90/08/01, while the lower plot shows the similar event after the ssc at 05:43 UT on 90/08/26. The observed series of Pc 3 must be a response of local field line resonator in the magnetosphere during the interval the enhanced level of the solar wind turbulence behind the front of a shock wave. Examples of enhanced wave activity downstream of collisionless shocks were reported by Farris et al. (1994). The Pc 3 activity were not observed at other stations situated in the unfavorable sectors of the magnetosphere. The presented examples indicate that the resonant properties of the magnetosphere may effectively form the spectral content of dayside Pc pulsations. Hence, the relative roles of the solar wind factors and of the magnetospheric Alfvén resonances, controlling the frequency of common Pc 3 pulsations need further clarification.
The long-period cavity-like oscillations after intense SSC which lasted for 20 min were found by Yumoto et al. (1992). The irregular variations of magnetic field for this event (91/03/24, SSC at 03:42 UT), were observed at the 210°MM network stations as shown in Fig. 9 (left panel). To reveal the occurrence of global oscillations by the spectral analysis Yumoto et al. (1992) used the FFT method, which may give inconsistent spectral estimates (Jenkins and Watts, 1968). To verify their results we have applied to the same event the maximum entropy method (MEM) which is superior to the FFT in revealing weak signals. The MEM spectra of the H-component
really reveal certain frequencies, at which the power spectral density is somewhat enhanced as compared with the turbulent background (Fig. 9, right panel). The enhanced level of the power spectral density is observed along the magnetic meridian at frequencies 12 and 24 mHz. So, the physical conclusion made by Yumoto et al. (1992) is supported by the MEM spectral analysis. However, the exact values of the frequencies are somewhat different from the ones (15.5, 25, and 31 mHz) estimated by the FFT technique. Moreover, the MEM has enabled us to reveal the additional frequency \( \approx 3 \) mHz of global oscillations. The spectral peaks at \( f \approx 46 \) mHz at BSV and MSR are due to the local field line oscillations.

We suppose that the observed enhancement of certain low frequency components of the magnetospheric turbulence is caused by the frequency-dependent absorption properties of the magnetospheric cavity. From general physical consideration, the coupling between the solar wind wave disturbances and the magnetosphere is more efficient when the excitation of global eigen oscillations of the magnetospheric volume takes place. In some sense, the magnetosphere as a whole reacts to the incident solar wind as a hydromagnetic resonator, effectively absorbing MHD turbulence at certain frequencies (Pilipenko, 1990). However, this explanation could be adopted only after a proper simulation of this process with a 3D numerical or analytical model.
Fig. 9. A global cavity-like oscillation excited after the ssc event on 91/03/24. Left panel; detrended variations of the $H$ component (in nT) along the 210°MM network, and right panel; the corresponding MEM spectra (in db). AR order is 7% of the total point number. The vertical lines indicate the frequencies of enhanced power spectral density.

5. Conclusion

The analysis of ssc events recorded simultaneously at the latitudinal and longitudinal networks showed the large variety of ssc-associated ULF wave phenomena. Though most of them are more or less known for a long time, there are still no adequate theoretical interpretation of some
features of these signals. In particular, we’d like to draw attention to the following problems of the ssc-stimulated disturbances:

a) The apparent equatorward propagation of MI still needs qualitative interpretation.
b) The most vague understanding remains in the physics of PI impulse. None of the suggested so far explanations of PI seem fully satisfactory.
c) A serious attention should be paid to the theoretical treatment of the possibility of the magnetospheric origin of low-latitude PI.
d) The Q-factors of transient Psc 3 pulsations observed at low latitudes are much lower than those from the existing models of the ionospheric dissipation.
e) If the transient global oscillations with periods about 2 min are really a cavity oscillation, then the physical nature of this cavity should be understood. The existing models of compressional cavity oscillations should be supplemented with the account for the leakage of energy in the azimuthal direction towards the nightside magnetosphere.
f) Does the appearance of ssc-triggered long-lasting Pc 3 pulsations mean that the band-limited spectrum of common Pc 3 is formed also mainly by local field line resonances, but not by solar wind sources?

We paid special attention to the theory of the instantaneous PI transmission in the earth-ionosphere waveguide of Kikuchi and Araki (1979a). This theory has serious difficulties: the low efficiency of an electric mode excitation by a magnetospheric Alfvén wave, and the requirement of large amplitudes of the vertical component of a wave electric field in the atmosphere. Our experimental data did not support the theory of the atmospheric PI propagation. Time delays between PI at separated stations have been detected, and no disturbance of $E_z$ associated with the PI has been observed. Our analysis has been done on rather limited experimental database, and the declared time accuracy about 1 sec at the stations of 210°MM and LAQ can not be guaranteed, also. Nevertheless, we believe that the results obtained should not be totally disregarded. A further progress in the understanding of the physics of ssc-related disturbances would require special experiments with a wide latitudinal network of magnetometers at high precision of time synchronization.

We have to stress that we do not mean that the electric TH$_0$ mode, described by Kikuchi and Araki (1979b) can not exist at all. We have suggested only that this mode can not be the physical reason of PI. The theoretical estimates show that the detection of TH$_0$ mode excited by a magnetospheric disturbances is possible with the existing technique for the atmospheric electricity measurements (“field-mill” fluxmeters and current net collectors). But, for that the organization of a special experiment would be necessary.

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