NATURAL OSCILLATIONS OF THE EARTH MAGNETOSPHERE ASSOCIATED WITH SOLAR WIND SUDDEN IMPULSES

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We have studied Pc-5 magnetic pulsations using data from ACE, Wind, Polar Cluster, Geotail, and Goes10 spacecrafts and Earth-based magnetic field measurements from the Intermagnet archive. The solar wind on the Earth's orbit is a quasistationary formation with tangential discontinuous, fast and slow shock waves. We accentuate our study on the geomagnetic pulsations associated with Sudden Storm Commencements (SSC) and Sudden Impulses (SI). Disturbances of the magnetopause surface produce the fast MHD wave front which penetrates into the magnetosphere. Pulsations associated with fast waves were detected on spacecrafts and on the Earth surface with the same frequency. The excitation of pulsations can be considered as one of the energy transport mechanisms from the solar wind to the ionosphere. The polarization and frequency characteristic of observed waves are discussed in dependence on the geometry of the interaction of a solar-wind shock wave with the magnetosphere. Pulsations with different frequencies were observed simultaneously on different magnetic latitudes. The appearance of spectral maxima after the wideband fast MHD wave propagation testifies to the magnetosphere property to select particular spectral peaks and to produce ULF pulsations with expressed periodicities. The Earth magnetosphere is assumed to be a resonance system for hydromagnetic waves excited due to the shocks outside the magnetosphere.

1. Introduction

Analytical investigations (see, e.g., [1, 3, 11] and references therein) predict the existence of characteristic toroidal Alfven and poloidal surges in Earth magnetosphere representing a hybrid poloidal Alfven modes and slow magnetosonic modes. The frequencies of these oscillations lie in the range from several mHz up to a gyrofrequency of ions (about 1 Hz in external areas of a magnetosphere) The usually proposed mechanism of wave generation in the magnetosphere is the Kelvin–Helmholtz instability developing on a magnetopause [7, 12]. Pursuant to this gear, the surge from the surface of a magnetopause dives inside the magnetosphere. If the frequency of a surface wave coincides with the natural frequency of magnetosphere oscillations, the increase in the amplitude of disturbances takes place [8, 11, 12]. This circumstance testifies also to the validity of this gear, that the meaning of rotation of the polarization vector of surges variously at latitudes is higher than that below the peak (amplitude) maximum [11–13].

The quasiperiodic changes of the solar-wind dynamic pressure are also considered to be a possible generation mechanism of MHD waves in the magnetosphere. The correlation of magnetic field disturbances in the magnetosphere during oscillations of the solar-wind parameters with frequencies close to natural frequencies of the magnetosphere is observed in a series of events [4].

The above-noted mechanisms well explain the independence of the oscillation frequency on the magnetic latitude observed on the ground. But they do not respond on the following problems. Is the simultaneous excitation of natural magnetosphere oscillations with different frequencies possible on different geomagnetic shells, and what kind of generation source needs to be realized for this? These problems become especially topical for the Pc5 generation. The question about their generation mechanism still remains open. In terms of natural oscillations in the magnetosphere, their generation can be originated by the effect of an external source with wideband spectrum. Fast changes of the solar-wind dynamic pressure can be considered to be a source with such a characteristic [6, 7, 10, 12]. The increase of the solar-wind dynamic pressure increases the surface currents on the magnetopause. As a result, the magnetic field in the magnetosphere increases. In this case, the magnetopause became a source of generation of ULF waves of several types [5, 7, 12]. A pressure disturbance propagates through the magnetosphere with the speed of a fast MHD wave [2, 12]. In the day sector of the magnetosphere, this velocity is close to the Alfven speed (from 400 up to 10000 km/sec) and can exceed that of a shock wave in the solar wind which is usually in the range 400–800 km/s.

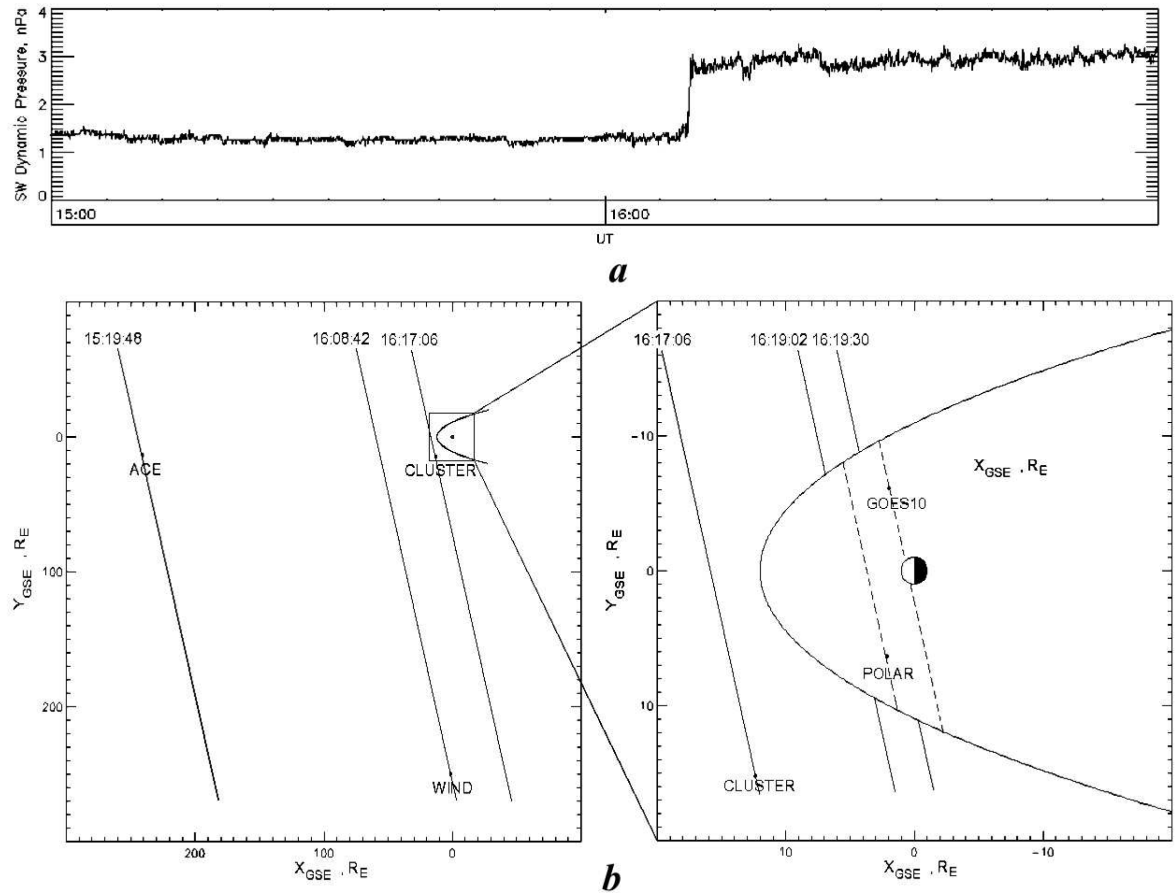


Fig. 1. *a* – solar wind dynamic pressure shows the propagation of discontinuities in the interplanetary space associated with a fast shock wave. *b* – wind measurements reconstructed discontinuous surface propagating in the interplanetary space and a fast MHD wave in the magnetosphere (measurements of Wind, ACE, Cluster, Polar, Goes10)

In the idealized model of an inhomogeneous magnetosphere with straight magnetic field lines and two superconductive ionospheres, the dispersion equation for a fast MHD wave contains a singularity, when the wave period agrees with the period of Alfven eigenmodes along a magnetic field line [12,13]. Let the background magnetic field be along Z, and let the inhomogenity be along X. We introduce the radial distance from the Earth in the Earth magnetosphere and direct the Y axis along the east. Then the electric and magnetic field disturbances are

$$\vec{E} = \{E_x(x), E_y(x), 0\} \exp[i(k_y y + k_z z - \omega t)],$$

$$\vec{b} = \{b_x(x), b_y(x), b_z(x)\} \exp[i(k_y y + k_z z - \omega t)],$$

where ω is the cyclic frequency, k_y and k_z are the wave vector components; B_0 and ρ are, respectively, the undisturbed magnetic field and the plasma density. In the case of the magnetic field line finiteness, the wavelength along a magnetic field line $2\pi/k_z$ has to be equal to $2l/n$, where n is integer. Taking into account only linear terms and considering the case of a cold plasma, one can obtain the following relation for the current:

$$\vec{j}_\perp = \{E_x(x), E_\gamma(x)\} \frac{i\omega\rho}{B_0^2} \cdot \exp[i(k_y y + k_z z - \omega t)].$$

Inserting the $\vec{E}$, $\vec{b}$, and $\vec{j}$ in the equation rot $\vec{b} = \mu_0 \vec{j}$ and using the equation rot $\vec{E} = -\partial\vec{b}/\partial t$, one can obtain the relation for electric field components:

$$\left(\frac{\mu_0\rho}{B_0^2}\omega^2 - k_z^2\right) E_x = ik_y \left(\frac{\partial E_y}{\partial x} - ik_y E_x\right),$$

$$\left(\frac{\mu_0\rho}{B_0^2}\omega^2 - k_z^2\right) E_y = -\frac{d}{dx} \left(\frac{\partial E_\gamma}{\partial x} - ik_y E_x\right).$$

Thus, the equation for E_y takes the form

$$\frac{d}{dx}\left(\frac{\omega^2/V_A^2-k_z^2}{\omega^2/V_A^2-k_z^2-k_y^2}\frac{d\mathrm{E}_\gamma}{dx}\right)+\left(\omega^2/V_A^2-k_z^2\right)\mathrm{E}_y=0$$

and can be rewritten as

$$\frac{d^2E_y}{dx^2}-k_y^2\frac{d\left(\omega^2/V_A^2\right)}{dx}\frac{1}{\left(\omega^2/V_A^2-k_z^2\right)\left(\omega^2/V_A^2-k_z^2-k_y^2\right)}\times$$
$$\times\frac{dE_y}{dx}+\left(\omega^2/V_A^2-k_z^2-k_y^2\right)E_y=0.$$

In the case of an inhomogeneous plasma, the equation will transform to the dispersion relation of a fast MHD wave. In this case, for the azimuthal wave propagation, a singularity will be in the equation, when $x = x_0$. If $\omega^2/V_A^2 - k_z^2 = 0$, then the period of a standing Alfven wave along a magnetic field line is close to the propagating source wave period, and the electric field component E_y has a logarithmic divergence on $x = x_0$. This singularity was interpreted as the generation of Alfven waves on the resonant field line. The wideband magnetosonic front can be formed on the magnetopause, then the temporal scale of changes of the solar wind parameters is less than the MHD disturbance propagation time through the magnetosphere (about 10 min) [7,12]. Such a scale is usual for fast shockwaves in the solar wind. The solar wind dynamic pressure can be strongly changed during a time interval of tens of seconds.

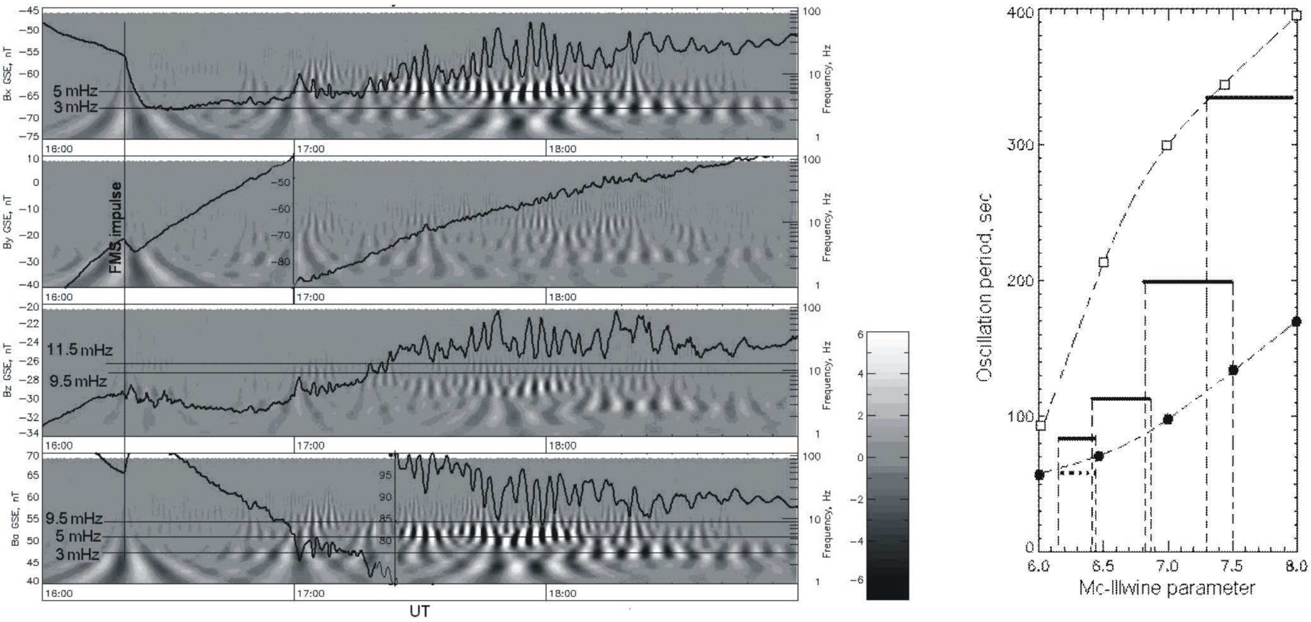
As an example of the shockwave, we consider the event observed on April 10, 2001 in the solar wind to study the magnetosphere effects. The GSE coordinates of spacecrafts together with the time moments of the disturbance registration and normales to the disturbance surface are listed in the Table. At 16:19:40 UT 10.01.2001, Polar has observed an impulsive disturbance in all magnetic field components (Fig. 2). This time moment is noted in Fig. 2 by a vertical line. After passing of the fast MHD disturbances, Polar observed oscillations in the magnetic field and plasma parameters during three hours. The quasiperiodic disturbances on sequentially varying frequencies 11.5, 9.5, 5, and 3 mHz with amplitudes 1, 1.5–2, 4–5, and 3–4 nT, respectively, were found in the X_{GSE} and Z_{GSE} components of the magnetic field. The linear polarization of oscillations was detected with the analysis of minimum variations of a magnetic field (MVAB). The oscillation frequencies are marked in Fig. 2 by horizontal lines. The relation of observed frequencies to the McIlwain L parameter is shown in Fig. 2,*b*. The poloidal and toroidal modes are shown by solid and dotted lines, respectively. The theoretical prediction of poloidal modes is shown with white squares and of toroidal ones – with black circles. The observed frequencies are in a good accordance to the analytical prediction.

The poloidal modes display themselves as a hybrid of poloidal Alfven modes and slow magnetosonic waves. The presence of a slow magnetic sound in the poloidal modes is confirmed by the behavior of the perturbed hydrostatic plasma pressure and the perturbed magnetic field pressure. They oscillate in opposite phases. Such a behavior is characteristic of slow magnetosonic waves [1,9,11]. Polar moves from a magnetic shell with the McIlwain parameter L=6 to a shell with $L = 8$. Thus, the intermittent variation of the oscillation frequency was observed. Taking into account the linear polarization of disturbances (shown in Fig. 1), the relation is in a good accordance to the relation of geomagnetic pulsations periods to the geomagnetic latitude which was obtained earlier in [1,6,7,11] (the poloidal modes are shown in Fig. 2,*a* with white squares) and the counted period of Alfven natural oscillations (the toroidal modes are shown in Fig. 2,*b* with black circles). Based on the observation of oscillations with the same period, the width of a magnetic field tube was determined. The characteristic size in the geomagnetic equatorial plane is about 0.5 R_E.

During the interaction of a shockwave in the solar wind with the Earth magnetosphere on January 13, 2001, Goes10 and the ground-based magnetic observatory in Meanook observed oscillations with same temporal and frequency characteristics [10]. The

Time and coordinate of the shockwave registration of the 10.01.2001 event in the system GSE along the Earth radii and in the normal direction to the surface of a shock front obtained with the MVAB technique

KA	UT	$R, [R_E]$			n		
		X_{GSE} $[R_E]$	Y_{GSE} $[R_E]$	Z_{GSE} $[R_E]$	X_{GSE} $[R_E]$	Y_{GSE} $[R_E]$	Z_{GSE} $[R_E]$
ASE	15:19:28	241.03	10.13	18.59	–0.84	–0.43	0.34
WIND	16:09:05	0.33	247.1	–17.5	–0.95	–0.1	0.29
Polar	16:19:40	1.41	8.81	1.98	–0.26	0.55	0.79
Cluster	16:17:26	13.08	14.53	0.78	–0.93	–0.21	–0.30
G10	16:19:20	1.36	6.45	–0.55	–0.88	–0.47	–0.09
Geotail	16:21:17	–6.73	–27.44	3.69	–0.87	0.48	0.06



a *b*

Fig. 2. *a* – waveforms of the magnetic field GSE components measured by Polar 10.01.2001; with their wavelet spectra on a background (color scale is in nT/sec). *b* – the dependence of the observed period of oscillations on the Polar geomagnetic shell. Poloidal modes are shown with solid lines; toroidal modes are shown with dotted lines. Theoretical predictions of poloidal modes are shown with white squares and toroidal – with black circles

Meanook station was in the magnetic conjugate zone with Goes10 spacecraft. Other magnetic stations of Canadian and US arrays have reiterated no similar disturbances. This confirms that the bserved oscillations were eigenmodes of the magnetosphere. Thus, the Earth magnetosphere is considered to manifest itself as a resonant system with a collection of eigenmodes which can be excited by an external wideband source.

2. Conclusions

In the present work, the experimental study of the ULF wave activity associated with field line resonance modes has been carried out. The research has shown that the fast shockwaves in the solar wind can initiate the magnetopause surface disturbances which produce a fast MHD wave penetrating into the magnetosphere with nearly the Alfven velocity. Fast MHD disturbances during the propagation generate the natural ULF oscillation modes of the magnetosphere.

The polarization and the frequency characteristic of the observed waves are discussed in dependence on the geometry of the interaction of a solar-wind shock wave and the magnetosphere. Depending on the pitch angle of a fast MHD front to a magnetic field line, the toroidal and poloidal modes can be generated. Toroidal oscillations are pure Alfven modes, and poloidal oscillations are a hybrid of poloidal Alfven and slow magnetosonic waves. The frequencies of poloidal modes are below 10 mHz. On different magnetic shells, the pulsations with different frequencies were observed simultaneously. Pulsations with similar frequencies were detected on spacecrafts and on the Earth surface simultaneously on the same magnetic shell. This confirms that natural magnetosphere modes were observed. Thus, sudden impulses in the solar wind can be estimated as one of the possible channels of energy transport from the solar wind to the Earth's magnetosphere and ionosphere. The Earth magnetosphere is assumed to be a resonance system for MHD waves excited due to the shocks outside the magnetosphere.

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ВЛАСНІ КОЛИВАННЯ МАГНІТОСФЕРИ ЗЕМЛІ, ЩО ПОВ'ЯЗАНІ З РАПТОВИМИ ІМПУЛЬСАМИ В СОНЯЧНОМУ ВІТРІ

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Р е з ю м е

Розглядаються магнітні пульсації Pc5 на основі даних супутників ACE, Wind, Polar, Cluster, Geotail, GOES 10 та наземної сітки магнітометрів Intermagnet. На орбіті Землі сонячний вітер являє собою квазістаціонарне утворення зі швидкими та повільними ударними хвилями. Ми приділяємо особливу увагу геомагнітним пульсаціям, що пов'язані з раптовими початками бур (SSC) та раптовими імпульсами (SI). Збурення поверхні магнітопаузи генерує швидкі МГД-хвилі, що поширюються вглибину магнітосфери. Пульсації, пов'язані зі швидкими хвилями, були виявлені на супутниках та на поверхні Землі з однаковою частотою. Збудження пульсацій може вважатися одним з механізмів передачі енергії від сонячного вітру до іоносфери. Поляризація та частотні характеристики хвиль, що спостерігаються, аналізуються у залежності від геометрії взаємодії ударної хвилі у сонячному вітрі з магнітосферою. На різних магнітних широтах одночасно спостерігалися пульсації з різною частотою. Існування спектральних піків після поширення широкополосної швидкої МГД-хвилі підтверджують властивість магнітосфери підсилювати окремі частоти та збуджувати УНЧ-пульсації з явною періодичністю. Таким чином, магнітосфера Землі є резонансною системою для гідромагнітних хвиль, що збуджуються ударними хвилями ззовні магнітосфери.