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Effects in the Geomagnetic Field and Absorption of Cosmic Radio Emission Caused by the Negative Pressure Discontinuity of the Solar Wind: Analysis of a Particular Event

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Abstract—An abrupt decrease in the solar wind pressure and its effect on the magnetosphere and ionosphere during the event occurring on April 4, 1971, are studied. This event differs fundamentally from a typical sudden commencement (SC) of a geomagnetic storm or from a positive sudden impulse (SI^+) and is determined as a negative sudden impulse (SI^-). The geomagnetic variations at different latitudes and the cosmic radio emission in the auroral zone are analyzed. From the data of low-latitude geomagnetic observatories, several subsequent negative impulses observed with a periodicity of ~45 min were found. At the same time, a sudden decrease in the absorption of cosmic radio emission in the auroral zone was revealed. Possible physical explanations of the observed changes are discussed.

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1. INTRODUCTION

It is known that the interaction of shock waves and different discontinuities in the solar wind with the magnetosphere leads to quite sharp changes in the geomagnetic field, which are registered nearly simultaneously on the majority of the Earth. Positive pressure jumps in the solar wind cause magnetospheric compression and, consequently, an increase in the horizontal component H of the geomagnetic field (sudden commencements (SCs)) and positive sudden impulses (SI^+s). The negative pressure jumps in the solar wind result in the sudden magnetosphere expansion and planetary decrease in the H-component of the geomagnetic field. As is known, SCs and SI^+s are accompanied with a complex of geophysical phenomena: geomagnetic pulsations in different frequency ranges (for example, Fukunishi, 1979; Takahashi et al., 1988; Shumilov et al., 1996; Kangas et al., 1998; Kleimenova et al., 1999, VLF radiations (for example, Kleimenova and Osepyan, 1982), aurorae (Vorobiev et al., 2008; Zhou et al., 2009), and absorption of the cosmic radio emission (classified as a particular type of SCA and SIA) (Perona, 1972; Brown, 1973; Shumilov et al., 1996). One of the results of interaction between the positive pressure jumps in the solar wind and the magnetosphere is the generation of geomagnetic pulsations due to the field line resonances and the Kelvin—Helmholtz instability arising at the magnetopause or at the surface between the low-latitude boundary layer and the central plasma layer (for example, Baumjohann et al., 1984; Takahashi et al., 1988; Shumilov et al., 1996). Another possible effect of the sudden magnetosphere compressions is the modulation of the pitch-angle distribution of particles captured into the magnetosphere. The results of such a modulation are registered at the Earth's surface as the changes in the intensity of the electromagnetic VLF radiation and in the value of cosmic radiation absorption (SCA and SIA events) (for example, Perona, 1972; Brown, 1973; Ranta and Ranta, 1990; Manninen et al., 2010). The SCA and SIA events caused by electron precipitation from the quasi-capture region in the magnetosphere are localized mainly in the auroral zone (Brown, 1973), are accompanied in some cases by a particular type of aurora (the θ-structure), and may be observed inside the polar cap (Shumilov et al., 1996).

At the same time, until recently, little attention was paid to the phenomena occurring during the interaction between the negative pressure jumps in the solar wind and the magnetosphere leading to its expansions and negative impulses SI^-s. For example, it was shown that sudden magnetosphere expansions can lead to the appearance of oscillations at the magnetopause and inside the magnetosphere with periods of $T > 400$ s (Parkhomov et al., 1998; Zhang et al., 2010), a change in auroral activity (Liou et al., 2006; Belakhovsky et al., 2011), and an abrupt cessation of the VLF-radi-

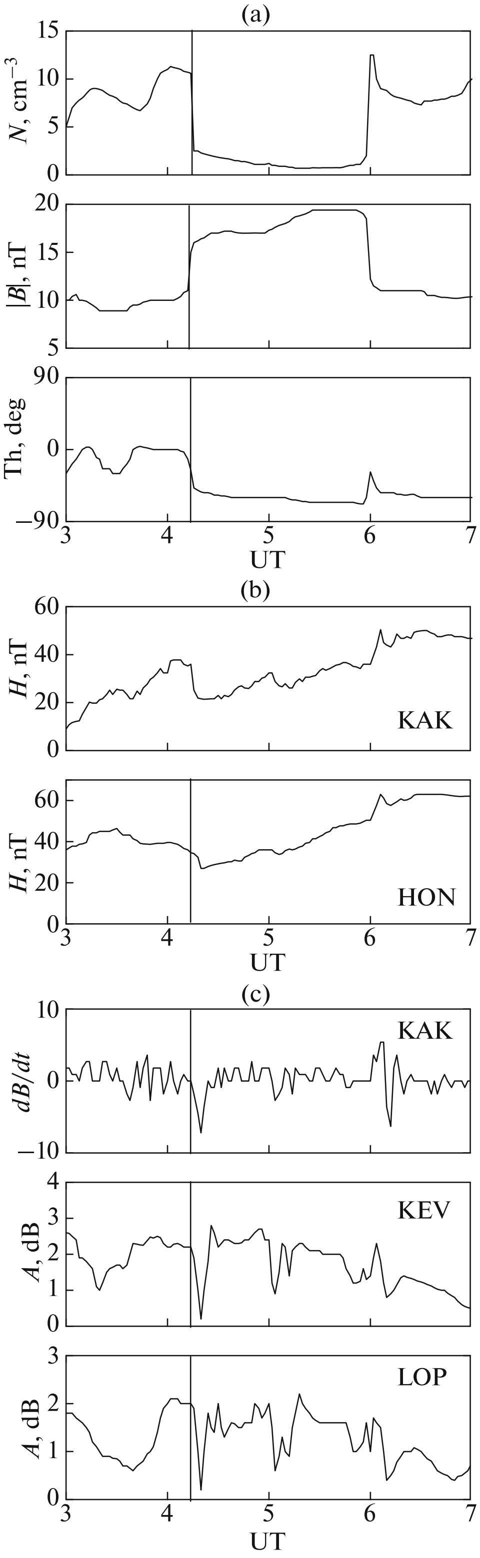

Fig. 1. Solar wind parameters from the data of the AES Explorer-43 (Nishida, 1980) (from the top downward): (a) the solar wind plasma density N (cm^{-3}), interplanetary magnetic field strength B (nT), latitudinal angle of the interplanetary magnetic files in the solar-ecliptic coordinate system Th (deg.); (b) magnetograms of low-latitudinal observatories (Kakioka, Honolulu) and variations of the derivative of the H-component of geomagnetic field $\partial B/\partial t$ calculated with the use of the magnetogram of the Kakioka observatory; (c) riometric data of Loparskaya and Kevo auroral observatories. The discontinuity in solar wind corresponding to the SI$^-$ is marked by a vertical line.

ation generation (Manninen et al., 2016), as well as to the appearance of electric fields and ionospheric current systems during an SI$^-$ (Araki and Nagano, 1988; Sastri et al., 1995; Takeuchi et al., 2000). At present, the authors know only single works that have to do with the reduction in the cosmic radiation absorption during a SI$^-$ (Brown, 1974; Pytte et al., 1974; Belakhovsky et al., 2011).

The goal of this work is to study the effects of a negative jump of the solar wind pressure on the absorption of cosmic radio emission and in the magnetic field by the example of the analysis of the geomagnetic and riometric observation data obtained during a SI event that occurred at 0415 UT on April 4, 1971. The unique particularity of this event is the quasi-periodical (~45 min) magnetic oscillations and short-time reductions in the cosmic radiation absorption in the morning sector of the magnetosphere.

2. RESULTS OF ANALYSIS OF OBSERVATIONS

In this work we consider the SI$^-$ event that occurred on April 4, 1971 (Nishida, 1980). In the analysis, we used the geomagnetic and riometric data of the Finland station array (www.sgo.fi), the data from observations of the Loparskaya observatory of the Polar Geophysical Institute, and the MCD data (Moscow) on solar–terrestrial physics (http://www.wdcb.ru/stp/stp.ru). To investigate the variations of solar wind parameters, we used the data of measurements on the artificial Earth satellite Explorer-43 (the perigee is 1845 km, the apogee is 203130 km, and the orbit tilt angle is 31.2°) presented by Nishida (1980).

Figure 1 shows the data of the AES Explorer-43 (Nishida, 1980) and the effects in the geomagnetic field and in the absorption of cosmic radio emission associated with this event. The coordinates of the used observatories and the MLT time corresponding to the SI$^-$ impulse are presented in Table 1. One can see in Fig. 1a that the discontinuity in the solar wind is characterized by a decrease in the proton density from 12 to 2 cm^{-3} and an increase in the magnetic-field strength from 10 to 17 nT; the flow velocity remained unchanged (480 km s^{-1}). These characteristics let us assume that the tangential discontinuity in the solar wind, which corresponds to the SI$^-$, was the rising edge of the magnetic cloud possessing the following properties: a strong magnetic field, smooth rotation of the magnetic field direction, and low ion temperatures (Freeman and Farrugia, 1999) (Fig. 1a). The tailing

Table 1. Coordinates of observatories

Observatory	Code	Geogr. coord. N, E, deg.	Geomag. coord. corr. N, E, deg.	$\mathrm{MLT_{SI}}$ (h:min)
Godhavn	GDH	69.25, 306.47	75.80, 40.39	0206
Narsarsuaq	NAQ	61.16, 314.56	66.31, 43.91	0218
Abisko	ABK	68.35, 18.82	65.30, 101.75	0702
Kiruna	KIR	67.84, 20.42	64.69, 102.64	0706
Loparskaya	LOP	68.63, 33.25	64.94, 113.60	0745
Apatity	APT	67.58, 33.31	63.86, 112.9	0745
Voeikovo	SPB	59.95, 30.3	56.10, 118.4	0718
Kevo	KEV	69.76, 27.01	66.32, 109.2	0732
Sodankylä	SOD	67.37, 26.63	63.92, 107.3	0724
Oulu	OUL	64.52, 27.23	60.99, 106.1	0718
Heiss Island	HIS	80.62, 58.05	75.10, 144.6	0933
Dikson	DIK	73.50, 80.60	68.30, 155.9	1006
Podkamennaya Tunguska	POD	61.60, 90.00	56.40, 163.0	1024
College	COL	64.90, 212.2	65.00, 262.3	1648
Sitka	SIT	57.03, 224.4	60.40, 277.6	1803
Kakioka	KAK	36.23, 140.18	28.90, 211.2	1308
Honolulu	HON	21.32, 202.00	21.80, 269.2	1700

edge of the cloud was observed at about 18 UT on April 4, 1971 (it is not presented here); after that, the magnetic field rotations stopped and the temperature started to rise.

A negative sudden impulse caused by an abrupt decrease in the dynamic pressure of the solar wind, which was registered at about 0415 UT and is clearly seen in the variations of the H-components of the magnetic field, according to the data of three low-latitude observatories (Fig. 1b). As one can see in Fig. 1b, the principal peculiarity of the magnetic variations are damped quasi-periodical (~45 min) oscillations: the main negative impulse SI^- was observed for the first time at 0415 UT; it then repeated at 0500 UT and, possibly, at 0545 UT. Among these three impulses, only the first was related to the sudden decrease in the solar wind pressure; the two others were observed against the background of a quiet solar wind (Fig. 1). It is seen from Fig. 1b that quasi-periodical oscillations against the background of the gradually increasing value of magnetic field were clearly registered at the magnetograms near the local noon (the Kakioka observatory). According to the data of observatories located in the night (San Juan) (not shown here) and evening (Honolulu) sectors of the magnetosphere, the two last impulses manifest themselves not as clearly as compared with the SI^- itself.

In the lower part of Fig. 1c, one can see the riometric registrations made by two auroral observatories (Loparskaya and Kevo) located in the morning sector of the magnetosphere during the observations. It is seen from Fig. 1 that the negative magnetic impulse SI^- caused some reduction in the cosmic radiation absorption of auroral type (AA). The variations of absorption had the same quasi-periodical character (~45 min) as the magnetic oscillations registered in the magnetograms of low-latitude observatories: the second and third negative absorption peaks were observed at 0500 and 0545 UT, respectively (Fig. 1c). Absorption oscillations, the form of which is reminiscent of sharp negative impulses, differ from that of magnetic oscillations that have a stepped structure. The duration of the negative impulse of cosmic radio noise absorption was 5–6 min in the first peak and ~20 min in the two consequent peaks; after abrupt decreases, the value of absorption quickly returned to its initial level. It is easy to see that such changes in the absorption remind in their shape variations of the magnetic field derivative ($\partial B/\partial t$) that are shown in the third panel at the bottom of Fig. 1c.

Figure 2 presents magnetograms of low- and middle-latitude observatories for April 4, 1971. One can see that the magnetic variations in the auroral zone and at the low latitudes are different. Against the background of magnetic variations, it is nearly impossible to distinguish the third negative impulse, though the first two are well observable. According to the data of auroral observatories located in the morning sector of the magnetosphere (Abisko, Sodankylä), a negative impulse SI^- was observed as a short-term decrease in the H-component and D-component (it is not shown) of the magnetic field with a subsequent quick recovery.

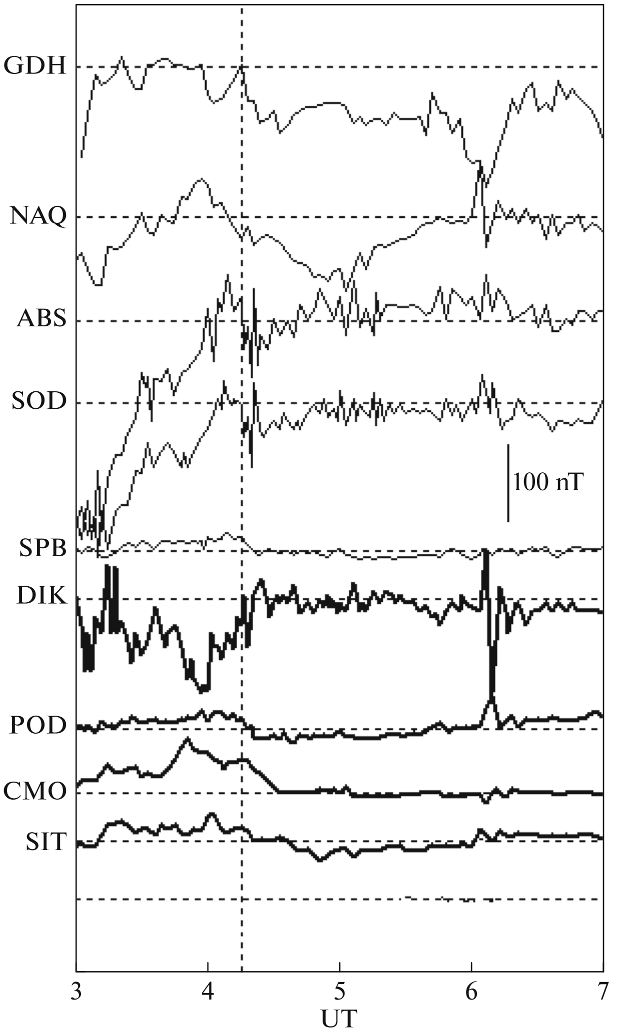

Fig. 2. Megnatograms of the *H*-component from ground-based observatories for a period from 0300 to 0700 UT on April 4, 1971. The starting moment of the SI^- is shown by a vertical dashed line.

In the afternoon sector (Dikson), variations of the *H*- and *D*-component during the SI^- take an opposite form: a sharp positive impulse is followed by a quick decrease. In the evening sector of the magnetosphere (College, Sitka), the magnetic field variations during the SI^- are small and manifest themselves only in the *H*-component: a stepped negative impulse preceded by a very small positive value (Fig. 2). In the polar night zone (Godhavn, Narsarsuaq), the magnetic variations show a similar behavior, mainly in the *D*-component (it is not shown).

Apparently, such a character of the magnetic changes is associated with the ionosphere current system generated during the SI^- at 0415 UT, when a preliminary impulse (PI) is superimposed on a gradual decrease in the magnetic field related to the main impulse (Araki and Nagano, 1988). A similar current system arises during SCs and positive SI^+s and is associated with the electric field that is transmitted into the polar ionosphere along magnetic field lines during compression wave propagation in the magnetosphere (Araki and Nagano, 1988). The ionosphere current system related to the PI consists of two vortices with opposite directions (Araki and Nagano, 1988). The inversion of magnetic impulses observed in our case in the morning and afternoon sectors of the magnetosphere can be explained by the opposite directions of the currents in the two current vortices during the SI^-.

The riometric enregistrations made by high-latitude stations for the SI^- event occurring on April 4, 1971, are presented in Fig. 3. It is seen from Fig. 3 that, in the auroral zone, a moderate (<2 dB) auroral absorption (the AA-type absorption) during the period preceding the SI^- with clearly pronounced decreases at 0415, 0500, and 0545 UT, not only in the morning (Apatity, Kevo, Sodankylä, Abisko, and Kiruna) but also in the afternoon sector (Dikson). According to the magnetometric data of the Loparskaya station, the discussed event was preceded by a series of substorms with an amplitude of up to 500 nT, which provided some preliminary background in the riometric recordings up to ~3 dB (Kiruna) before the jump in the solar wind (Fig. 3). According to the riometric data of the stations located in the evening magnetosphere sector (they are not presented here), the absorption of cosmic radio emission during the considered period was not registered. A similar situation was observed at the Oulu station, which is located at a lower latitude in the polar cap zone (Heiss Island, Molodezhnaya (not presented here)), where the background absorption was weak and nearly disappeared before the SI^- (Fig. 3). Thus, one can claim that the effects of decreases in the absorption of cosmic radio emission are observed during morning hours, i.e., in the morning maximum zone in the diurnal variation of the auroral absorption of cosmic radio emission (Driatskii, 1974). It is seen from Fig. 3 that the negative impulses in the riometric absorption have a similar shape in all parts of the auroral zone with a duration of the first peak of ~5–6 min at 0415 UT and a smoother restoration in the two subsequent impulses at 0500 and 0545 UT.

3. DISCUSSION

As a result of magnetometric and riometric data, the following peculiarities are found:

(a) quasi-periodical (~45 min) impulses in the magnetic field and in the absorption of cosmic radio emission caused by the SI^- at 0415 UT on April 4, 1971;

(b) the behavior of the ionospheric absorption (short-term interruption with a quick restoration) during negative sudden impulses in the magnetic field.

As was noted above, during a negative magnetic impulse SI^-, the magnetosphere performs an expansion. To estimate the distance to the subsolar point before and after the SI^- , we use the formula obtained in the adiabatic expansion approximation for the case when the solar wind is perpendicular to the Earth dipole direction (Nishida, 1980):

$$r_s = (2M^2/\mu_0 nmV^2)^{1/6}, \qquad (1)$$

where M is the geomagnetic dipole moment with a value of 8×10^{15} Wb m^2, $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}, K is a coefficient characterizing the interaction between a blunt-nosed body and a supersonic stream with a value of 0.8, and n and V are the particle concentration and the solar wind velocity respectively. Substituting the corresponding values of solar wind parameters into (1), we obtain the following values for quantity r_s: 8.5 R_E and 11.5 R_E (before and after the expansion, respectively). In other words, as a result of the expansion, the magnetopause shifted by a distance of about 3 R_E from the Earth.

Such a sudden magnetosphere expansion supposedly resulted in quasi-periodical (~45 min) impulses in the mangetic and riometric recordings (Fig. 1). The global character of these oscillations and their considerable period let us suppose that they are caused by the fluctuations of the entire magnetosphere. It is known from the results of previous investigations that the entire magnetosphere in this case is considered to be a cavity in which resonance oscillations conditioned by the magnetosphere sizes appear with periods $T < 13$ min (e.g., Samson et al., 1992). At that, in the case of longer periods ($T > 20$–27 min), the magnetospheric radius must exceed 30 R_E, which is unreal. The existence of long-period (40–60 min) pulsations in the magnetosphere and ionosphere were also observed earlier (e.g., Rinnert, 1996; Lessard et al., 1999; Huang et al., 2000). Huang et al. (2000) supposed that the ionospheric disturbances or internal gravitational waves with a period of 40 min observed by low-latitude radar are associated with the resonance oscillations of the night magnetic field lines. According to some model calculations (e.g., Usadi et al., 1993) and experimental data (Chen and Kivelson, 1991), the geomagnetic tail, as a possible resonator apparently may be responsible for the observed long-period (40–60 min) geomagnetic pulsations. Apparently, when the global character, long period of observed fluctuations, and inhomogeneity in the latitude distribution (Fig. 2) are taken into account, it is apparently impossible in our case to exclude the role of the magnetosphere tail in the periodical expansions and compressions of the entire magnetosphere.

One more peculiarity found in this study is the unusual character of the absorption of cosmic radio emission associated with the observed magnetic pulsations; it can be described as repeating negative impulses.

The cosmic radio emission, which is the natural radiation of an infinite number of celestial bodies situated in the outer space, is continuously registered on the Earth with the help of riometers (relative ionospheric opacity meter) (Driatskii, 1974). While passing through the ionosphere, radio waves transfer their energy to electrons; they, in their turn, lose a part of this energy when colliding with other particles. Thus, the cosmic radio emission is absorbed. With a change in the electron concentration in the D and E ionosphere layers changes during different magnetosphere–ionosphere disturbances, the value of the absorption of cosmic radio emission changes. The absorption of cosmic radio emission can be quantitatively represented by the expression (Driatskii, 1974)

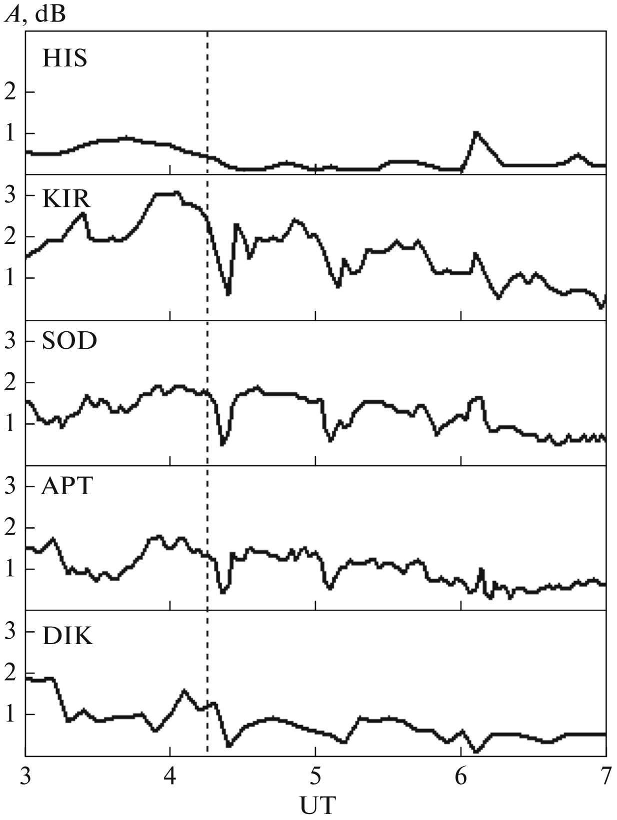

Fig. 3. Riometric data from high-latitude observatories for the period from 0300 to 0700 UT on April 4, 1971. The starting moment of the SI$^-$ is shown by a vertical dashed line.

$$A = -20\log\frac{E}{E_0} = \frac{8.69}{(\omega \pm \omega_L)^2}\frac{2\pi e^2}{mc}\int_S N\nu\, ds, \qquad (2)$$

where A is the value of the absorption (dB), E_0 is the field strength of the incident plane wave; E is the field strength of the wave, which passed some distance s in the ionized medium; e and m are the electron charge and mass, respectively; μ is the refraction index in the ionized medium with the electron density N and the frequency of electron collisions ν; w is the angular frequency of the incident wave; and w_L is the angular gyromagnetic frequency corresponding to the longitudinal component of magnetic field. The plus sign in expression (2) designates the ordinary component of the radio wave; the minus sign indicates the extraordinary component.

It is follows from equation (2) that the increase in both electron concentration N and the electron collision frequency ν may cause an increase in the absorption of cosmic radio noise A. Therefore, the processes that increase the ionization in the regions where collision frequencies are significant (i.e., the energetic particle precipitations in the D-layer of the ionosphere) or the processes that increase the collision frequency in regions with a high electron density (i.e., the increase in the temperature in the E-layer of the ionosphere) can be a reason of appearance of the A absorption. Up to the present time, there are about ten known types and subtypes of anomalous absorption of cosmic radio emission.

As was noted above, the sudden short-term decreases in the absorption coincide with the negative magnetic impulses. Although quite a number of investigations are devoted to the pulsations in the electron precipitation associated with geomagnetic oscillations, the effects of negative impulses SI^- in the absorption of cosmic radio emission are not clearly understood. Apparently, this fact can be explained by the rarity of such a phenomenon as SI^-s. In addition, the necessity of the existence of background absorption directly before the event decreases the probability of discovering such events. According to the information the authors possess, there are few studies concerning this problem (Brown, 1974; Pytte et al., 1974; Belakhovsky et al., 2011), and none of them reports on pulsations in the absorption of cosmic radio emission after negative SI^-s.

The mechanism of the electron precipitation during SIs and SCs is based on the electron cyclotron instability caused by the pitch-angle anisotropy of captured particles (Perona, 1972; Trakhtengerts and Rycroft, 2008). During the period of magnetospheric compression, the pitch-angle anisotropy increases, since the kinetic energy of captured electron motion in the direction perpendicular to the magnetic field increases more than the energy of motion along it. Therefore, the increment of excitation of VLF-waves increases, which leads to growing instability, pitch diffusion, and the ingress of electrons into the loss cone and their subsequent precipitation into the ionosphere. As a result, the absorption of cosmic radio emission of SCA and SIA types is registered. In addition to the pitch-angle diffusion, the increase in the geomagnetic field B_{eq} in the equatorial plane during a sudden magnetosphere compression caused by the SC and SI^+ may result in the increase in the sizes of the loss cone and, thus, in the flows of precipitating particles (Zhou et al., 2009). In the case of a negative SI^-, it is logical to suppose a converse scheme, as was done by Araki and Nagano (1988) and Belakhovsky et al. (2011): a sudden magnetospheric expansion results in a decrease in the pitch-angle anisotropy, reduction of the electron cyclotron instability, and the cessation of electron precipitation into the ionosphere.

The data presented in this paper allow us to suppose the existence of other mechanisms responsible for the cessation of electron precipitation during a negative SI^-. In our case, the form of negative impulses in the riometric absorption is similar to short-term decreases in the variations of the derivative of H-component of geomagnetic field $\partial B/\partial t$ (Fig. 1c). It is possible that the observed cessation of electron precipitation may be caused by a vortex electric field $\mathrm{curl} E = -\partial B/\partial t$ that changes the velocity and energy of captured particles. The existence of such fields during negative SCs and negative SI^-s was found by Araki and Nagano (1988) and Zhang et al. (2010), as well as by Sastri et al. (1995), whose experimental data are evidence of the vertical plasma displacements associated with the SI^- electric field in the night equatorial low-latitude ionosphere.

4. CONCLUSIONS

The negative sudden impulse SI^- that occurred at 0415 UT on April 4, 1971 resulted in a magnetospheric expansion in the subsolar region about 3 R_E and to quasi-periodical (~45 min) oscillations in the magnetic field and in the absorption of cosmic radio emission. Taking into consideration the global character of the observed oscillations, their large period, and their inhomogeneity in the latitude distribution, apparently, one cannot exclude that the magnetic tail may play a role in the periodical expansions and compressions of the entire magnetosphere. The negative impulses in the riometric absorption are similar in their form to short-term decreases in the variations of the derivative of the H-component of geomagnetic field $\partial B/\partial t$. It is possible that the short-term cessations of the electron precipitations are caused by vortex electric fields that change the velocity and energy of captured particles.

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