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Geophysical effects of the interplanetary magnetic cloud on October 18–19, 1995, as deduced from observations at Irkutsk

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Abstract

During an interaction of the Earth's magnetosphere with the interplanetary magnetic cloud on October 18–19, 1995, a great magnetic storm took place. Extremely intense disturbances of the geomagnetic field and ionosphere were recorded at the midlatitude observatory at Irkutsk ($\Phi' \approx 45°$, $\Lambda' \approx 177°$, $L \approx 2$) in the course of the storm. The most important storm features in the ionosphere and magnetic field are: a significant decrease in the geomagnetic field Z component during the storm main phase; unusually large amplitudes of geomagnetic pulsations in the Pi1 frequency band; extremely low values of critical frequencies of the ionospheric F2-layer; an appearance of intense E_s-layers similar to auroral sporadic layers at the end of the recovery phase. These magnetic storm manifestations are typical for auroral and subauroral latitudes but are extremely rare in middle latitudes. We analyze the storm-time midlatitude phenomena and attempt to explore the magnetospheric storm processes using the data of ground observations of geomagnetic pulsations. It is concluded that the dominant mechanism responsible for the development of the October 18–19, 1995 storm is the quasi-stationary transport of plasma sheet particles up to $L \approx 2$ shells rather than multiple substorm injections of plasma clouds into the inner magnetosphere.

1. Introduction

The physical processes responsible for the transfer of energy and matter from the solar wind into the magnetosphere in the course of a geomagnetic storm are the most challenging problems of present space geophysics. The great number of publications dealing with storms is an indicator of a lively interest in the exploration of this unique natural phenomenon. Statistical investigations of the storm-time disturbances have been done in some of them (Taylor et al., 1994; Loewe and Prolls, 1997; Yokoyama and Kamide, 1997; Grafe, 1999), and detailed studies of specific cases in others (Yeh et al., 1994; Kleymenova et al., 1996; Araki et al., 1997; Xinlin et al., 1997). Gonzalez et al. (1994) give a review of the most important publications on the determination of the D_{st} origin.

The experimental data obtained in the interplanetary medium, inner and upper magnetosphere and on the Earth's surface are so complex and variable that it has been impossible to describe the geomagnetic storm's manifestations in the context of a unified physical

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model so far. The physical mechanisms producing a depression of the storm-time D_{st} index and the efficiency of each of them under different conditions in the solar wind and in the magnetosphere still remain obscure. That is the reason why the problem 'what is a geomagnetic storm?' has become an interesting topic once again.

As a result of investigations, it becomes clear that a storm is not simply a superposition of substorms as it has been assumed previously. Different mechanisms of the storm-time ring current formation are discussed by Gonzalez et al. (1994). Each of them causes an acceleration of magnetospheric particles, but two mechanisms can transport the magnetotail plasma in the inner magnetosphere: substorm injection and large-scale convection. It seems that an intensification of both mechanisms is a necessary condition for a storm to develop.

The intensification of large-scale convection is associated with a global increase in the convection electric field strength, E_c (Sergeev and Tsyganenko, 1980; Lyons and Williams, 1984; Roederer and Hones, 1974). It is known as the 'directly driven' process of the solar wind–magnetosphere interaction. Substorm injection is associated with longitudinally limited disturbances of magnetic and electric fields (Nishida, 1978; Huang et al., 1992; Carpenter et al., 1972; Bogott and Mozer, 1973; Roederer and Hones, 1974). It is called the 'loading–unloading' process of the solar wind–magnetosphere interaction. Representative times of E_c variations for these mechanisms are also different: $\tau \approx 5$–20 min for substorm injection, and $\tau \geq 3$ h for large-scale convection (Lui et al., 1992; Gonzalez et al., 1994; Chen et al., 1994). Either process could cause the formation of the ionospheric and field-aligned currents and produce a decrease of D_{st} under strong dawn-to-dusk electric field condition (Sergeev and Tsyganenko, 1980; Takahashi et al., 1991; Arykov et al., 1996). Since both, substorm injection and enhanced large-scale convection go on concurrently, it is difficult to separate the contribution of either mechanism in the ring current formation. We believe that the problem of separation may be solved partially by using information contained in geomagnetic pulsations.

It is well known that pulsation properties are essentially determined by the structure of the magnetosphere and the processes taking place within and beyond it (Guglielmi and Pokhotelov, 1994; Kangas et al., 1998). Potapov and Polyushkina (1992) have demonstrated the diagnostic possibilities of geomagnetic pulsations. In this work the phenomenological model of the D_{st} storm-time variation is established founded on the ground-based data on geomagnetic pulsations. The authors use Pi2 pulsations for estimating the rate of energy injection into the ring current.

There is a one-to-one correspondence between a spatially limited magnetotail magnetic field dipolarization and a Pi2 train (Yumoto et al., 1989). Thus, a Pi2 train is a good indicator of substorm injection and is traditionally used as a substorm timer. But timing can be correctly done only for isolated substoms developing against a quiet magnetic field background. In more complicated cases such as a substorm with a growth phase and multiple onsets or a continuous substorm activity, there is no one-to-one correlation between the westward electrojet intensifications and Pi2 trains. An increase in the magnetic activity is associated with a transition from isolated Pi2 trains to long-lasting irregular geomagnetic pulsations, that have the same period as a Pi2 train but an arbitrary wave form (long-lasting Pi2 series). Examples of two isolated Pi2 trains and a part of long-lasting Pi2 series are presented in Fig. 1(a) and (b).

Zolotukhina and Kharchenko (1990, 1994) have done an exploration of temporal variations of midlatitude geomagnetic pulsations in the Pi2 frequency band and an equivalent ionospheric current development. The CDAW-6 periods of the isolated (March 22, 1979) and continuous substorm activity (March 31, 1979) have been studied. It was shown that an individual injection is accompanied by a Pi2 train, multiple injections are attended by a series of Pi2 trains, and an enhancement of large-scale magnetospheric convection occurs together with a long-lasting Pi2 series.

This paper presents the observations and analysis of anomalous disturbances of the geomagnetic field and ionosphere recorded at the midlatitude observatory at Irkutsk ($\Phi' \approx 45°$, $\Lambda' \approx 177°$, $L \approx 2$) in the course of the large storm on October 18–19, 1995. We investigate the morphological properties of the storm-time geomagnetic pulsations and analyze the information they have about magnetospheric processes leading to such unusually strong magnetic and ionospheric midlatitude disturbances.

The following original data from the magnetic and ionospheric observatories located near Irkutsk are used: standard magnetograms, analog recordings of geomagnetic pulsations with scan rates of 30 mm/min and 180 mm/h, digitally registered data of the magnetic field with a time resolution $\Delta t = 1$ min and of geomagnetic pulsations with $\Delta t = 0.1$ s, *f*-plots, vertical-incidence ionograms and backscatter ionograms for the Irkutsk–Magadan path. As to the information on the physical conditions in the interplanetary space, we refer to the work by Lepping et al. (1997), in which the measurements of the solar wind parameters by the WIND spacecraft are reported. WIND was located at the distance $R \approx 175$ R_E (R_E is the Earth's radius) upstream of the Earth at the time of interest.

2. Magnetic storm on October 18–19, 1995: general description

The intense magnetic storm on October 18–19, 1995 is due to the interaction of the Earth's magnetosphere with the interplanetary magnetic cloud. A summary picture of the storm-induced disturbances on October 18–19 as shown by the K_p and D_{st} indices, as well as by the magnetic field and ionospheric measurements in Irkutsk and by geomagnetic pulsations is presented in Fig. 2(a)–(e). Four vertical dashed lines correspond to the instants of time at which solar wind parameters undergo the strongest changes. These data are given by Lepping et al. (1997) and are designated as A, B, C and D1. On October 18 at 10:42 UT, WIND observed the interplanetary shock wave (line A in Fig. 2), followed at $\Delta t = 39$ min by an SSC* (Solar–Geophysical Data, 1995). The main geophysical consequence of the shock wave is a drastic decrease in the magnetospheric size. According to estimates made by Lepping et al. (1997), at the time of the SSC* the distance to the magnetospheric subsolar point (R_m) decreased from $R_m \approx 10.6$ to 7.5 R_E. The initial phase of the geomagnetic storm lasted for 9 h till $\approx$20:00 UT on October 18.

The main phase started 1 h after the abrupt change of solar wind parameters at the leading edge of the magnetic cloud (line B in Fig. 2). At 18:58 UT, solar wind density dropped from 50 to 5 cm^{-3}, and the IMF B_z component changed from $B_z \approx 10$ nT to $B_z \approx -20$ nT (Lepping et al., 1997). The ring current field reached the maximum intensity $D_{st} \approx -120$ nT within a very short time: $\Delta t \approx 3$ h. The October 18–19 storm was an intense one (Gonzalez et al., 1994). A longer D_{st} drop (≈ 14 h) characterizes the storms of this class (Yokoyama and Kamide, 1997).

The recovery of the magnetic field to a quiet level is also associated with the IMF change. It started at $\approx$08:00 UT on October 19 after the IMF B_z component had become positive. Between 08:00 and 20:00 UT on October 19, D_{st} increased from -103 to -1 nT. This time interval can be defined as the storm recovery phase the duration of which (14 h) is short for an intense storm (Yokoyama and Kamide, 1997). The data provide evidence that the 18–19 October storm is distinctly associated with processes in the interplanetary space environment.

The next interplanetary shock was recorded on October 19, 1995 at 17:51 UT (line C in Fig. 2) where the interplanetary magnetic field increased without a change of sign of B_z (Lepping et al., 1997). It is possible that this shock wave made some contribution to the increase of D_{st} to positive values. Judging from a small decrease of the value of R_m ($\Delta R_m \approx 1 R_E$, Lepping et al., 1997) this contribution is of a minor nature.

The fourth solar wind inhomogeneity (D1) was

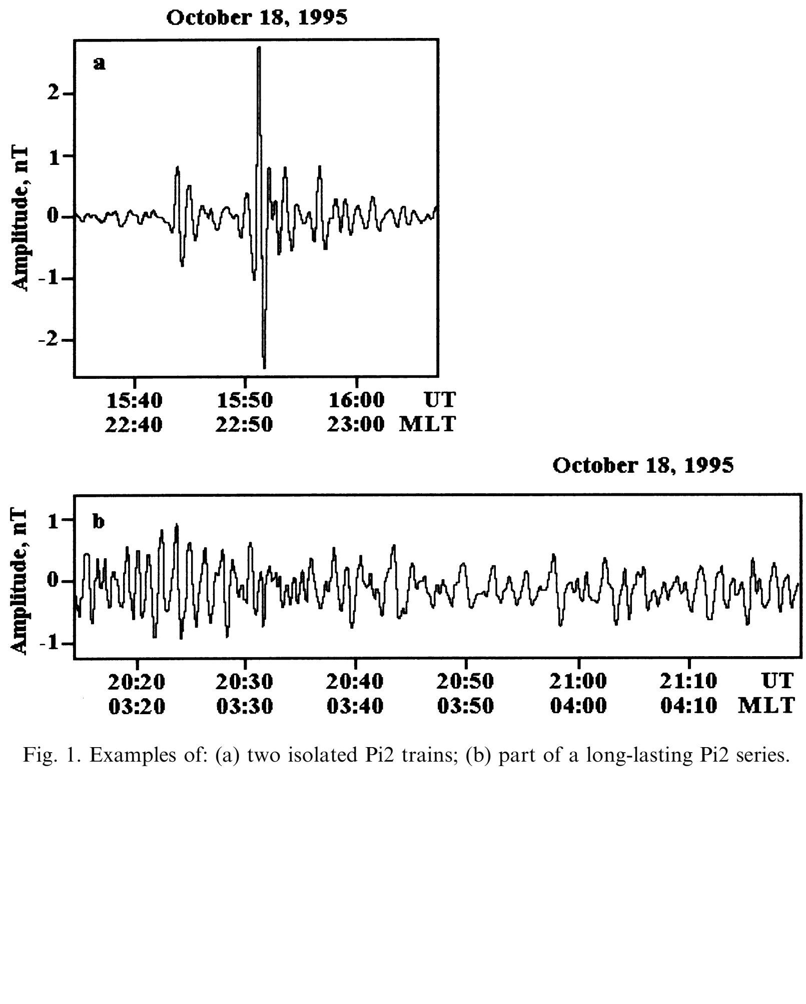

Fig. 1. Examples of: (a) two isolated Pi2 trains; (b) part of a long-lasting Pi2 series.

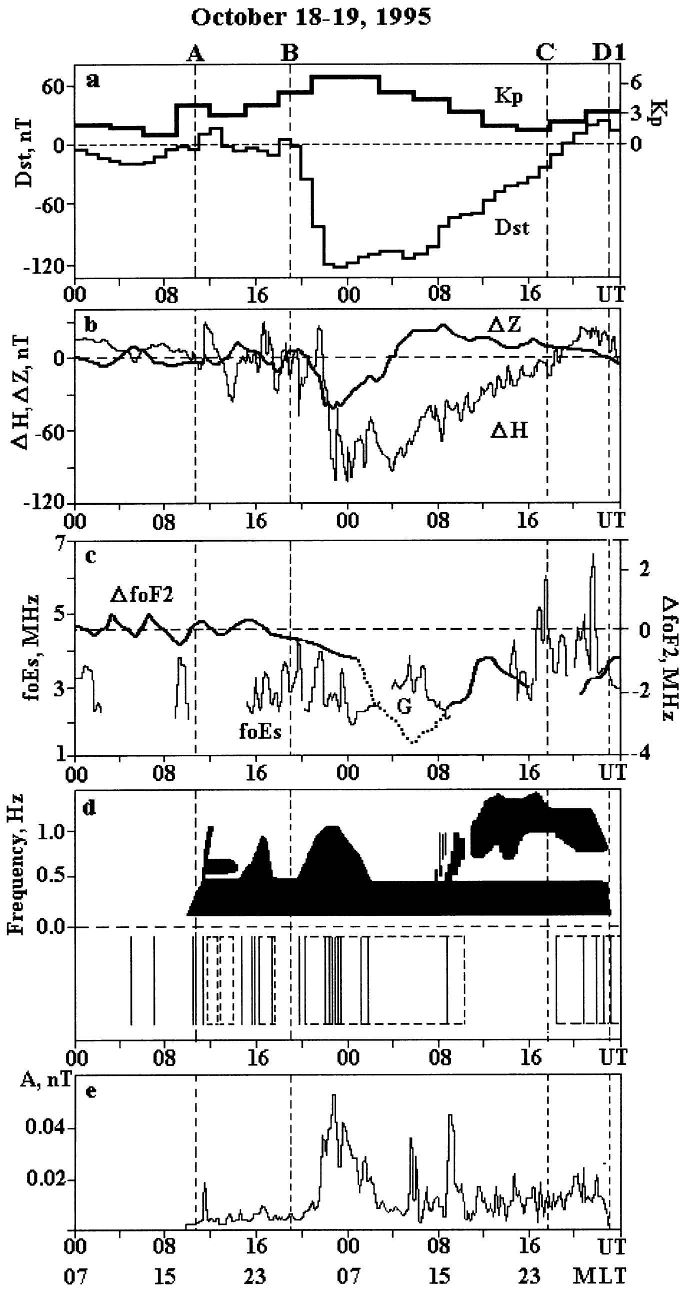

Fig. 2. Summary picture of the development of storm-induced disturbances on October 18–19, 1995: (a) the D_{st} and K_p indices; (b) the deviations of the H and Z components of the magnetic field (ΔH and ΔZ) from the quiet levels; (c) E_s critical frequency (f_0E_s) and deviations of critical frequency of the F2-layer from monthly median values (Δf_0F2); (d) upper panel — a schematic representation of pulsation dynamic spectra in the Pi1 frequency band, lower panel — commencement of isolated Pi2 trains (solid vertical lines) and time intervals of long-lasting Pi2 series (dashed squares); (e) the pulsation mean amplitude $A(t)$ in the Pi1 frequency band. Vertical dashed lines correspond to the instants of time when solar wind parameters underwent the strongest changes (Lepping et al., 1997).

registered at 22:54 UT. It is characterized by a low density and a high temperature of solar wind plasma, and coincides with the beginning of the main phase of the October 20–26, 1995 storm.

3. The peculiarities of the magnetic field variations at Irkutsk

The development of the storm activity on October 18–19 is well traceable on magnetograms from Irkutsk. The time variations of the K_p and D_{st} indices and deviations of the H and Z components of the magnetic field from the quiet levels (ΔH and ΔZ) are presented in Fig. 2(a) and (b). Intense bay-like disturbances of the H and D magnetic field components lasting from 40 min to 2 h and with amplitudes $\approx$10–50 nT are observed during the initial and main phases of the storm. Two of them seem to be connected with A and B solar wind inhomogeneities. At the time of the SSC* there is a positive impulse $\Delta H \approx 30$ nT. The start of the storm main phase coincides with an onset of the abrupt bay-like decrease of the H component at Irkutsk at 19:40 UT ($\Delta H \approx -50$ nT in about 5 min). The time delay ($\Delta t \approx 40$ min) between the polarity reversal of the IMF B_z component (line B in Fig. 2) and the bay commencement is the same as the delay between the interplanetary shock front observed by WIND (line A) and the SSC*.

A significant inconsistency of the time variations of ΔH and D_{st} during the storm is observed between 19:55 and 23:00 UT on October 18 only. A bay-like growth of the H component superimposed on the ring current field is observed during this time interval. Irregular fluctuations of the magnetic field are typical for storms. The distinctive property of the October 18–19 storm is that the bay amplitudes in the D component are comparable to those in the H component. An interesting and unusual feature of this disturbance is also the fact that from $\approx$20:00 UT on October 18 to $\approx$04:00 UT on October 19, the deviation of the Z component from its quiet level is negative and reaches its minimum ($\Delta Z \approx -50$ nT) at 22:45 UT. Then ΔZ is positive to the end of the recovery phase. In this section, we will not discuss the factors responsible for the anomalous behavior of the Z component in the course of the October 18–19 storm, this issue will be taken up later in the text.

4. Ionospheric manifestations of the storm activity

The most pronounced ionospheric effects of the October 18–19 storm are the significant F2-layer depletion and the generation of sporadic E-layers. They are observed over the entire northeastern region of Russia (Polekh et al., 1998). Here we will discuss only the ionospheric data essential to the present study.

Deviations of the critical frequency of the F2-layer from the monthly mean median values (Δf_0F2) and the time variation of $f_0 E_s$ over Irkutsk are shown in Fig. 2(c). It is seen, that from $\approx$20:00 UT, October 18 till $\approx$24:00 UT, October 19 there are two dramatic drops of f_0F2 with the daytime and nighttime maxima of disturbances. Both day and night minima are about 40–50% of f_0F2 median values. The peak plasma frequency of the F2-layer is less than f_0F1 ('G condition') during the October 19 daytime decrease. The multiple F1 and E traces are observed during the same time interval (Polekh et al., 1998).

Sporadic E-layers are almost uninterruptedly registered over Irkutsk from 15:15 UT, October 18 till the end of the storm except the time interval 09:15–14:00 UT, October 19. Critical frequencies of the layers vary nonmonotonically in the range from 1.8 MHz (00:00 UT, October 19) to 6.5 MHz (21:45 UT, October 19). The intensive sporadic E_s-layers located at distances $S \leq 1000$ km to the north of Irkutsk, are observed in backscatter ionograms for the Irkutsk–Magadan path from 16:37 till 23:07 UT, October 18. The minimal values of $S \approx 400$–500 km are registered from 19:00 to 23:07 UT, October 18. An example of the main phase backscatter ionogram with reflection from E_s-layer is given on Fig. 3.

It should be emphasized that intense sporadic E_{sa}-layers are generated over Irkutsk during the storm recovery phase within the time interval 14:00–22:00 UT October 19. During the same interval, the F-region traces are extended in height as in the midlatitude trough. An example of the vertical incidence ionogram is shown in Fig. 4.

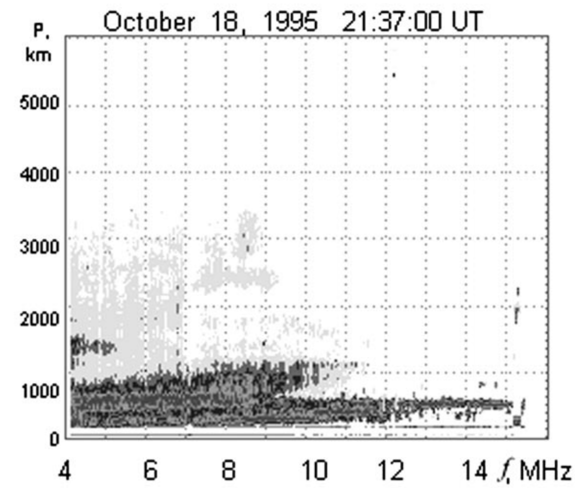

Fig. 3. Example of a backscatter ionogram for the Irkutsk–Magadan path.

5. Geomagnetic pulsations in Pi1 frequency band

Since the manifestations of the October 18–19, 1995 storm in geomagnetic Pi1 pulsations at Irkutsk are anomalous in both amplitude and frequency, the determination of the types of pulsations observed is difficult. We will give only a general picture of the storm development in the Pi1 frequency band and a description of the most interesting wave phenomena. The schematic presentation of the pulsation dynamic spectra, $f(t)$, and the time variation of the mean amplitude, $A(t)$, are plotted in the upper panel of Fig. 2(d) and (e), respectively.

Magnetic pulsations associated with the storm, appear already at the time of the SSC*. They are represented by broadband damped oscillations with periods $T \approx 660$ s, an isolated train of Pi2 and a high-frequency noise emission shown by the dynamic spectrum in Fig. 5. The frequency and amplitude characteristics of the emission are very similar to those observed during SSC at polar and auroral observatories (Guglielmi, 1979). Note that all midlatitude wave events accompanying and following the SSC* (let it be symbolized as Psc) have unusually large amplitudes. This is most likely associated with the abrupt decrease in the size of the dayside magnetosphere (as pointed out in Section 2) that led to a displacement of the Psc pulsation sources towards the Earth.

A noise emission at frequency $f \approx 0.1$–0.25 Hz persisting until $\approx$23:00 UT on October 19, starts already before the SSC*. Dramatic changes of the amplitude and frequency of the noise emission occur during two time intervals. During the first interval (14:50–17:20 UT on October 18, initial phase of the storm), a dome-like noise expansion to $f \approx 0.8$ Hz is observed but the pulsation amplitude increases only insignificantly (see Fig. 2(d) and (e)). During the second one (20:00–02:00 UT, October 18–19, 1995, main phase of the storm), an expansion of the spectrum to $f \approx 1$ Hz is caused by short-duration bursts similar to Pi1(b) following each other with a quasiperiod $\Delta t \approx 15$ min. The mean amplitude reaches the greatest value ≈ 0.05 nT, at 22:40–22:50 UT on October 18, 1995. The amplitudes of some oscillations are as large as 0.2 nT. Dynamic noise spectra during the two intensification periods are similar to those of high-latitude geomagnetic Pi1(c) pulsations, which permits the entire event to be interpreted as midlatitude Pi1(c).

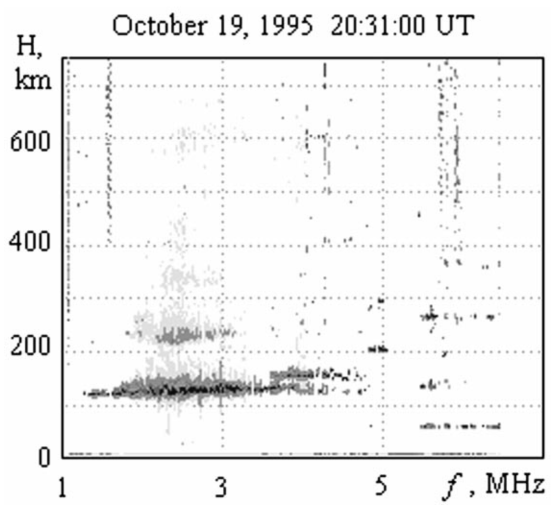

Fig. 4. Example of a vertical-incidence ionogram for Irkutsk.

Further changes of the pulsation spectra and the appearance of local $A(t)$ maxima (Fig. 2(e)) are caused by other types of pulsations: the dual monochromatic structures at $\approx$06, $\approx$07 and $\approx$08 UT with $f \approx 0.3$ Hz (Fig. 6) and the series of bursts of increasing frequency in 07:40–08:40 UT (Figs. 6 and 7). It is impossible to identify the type of these bursts. They may be both midlatitude Pi1(b) and the IPDP separate elements, which are more likely to be observed in the morning rather than in the afternoon sector. In the view of Kangas et al. (1987) such dynamic spectra are formed by the IPDP waveguide propagation in the nighttime ionosphere. In our case, at that time $f_0F2 \approx 3.6$ MHz which under usual conditions corresponds to the nighttime and early-morning F2-layer. The next wave phenomenon (starting at 08:54 UT) with nonstationary spectrum is a typical IPDP wave event (see Fig. 7).

From $\approx$11:00 to $\approx$23:00 UT on October 19, 1995, sonograms show a quasi-continuous emission with $f \approx 0.8$–1.5 Hz, $\Delta f/f \approx 0.5$–0.6. The parts of the dynamic spectrum of this emission are given in Figs. 7 and 8. The mean pulsation frequency increases gradually from $f \approx 0.9$ Hz, reaches its maximum $f \approx 1.25$ Hz by 16:30 UT, and again drops to values of $f \approx 1.0$ Hz by the end of the phenomenon. The structure and shape of the dynamic spectra are close to those of unstructured and semistructured Pc1-2 reported by Heacock (1970), except the fact that their frequencies rarely exceed 0.25 Hz. Notice that some structures of the dynamic spectrum may be interpreted as pulsation intervals of increasing (IPIP) and decreasing (IPDP) period (Gendrin, 1970).

6. Geomagnetic pulsations in Pi2 frequency band

The schematic representation of the Pi2 frequency band pulsations is shown in the bottom panel of Fig. 2(d). Solid vertical lines and dashed squares mark the commencements of isolated Pi2 trains and time intervals of long-lasting Pi2 series, respectively.

The SSC* is preceded by two isolated Pi2 trains observed at 10:36 and 10:44 UT. The first train co-

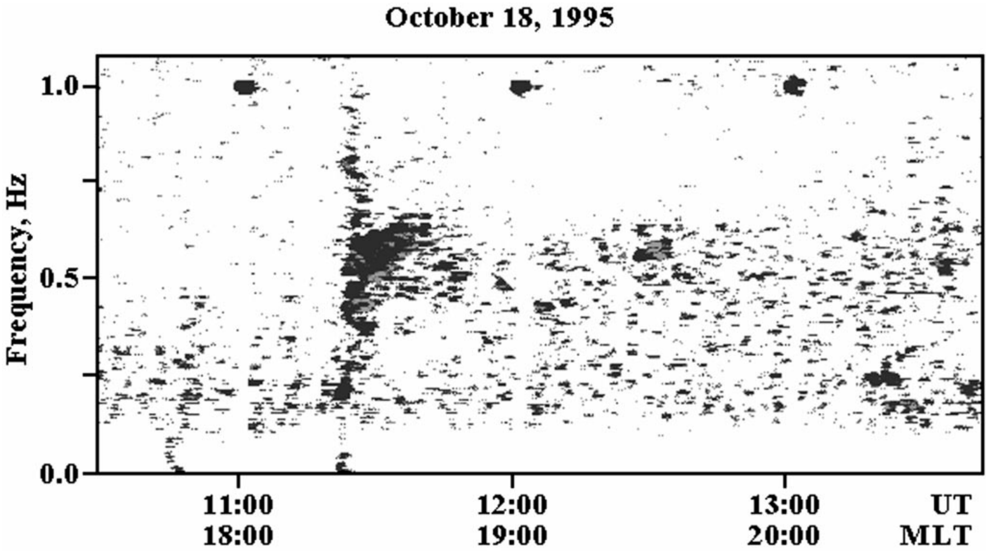

Fig. 5. Dynamic spectrum of the noise emission accompanying and following the SSC*.

incides with the start of the weak noise emission in the Pi1 frequency band. The SSC* is accompanied by another Pi2 train. The initial storm phase shows two long-lasting Pi2 series of a duration of about 1 h each, and four isolated Pi2 trains observed within 14:48–16:20 UT. The last train passes into the third long-lasting Pi2 series persisting till 17:40 UT. The fifth Pi2 train is observed at the end of the series, at 17:23 UT. These five Pi2 trains coincide in time with the dome-like expansion of the Pi1(c) dynamic spectrum. The beginning of the third long-lasting Pi2 series is close to the appearance of the intense reflections in backscatter ionograms.

The start of the storm main phase and the onset of the second interval of the Pi1(c) spectrum expansion coincide with the next two Pi2 trains recorded at 19:42 and 20:13 UT on October 18, 1995, respectively. The second train passes into a continuous Pi2 series lasting till 10:12 UT on October 19. From 21:57 to 23:25 UT on October 18, one can see a group of six Pi2 trains within the time interval of the main maximum of Pi1(c) amplitudes (Fig. 2(d) and (e)). Two Pi2 trains are registered at 01:06 and 01:44 UT on October 19.

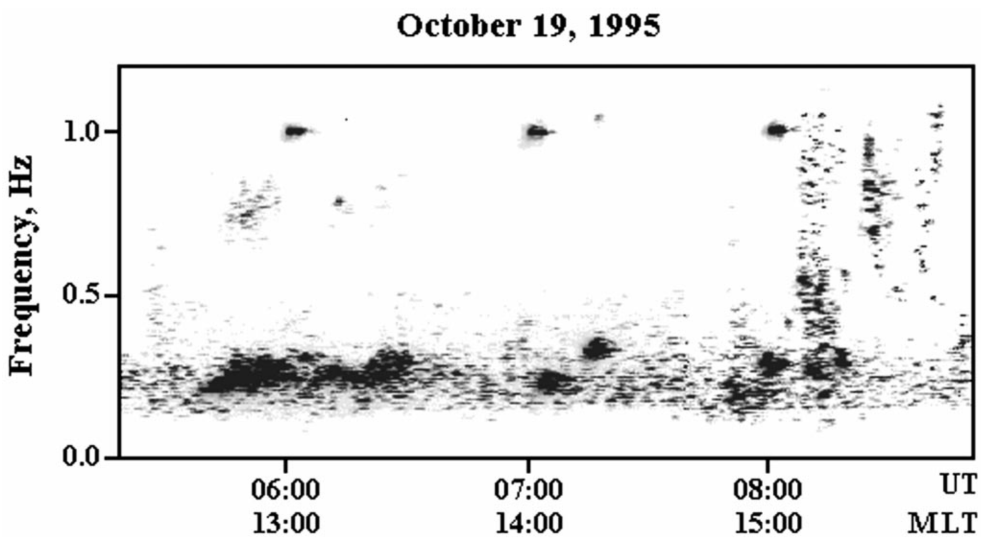

Fig. 6. Dynamic spectrum of the dual monochromatic structures and high frequency bursts.

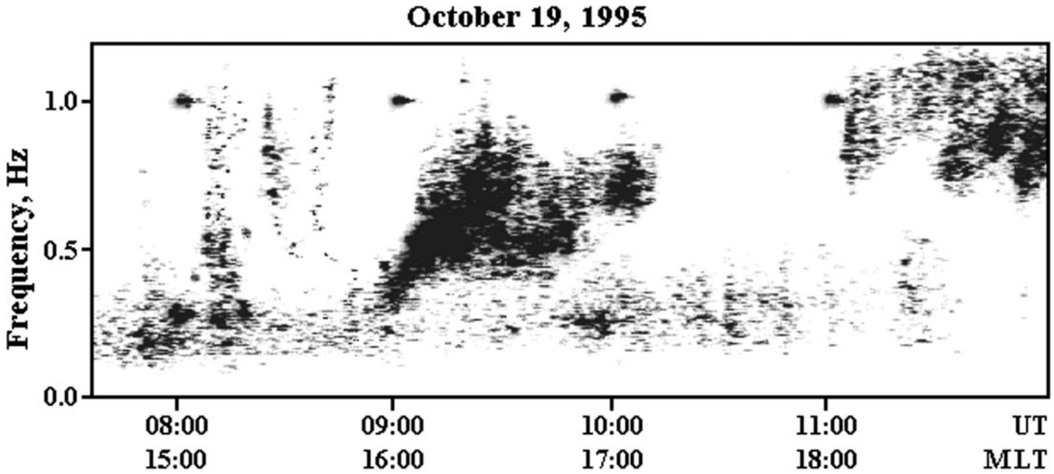

Fig. 7. Dynamic spectrum of the high frequency bursts, IPDP and the onset of the Pc1 quasi-continuous emission.

The only Pi2 train during the storm recovery phase is recorded at 08:48 UT on October 19.

7. Large-scale convection electric field and plasma boundary locations during the storm: indirect estimates

Let us estimate the large-scale convection electric field strength E_c. Following the investigations by Vasyliunas (1968), we can calculate the magnitude of E_c based on the values of $K_p = 4$ (15:00–18:00 UT) and $K_p = 7_-$ (21:00–24:00 UT) on October 18. In such a manner we obtain $E_c \approx 1.2 \times 10^{-3}$ V/m for the storm initial phase and $E_c \approx 4.5 \times 10^{-3}$ V/m for the main phase.

An analysis of the data on E_c for different conditions in the solar wind (Nishida, 1978; Lyons and Williams, 1984) shows that the value $E_c \approx 1.2 \times 10^{-3}$ V/m during the initial phase is rather overstated. We may calculate E_c by another way. Before 19:00 UT, $B_z > 0$ so the potential difference across the polar cap is $\Delta\varphi \approx 20$ kV (Sergeev and Tsyganenko, 1980). Considering the tail width $D \approx 25 R_E$ at $L \approx 10$, we have $E_c \approx 1.2 \times 10^{-4}$ V/m for the initial phase.

Now we will estimate the value of $\Delta\varphi$ for the time interval 20:00–24:00 UT in the following manner. The mean potential difference across the polar cap corresponding to the mean value of $B_z \approx -5$ nT, the solar wind velocity $v \approx 400$ km/s and the electric field strength in the interplanetary space $E_Y = -v \cdot B_z \approx 2 \times 10^{-3}$ V/m, is $\Delta\varphi \approx 40 \div 65$ kV (Nishida, 1978; Lyons and Williams, 1984). Under these conditions, the growth rate of the ring current field does not exceed the level $\Delta D_{st}/\Delta t \approx -10$ nT/h (Nishida, 1978). The value of $\Delta D_{st}/\Delta t \approx -40$ nT/h observed during the storm main phase, requires $E_Y \approx 9 \times 10^{-3}$ V/m, which

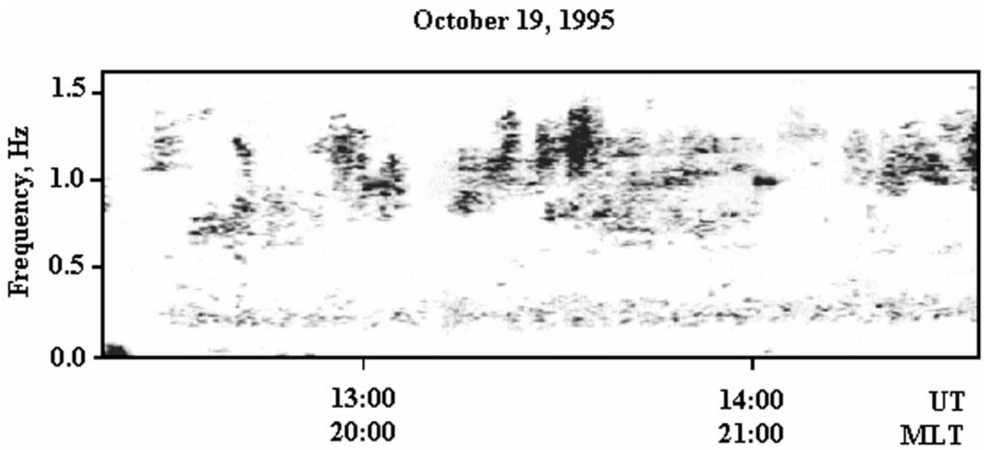

Fig. 8. Part of the dynamic spectrum of the Pc1 quasi-continuous emission.

for a given $B_z \approx -20$ nT can be obtained at $v \approx 450$ km/s. Assuming a linear relation between E_Y and $\Delta\varphi$, we find that the value of $\Delta\varphi$ could be as large as $\Delta\varphi \approx 180 \div 290$ kV during the time interval 20:00–24:00 UT on October 18. It gives the convection electric field strength $E_c \approx 1.1 \times 10^{-3}$ V/m for the onset of the storm main phase.

The estimate of $\Delta\varphi$ obtained by indirect data analysis, is rather large, but it is close to $\Delta\varphi = 200 \pm 50$ kV indicated by Chen et al. (1994). At present there is no unique way of indirect deduction of the exact value of E_c. In the following, we shall use the average values of $E_c \approx 6.6 \times 10^{-4}$ V/m and $E_c \approx 2.8 \times 10^{-3}$ V/m from those obtained on the basis of K_p and $\Delta\varphi$, corresponding to the end of the initial phase and the beginning of the main phase of the storm, respectively.

The hypothetical plasmapause locations in the evening sector $L_{pp} \approx 4.7$ and $L_{pp} \approx 2.2$ correspond to the above mentioned values of E_c (Nishida, 1978). As a result the abrupt increase in E_c leads to a dramatic decrease in the size of the trapping region. As it takes place, the 'old' plasmasphere's cold particles that fall outside the finite drift trajectories (at $L > L_{pp}$) after $\approx$19:30 UT on October 18, are transported to the periphery of the magnetosphere during a time interval determined by their initial position and by the value of E_c. At this time, the observatory at Irkutsk is in the morning MLT sector.

The time necessary for the 'old' plasmasphere particles to leave the morning sector may be estimated by integrating along trajectories similar to those reported by Chen et al. (1994). Taking into account the dependencies of the velocity of the gradient, corotation and electric field drifts on L and Λ, we find that for constant E_c the 'old' plasmasphere particles will leave the space over Irkutsk during a time interval from $\Delta\tau_1 \approx 30$ min (morning sector plasma) to $\Delta\tau_2 \approx 5$ h (midnight population of particles) after the increase of E_c. During the same time interval the morning sector shells with $L > L_{pp}$ can be filled with plasma having initially arrived from the morning part and then from the entire cross-section of the plasma sheet. Based on data from the work by Lepping et al. (1997), we may assume that from $\approx$19:30 UT on October 18 to $\approx$00:30 UT on October 19, the value of E_c changed slightly and the process to substitute the total particle population could be completed at $\approx$00:30 UT on October 19.

From 00:30 to 18:30 UT on October 19, E_c decreases monotonically to $E_c \approx 6 \times 10^{-4}$ V/m, which gives $L_{pp} \approx 4.9$, close to the prestorm value.

8. Discussion

The storm on 18–19 October 1995 differs from other storms in this class by the high rate of the D_{st} drop during the main phase and subsequent fast recovery of the D_{st} index. Another peculiarity of the storm is that magnetic field and ionospheric disturbances, typical in auroral regions, have been observed deep inside the plasmasphere ($L \approx 2$). Now we attempt to analyze the factors responsible for these peculiarities at Irkutsk, through the use of information extracted from geomagnetic pulsations.

Judging from the presence of only two Pi2 trains and the long-lasting series of Pi2 during the first 2 h of the October 18–19 storm main phase, the dominant contribution to the storm ring current enhancement is not due to substorm injections but due to the convective transport of plasma sheet particles deep into the magnetosphere.

To test this assumption, let us compare the L_{pp} and $\Delta\tau_{1,2}$ estimates obtained in Section 7 with the experimental data. The storm main phase starts at Irkutsk as Pi2 train and as an abrupt short-term decrease of the magnetic field H component at $\approx$19:40 UT when the second solar wind inhomogeneity (line B in Fig. 2) comes into contact with the Earth's magnetosphere. The first evidences of a significant amplification and an advance of the magnetospheric convection current system towards the Earth appear at Irkutsk with a time delay of $\Delta t_1 \approx 20$ min (at $\approx$20:00 UT) as long-lasting Pi2 series; as growth in Pi1(c) amplitude and expansion of the Pi1(c) dynamic spectrum; as decrease of f_0F2; as decrease of the distances to the sporadic E_s-layers located to the north of Irkutsk, and as bay-like negative variation of the Z component of the geomagnetic field.

Maxima of magnetic and ionospheric disturbances occur much later: within $\Delta t_2 \approx 4$, 10 and 4 h for ΔZ (Fig. 2(b)), Δf_0F2 (Fig. 2(c)) and geomagnetic pulsation amplitudes (Fig. 2(e)), respectively.

The estimates of L_{pp} and $\Delta\tau_{1,2}$ found in a drift approximation are close to the Irkutsk's L-shell and to the above-indicated experimental values of $\Delta t_{1,2}$. It follows that the abrupt increase in the field strength of the large-scale magnetospheric convection may be responsible for the development of the main phase geophysical disturbances observed in the morning sector. The increase in E_c implies a rapid transfer of particles of the peripheral plasmasphere to the magnetopause and allows the plasma sheet particles to access easily the shells with $L \approx 2$. Without going into details we simply note that an asymmetric ring current can be formed as a result of an intense convective transport of plasma sheet particles along the infinite drift trajectories passing near the Earth (Gonzalez et al., 1994; Takahashi et al., 1991). The development of this current is accompanied by the formation of strong field-aligned and ionospheric currents that give disturbances of the H, D and Z components of the geomagnetic field at middle latitudes of the morning sector similar to those presented in Fig. 2(b) and in Section 3. In the same approximation, a rapid decrease and fast recovery of the D_{st} index may be attributed to the fact that the contribution of the asymmetric component of the ring current to the value of D_{st} dominates the contribution of its symmetric component.

We return to Fig. 2 to analyze the midlatitude effects of the storm recovery phase. Discrete plasma injections seem to have occurred at 07:40 UT (high-frequency bursts of increasing frequency) and at 08:48 UT (Pi2 train). Thus, we can suppose that the recovery phase development is principally determined by the current system of large-scale magnetospheric convection. Since the value of E_c has been gradually decreasing during at least 18 h, plasma sheet particles with $\varepsilon \geq 20$ keV move away from the Earth without making a detectable contribution to the symmetric ring current formation.

Pi2 pulsations give the information on the persistence of substorm injection or enhanced large-scale convection only. Some quantitative information on magnetospheric processes can be obtained through the use of the Pi1 frequency band pulsations.

The depth of the plasma sheet inner edge penetration can be estimated by Pil(c) amplitudes. In accordance with an investigation by Kalisher et al. (1974), a Pil(c) amplitude ≈ 0.2 nT can be observed at a distance of $S \approx 400$–1000 km to the south of their generation region, connected with a pulsating electron stream off the inner edge of plasma sheet. This allows to suppose that the inner edge of the plasma sheet is located at a distance of about 4–10° to the north of Irkutsk (at $L \approx 2.4$–3.0) during the October 18–19, 1995 storm maximum.

Information on the ion composition and on the location of the symmetric ring current can be obtained by the analysis of the dual monochromatic structures and the quasi-continuous emission. The dual monochromatic structures can be generated by the convective ion-cyclotron instability of magnetospheric plasma enriched with the heavy ionospheric ions in the course of the storm development. The most likely region of their generation is the plasmapause re-established after a geomagnetic disturbance. A similar wave phenomenon at $f \approx 0.1$ Hz, near the oxygen cyclotron frequency, has been observed by ISEE 1 and 2 at $L \approx 6.6$ (Fraser et al., 1992). In the framework of the same generation mechanism the waves with $f \approx 0.3$ Hz can be emitted at $L \approx 3.8$–4.3. In our case $D_{st} \approx -100$ nT and the dual monochromatic structures could be generated at $L < 3.8$.

Now we turn our attention to the above-mentioned quasi-continuous emission appearing at 11:00 UT on October 19. It is hard to tell whether these intense (for middle latitudes) pulsations could make a detectable contribution to the fast ring current decay. We have pointed out that these pulsations are similar to semi-structured Pc1-2 observed at College ($L \approx 5.4$). Zolotukhina (1982) suggests a generation mechanism for such emissions by protons of the inner edge of the plasma sheet. A mathematical model for determining the depth of penetration and the energy of the particles is suggested by Guglielmi (1979). The emission frequency $f \sim \Omega \cdot A/\mathrm{w}$, where velocity $w = \sqrt{2\varepsilon/m}$; m, Ω and ε are the mass, gyrofrequency and energy of emitting particles, respectively, and $A = H/\sqrt{4\pi\rho}$—the Alfven velocity. Assuming $\Omega \sim m^{-1}L^{-3}$, plasma density $\rho \sim L^{-\nu}$, with $5 \leq \nu \leq 6$ and the particle energy in the part of drift trajectories nearest to the Earth $\varepsilon \sim L^{-1}$, we obtain $f \sim \mathrm{m}^{-1/2} \cdot L^{(\nu-11)/2}$. If at $L \approx 5.4$ emitting particles are protons and the emission frequency $f \approx 0.25$ Hz, we find that at $L \approx 2$ such a mechanism will give oscillations with $f \approx 1$ Hz for the mass m_i of emitting particles $24m_p \geq m_i \geq 9m_p$. This most closely corresponds to singly charged nitrogen and oxygen ions which have a rather high concentration at polarization jet latitudes (Galperin et al., 1997; Rodger et al., 1992). Thus, the presence of a quasi-stationary noise band with $f \approx 1$ Hz during the recovery phase of the October 18–19 storm indicates ionospheric ions to be one of the components of the ring current during this storm.

The drift approximation gives only a rough description of the complicated storm magnetospheric processes. Among other things, we neglect the contribution of discrete injections, occurring from 21:57 to 23:25 UT on October 18 as judged by the Pi2 trains. We also ignore the screening of the large-scale magnetospheric convection field over the region where hot plasma of plasma sheet and cold plasmaspheric plasma are in contact. It leads to the development of the polarization jet which coincides with or lies inside the plasmapause in the morning sector (Galperin et al., 1997; Rodger et al., 1992).

We suppose that it is the relatively inert eastern polarization jet with a width of about 100 km flowing at $h \approx 100$ km, that is able to cause a marked, 8-h long, smooth decrease of the Z component of the geomagnetic field together with a bay-like growth of the H component superimposed on the ring current field, pointed out in Section 3. Judging from the bay amplitude ratio ($\Delta Z/\Delta H \approx -2/3$) at the maximum of disturbances, the center of the jet is ≈ 70 km southward of the observation point (and with induction taken into account, ≈ 150 km). If the westward auroral electrojet located to the north of Irkutsk had been the reason for the negative ΔZ disturbance, the time evolution of ΔZ could not have been so smooth as it is seen in Fig. 2 (b). The presence of the polarization jet near Irkutsk's latitude is a further evidence of the dominating role of enhanced magnetospheric convection in the development of the main phase of the October 18–19 storm.

Summarizing the observations and estimates presented above, it is shown that the auroral phenomena over Irkutsk during the storm main phase are due to the displacement of their generation regions deep into the magnetosphere. This confirms our conclusion based on the Pi2 analysis, that enhanced magnetospheric convection could be the primary factor in the development of the October 18–19, 1995 storm. It is interesting to note that Jordanova et al. (1998) have arrived at the same conclusion by the kinetic modeling. Since, according to Lepping et al. (1997), the solar wind density is reduced by an order of magnitude at 19:00 UT on October 18, the southward displacement of the auroral activity after 19:40 UT is not associated with a change in the size of the magnetosphere as a whole.

9. Conclusions

The intense October 18–19, 1995 magnetic storm is due to the interaction of the Earth's magnetosphere with the interplanetary magnetic cloud. The initial and main storm phase onsets are distinctly associated with the abrupt changes in the interplanetary space environment. The recovery phase starts after the IMF B_z component has become positive.

The October 18–19 storm differs from storms of such class by the high rate of D_{st} drop during the main phase and subsequent fast recovery of the D_{st} index. The following distinctive peculiarities of the storm are observed at the midlatitude observatory at Irkutsk ($\Phi' \approx 45°$, $\Lambda' \approx 177°$, $L \approx 2$).

The amplitudes of bay-like variations of the magnetic field D component are comparable to those of the H component. The deviation of the magnetic field Z component from its quiet level is negative from $\approx$20:00 UT on October 18 to $\approx$04:00 UT on October 19, and gets its minimum ($\Delta Z \approx -50$ nT) at 22:45 UT.

A significant F2-layer depletion is observed during the main and recovery phases. The f_0F2 minima correspond to about 40–50% of median values. The intense sporadic E_s-layers located at distances $S \leq 1000$ km to the north of Irkutsk, are observed during the initial and main phases. The intense sporadic E_{sa}-layers are generated over Irkutsk during the storm recovery phase.

Intense high-frequency geomagnetic pulsations are registered: the high frequency noise emission accompanying the SSC*; Pi1(c), Pc1 at $f \approx 0.3$ Hz and Pc1 at $f \approx 1$ Hz.

The above-mentioned magnetic field and ionospheric disturbances are similar to those observed over the auroral region and are extremely rare in middle latitudes.

The estimates of the plasmapause location and of time delays between the B_z reversal and the onset and maximum of the storm activity found in a drift approximation are close to the value of Irkutsk's L-shell and to experimentally determined time delays, respectively.

Our findings on the basis of observations of solar wind parameters, geomagnetic pulsations, magnetic fields and ionospheric layers along with indirect estimates of the electric field strength of the large-scale magnetospheric convection during October 18–19, 1995, allow us to make the following main conclusion.

The October 18–19, 1995 storm is the limiting case where the dominant mechanism responsible for the development of storm-induced disturbances is not the substorm injections of plasma clouds into the inner magnetosphere but the quasi-stationary transport of plasma sheet particles as deep as $L \approx 2$ due to the enhanced magnetospheric convection. This process has become possible by the gradual and slow increase of the IMF B_z component after the abrupt B_z reversal, in the magnetic cloud surrounding the Earth.

The existence of storms similar to the October 18–19, 1995 storm gives support to the view by Gonzalez et al. (1994) that the model representing all storms as a superposition of substorms is not universally true.

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