ISSN 0016-7932, Geomagnetism and Aeronomy, 2016, Vol. 56, No. 6, pp. 682–693. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © V.G. Vorobjev, O.I. Yagodkina, V.L. Zverev, 2016, published in Geomagnetizm i Aeronomiya, 2016, Vol. 56, No. 6, pp. 721–732.

Investigation of Isolated Substorms: Generation Conditions and Characteristics of Different Phases

V. G. Vorobjev*, O. I. Yagodkina, and V. L. Zverev

Polar Geophysical Institute, Russian Academy of Sciences, Apatity, Murmansk oblast, 184200 Russia

**e-mail: vorobjev@pgia.ru*

Received May 10, 2016

Abstract—Characteristics of isolated substorms selected by variations in the 1-min values of the *AL* index are analyzed. The substorms were divided into several types with respect to the behavior of the *Bz* component of the interplanetary magnetic field (IMF) during the expansion phase. The probability of observations of substorms associated with the northward turn of the *Bz* component of IMF was ~19%, while the substorms taking place at $Bz < 0$ were observed in 53% of cases. A substantial number of events in which no substorm magnetic activity was observed in the auroral zone after a long (>30 min) period of the southward IMF and a following sharp turn of the *Bz* component of IMF before the north was detected. The data suggest that a northward IMF turn is neither a necessary nor sufficient condition for generating substorms. It has been shown for substorms of the both types that the average duration of the southward IMF to moment T_0 and the average intensity of the magnetic perturbation in the maximum are approximately the same and amount to ~80 min and –650 nT, respectively. However, for substorms at $Bz < 0$, their mean duration, including the expansive and recovery phases, is on average 30 min longer than that at a northward turn of IMF. Correlations between the loading–unloading processes in the magnetosphere in the periods of magnetospheric substorms were investigated with different functions that determine the efficiency of the energy transfer from the solar wind to the magnetosphere. It has been shown that the highest correlation coefficient ($r = 0.84$) is observed when the function suggested by Newell et al. (2007) is used. It has been detected that a simple function VB_S yields a high correlation coefficient ($r = 0.75$).

DOI: 10.1134/S0016793216060165

1. INTRODUCTION

The substorm concept was suggested by Akasofu (1964) for interpretation of the morphology of auroras and their dynamics during the transition of the magnetosphere from a quiet state to a disturbed one. From time to time, the planetary distribution of auroras typical for quiet conditions substantially changes due to a sharp increase in brightness of the nightside discrete forms and their mobility. Such an explosive manifestation of the activity is termed an auroral substorm. An auroral substorm is a constituent of the magnetospheric substorm covering geophysical phenomena in the whole magnetosphere. According to Akasofu, an original version of the scenario of the substorm development contains only the nighttime sector of the auroral zone; in a paper by Feldstein and Starkov (1967) and, later, in a paper by Akasofu (1968), it was supplemented by auroras of the daytime sector. In these scenarios, a substorm was actually represented by two phases—an expansion phase, the start of which will be hereinafter designated as T_0, and a gentler recovery phase, during which the magnetosphere returns to its quiet state.

Later, Starkov and Feldstein (1971) improved the model of an auroral substorm and supplemented it with a scheme of an isolated auroral substorm that starts after a quiet magnetic period. In the behavior of discrete auroras, before the expansion phase of a substorm, specific changes indicating the substorm manifestation were noticed; they were called the growth phase ($-60 < T_0 < 0$ min). McPherron (1970) was the first to publish, a year earlier, the supposition on a substorm growth phase, which was based on the analysis of variations of the magnetic field, preceding moment T_0. It is accepted that, in the growth phase of a substorm tightly coupled with the southward turn of the *Bz* component of IMF, the energy is accumulated in the magnetosphere tail (McPherron et al., 1973) and further dissipates during the expansion phase.

A somewhat original conclusion was made by Kallio et al. (2000) from their analysis of the loading–unloading energy in the system of the solar wind, magnetosphere, and ionosphere. These authors performed a statistical analysis of the substorms registered by the IMAGE magnetometer network (where IMAGE stands for International Monitor for Auroral Geomagnetic Effects) and found that, in the growth phase of a substorm, energy loading of the magnetosphere is required only for changing its configuration before moment T_0, while the intensity of a substorm itself is determined by the energy inflow straightly in the expansion phase. This suggests that the intensity of the subsequent substorms will be very low if the energy inflow to the magnetosphere stops immediately before moment T_0. However, this inference contradicts the results by Hsu and McPherron (2004), who came to the conclusion that the substorms triggered by the northward IMF turn are systematically stronger than the untriggered ones. Morley and Freeman (2007) explained such a difference in the intensity of substorms by the circumstance that, in the data used by Hsu and McPherron (2004), the energy contribution of the solar wind before moment T_0 was statistically higher for the substorms associated with the northward IMF turn than that for the substorms free of such a trigger. For example, for substorms of the first type, the mean value of the *Bz* component of IMF was −3.5 nT before the beginning of the expansion phase, while it was −2.5 for untriggered substorms. Thus, one may expect that, the intensity of substorms of both types will be approximately the same under the same values of the *Bz* component of IMF and all other conditions being equal.

The above speculations suggest that there are two classes of substorms—triggered and untriggered. The fact is that, up to now, the question on whether the generation of substorms requires drastic changes in the environment parameters (triggers) or substorms are spontaneously generated due to the development of instabilities in the plasma sheet of the magnetosphere is still under discussion. The range of opinions is extremely wide. For example, Lyons (1996) supposed that most, or probably all, substorms are triggered by a decrease in the large-scale electric field brought to the magnetosphere from the solar wind if this process is preceded by a growth phase longer than 30 min. The main cause of the decrease in the electric field is the northward turn of the vertical component of IMF. The same year, from complex ground—satellite observations, Henderson et al. (1996) showed with a great degree of reliability that substorms appear without any noticeable trigger in solar wind plasma and IMF. The publication of these papers induced a noticeable growth of activity in the studies of magnetospheric substorm generation.

To determine the IMF changes that can be mostly effective in the substorm triggering, Lyons et al. (1997) suggested some quantitative criteria. With such criteria, these authors found that 14 from 20 substorms considered in that study (i.e., 70%) can be reckoned as triggered ones. Hsu and McPherron (2003) made a list of substorms identified by a sharp long-lasting decrease in the values of the *AL* index and showed that around 60% of substorms are triggered. Gallardo-Lacourt et al. (2012) analyzed the substorms, the expansion phases of which were determined from optical observations by the all-sky cameras of the THEMIS (Time History of Events and Macroscale Interactions during Substorms) ground-based network stations and from observations of the IMAGE satellite in the ultraviolet spectral range. With the use of criteria introduced by Lyons et al. (1997), Gallardo-Lacourt et al. (2012) found that only 17 and 22% of substorms identified from the THEMIS and IMAGE data, respectively, are triggered. However, the proportion of triggered substorms increased to ~50% if the authors used the weaker criteria than those suggested by Lyons et al. (1997). From these data, a clear inference can be seemingly drawn. Since there are a lot of substorms not associated with the presence of a trigger, the start of substorms is a manifestation of instabilities developing inside the magnetosphere. At the same time, the manifestation of such instabilities turns out to be sensitive to perturbations in the environment.

Wild et al. (2009) considered 260 substorms to determine the probable interrelation between the time of their onset and the northward IMF turn. The substorms selected from the optical observations of the IMAGE satellite (Frey et al., 2004) were analyzed, and the parameters of the solar wind and IMF were determined from the simultaneous observations of the *Cluster* satellite, which was in the solar wind not farther than 5 Re from the bow shock front. This study revealed that only a small proportion of substorms (<25%) can be related to the northward turn of IMF. At the same time, most substorms (>70%) indicate the presence of a growth phase, during which the magnetosphere is loaded by the solar-wind energy. Wild et al. (2009) came to the conclusion that the southward IMF should exist during 22 min or longer in the half-hour preceding substorm onset so that the substorm begins and there is no additional need for the northward turn of IMF. Infrequent coincidences of the northward turn of IMF with the substorm onset can be rated as occasional events connected with the increased probability of the turn of the southward IMF to the north.

Newell and Liou (2011) showed that the so-called northern trigger is observed in 23% of the randomly chosen data, in 24% of the real substorms, and in 27% of the cases after an accidental increase of the solar-wind energy. A sufficient number of accidental events can be always found on both the northward and southward turn of IMF to confirm any of the hypotheses. Newell and Liou (2011) supported the viewpoint of Wild et al. (2009) and came to the conclusion that an initial increase in solar-wind activity is actually required for substorms; however, there is no evidence that the external triggering exists.

In this paper, the characteristics of isolated substorms selected by variations in the 1-min values of the *AL* index are analyzed. To select the substorms, we used special criteria that, in our view, allow the substorm activity to be distinguished from the "convective" (Sergeev 1977; Pytte et al., 1978) and "compressive" (Liou et al., 2004) magnetic bays. According to the behavior of the *Bz* component of IMF in the period preceding moment T_0, the substorms were divided into several types.

The purpose of the paper is to study the temporal and amplitude characteristics of substorms of different types and to analyze the conditions in the solar wind and IMF in the period of their generation.

2. DATA

To extract isolated substorms, we considered the analog records (http://wdc.kugi.kyoto-u.ac.jp/) and 1-min digital values (http://cdaweb.gsfc.nasa.gov/) of the *AL* index of magnetic activity in the auroral zone for all of the winter seasons (November, December, and January) from 1995 to 2012. To select the isolated substorms, the following criteria were used:

(1) The temporal interval from the preceding disturbance is not less than 3 h.

(2) The intensity of a magnetic bay is $250 < \mathrm{Max}|AL| < 1300$ nT in maximum.

(3) The substorm duration is less than 3 h.

(4) The substorm terminates at the moment (expressed in UT) after which the disturbance strength is $|AL| < 0.2\mathrm{Max}|AL|$.

By criteria 1–3, the substorms were selected by visual examination of the diurnal variations in the *AL* index. An additional sign of the substorm manifestation was the presence of the corresponding variations in the indexes of magnetic activity SYM/H(D) and ASYM/H(D).

The following automatic procedure was used to determine the onset of the expansion phase of a substorm T_0.

(1) The preceding level is subtracted from each of the 1-min values of *AL*, which results in ΔAL_1. If $\Delta AL_1 > 60$ nT, the moment of the preceding *AL* level is considered as the expected value of T_0 and the current time is $T_0 + 1$.

(2) The next value of *AL* is taken at $T_0 + 2$, and the difference is calculated as

$$\Delta AL_2 = AL(T_0 + 2) - AL(T_0).$$

If this value $\Delta AL_2 > 100$ nT, moment T_0 is considered as the substorm onset and the substorm itself is considered as a candidate for the list of isolated substorms.

For all of the substorms selected in this way, the data on the parameters of the plasma of the solar wind and IMF were taken from the OMNIWeb database (http://cdaweb.gsfc.nasa.gov/). For each of the substorms, the data were taken in an 8-h interval (UT) chosen in such a way that moment T_0 was approximately in the middle of it. Only the events for which OMNI observational data contained no gaps longer than 10 min and no shorter gaps located close to the beginning of the substorm expansion phase were included in the list of isolated substorms. Approximately 20% of the total number of substorms was discarded due to substantial gaps in the OMNI data.

In 1995–2012, observations from satellites in the upstream solar wind at different distances from Earth's bow shock (up to libration point L1) were used to create the OMNI database on the interplanetary medium. To control the lag time of the ground-based observations relative to the OMNI data, we additionally considered variations in the *PC* index of magnetic activity in the polar cap. It is known that the *PC* index represents the value of the "effective" electric field penetrating from the solar wind to the polar ionosphere, and its variations are approximately proportional to variations in the *Bz* component of IMF (Troshichev et al., 2000).

The use of special criteria for the selection of isolated substorms and the analysis of simultaneous data on the parameters of the interplanetary medium and on the magnetic activity levels in different latitude zones of the Earth's surface allow, in our opinion, the substorm activity to be rather reliably distinguished from the convective (Sergeev, 1977; Pytte et al., 1978) and compressive (Liou et al., 2004) magnetic bays.

In total, for the winter seasons of 1995–2012, 112 substorms, satisfying the above formulated conditions were selected. If we suppose that substorms are homogeneously distributed through years and seasons, we obtain that our database could have contained ~30 substorms per year on average. It is a small number of events, as compared to the substorm lists considered in the studies cited in the previous section. For example, the substorm list selected by Frey et al. (2004) from the FUV IMAGE observations in the period from May 2000 to December 2002 contains 2437 events. The list used by Newell and Liou (2011) contains 1893 substorms registered in the northern hemisphere by the Ultraviolet Imager (UVI) of the *Polar* satellite from March 1996 to December 1999. The list of substorms obtained by Nishimura et al. (2010) from observations by the ground-based all-sky cameras of the THEMIS network contains 190 substorms only for one winter season of 2007–2008. The main difference is that no requirements for the isolation of the events were applied to the selection of substorms in those studies, while the present analysis uses a rather strong criterion to determine the isolation of substorms.

3. TYPES OF SUBSTORMS AND THEIR CHARACTERISTICS

All of the events included into the list of isolated substorms were selected by the criteria based on the character of the ground geomagnetic variations. To

Table 1. Mean characteristics of substorms

Type	T_{grow}	$\lvert AL\rvert_{max}$	T_{exp}	T_{rec}	T_{sub}	N	%
1	84	630	25	82	107	59	52.7
2	–	370	14	42	56	4	3.6
3	78	670	20	58	78	21	18.8
4	84	560	25	77	102	19	16.9
5	96	720	21	65	86	9	8.0

study the substorms and the averaged statistical characteristics of their different phases in more detail, all of the substorms were divided into several types depending on the behavior of the Bz component of IMF at the beginning of the expansive phase.

Type 1: $Bz < 0$ before and after T_0 for the period equal to or longer than 0.5 h.

Type 2: $Bz \geq 0$ before and after T_0 for the period equal to or longer than 0.5 h.

Type 3: $Bz < 0$ before T_0 for the period equal to or longer than 0.5 h, but it turns northward during the interval of $T_0 \pm 10$ min; the magnitude of the change is $\Delta Bz > 2$ nT for the time $\Delta t \leq 10$ min.

Type 4: all of the events not included into types 1–3; i.e., the Bz component of IMF is sign-changing before and after T_0, or the sign is changing very slowly in the interval of $T_0 \pm 10$ min.

Type 5: $Bz < 0$ before and after T_0 for the period equal to or longer than 0.5 h, but it shows a positive impulse of 5–15 min long in the interval of $T_0 \pm 10$ min.

Table 1 presents the average characteristics of substorms of different types. In the first column, the substorm type is shown. In the second column, T_{grow} indicates the substorm growth phase, duration of which for each of the substorms was determined by the southward turn of IMF. For some substorms, especially those of type 4, such an assignment is rather subjective. In the third column, $|AL|_{max}$ is the mean value of the substorm intensity in the maximum. The fourth, fifth, and sixth columns display the mean durations of the expansion (T_{exp}) and recovery (T_{rec}) phases and the whole substorm ($T_{sub} = T_{exp} + T_{rec}$), respectively. The total number N of substorms of a specified type and their percentage are in the seventh and eighth columns, respectively. All of the intervals are specified in minutes, and the values of AL are in nanoteslas.

As is seen from Table 1, when Bz was oriented northward, only four substorms with a mean intensity of ~370 nT in the maximum were registered. The substorms of type 1 were observed with the highest probability, ~53%; their expansion phase developed during a southward orientation of IMF. The registered substorms of type 3, the onset of which was associated with a northward turn of the Bz component of IMF, amount to only approximately 19%, and the registered substorms of types 4 and 5 make up approximately 17 and 8%, respectively.

This study will be mainly focused on the substorms of types 1 and 3; in a range of scientific research, they are referred to as untriggered and triggered, respectively. Contrary to the conclusions of the paper by Hsu and McPherron (2004), the mean intensity of substorms of both types is approximately the same and amounts to 630 and 670 nT. The duration of the existence of the southward IMF before the beginning of the substorm expansive phase is also approximately the same (84 and 78 min). However, type 1 substorms exhibit a longer expansive phase (by ~20%) and a substantially longer recovery phase as compared to those of type 3 substorms. In general, the duration of the type 1 substorms, the expansive phase of which goes under the negative Bz values of IMF, is ~30 min longer than that of the so-called triggered substorms.

Since the overwhelming majority of substorms contained in the considered sampling are of type 1, the northward turn of the Bz component of IMF cannot be considered as a necessary condition for generating substorms. By way of illustration, in Fig. 1, the characteristics of the interplanetary medium and the magnetic activity variations are shown for the interval from 1100 to 1900 UT of November 1, 2006. In the plot, from top to bottom, the variations of the By and Bz components of IMF in the GSM coordinate system, the dynamic pressure of the solar wind, and the AL and PC indices of magnetic activity are presented. The substorm expansive phase onset registered at 1400 UT is marked by a vertical dashed line. The substorm began during the southward Bz component of IMF that turned to the north approximately 40 min after the substorm onset. At moment T_0 and in the preceding period, no noticeable changes that could be considered as a trigger were detected in the conditions in the interplanetary medium. The weak increase in the positive values of the By component of IMF occurring in this period cannot be considered as a substorm trigger, since it took place after moment T_0. Moreover, according to variations in the PC index, on the Earth's surface, the changes in magnetic activity lag relative to the Bz variations of IMF by approximately 10–15 min.

In Fig. 1, there is one more prolonged interval of the southward IMF that started at ~1540 UT and terminated at ~1730 UT by a sharp northward turn of the Bz component of IMF. The good correlation between the Bz variations of IMF and the PC index indicates an increase of the effective electric field in the north cap following the southward Bz turn, and the subsequent sharp decrease of this electric field to zero level following the northward Bz turn. According to the theory by Lyons (1995), a drastic fall of the electric field of the solar wind should have led to the development of a strong magnetospheric substorm. However, Fig. 1 shows only a weak gentle increase of the AL index by

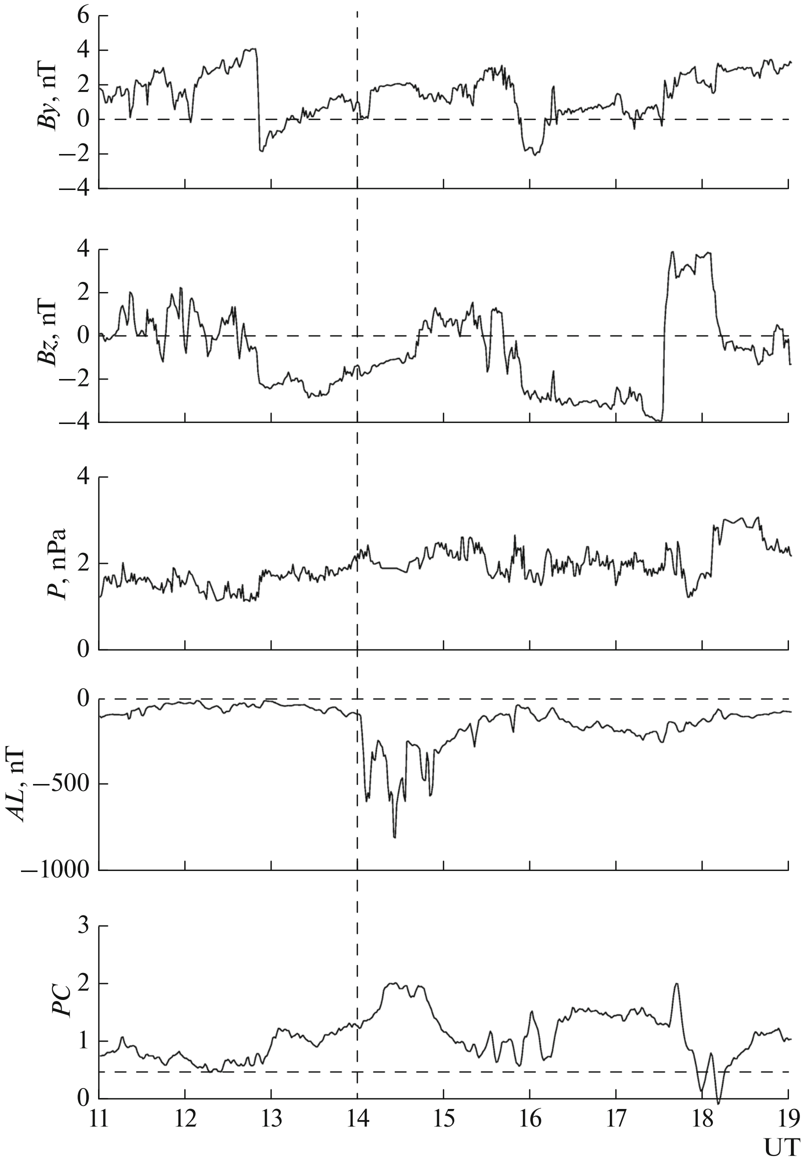

Fig. 1. Interplanetary medium characteristics and magnetic activity variations on November 1, 2006 in the interval from 1100 to 1900 UT. From top to bottom: variations of the *By* and *Bz* components of IMF in the GSM coordinate system, dynamic pressure of the solar wind, and *AL* and *PC* indices of magnetic activity. The substorm onset registered at 1400 UT is marked by a vertical dashed line.

100–150 nT accompanying the southward excursion of the *Bz* component of IMF.

In the frames of this study, we did not specially select events similar to that described above. However, even within the limited set of the data, we found a substantial number of examples in which no development of the substorm activity in the auroral zone was observed after a long (>30 min) period of the existence of the southward IMF and the subsequent sharp northward turn of the *Bz* component. All of the data suggest that neither the presence of a long period (>30 min) of the southward IMF nor the subsequent northward turn of the *Bz* component of IMF is a sufficient condition for generating substorms.

Figure 2 shows the mean characteristics of the interplanetary medium and magnetic activity for substorms of types 1 (a) and 3 (b); they were obtained by the method of superposed epoch in an interval of ±3 h relative to moment T_0. In Fig. 2, the sequence of the data presentation is the same as that in Fig. 1. Since the curves in Fig. 2 illustrate the geophysical parameters averaged over the time relative to T_0, their variations by amplitude and duration differ from the mean values presented in Table 1.

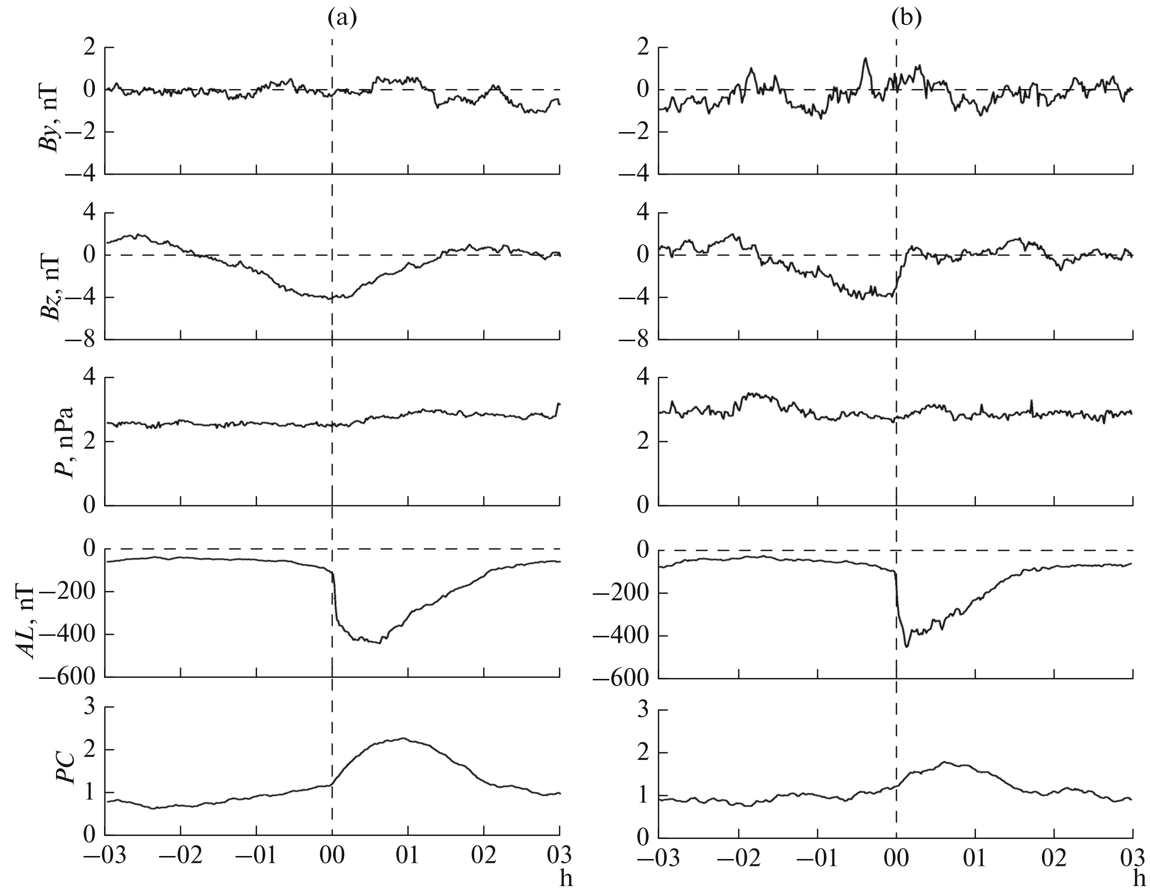

Fig. 2. Mean characteristics of the interplanetary medium and magnetic activity for substorms of types 1 (a) and 3 (b); they are obtained by the method of superposed epoch in the interval of ±3 h relative to moment T_0. The sequence of data presentation is the same as that in Fig. 1.

From the analysis of Figs. 2a and 2b, it is worth noting that a substantial interval of the southward IMF is present before moment T_0; according to Table 1, its mean duration is ~80 min and the value of the *Bz* component of IMF is approximately –4 nT before the substorm onset. Note the absence of any systematic or significant variation in the *By* component of IMF, which could be a trigger of the substorm. The values of the dynamic pressure of the solar wind and the variations in the *PC* index of activity in the polar cap are approximately the same for the both types of substorms. As in Table 1, the duration of the expansive and recovery phases of the type 1 substorms is somewhat larger than those of the type 3 substorms. Such a difference may be caused by an additional input (release) of the solar wind energy to the magnetosphere (ionosphere) for substorms of type 1 if the *Bz* component of IMF is negative.

Figure 3 shows the mean characteristics of the interplanetary medium and magnetic activity for substorms of types 4 (Fig. 3a) and 5 (Fig. 3b). The format of the plot is the same as that in Fig. 2. According to Table 1, the mean intensity of the type 4 substorms is ~100 nT lower than that of the substorms of types 1 and 2. This is most likely connected with the fact that, before the beginning of the type 4 substorm, the mean values of the southward component of IMF are small ($Bz > -1$ nT), while they reach the values of –4 nT for the substorms of types 1 and 2. For type 4 substorms, the mean values of the *By* component of IMF are negative in the whole considered interval (Fig. 3a). In the vicinity of moment T_0, there are no noticeable changes in both the *By* component of IMF and the dynamical pressure of the solar wind.

The type 5 substorms, the expansive phases of which were preceded by a short positive impulse in the *Bz* component of IMF, are shown in Fig. 3b. According to Table 1, these substorms, which exhibit the mean value $|AL|_{max} \approx 720$ nT, turned out to be strongest among the substorms of all types. This fact is simply explained if we take into account that the mean values of the *Bz* component of IMF reached a level of approximately –6 nT before the northward turn, while they were approximately –4 nT for the substorms of types 1 and 3 and approximately –1nT for the type 4 substorms. Over the entire considered time interval,

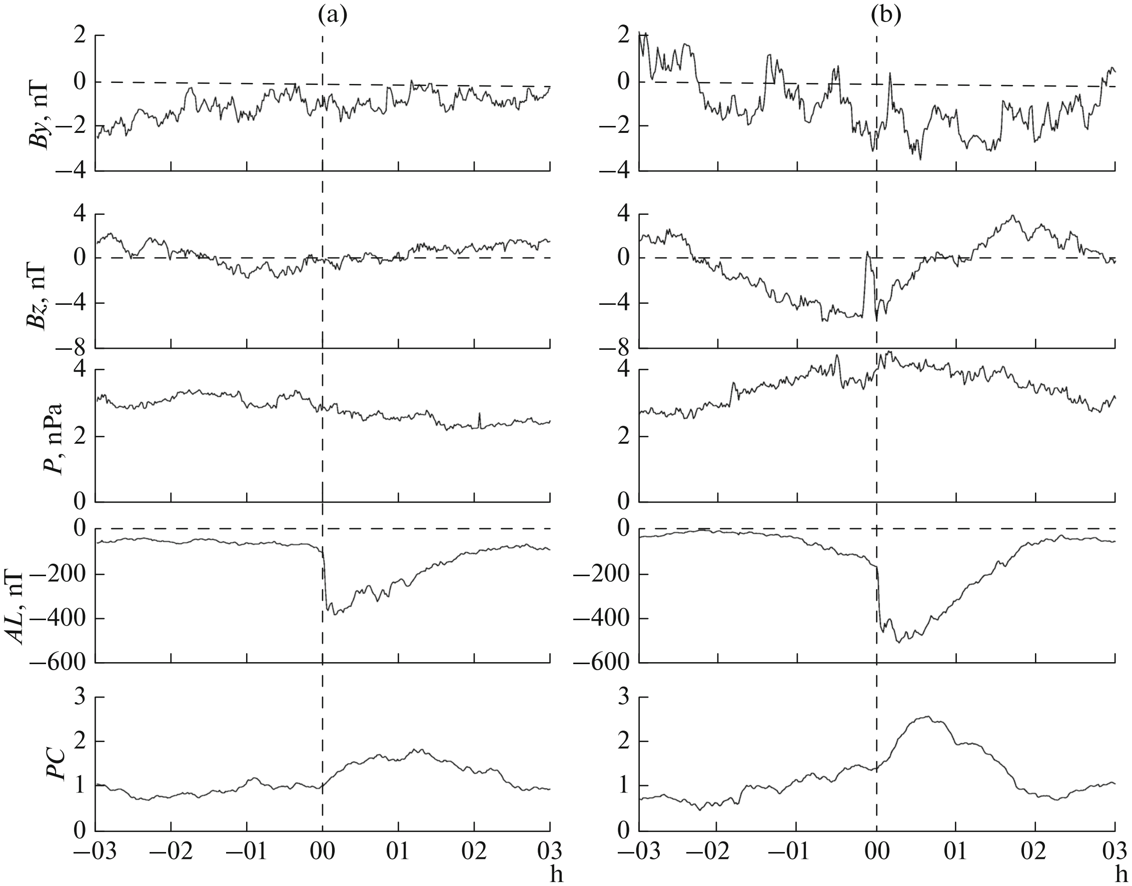

Fig. 3. Mean characteristics of the interplanetary medium and magnetic activity for substorms of types 4 (a) and 5 (b). The format of the plot is the same as that in Fig. 2.

the *By* component of IMF shows significant variations. This variability of *By* can be connected with a small number of this type substorms.

4. SOLAR WIND ENERGY AND SUBSTORM INTENSITY

The solar wind plasma and interplanetary magnetic field are sources of magnetospheric substorm energy. Though the velocity, density, and dynamic pressure of the solar wind determine the characteristic sizes of the magnetosphere because the pressure on the magnetopause should be balanced, these quantities themselves cannot be a source of substorm energy. Figure 2 shows that variations in the dynamical pressure and, consequently, the velocity and density of the solar wind are, on average, negligible in the intervals of substorm observations. A more important factor is the presence of the southward IMF interval before the before the substorm onset, which provides the magnetic reconnection. The energy connection between the solar wind and the magnetosphere can be expressed by different functions containing both the southward component of IMF and its combinations with the other parameters of the solar wind. Such functions and the efficiency of their influence on different geophysical parameters, which determine the magnetosphere state, are reviewed by Newell et al. (2007).

In this paper, we use some of these functions to study the interrelation between the loading of the magnetosphere by the solar wind energy and the subsequent energy dissipation in the periods of substorms. We used (i) the southward component of IMF B_S ($B_S = 0$, if $Bz \geq 0$, and $B_S = |Bz|$, if $Bz < 0$), (ii) the function VB_S, where V is the solar wind velocity, (iii) the Kan–Lee electric field $E_{KL} = VB_T \sin^2(\theta/2)$ (Kan and Lee, 1979), where $B_T = (By^2 + Bz^2)^{0.5}$ and the o'clock angle of IMF $\theta = \arctan(By/Bz)$, and (iv) the flux changing rate for the open lines of force at the magnetopause $d\Phi/dt = V^{4/3} B_T^{2/3} \sin^{8/3}(\theta/2)$ (Newell et al., 2007). The first two functions are proportional to the electric field of the solar wind, while functions (iii) and (iv) approximately take into account the reconnection line geometry on the daytime magnetopause and the efficiency of the reconnection process itself.

In this section, the processes of the magnetosphere loading–unloading in the periods of magnetospheric

Table 2. Correlation coefficients for the loading-unloading processes

Function type	Version 1		Version 2	
	type 1	type 3	type 1	type 3
B_S	0.31	0.30	0.05	0.52
VB_S	0.75	0.51	0.21	0.67
E_{KL}	0.71	0.56	0.18	0.61
$d\Phi/dt$	0.84	0.62	0.16	0.66

substorms of types 1 and 3 are analyzed. The energy contribution of the solar wind was determined by separate integration of each of the above-listed functions in the time interval from (T_0 – 2 h) to the end of the substorm. In our data set, the mean duration of the growth phase of a substorm is ~1.5 h. Thus, the chosen 2-h interval to moment T_0 includes the growth phases of all of the considered substorms of types 1 and 3.

In the real events, the vertical component of IMF experiences variations of different periods, including those occurred with a change of the *Bz* sign. For the purposes of this study, we chose the most "regular" events, i.e., the substorms during which the *Bz* variations of IMF most resembled the samples shown in Figs. 2a and 2b. Thus, 22 and 18 substorms of types 1 and 3, respectively, were selected for subsequent studies.

The energy dissipation during each of the substorms was estimated by the power of auroral precipitations according to a simple linear relationship derived by Vorobjev and Yagodkina (2008). We removed a constant term (indicating the energy release level at $AL = 0$) from the regression equation (Vorobjev and Yagodkina, 2008), since we suppose that it corresponds to the loading–unloading balance when magnetic disturbances are completely absent. In this case, the relationship between the strength of auroral precipitations and the magnetic activity level in the auroral zone will take the simple form $U_A = 0.12|AL|$, where AL and U_A are expressed in nanoteslas and gigawatts (1 GW = 10^{16} erg/s), respectively. The total energy of auroral precipitations (W_A) was determined by integration of U_A from moment T_0 to the substorm end. This choice of integration intervals for determination of the loading–unloading energy of the magnetosphere is designated as "Version 1" in Table 2. Note that the power of auroral precipitations is only a part of the energy budget of a substorm, along with the Joule heating and the energy of the ring current and the plasma sheet.

In Fig. 4, the interrelations between the energy of auroral precipitations W_A and the energy contribution of the solar wind determined by the functions B_S, VB_S, E_{KL}, and $d\Phi/dt$ are shown from top to bottom, respectively. The energy of auroral precipitations is expressed in terajoules (1 TJ = 10^{19} erg), while the energy loading of the magnetosphere is in terms of special units corresponding to each of the functions, where the IMF components and the solar wind velocity are expressed in nanoteslas and kilometers per second, respectively. The values are approximated by a linear function, and the corresponding correlation coefficients *r* are specified in the bottom right of each of the plots. The data for substorms of types 1 and 3 are shown in Figs. 4a and 4b, respectively.

As is seen from Fig. 4, the correlation coefficients, as a rule, increase while moving from function (i) to function (iv). The correlation of W_A is weakest with B_S ($r = 0.3$) and strongest with $d\Phi/dt$, where $r = 0.84$ and 0.62 for the substorms of types 1 and 3, respectively. Note the rather high correlation coefficient of W_A with the function VB_S ($r = 0.75$) for the type 1 substorms. The corresponding correlation coefficients are shown in the columns named "Version 1" in Table 2.

The correlation relations of the magnetosphere loading–unloading in the periods of substorms can be also estimated in a different way if the energy dissipation during the expansive phase of a substorm is assumed to be proportional to the energy accumulated in the magnetosphere before moment T_0. For this, functions (i)–(iv) were integrated over the time interval from (T_0 – 2 h), as in the previous case, but only to the moment T_0, not to the substorm end. The energy of auroral precipitations W_A was calculated by integration of the precipitation power over the interval from T_0 to the end of the substorm expansion phase. In Table 2, this choice of integration intervals is called "Version 2." These relations are not illustrated by corresponding plots, but the following important characteristics may be mentioned. For type 1 substorms, the correlation coefficients *r* drastically fell and amounted to 0.05, 0.21, 0.18, and 0.16 for functions (i)–(iv), respectively. For type 3 substorms, on the other hand, the correlation coefficients increased for all types of functions of magnetosphere loading and amounted to 0.52, 0.67, 0.61, and 0.66 for functions (i)–(iv), respectively. All of the correlation coefficients are listed in the columns named "Version 2" in Table 2. As in the previous variant, note the rather high correlation coefficient of W_A' with the function VB_S ($r = 0.67$) and $d\Phi/dt$ ($r = 0.66$) for the type 3 substorms.

5. DISCUSSION

The characteristics of isolated substorms selected by variations in the 1-min values of the *AL* index were analyzed. Special criteria were used to select the substorms; they allow substorm activity to be distinguished from the convective (Sergeev, 1977; Pytte et al., 1978) and compressive (Liou et al., 2004) magnetic bays. In total, 112 substorms satisfying all of the conditions formulated in section 2 were selected for the winter seasons of 1995–2012.

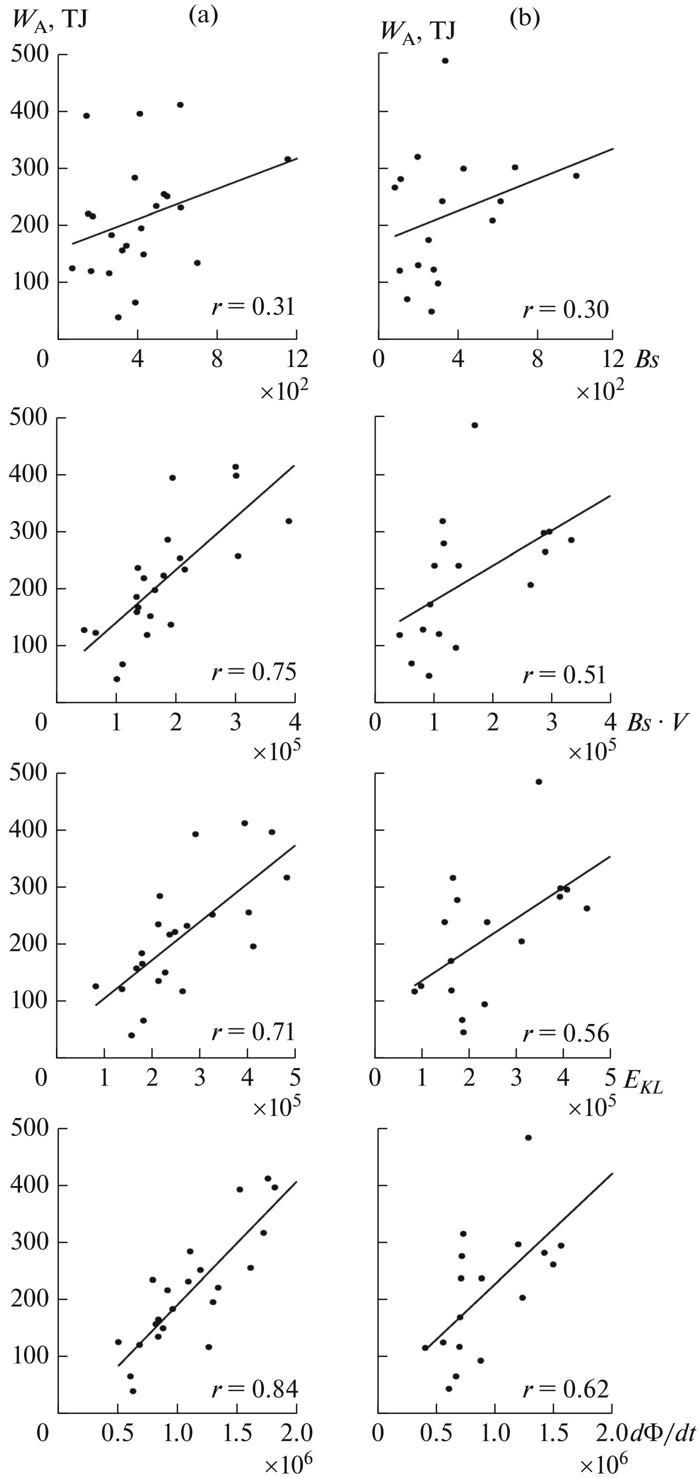

Fig. 4. Correlation between the energy of auroral precipitations W_A and the energy contribution of the solar wind determined by different functions are shown from top to bottom. The correlation coefficients r are specified in the bottom right of each plot. The data for substorms of types 1 and 3 are shown in panels (a) and (b), respectively.

By the behavior of the *Bz* component of the IMF during the expansive phase, all of the chosen substorms were divided into the types described in section 3. Type 1 substorms, the expansion phase of which developed under the southward orientation of IMF, were observed with the highest probability (~53%). Type 3 substorms, the start of which was associated with a northward IMF turn, amounted to approximately 19%. The other types of substorms and their characteristics are described in section 3 and Table 1.

This study is mainly focused on substorms with an expansion phase that developed under a southward IMF orientation (type 1) and substorms with an onset associated with the northward turn of the *Bz* component of the IMF (type 3). In some scientific researches, they are referred to as untriggered and triggered, respectively.

Note that there is a substantial interval of the southward IMF preceding the start of the expansion phase of substorms. For substorms of types 1 and 3, the mean duration of the southward IMF before moment T_0 and the mean intensity of the magnetic perturbation in the maximum are approximately the same and amount to ~80 min and –650 nT, respectively. Approximately the same intensity was obtained for substorms of types 1 and 3, which contradicts the report by Hsu and McPherron (2004), who came to the conclusion that the substorms triggered by the northward turn of IMF are systematically stronger than the untriggered ones. According to Morley and Freeman (2007), such a difference in the intensity of substorms can be simply explained by the fact that, in the data used by Hsu and McPherron (2004), the mean value of the *Bz* component of the IMF before the start of the expansive phase of triggered substorms was –3.5 nT, while it was –2.5 for untriggered ones. Thus, one may expect that the intensity of substorms of both types will be approximately the same under the same values of the *Bz* component of IMF and all other conditions being equal.

For substorms during $Bz < 0$, the mean duration of substorms, including the expansion and recovery phases, is on average 30 min longer than that of substorms associated with the northward turn of IMF. For type 1 substorms exhibiting a negative *Bz* component of the IMF during the expansion phase, such a difference may be caused by an additional input (release) of solar wind energy to the magnetosphere (ionosphere).

A substantial number of events in which no substorm magnetic activity was observed in the auroral zone after a long (>30 min) period of the southward IMF and a following sharp turn of the *Bz* component of IMF to the north were detected. These observations, as well as the presence of a substantial number of substorms developing under $Bz < 0$, suggest that the northward turn of IMF is neither a necessary nor sufficient condition for substorm generation.

In a certain sense, the results of this study support the conclusions made by Wild et al. (2009) and Newell and Liou (2011) that a starting increase in the solar-wind activity is actually required for substorms and there is no evidence of the presence of external triggering. It is reasonable to consider infrequent coincidences of the northward turn of IMF with the beginning of the expansive phase of a substorm as occasional events. Along with this, there is no evidence that external triggering cannot manifest itself in any circumstances. We do not exclude that, if the solar wind activity is sufficient and the magnetosphere is in the presubstorm state, a northward turn of *Bz* together with the changes in the other parameters of IMF and solar-wind plasma may favor substorm generation. Of the 59 type 1 substorms developing at the IMF component $Bz < 0$, four began simultaneously with the enhancement of the dynamic pressure of the solar wind (P_{dyn}), three substorms began when the *By* component of IMF turned from negative values to positive ones, two substorms began when this IMF component turned from positive values to negative ones, and one substorm began at a sharp fall of P_{dyn}.

The magnetosphere state allowing external triggering can be compared to the effect of "an overfull cup." The water in a glass is above the level of its upper edge but does not spill and is kept by the surface tension force. Water may be spilt by both additional one or two liquid drops (an additional energy input to the magnetosphere) or any, even insignificant, external action.

The difference in the morphology of substorms of types 1 and 3 is indirectly confirmed by the different character of the interrelation of the processes of loading and unloading of the magnetosphere in substorm periods. For type 1 substorms, the best correlation is observed when the energy dissipation during a substorm is compared to the energy input during all of its phases—the growth, expansive, and recovery phases. At the same time, there is no connection between the energy that came during the growth phase of a substorm and the release of energy during its expansive phase. This is apparently caused by the fact that, for type 1 substorms, the solar wind energy continuously comes (releases) to the magnetosphere (ionosphere) during the whole interval of the negative *Bz* component of IMF.

For type 3 substorms with an expansive phase that develops at the IMF component $Bz > 0$, somewhat higher correlation coefficients are observed between the energy inflow during the growth phase and the energy outflow during the expansive phase. In the recovery phase of type 3 substorms, the additional energy (the amount depends on the energy state of the magnetosphere in this period) is probably spent.

The largest correlation coefficients between the processes of loading and unloading of the magnetosphere were obtained with the function suggested by Newell et al. (2007). It was observed that the simple function VB_S yields a high correlation coefficient, which may indicate an important role of the solar wind velocity in the processes generating the substorm activity.

6. CONCLUSIONS

The characteristics of isolated substorms selected by variations in the 1-min values of the *AL* index were analyzed. To select the substorms, we used special criteria allowing the substorm activity to be distinguished from the convective (Sergeev, 1977; Pytte et al., 1978) and compressive (Liou et al., 2004) magnetic bays.

According to the behavior of the *Bz* component of the IMF in the period preceding moment T_0, the substorms were divided into several types. In total, 112 substorms satisfying the criteria formulated for substorm selection were chosen for the winter seasons of 1995–2012.

The substorms were divided into several types with respect to the behavior of the *Bz* component of the IMF in the expensive phase. The substorms with an expansion phase developed at the southward IMF orientation were observed with the highest probability (~53%). At the same time, the amount of registered substorms with an onset associated with a northward IMF turn was only ~19%. In a number of scientific researches, these are referred to as untriggered and triggered, respectively. The other substorm types and their characteristics are described in section 3 and Table 1.

We detected a substantial number of events in which no substorm magnetic activity was observed in the auroral zone after a long (>30 min) period of southward IMF and a subsequent sharp turn of the *Bz* component of IMF to the north. The data suggest that the northward IMF turn is a neither necessary nor sufficient condition for substorm generation. It is reasonable to considered the infrequent coincidences of the northward turn of IMF and the onset of a substorm expansion phase as occasional events. However, there is no clear proof that external triggering cannot manifest itself in any circumstances. We do not exclude that, if the solar wind activity is sufficient and the magnetosphere is in the presubstorm state, a northward turn of *Bz,* equally with the changes in the other parameters of IMF and solar wind plasma, may favor substorm generation.

It has been shown for triggered and untriggered substorms that the mean duration of the southward IMF before moment T_0 and the mean intensity of the magnetic perturbation in the maximum are approximately the same and amount to ~80 min and –650 nT, respectively. However, for substorms at $Bz < 0$, their mean duration, including the expansive and recovery phases, is on average 30 min longer than that after a northward IMF turn.

Correlations between the processes of loading and unloading of the magnetosphere in the periods of magnetospheric substorms were studied with different functions determining the efficiency of the energy transfer from the solar wind to the magnetosphere. It has been shown that the highest correlation coefficient ($r = 0.84$) is observed when the function suggested by Newell et al. (2007) is used. It has been detected that the simple function VB_S (where V is the solar wind velocity and B_S is the southward component of IMF) yields a high correlation coefficient ($r = 0.75$).

ACKNOWLEDGMENTS

The study was supported by the Presidium of the Russian Academy of Sciences (Programs 7). The data on the parameters of IMF, solar wind plasma, and the level of magnetic activity were taken from the web-sites http://wdc.kugi.kyoto-u.ac.jp/ and http://cdaweb.gsfc.nasa.gov/.

REFERENCES

Akasofu, S.-I., The development of the auroral substorm, *Planet. Space Sci.*, 1964, vol. 12, no. 4, pp. 273–282.

Akasofu, S.-I., *Polar and Magnetospheric Substorms*, Dordrecht: D. Reidel, 1968.

Feldstein, Y.I. and Starkov, G.V., Dynamics of auroral belt and polar geomagnetic disturbances, *Planet. Space Sci.*, 1967, vol. 15, no. 2, pp. 209–229.

Frey, H.U., Mende, S.B., and Angelopoulos, V., Substorm onset observations by IMAGE-FUV, *J. Geophys. Res.*, 2004, vol. 109, A10304. doi 10.1029/2004JA010607

Gallardo-Lacourt, B., Nishimura, Y., Lyons, K.R., and Donovan, E., External triggering of substorms identified using modern optical versus geosynchronous particle data, *Ann. Geophys.*, 2012, vol. 30, pp. 667–673. doi 10.5194/angeo-30-667-2012

Henderson, M.G., Reeves, G.D., Belian, R.D., and Murphree, J., S., Observations of magnetospheric substorms occurring with no apparent solar wind/IMF trigger, *J. Geophys. Res.*, 1996, vol. 101, no. A5, pp. 10773–10791.

Hsu, T.-S. and McPherron, R.L., Average characteristics of triggered and nontriggered substorms, *J. Geophys. Res.*, 2004, vol. 109, A07208. doi 10.1029/2003JA009933

Kallio, E.I., Pulkkinen, T.I., Koskinen, H.E.J., et al., Loading-unloading processes in the nightside ionosphere, *Geophys. Res. Lett.*, 2000, vol. 27, no. 11, pp. 1627–1630.

Liou, K., Newell, P.T., Meng, C.-I., Wu, C.-C., and Lepping, R.P., On the relationship between shock-induced magnetic bays and solar wind parameters, *J. Geophys. Res.*, 2004, vol. 109, A06306. doi 10.1029/2004JA010400

Lyons, L.R., A new theory for magnetospheric substorms, *J. Geophys. Res.*, 1995, vol. 100, no. A10, pp. 19069–19082. doi 10.1029/95JA01344

Lyons, L.R., Substorms: Fundamental observational features, distinction from other disturbances, and external triggering, *J. Geophys. Res.*, 1996, vol. 101, no. A6, pp. 13011–13026. doi 10.1029/95JA01987

Lyons, L.R., Blanchard, G.T., Samson, J.C., Lepping, R.P., Yamamoto, T., and Moretto, T., Coordinated observations demonstrating external substorm triggering, *J. Geophys. Res.*, 1997, vol. 102, no. A12, pp. 27039–27051.

McPherron, R.L., Growth phase of magnetospheric substorms, *J. Geophys. Res.*, 1970, vol. 75, no. 28, pp. 5592–5599.

McPherron, R.L., Russell, C.T., and Aubry, M.P., Satellite studies of magnetospheric substorms on August 15, 1968: 9. Phenomenological model for substorms, *J. Geophys. Res.*, 1973, vol. 78, no. 16, pp. 3131–3149.

Morley, S.K. and Freeman, M.P., On the association between northward turnings of the interplanetary magnetic field and substorm onsets, *Geophys. Res. Lett.*, vol. 34, L08104. doi 10.1029/2006GL028891

Newell, P.T., Sotirelis, T., Liou, K., Meng, C.-I., and Rich, F.J., A nearly universal solar wind–magnetosphere coupling function inferred from 10 magnetospheric state variables, *J. Geophys. Res.*, 2007, vol. 112, A01206. doi 10.1029/2006JA012015

Nishimura, Y., Lyons, R.L., Zou, S., and Angelopoulos, V., Substorm triggering by new plasma intrusion: THEMIS all sky imager observations, *J. Geophys. Res.*, 2010, vol. 115, A07222. doi 10.1029/2009JA015166

Pytte, T., McPherron, R.L., Hones, F.W.Jr., and West, H.I., Multiple-satellite studies of magnetospheric substorms: Destination between polar magnetic substorms and convection-driven magnetic bays, *J. Geophys. Res.*, 1978, vol. 83, no. 2, pp. 663–679. doi 10.1029/JA083iA02p00663

Sergeev, V.A., On the state of the magnetosphere during prolonged period of southward oriented IMF, *Phys. Solariterr. Potsdam*, 1977, vol. 5, pp. 39–48.

Starkov, G.V. and Fel'dshtein, Ya.I., Auroral substorms, *Geomagn. Aeron.*, 1971, vol. 11, no. 3, pp. 563–565.

Troshichev, O.A., Lukianova, R.Yu., Papitashvili, V.O., Rich, F.J., and Rasmussen, O., Polar cap index (PC) as a proxy for ionospheric electric field in the near-pole region, *Geophys. Res. Lett.*, 2000, vol. 27, no. 23, pp. 3809–3812. doi 10.1029/ 2000GL003756

Vorobjev, V.G. and Yagodkina, O.I., Empirical model of auroral precipitation power during substorms, *J. Atmos Sol.–Terr. Phys.*, 2008, vol. 70, pp. 654–662. doi 10.1016/j.jastp.2007.08.046

Wild, J.A., Woodfield, E.E., and Morley, S.K., On the triggering of auroral substorms by northward turning of the interplanetary magnetic field, *Ann. Geophys.*, 2009, vol. 27, pp. 3559–3570.

Translated by E. Petrova