ISSN 0016-7932, Geomagnetism and Aeronomy, 2008, Vol. 48, No. 2, pp. 165–174. © Pleiades Publishing, Ltd., 2008.
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Nature of Sudden Auroral Activations at the Beginning of Magnetic Storms

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Received May 16, 2007

Abstract—Certain large magnetic lays, registered by magnetometers in the auroral and subauroral zones simultaneously with SC instant and accompanying events, substantially differ from activations at the beginning of auroral substorm. Such basic substorm elements as energy accumulation during the growth phase and breakup—activation in the localized region near midnight—are absent. During such sudden auroral activations (SAs), a disturbance begins in a wide sector of longitudes and latitudes. It is proposed to combine SAs into an individual class of magnetospheric disturbances. The particle acceleration and injection mechanism, which causes SAs, is considered.

PACS numbers: 94.30.Lr; 94.20.Qq

DOI: 10.1134/S0016793208020059

1. INTRODUCTION

Studying magnetospheric substorms is still far from being finished; however, several characteristic substorm elements have been established reliably. Energy accumulation in the magnetosphere, related to an enhancement of a large-scale electric field and to a reconfiguration of the magnetosphere, is such an obligatory element. Magnetic field lines on the nightside of the Earth stretch antisunward, and an enhanced convective electric field causes particles in the central plasma sheet to move toward the Earth and heats these particles; thus, the store of the magnetic and kinetic energies increases. The magnetosphere becomes unstable, and the substorm growth phase is replaced by the development of instability, magnetic field dipolarization, appearance of a current wedge, auroral brightening, and energetic particle acceleration during a relatively prolonged (20–40 min) period of accumulation. These processes continue for 1–2 min in a narrow localized sector of the auroral magnetosphere from 2200 to 0200 MLT. Only subsequently, during the expansion phase, the disturbance region expands along latitude and longitude.

These main substorm elements are absent in disturbances during sudden commencement (SC) of certain strong magnetic storms: energy is not accumulated, and disturbance is not localized and begins simultaneously from the midnight to dawn sectors. Nevertheless, these disturbances are usually considered among magnetospheric substorms owing to large magnitudes of magnetic bays. Yamauchi et al. [2004] for the first time noted that disturbances were unusual at the beginning of the magnetic storm of October 29, 2003. Subsequently, Lazutin [2006] assumed that this unusual disturbance is independent of substorm activation and results from the precipitation of particles accelerated during their $E \times B$ injection toward the Earth. The virtual conference on magnetic storms was held in the Internet in November 2006. In the course of this conference, several researchers (including the authors of the present work) contended that such disturbances differ from substorms and proposed to combine these disturbances into an individual class: sudden auroral activations. We should note that the existence of two types of bursts during SC was referred to in the earlier works on auroral absorption [Osepyan, 1983, 1984; Lazutin et al., 1973]: SC impulse triggers substorm in some cases, and substorm is not observed in other cases. These cases of auroral electron precipitation without previous energy accumulation in the magnetosphere belong to SAs considered in the present work.

Here, we present arguments for such an identification of SAs as individual phenomena and propose the possible explanation of the processes proceeding during SAs. We assume that researchers will continue studying the processes proceeding at the beginning of strong magnetic storms (specifically, the work [Kozyreva and Kleimenova, 2007] already appeared), and the remaining confusion between SAs and substorms causes unnecessary complications.

2. ANALYSIS OF MEASUREMENTS

2.1. October 29, 2003

An extreme magnetic storm of October 29–31, 2003, was considered in detail in many works (see, e.g. [Panasyuk et al., 2004]); therefore, we only summarize

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[†] Deceased.

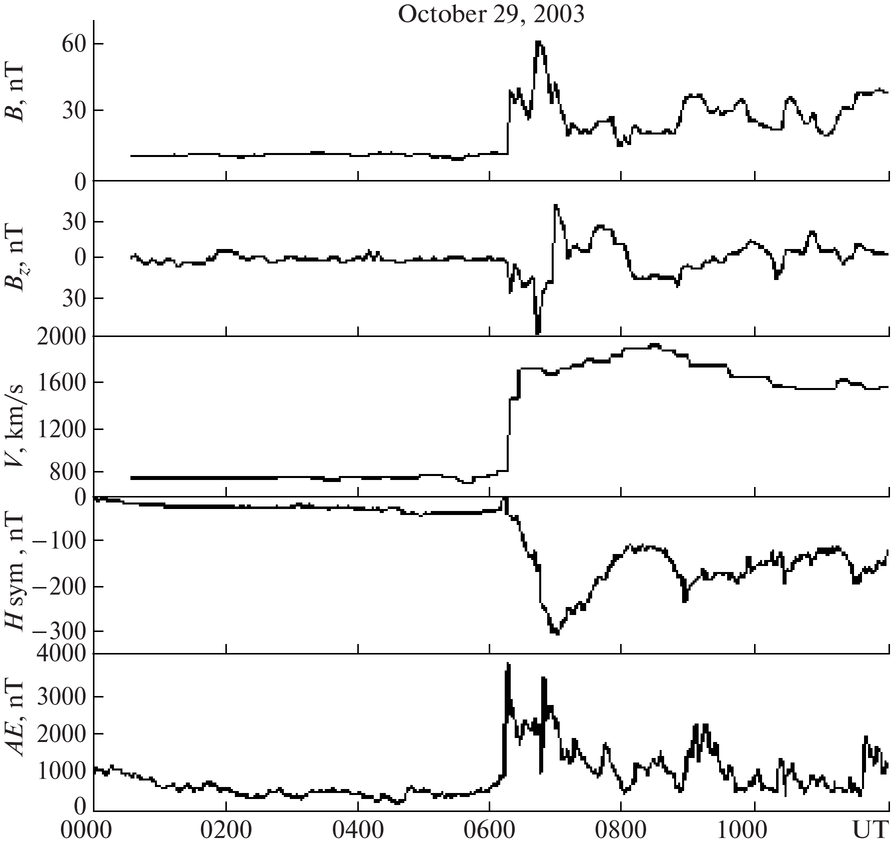

Fig. 1. The solar wind and magnetic disturbances on October 29, 2003.

the data on the solar wind (see Fig. 1). We should note that, at the SC instant, the solar wind velocity suddenly changed simultaneously with a southward turning of B_z and with an increase in the *Ae* index of magnetic activity.

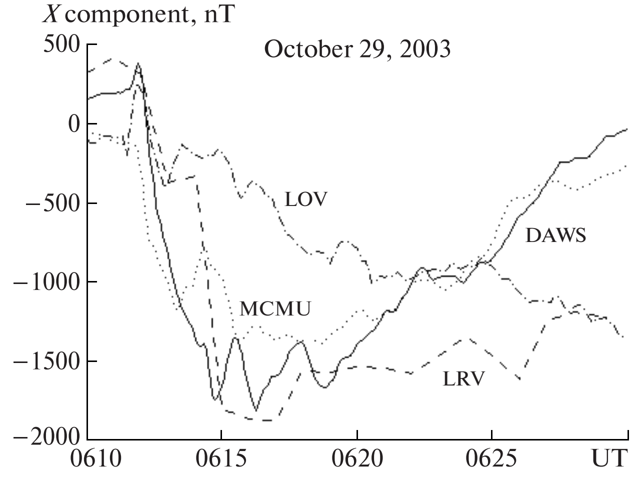

Fig. 2. Magnetograms of the auroral zone for October 29, 2003.

Figure 2 shows the rate of an increase in magnetic activity and presents the *H* components of the magnetograms from four stations in the auroral zone during SC at 0612 UT on October 29, 2003. The coordinates of all stations used in the work are given in table. A minute later, the negative disturbance was not less than 400 nT at all stations; 2 min later, this disturbance was larger than 1000 nT at two stations. We should note that substorm activity was high 10–12 h before SC but decreased during the last 6 h, which can be identified as a substorm recovery phase.

Figure 3 presents four IMAGE satellite photographs. A comparison of the first and second photographs, taken before SC, and the third photograph, made 2 min later, when all magnetograms already demonstrated that the deviation was larger than 400 nT, indicates that only the luminosity brightness changed, and the shape and position of auroras remained unchanged. It is interesting that a typical breakup—a localized burst of auroras not only in the midnight sector but also at other longitudes of the nightside oval—was absent. Only the fourth photograph shows a certain local brightening near midnight, which can be associated with breakup. An extensive bay on the Lovozero magnetogram indicates that substorm actually started developing beginning from that instant. However, a synchronous decrease in the *H* component, which was observed during several minutes after SC and indicates that particles precipitated into the ionosphere, was not related to this substorm but possibly prepared this phenomenon.

An increase in the fluxes of electrons and protons was registered on several LANL geostationary satellites, and a detailed consideration indicates that a disturbance impulse moved from the dayside to the nightside. Figure 4 presents the plots of electron enhancement in the channels (~40 keV) of six satellites; left-hand numerals indicate the local time of the sector where a satellite was located. In addition to the above time shift of the SC effect, the velocity of which approximately corresponds to that of the solar wind that flowed around the Earth's magnetosphere, it is also evident that the enhancement amplitude was maximal in the morning hours. This agrees with the fact that the maximal brightening of auroral was observed in the morning hours. An enhancement was absent in the dusk sector.

2.2. July 27, 2004

Before magnetic storm SC at 2249 UT on July 26, 2004, the solar wind velocity (*V*) was about 600 km/s, dynamic pressure (*P*) varied within 1–2 nPa, IMF *B* was lower than 5 nT, and B_z was close to zero (Fig. 5). After SC, the solar wind velocity increased to 900 km/s, dynamic pressure increased insignificantly, magnetic field abruptly increased to 20 nT, and IMF B_z strongly fluctuated and was mainly negative. Such solar wind characteristics remained to 0300 UT on July 27, when the solar wind pressure strongly changed. We assume that SC was caused by the shock front; the Earth was in the transition region until 0300 UT and entered into a coronal mass ejection (CME) only at 0300 UT.

Before SC, the IMF B_z component was positive; i.e., the substorm growth phase was absent, and magnetic conditions were quiet. During SC, the magnetograms from the auroral and subauroral stations indicated the beginning of a sharp bay. Figure 6, where the *H* components of the magnetograms from three stations are presented, indicates that the negative burst minimum was reached 2–4 min after SC. The minimal value (800 nT) was registered in the dawn sector. In going to the dayside sector (Tixie Bay, 0700 LT; data are not presented), the negative bay was not more than 50 nT. SA was also not observed at Vize Island station, located in the dawn sector but at higher latitudes than Dixon Island station. Without a thorough analysis, this bay-like disturbance could be associated with substorm; however, the above circumstances allow us to classify this disturbance as SA.

Coordinates of used observatories

Name of observatories		Geographic longitude	Corrected geomagnetic latitude
Cape Chelyuskin	CCE	104.28	71.6
Vise Island	VIZ	77.0	73.6
Dixon Island	DIK	80.56	68.3
Tixie Bay	TIK	128.9	65.6
Lovozero	LOV	33.05	64.2
McMurdo	MCMU	248.8	64.7
Dawson	DAWS	220.9	65.7
Kiruna	KIR	20.42	64.7
Leirvogur	LRV	338.3	65.3
Narsarsuaq	NAR	314.5	66.1
Port Balein	PBQ	282.2	66.4
Kakioka	KAK	140.2	28.9

We also note that all stations registered a positive deviation of the magnetic field *H* component immediately after SC. Solovyev et al. [2003, 2006] indicated that the global reconfiguration of the current systems is observed during SC, and the local direction of the electrojet in the dawn sector is often eastward. The above examples indicate that, in the cases when SC causes an SA-type disturbance, the following electron

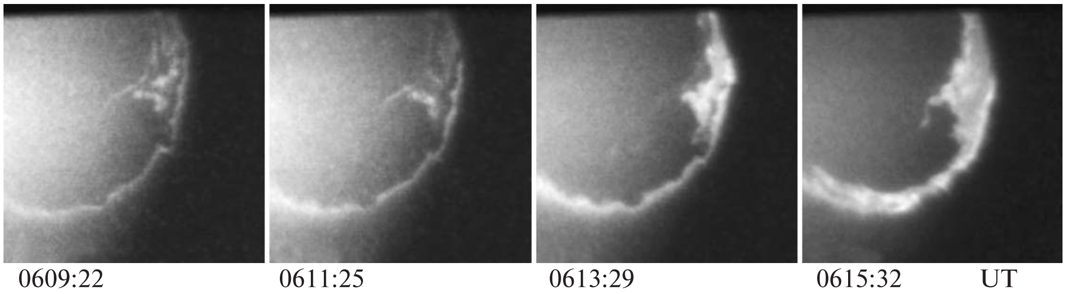

Fig. 3. The IMAGE photographs of auroras before and after SC that occurred at 0612 UT on October 29, 2003.

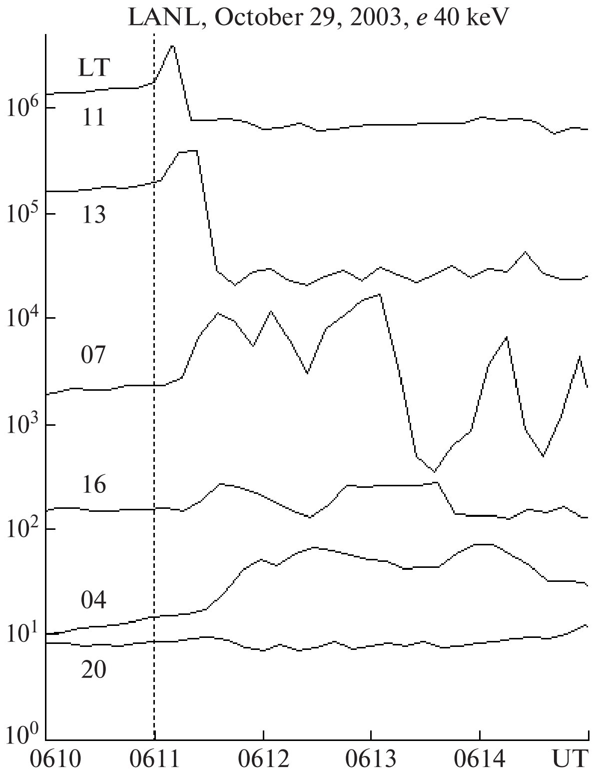

Fig. 4. The SC effect in the first electron channels (50 keV) of the LANL satellites. Numerals on the left indicate the local time of the satellite position.

precipitation also results in the development of the westward electrojet.

2.3. January 21, 2005

Figure 7 presents the variations in the solar wind characteristics and geomagnetic activity indices before and after SC at 1711 UT on January 21, 2005. An increase in the solar wind velocity and pressure and the southward turning of B_z cause an abrupt bay-like disturbance with the *Ae* index larger than 2000 nT. The absence of a pronounced previous magnetic activity also allows us to consider this event among SA-type disturbances.

2.4. May 15, 2005

An extremely large magnetic storm of May 15, 2005, had a complex time history. Two successive solar flares generated shocks that run one after another. As a result, the first SC at 0230 UT was followed by the 4-h period of a disturbed solar wind with a rapidly varying structure of the magnetic field and by a new pressure pulse at 0615 UT and transition of IMF B_z to negative values. Magnetic disturbances, registered at the global network of magnetometers, also had a rather complex structure. A disturbance at the SC instant, which is considered among SAs, began at 0230 UT and was characterized by a sharp bay in the magnetic field *H* component at the noon and morning meridians (for more detail, see [Kozyreva and Kleimenova, 2007]). This event was also characterized by an increase in the solar wind velocity and pressure without a substantial change in the B_z component.

The second shock approached the Earth at about 0600 UT and caused a powerful substorm disturbance, which is called super-substorm by some researchers. It is quite possible that the effects typical of SA were also observed here; however, it is difficult to detect these effects in a pure form. The IMAGE satellite photographs of auroras demonstrated a localized auroral brightening near midnight, which was very similar to breakup. This allows us to doubt once again that this disturbance was related to SA.

Several opinions about unusual disturbances observed on May 15 were expressed during the virtual conference on super-substorms held in November 2006 [*Super-substorm* ...]. Echer et al. [2006] characterized the disturbance that occurred at 0230 UT as a usual substorm triggered by SC and the event observed at 0620 UT as a super-substorm coincident with the superstorm. These researchers assumed that a search for the trigger of this superstorm indicate that this event was caused by a rapid change in pressure or B_z.

According to Kozyra et al. [2006], the super-substorm began at 0942 UT and continued to 1130 UT, i.e., during the storm main phase (at a maximum). The third viewpoint [Lyons et al., 2006] coincides with our opinion. These researchers distinguished the class of “not substorms,” caused by a dynamic pressure impact, and considered that the disturbance that occurred at 0230 UT belong to this class. The authors assume that the signatures of dynamic pressure disturbances are the absence of the preparation period, as a result of which a substorm is triggered, and a global enhancement of auroral activity and the DP2 current system without additional brightening in the region of the Harang discontinuity and without a substorm current wedge.

In contrast to the cases considered above, when the pressure jump was accompanied by the formation of the negative B_z values, these two phenomena can be separated for the event of May 15, 2005. The first disturbance (at 0230 UT) occurred without a change of sign of the IMF vertical component, and we can state that all SA effects were caused only by a sudden change in the solar wind dynamic pressure.

2.5. March 24, 1991

At the instant of SC (0341 UT) of the magnetic storm that occurred on March 24, 1991, the CRRES satellite registered the appearance of newly accelerated electrons and protons at $L < 3$ [Blake et al., 1992], which was interpreted as an injection with accelera-

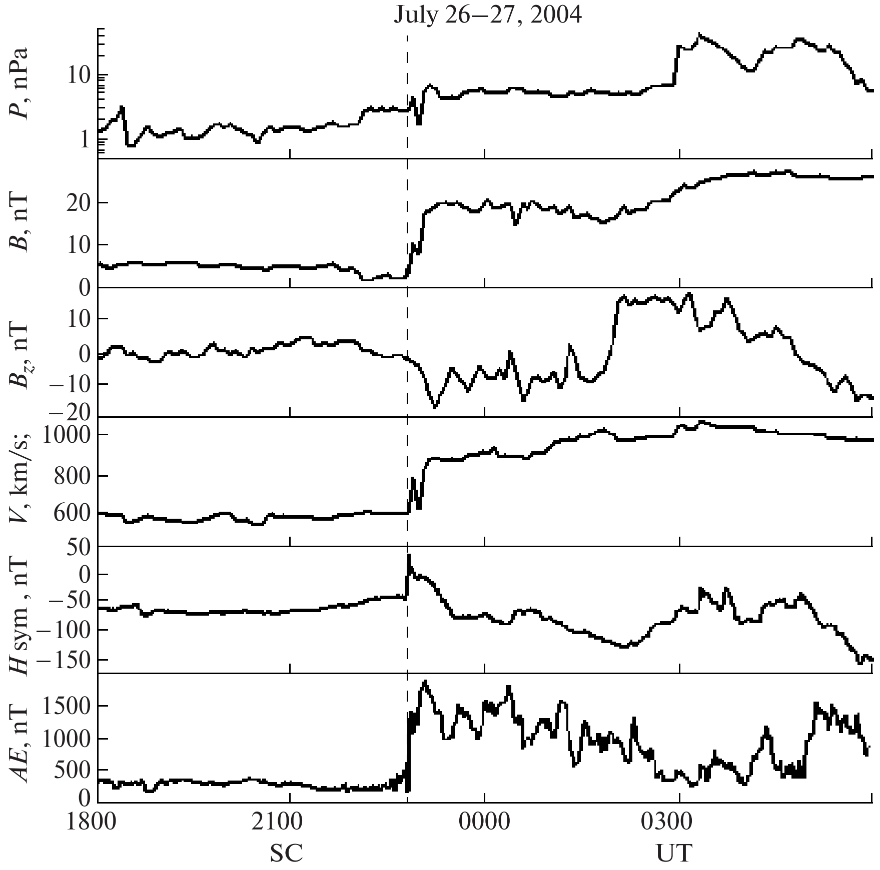

Fig. 5. The solar wind and magnetic disturbances on July 26–27, 2004.

tion caused by an induction field of the SC impulse. We can anticipate that the effect of the $E \times B$ drift of outer belt electrons, which results in an SA-class phenomenon, should also be observed in the auroral zone. Figure 9 demonstrates the magnetograms from four magnetic stations, obtained at the instant indicated above. We are sure again that, 2 min after SC, the negative deviation in the field H component reached 500–1400 nT at an absolutely undisturbed field during the previous hours and minutes.

3. DISCUSSION

A change in the solar wind dynamic pressure is considered as one of the main substorm triggers. Many researchers studied substorms triggered by an SC impulse. It was established that the substorm power depends on the duration of the previous period of energy accumulation in the magnetosphere: substorm triggering becomes easier and substorm power increases with increasing duration of the growth phase.

The present work considers the disturbances without a growth phase, when rapid changes in the solar wind during SC cause acceleration and injection of auroral particles, i.e., are the source of energy rather than a simple trigger of a disturbance. The SA effect is evident and is observed at ones during only a few number of events. A cursory review of the magnetograms from the auroral stations, obtained during SCs of the

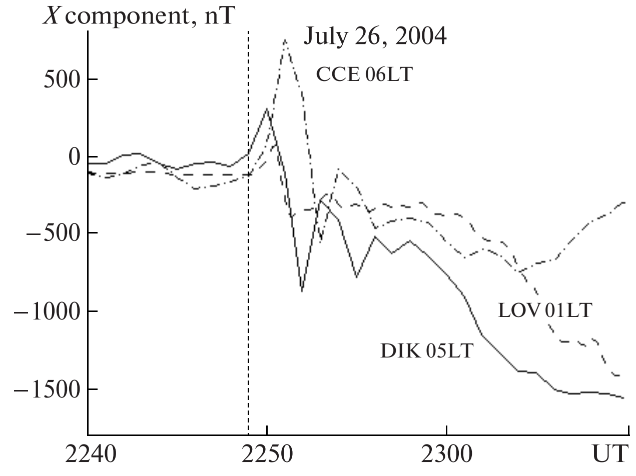

Fig. 6. Auroral station magnetograms for July 26, 2004.

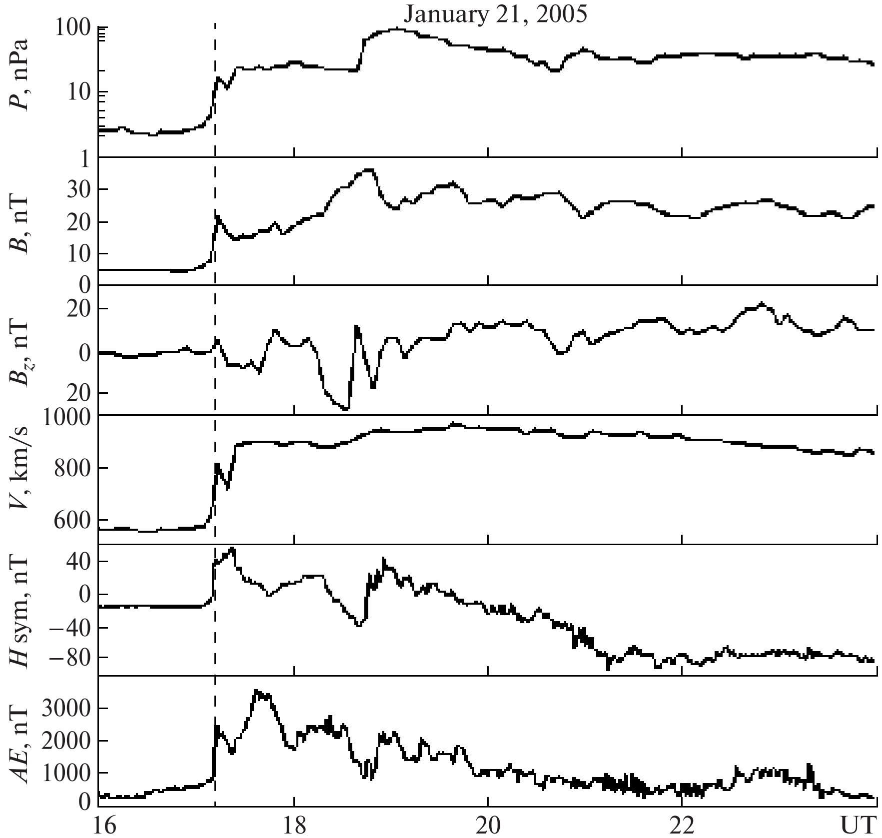

Fig. 7. The solar wind, *ASE*, and magnetic activity indices on January 21, 2005.

magnetic storms that occurred from August 2001 to June 2005, indicated that eight–ten (mainly very strong storms which are usually considered among extreme storms) of more than 50 moderate and strong storms (weaker than 100 nT) aroused suspicion.

If statistics is insignificant, it is difficult to precisely determine what SC type and combination of changes in the solar wind cause SA. Figure 10 presents the SC plots according to the magnetograms from Kakioka observatory. It is clear that the magnetic field changed differently after SCs of different storms because the solar wind characteristics were different when a disturbance approached the Earth. Shock appearance in the near-Earth space sometimes causes a short-term compression impulse. In other cases a shock is immediately followed by CME. The solar wind magnetic pressure also behaves differently. It is necessary to perform an additional analysis, using a larger data base, in order to distinguish the main disturbing parameters or their combinations.

It is natural to relate the acceleration mechanism to the appearance or enhancement of the electric field, associated with a rapid transition to large negative B_z values or with the field of SC induced by a magnetic impulse. The radial $E \times B$ shift of particles toward the Earth will cause betatron acceleration, which increases the transverse energy and Fermi acceleration of the particle velocity longitudinal component. Acceleration effects during radial drift have been repeatedly discussed since the 1970th in the model of rapid particle transfer from the magnetotail, where the substorm energy is supposedly accumulated and is released into the inner magnetosphere. It has become clear that the main acceleration processes proceed in the quasitrapping region, such a transfer is not required for large distances, but a certain $E \times B$ shift exists during dipolarization and makes an additional contribution to particle acceleration. Moreover, this effect apparently explains plasma heating in the central plasma sheet during the substorm growth phase.

The effects of energetic particle precipitation during the substorm growth phase were discussed as applied to the interpretation of increases in the auroral X-ray emission measured on balloons during this substorm phase. In contrast to impulsive bursts caused by injection of newly accelerated electrons with a soft energy spectrum, the energy spectrum of these increases was hard, and the precipitation character was sufficiently smooth, which was interpreted as the result of an additional acceleration of quasi-trapped electrons during radial transfer due to the $E \times B$ drift in a disturbed convection electric field [Lazutin, 1986].

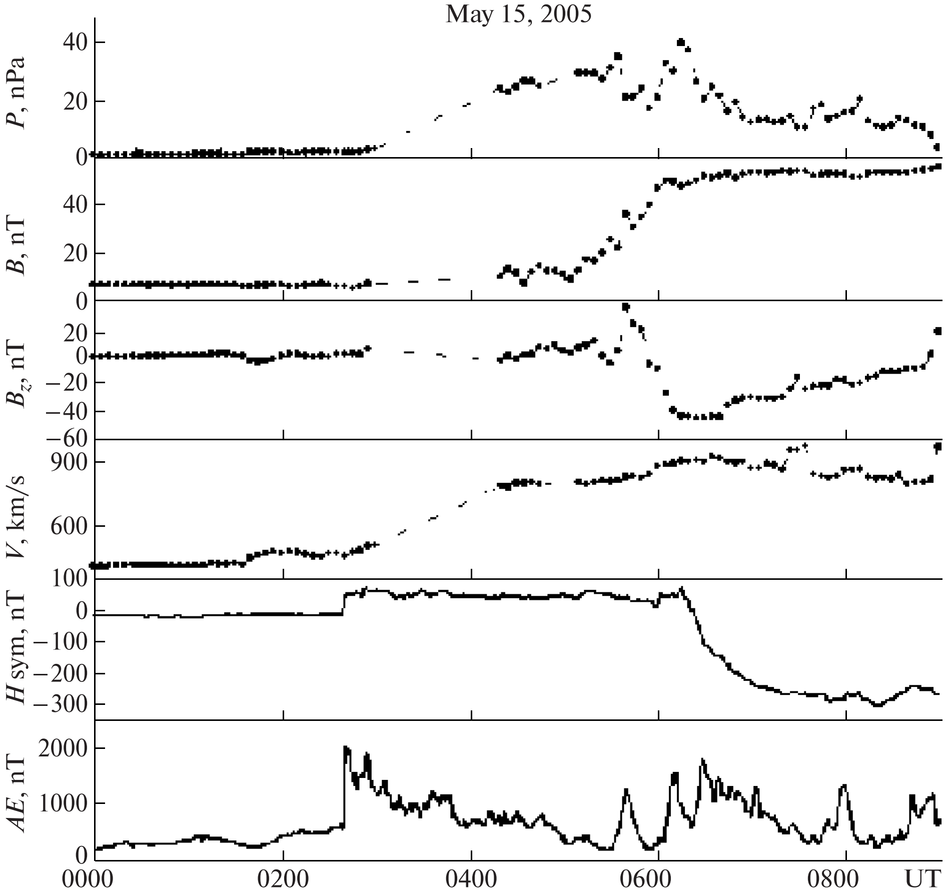

Fig. 8. The solar wind and magnetic disturbances on May 15, 2005.

One more allied class of phenomena is an additional acceleration of solar protons, registered by the ATS-1 geostationary satellite during SC at the beginning of the magnetic storm of November 20, 1968 [Lanzerotti et al., 1971]. A similar effect, which caused the replenishment of the inner proton belt during SC, was registered on the CRRES satellite on March 24, 1991 [Blake et al., 1992]. In the interpretation proposed in [Pavlov et al., 1993; Hudson et al., 1997], the leading role is assigned to the induction electric field, which is generated during SC. The effectiveness of this process depends on the particle energy and time parameters of a compression impulse. If the particle magnetic drift velocity is low, acceleration can be replaced by adiabatic cooling at an opposite impulse sign. After the event of March 1991, the effect was not observed in the explicit form; however, the cases of registration of additional fluxes of protons with energies of several MeV during and after strong magnetic storms are attributed to this effect.

Finally, enhancements of auroral absorption during SC, which were thoroughly studied by Osepyan [1983, 1984], are directly related to the considered class of phenomena. It was obtained that the absorption is related to precipitation of energetic electrons from the radiation belt outer shells under the action of magnetospheric compression, and the threshold ΔB values are ~40–50 and ~20–30 nT in the dayside and nightside sectors, respectively.

Thus, the radial transfer and acceleration of particles in the magnetosphere is a frequent phenomenon with rather diverse results and manifestations, which is natural since electric field sources, initial particle fluxes, and time and spatial characteristics of the processes are various. Considering again SAs, we should discuss the relationship between the contributions of Fermi and betatron accelerations to the generation of a precipitating electron flux. It is evident that Fermi acceleration immediately leads to an increase in a particle flux in the loss cone, which is maintained by the conservation of the second adiabatic invariant when particles go to shorter field lines. However, this mechanism is effective when particles are transferred from the region of field lines stretched far into the magnetotail on dipole lines. In the region of quasi-entrapment, where the main SA effect is observed, the field line length changes not so substantially as the magnetic field strength with decreasing distance to the Earth;

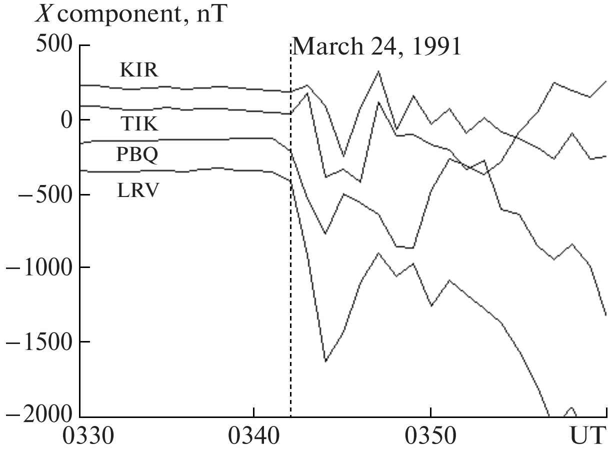

Fig. 9. Auroral station magnetograms (*H* component) for March 24, 1991.

therefore, acceleration of a betatron type plays the main role in this region. The flux of newly accelerated electrons evidently exceeds the Kennel–Petschek limit, and the regime of strong diffusion begins. An abrupt enhancement of wave activity, observed during SC on May 15, 2005, by Kozyreva and Kleimenova [2007], confirms this assumption. Lazutin et al. [2007] analyzed acceleration of auroral electrons at the substorm onset based on the CRRES satellite measurements. A bay-like disturbance with an amplitude of 400 nT was accompanied by an increase in the flux of electrons with an energy of 10–20 keV. Necessary acceleration was maintained by the betatron mechanism at a twofold change in the magnetic field strength. This gives us the lower limit of particle transfer during SC.

Electrons can be effectively accelerated only if an azimuthal electric field is generated or abruptly increases in the auroral magnetosphere. Two potential field sources exist: a large-scale electric field, caused by an increase in the IMF B_z component, and an induction field related to an impulse of magnetospheric compression by a shock.

In principle, both induction and convection fields can maintain the observed effect if a disturbance is suf-

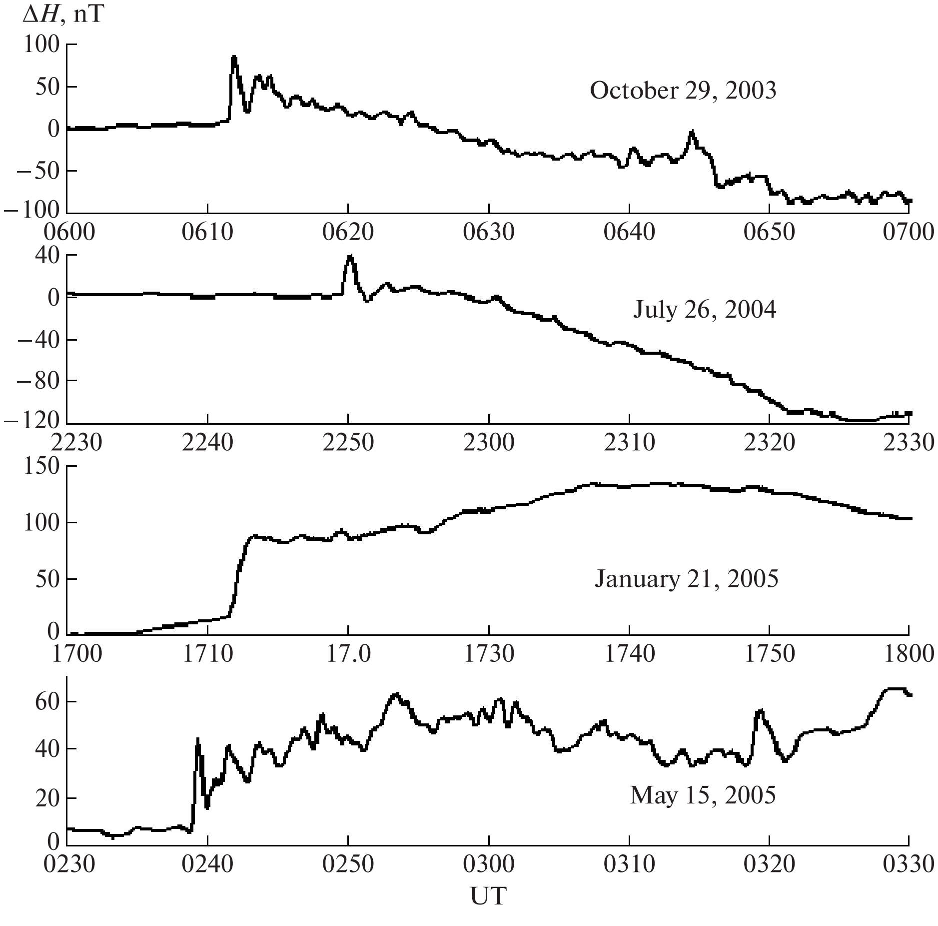

Fig. 10. Magnetograms from Kakioka observatory during certain SCs of magnetic storms for which sufficiently complete data on the solar wind are available.

ficiently powerful. It would be extremely important to separate the effect of these two sources. However, in the majority of the considered cases, such a separation is impossible because a joint action was observed, which possibly makes the effect stronger. In one case southward turning of B_z was not observed, so we can assume that injection and acceleration by a SC induction field can operate independently.

When separating SA as a specific phenomenon different from substorms, we should note that a normal substorm with poleward expansion develops immediately after SA. This is not surprising because IMF B_z always remains negative after SC too. Development of SA as if plays the role of a growth phase. Therefore, the following problem arises: when does the resultant electric field appear in the magnetosphere after the southward turning of B_z? If the electric field is generated as a result of untwisting of a convective plasma vortex, this process proceeds during not less than 10–15 min. If the appearance of the electric field is the instantaneous response to distortion of the magnetospheric structure [Antonova, 1981], the time of this appearance decreases to a minute. The development of a normal substorm with a prolonged growth phase does not make it possible to separate these two scenarios. The manner of the electric field appearance (instantaneous or gradual) is inessential for the development of convective transport. On the contrary, the entire process of SA proceeds for several minutes, and the following substorm active phase develops immediately after the previous phase; therefore, slow appearance of a convection electric field disagrees with observations.

4. CONCLUSIONS

Rapid changes in the solar wind parameters can trigger a magnetospheric substorm if the growth phase was observed previously; i.e., if the store of energy accumulated in the magnetosphere was sufficiently large. At the beginning of certain strong magnetic storms, the energy of sudden impulses is sufficient for SC to instantaneously cause considerable disturbances in the magnetic field and auroral luminosity without the preliminary phase of accumulation. One should not confuse these disturbances with substorms, convective disturbances, or super-substorms. According to the time and spatial characteristics and physical origin, these disturbances should be combined into the individual category called by us sudden auroral activations (SAs).

The main SA signatures are the absence of a previous substorm growth phase and rapid (during 1–3 min) development of a bay-like disturbance with the amplitude larger than 400 nT at the network of auroral and subauroral magnetometers in the wide midnight–dawn sector of the magnetosphere.

We propose to explain the observed disturbances by precipitation of electrons, accelerated during their rapid radial injection toward the Earth in the course of the $E \times B$ drift, from the region of quasi-entrapment. We assume that an impulsive electric field is generated when the IMF B_z sign changes from positive to negative or is induced by the impulse of compression of the Earth's magnetic field. It is necessary to perform additional studies in order to estimate the effectiveness of one or another effect or the combination of these effects.

ACKNOWLEDGMENTS

We are grateful to the staff of the geophysical observatories, the magnetic data from which were obtained on the AANII, PGI, CANOPUS, IMAGE, and WDC web-sites. We are also grateful to the LANL staff for presented data on fluxes of energetic particles.

This work was partially supported by the Russian Foundation for Basic Research, project no. 06-05-64225.

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