ISSN 0016-7932, Geomagnetism and Aeronomy, 2008, Vol. 48, No. 5, pp. 595–605. © Pleiades Publishing, Ltd., 2008.
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Comparative Analysis of Developed Substorm Breakup and Pseudobreakup

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Received August 28, 2007; in final form, January 28, 2008

Abstract—Pseudobreakup and substorm breakup are compared in two cases when these events followed each other at an interval of about an hour. Both ground-based measurements and data of satellite detectors of charged particles have been used. It has been indicated that pseudobreakups are characterized by a weak intensity of auroral activation and the field-aligned flux of low-energy electrons that caused this activation. In addition, the flux of energetic ions accelerated during pseudobreakup, and the energy of these ions are low as compared to these indicators at a substorm onset. Therefore, the above indicators are ineffective in creation of conditions for development of the following activation. At the same time, the flux of energetic electrons and the ionization degree are high, which results in a considerable release of energy stored in this sector.

PACS numbers: 94.30.Lr

DOI: 10.1134/S0016793208050046

1. INTRODUCTION

Pseudobreakups (PBs) were distinguished by Akasofu [1964] as weak substorms that began at a higher-latitude auroral arc than the equatorial arc. Davis and Hallinan [1976] considered PB among weak localized substorms. The following works mainly supported this viewpoint. At the same time, these and other researchers also indicate that PB is similar to breakup of a developed substorm in many signatures. McPherron [1991] noted that PB and breakup are accompanied by a train of Pi2 pulsations. Nakamura et al. [1994] detected magnetic field dipolarization and particle injection at ~6.6 R_E during PB. Koskinen et al. [1993] found that a very insignificant increase in the westward electrojet in the ionosphere during PB was accompanied by an enhancement of perpendicular fluxes of electrons with energies of 61–695 keV near the equatorial plane of the magnetosphere at ~8.7 R_E. These researchers noted that the considered PB occurred during the substorm growth phase. In addition, a low conductivity of the ionosphere could also be one of the causes of a limited disturbance development. Thus, many researchers are inclined to assume that PB is a weak substorm, and the main difference between PB and substorm breakup consists in that PB is not followed by expansion of a disturbed region and by development of a disturbance, which rapidly decays.

It is necessary to note that Kamide [1998] does not consider that PB is a weak substorm, He assumes that a weak substorm is weak because the energy, preliminarily accumulated during the substorm growth phase (specifically, in the form of a deviation from a stable configuration of the magnetosphere), is insufficient, whereas the PB energy is rather high, but an unknown mechanism suppresses further development of a disturbance. Thus, one term can characterize two types of disturbances: weak substorms (isolated activations of auroras), which are assumed to be PBs in several works, and PBs—special phenomena according to the Kamide [1998] definition.

The present work analyzes events of the second type. We will consider differences of PB from comparable part of a developed substorm. PB can evidently be compared with breakup, during which the substorm growth phase changes into the expansion phase. This is the set of several elementary events: localized short-term (lasting ~1–2 min) activations. The chain of these activations is summed up and composes the substorm expansion phase. It is clear that PB is a more elementary phenomenon than breakup. To all appearance, an isolated rather strong activation sometimes cannot generate the following activation and trigger expansion; such events belong to the class of PBs. We can list the following conditions hindering poleward (tailward) expansion of a disturbance:

(i) The energy stored before PB during the substorm growth phase is insufficient [Kamide, 1998].

(ii) A continued substorm growth phase (continued or enhanced large-scale convection) suppresses expansion.

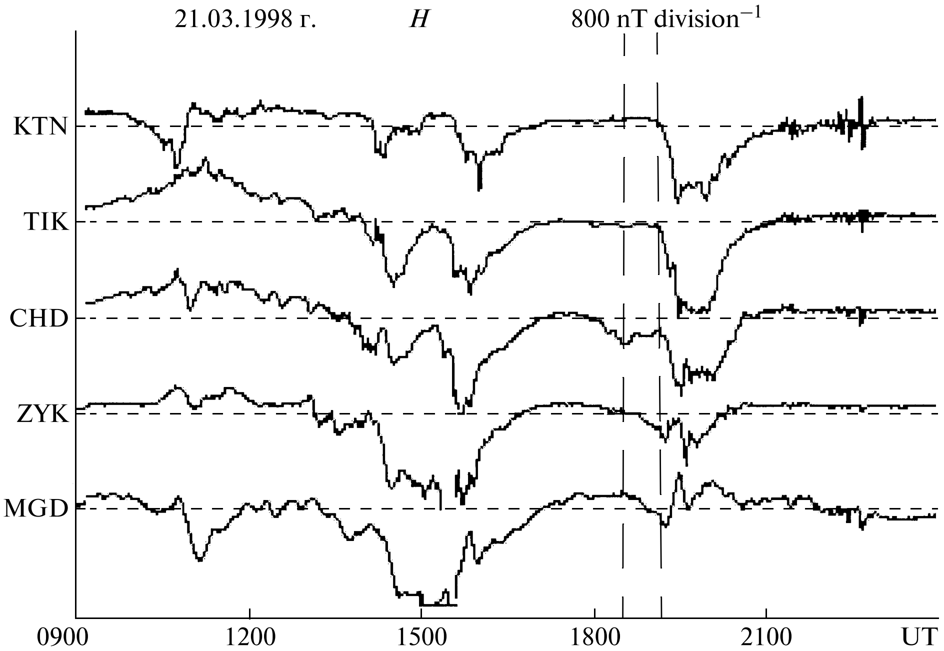

Fig. 1. Magnetograms from the ground-based stations obtained on March 21, 1998. From top to bottom: Kotelny (KTN, 69.9°, 201.0°), Tixie Bay (TIK, 65.6°, 196.9°), Chokurdakh (CHD, 64.7°, 212.2°), Zyryanka (ZYK, 59.6°, 216.8°), Magadan (MGD, 53.5°, 218.7°); geomagnetic coordinates.

(iii) The conditions of growth of the explosive instability can be locally satisfied but on a small scale. In such a case, the development of the instability will be stopped.

(iv) A low ionospheric conductivity and weak field-aligned currents [Koskinen et al., 1993; Aikio et al., 1999]. An increasing explosive instability can be suppressed if the ionosphere–magnetosphere system cannot be connected by field-aligned currents in order to form a substorm current wedge [Maynard et al., 1996; Pulkkinen, 1996; Erickson et al., 2000].

The observed fact that the expansion phase of a rather large number of substorms is initiated by and increase in large-scale convection (the B_z sign reversal) is an additional argument for the role of external conditions (i) and (ii) [Lyons et al., 2003]. The CRRES satellite studies of magnetospheric substorms made it possible to complete the known series of traditional breakup manifestations with new signatures. Specifically, several works indicated that injection of energetic particles is divided into electron and ion increases, apparently, of different origin [Kozelova et al., 1998; Lazutin et al., 2002; Lazutin and Kozelova, 2004]. In addition, a complex analysis of substorm activity, based on the ground network data and particle changes on CRRES, made it possible to conclude that an increase in energetic ions, leading magnetic field dipolarization, is related to the appearance of low-energy electron fluxes with anisotropy along magnetic field lines and can be of key importance in development of breakup instability [Lazutin et al., 2007a, 2007b]. Based on these additions to the general pattern of breakup development, we consider here two PB examples by using the magnetic data and auroras (the first example) and by analyzing the measurements of charged particle fluxes (the second example).

2. MEASUREMENTS OF FIELDS AND PARTICLES IN THE MAGNETOSPHERE AND ON THE EARTH

2.1. Substorm Activity on March 21, 1998

The event of March 21, 1998, was previously analyzed by Lazutin et al. [2001], who stressed on the substorm dynamics. These researchers indicated that PB was observed 40 min before the substorm (1835 UT) but did not analyze this phenomenon. Figure 1 illustrates the measurements of the magnetic field H component at several ground stations in the auroral zone. The substorm began at 1915 UT and was registered at all stations, whereas PB is observed as a weak local effect in the magnetic field only on the magnetogram of Chokurdakh station at the Yakutian chain. The POLAR satellite images of auroras (see Fig. 2) indicate that the response to PB had the form of auroral arc brightening, which was weak and local as compared to a powerful luminosity and expansion during the next substorm. At the same time, this weak and local activation, barely perceptible in the AE index, is accompanied by a powerful dipolarization effect in the magnetosphere at 6.6 R_E according to the behavior of energetic particles. Figure 3 illustrates the fluxes of auroral protons and electrons measured on two LANL satellites located at the 103.5°E (LANL084) and 69.8°E (LANL97a) meridians. Both satellites demonstrate dropout before PB: a decrease in particle intensity, indicating that drift shells are shifted due to stretching of magnetic field lines toward the magnetotail, which is typical of the substorm growth phase. The appearance of the satellite in the region of dropout is one of the main signatures of the substorm growth phase [Sauvaud and Winckler, 1980, Onsager et al., 2002]. Several minutes before PB, this decrease in the particle intensity accelerates, which is often observed before substorm breakup during the so-called effect of explosive growth phase [Ohtani et al., 1992].

PB is observed as a rapid withdrawal from dropout and particle flux recovery (but only on one satellite located in the eastern sector near local midnight, where PB was registered according to the ground magnetic data and auroras). Then, the substorm growth phase as if begins again in this local sector of the auroral zone. The second, western, satellite weakly responds to PB and does not leave dropout. The PB western edge only partially touches the meridian of the second satellite. Another pattern is observed at the substorm onset: recovery and acceleration of energetic particles is registered on both LANL satellites, which corresponds to the pattern of auroral activity in a wide longitudinal sector shown in the lower image of the POLAR satellite (Fig. 2).

An analysis of this PB makes it possible to state that the indications of weak substorm activation (localization along longitude, weak response in the ionosphere, absent expansion) are accompanied by substantial singularities: deep dropout before PB and rapid local dipolarization, withdrawal from dropout with recovery to a quiet state in this sector of the magnetosphere.

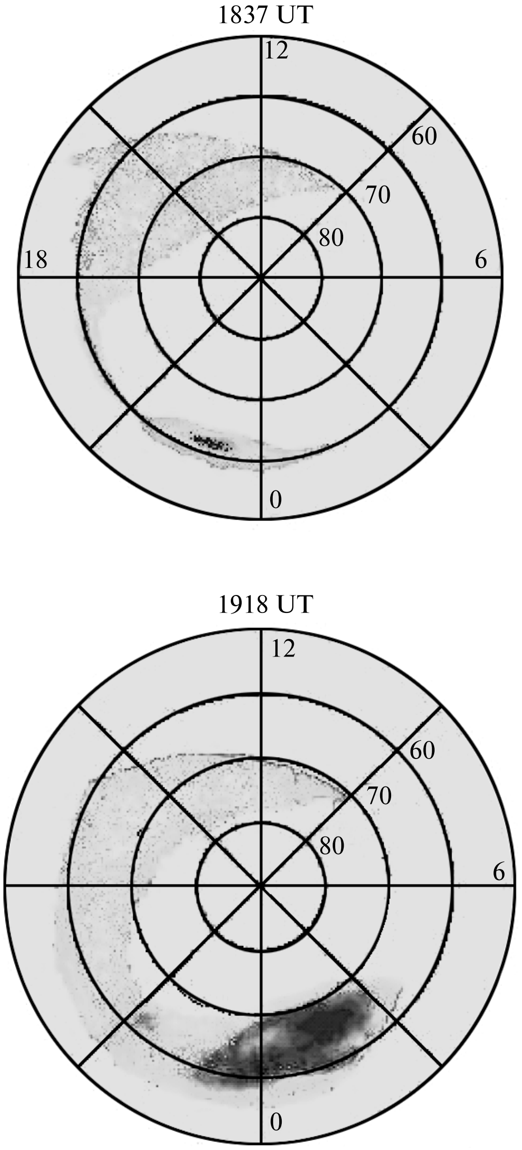

Fig. 2. Two POLAR auroral images (March 21, 1998) in coordinates magnetic latitude and magnetic local time (MLat, MLT): at 1837 UT during PB (top image) and at 1918 UT during substorm expansion (bottom image). The scale of intensities is conventional; gray color corresponds to the intensity lower than the intensity colored black by approximately two orders of magnitude.

2.2. PB and Substorm of January 24, 1991

One more comparison of PB with a full-value breakup is based on ground and CRRES satellite measurements performed on January 24, 1991, at 1600–1620 and 1657–1710 UT, respectively, when these two phenomena were observed at an interval shorter than an hour. The block of the LEPA satellite detectors measured fluxes of low-energy electrons and ions from 50–100 eV to 20 keV [Hardy et al., 1993]. The EPAS block operated in the low-energy range from several tens to several hundreds of kiloelectronvolts [Korth et al., 1992].

The main substorm with breakup at 1654 UT was analyzed in [Kozelova et al., 2002], but the aims of this analysis were different. The measurements of low-energy particles open up new possibilities. We also analyzed the behavior of energetic particles on the LANL-129 geostationary satellite at a longitude of 70°. CRRES was located at a longitude of 100° but closer to the Earth than LANL. The absence of energy dispersion in increases in electron and ion fluxes indicates that the disturbance epicenter was located at this meridian. Dixon Island observatory is located in the same longitudinal sector (80°).

Figure 4 presents the records of the *H* components at several magnetic stations in the auroral zone. A difference between two phenomena is clearly defined: breakup starts a prolonged disturbance with poleward expansion in a wide longitudinal region, whereas PB is registered only in the form of a short bay in a limited local sector in the region of Dixon Island. According

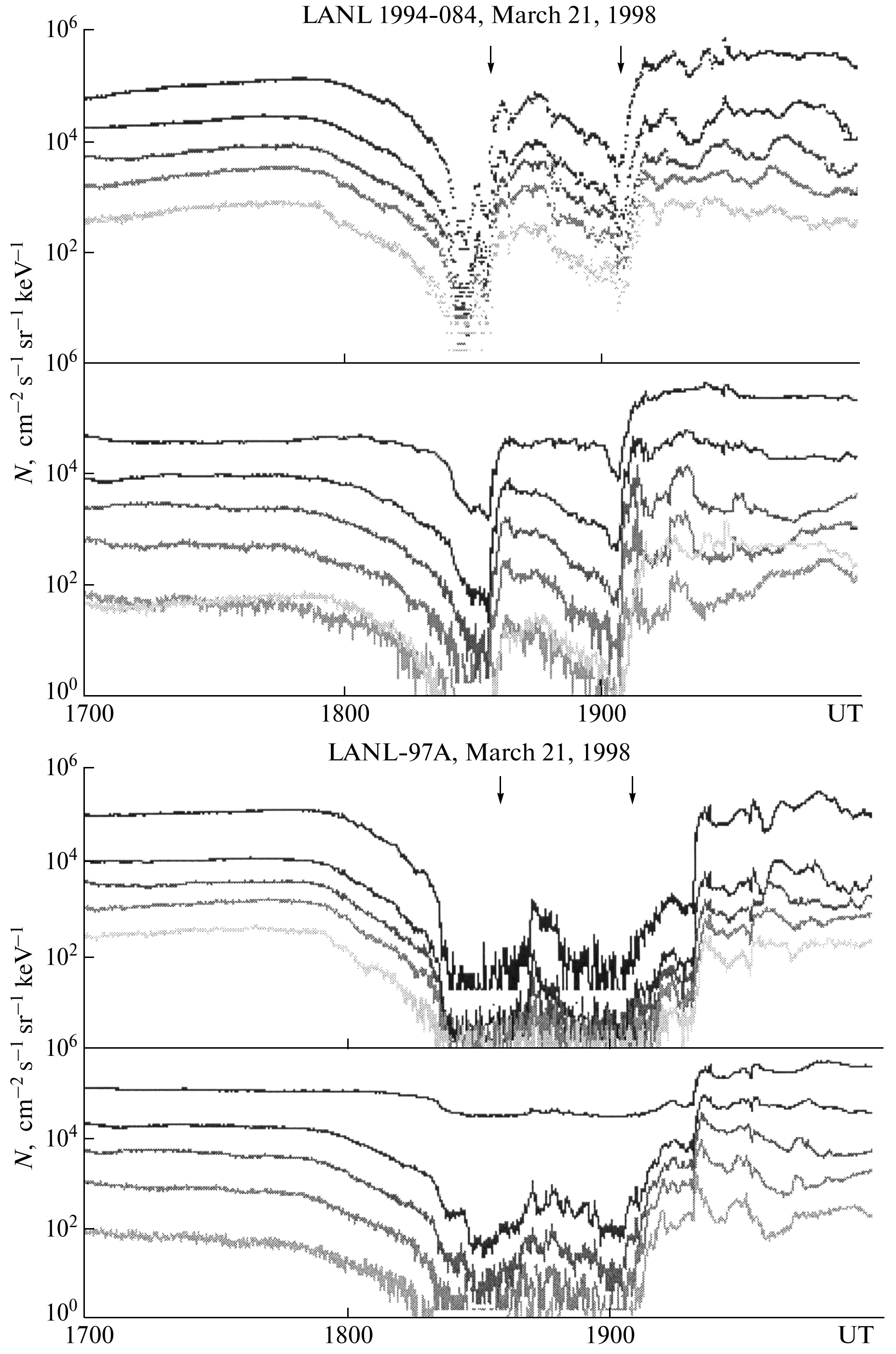

Fig. 3. Fluxes of electrons (upper panels) and protons (lower panels) on the LANL 1994-084 and LANL-97A satellites. From top to bottom: the electron energies are 50–75, 75–105, 105–150, 150–225, and 225–315 keV; the proton energies are 50–75, 75–113, 113–170, 170–250, and 250–400 keV.

to the IMP-8 data, the IMF B_z component was negative from 141- to 1640 UT (data are absent from 1640 to 1830 UT). Consequently, PB followed a rather developed growth phase, which, however, continued after PB. A magnetic bay related to PB started at 1605 UT and abruptly decayed after a maximum at 1610 UT. A disturbance related to breakup developed in several stages. The first stage was observed at 1653–1656 UT. A large amplitude of a magnetic bay on magnetograms of several stations and the same as in the

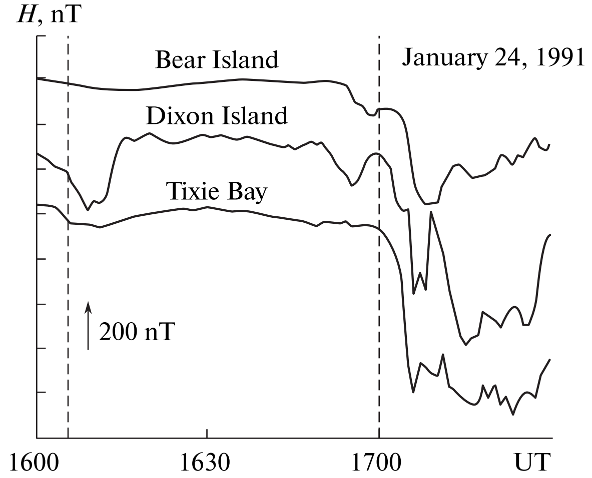

Fig. 4. Magnetograms from the auroral stations for January 24, 1991: Bear Island (71.56°, 108.1°), Dixon Island (73.5°, 80.6°), and Tixie Bay (65.6°, 196.9°).

first bay increase in the flux of energetic particles corresponded to the second intensification that began at 1700 UT.

Geostationary satellite observations. According to the LANL satellite data, the variations in the particle of energetic particles during PB of January 24, 1991, was almost identical to the patter shown in Fig. 3: rapid deep dropout began approximately 10 min before the onset of the explosive process and was followed by dipolarization and injection of energetic particles. Unfortunately, digital data of this satellite are absent. Figure 5 was taken from the site during the preview of data; although detailed structures are not observed, the time variations in dipolarization agree with the PB development according to the ground data. Electron flux recovery from dropout began at about 1602 UT and ended at ~1610 UT, which coincides with the magnetometer bay maximum at Dixon Island. Breakup of the main substorm developed according to the classical scheme with dropout and withdrawal from it during the same periods as was observed during ground-based measurements (at approximately 1652–1655 UT), after which several peaks of increases were registered. Subsequently, we will thoroughly consider the dynamics of energetic and low-energy electrons and ions and the magnetic field based on the CRRES data.

2.3. Measurements of Energetic Electrons

High-energy electrons are very sensitive to changes in the magnetic field in the auroral zone of the magnetosphere and, therefore, are good indicator of the substorm structure dynamics. Figure 6 presents the CRRES data on the time variations in the intensity of energetic electrons and the magnetic field during PB (left-hand panel) and the first minutes of substorm (right-hand panel), when the satellite was located at $L \sim 5.4$ and ~6.2, respectively. Increases of electrons with energies higher than 20 keV at 1600 and 1700 UT are comparable in intensity but are substantially different in structure.

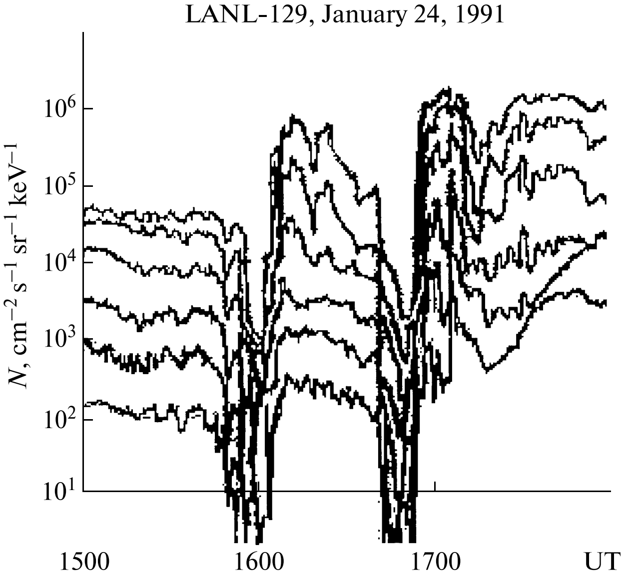

Fig. 5. Electron fluxes on LANL-129. From top to bottom: the electron energies are 30–45, 45–65, 65–95, 95–140, 140–200, and 200–300 keV.

Substorm developed as a complex disturbance with the cascade of activations and many particle bursts, and activations were related to the stages of the magnetic field dipolarization. After the first burst of electrons and the first stage of dipolarization, field lines stretch again toward the magnetotail, and the large-scale growth phase still continues and hinders expansion. However, the next bursts of particles and the field generally resulted in a larger-scale injection and dipolarization.

The structure of *pseudobreakup* in high-energy electrons on CRRES is not so complex. This structure is more smoothed and has only one stage of increase (at 1606–1608 UT), the intensity of which, however, is not less than that of an increase during breakup. The fact that the satellite was still deep ($L \sim 5.4$) in the region of quasi-dipole field lines and only went out of this region during PB affected the magnetic field variation character. This results in the observed stretching of magnetic field lines, which intensifies with a change in the magnetospheric configuration during the substorm growth phase. A resultant decrease in the magnetic field strength (B_z) was interrupted by PB at 1606–1609 UT and subsequently continued.

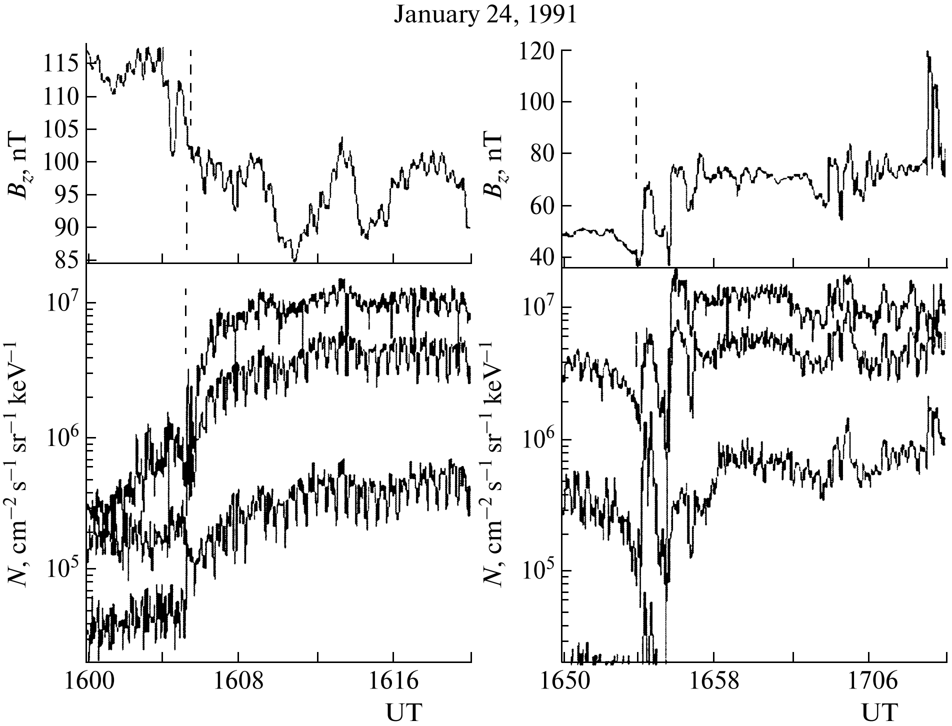

Fig. 6. Variations in the magnetic field B_z component and fluxes of energetic electrons on CRRES during PB and substorm onset on January 24, 1991. From top to bottom: the energy channels are 20–30, 30–40, and 50–60 keV.

2.4. Measurements of Energetic Ions

The time variations in the fluxes of energetic ions measured on CRRES are presented in Fig. 7. In contrast to electrons, increases in ions during breakup and PB differ not only in structure but also in energy. During PB an increase in ion fluxes is less intense and is observed only in two–three channels with the lowest energies (not higher than 70–80 keV), whereas the fluxes of ions with energies from 54 to 254 keV increase even during the earliest intensification at the substorm beginning (1653 UT); the fluxes with energies up to 600 keV, during the second intensification. Such a difference of the ion energy spectra was also observed on the LANL 1984-129 geostationary satellite (a figure is not presented); thus, a difference in the CRRES position during PB and breakup does not influence this effect.

2.5. Low-Energy Electrons and Ions

Figure 8 illustrates the fluxes of low-energy particles measured with the CRRES MEPA device. The channels of electrons and ions with energies of about 1 keV, typical of the plasma sheet, and a channel of 20 keV (for comparison) were selected from many energy channels. The data for electrons and ions are shown in the upper and lower panels, respectively. The fluxes of trapped particles are presented in the left-hand panels; the fluxes along field lines, in the right-hand channels.

It is first of all interesting that the intensity differs along and across magnetic field lines in ion channels; the flux o f trapped ions is higher by an order of magnitude, which corresponds to our ideas of the plasma sheet structure. The fluxes of low-energy ions are very scattered: up to three orders of magnitude at a resolution of 15 s (not shown). The response to PB and breakup is almost imperceptible in both channels, which sharply contrasts with the behavior of higher-energy ions. The dynamics of electrons with an energy of 20 keV is close to that of energetic electrons (Fig. 6), and the response to the disturbance onset is the same. Electrons with an energy of 1 keV are isotropic, which indicates that the magnetosphere–ionosphere coupling is active. In this case the flux of trapped particles (with a pitch angle of 90°) changes insignificantly, whereas increases in the electron flux along field lines are observed at the breakup onset and are less pronounced at the PB onset. Since electron fluxes accelerated along field lines during breakup are associated with the formation of substorm current wedge (one of the most important substorm elements), we should consider this effect in more detail. An analysis of electrons measured using the LEPA multichannel detector indicated that the field-aligned electron flux was weaker during PB, and (above all) the electron energy was not higher than 400 eV, whereas field-aligned fluxes during breakup and substorm expansion had maximums in the range 600–1000 eV. These features are illustrated in Fig. 9, which shows the electron

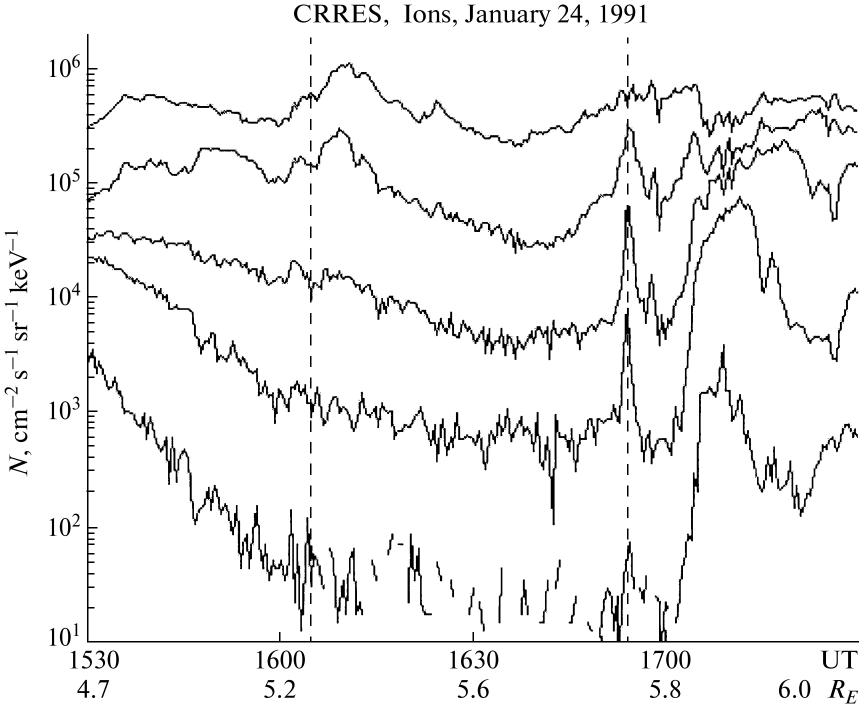

Fig. 7. CRRES measurements of energetic protons (ions) on January 24, 1991. From top to bottom: the energy is 37–54, 54–69, 85–113, 147–193, and 254–335 keV. UT and distance from the satellite to the Earth's center are plotted on the abscissa.

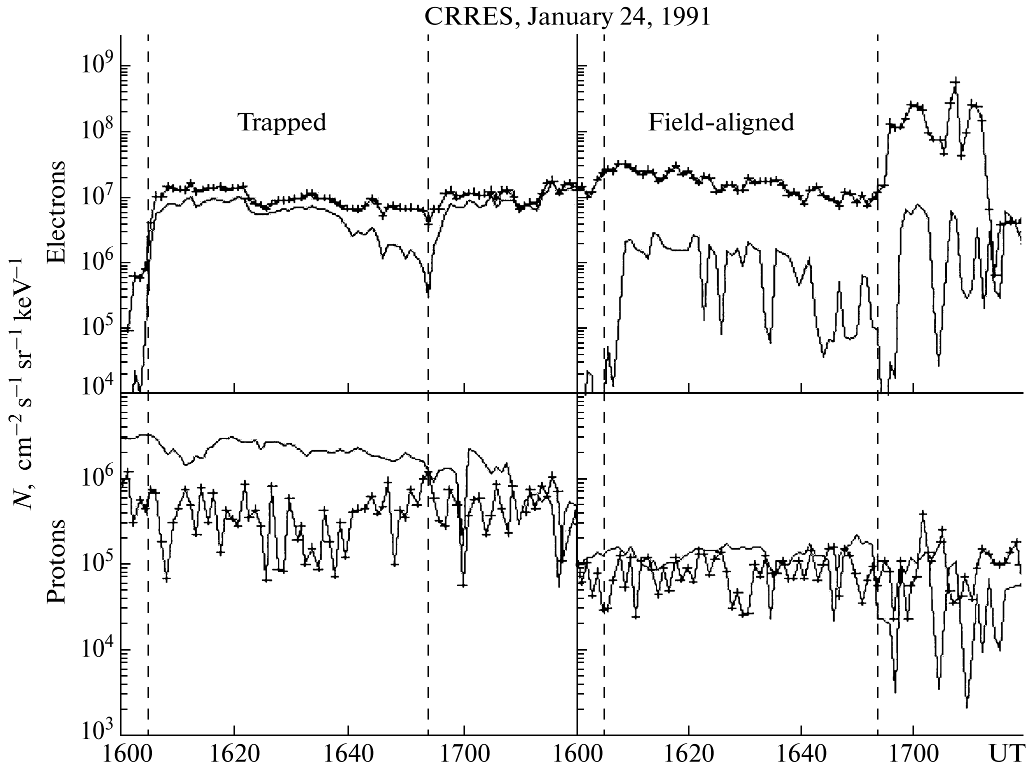

Fig. 8. Variations in trapped (on the left) and field-aligned (on the right) fluxes of low-energy particles with an energy of 1 keV (crosses) and 20 keV (solid line) on CRRES during PB and substorm breakup. The upper and lower panels correspond to electrons and ions (protons), respectively.

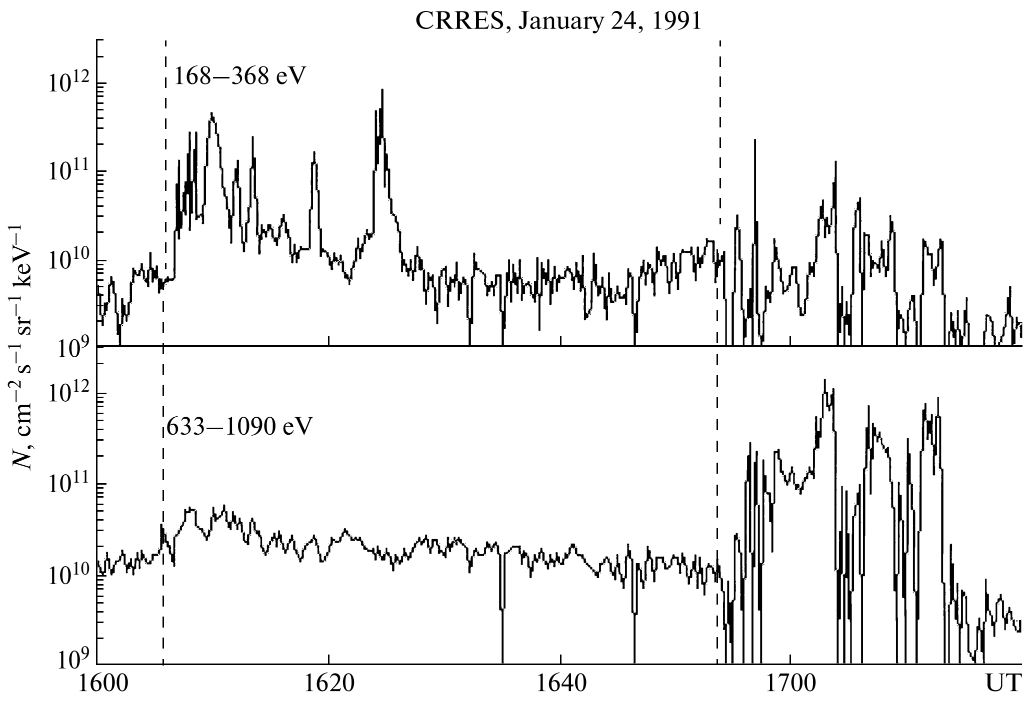

Fig. 9. Electron fluxes along magnetic field lines in two energy channels measured on CRRES on January 24, 1991.

fluxes obtained by summing in two energy channels (168–368 and 633–1090 eV). Field-aligned electron fluxes in the first of these ranges are detected during PB, and increases in the flux of particles with energies higher than 400 eV are not observed. On the contrary, substantial increases in the flux of low-energy electrons are absent during breakup, and only higher-energy particles increase. Auroral breakup is usually associated precisely with electron energies of 1–2 keV. It becomes clear why the auroral brightness and ionospheric response in electrojet are substantially less significant during PB: the energy is insufficient and the flux of precipitating particles is low.

3. DISCUSSION

At present, the ideas of the character and geometry of substorm processes are sometimes opposite and alternative in several substorm models. Since a difference of PB consists in that the transition from the growth phase to substorm expansion is terminated at a certain stage during PB, it is necessary to thoroughly consider the chain of events at the substorm onset. To make further consideration clear, we first summarize our ideas of substorm development based on [Lazutin and Kozelova, 2004; Lazutin et al., 2007a, 2007b].

First of all, we assume that the processes that cause auroral burst and expansion, field-aligned currents and electrojet, and bay-like magnetic disturbances and precipitation of auroral particles occur in the auroral magnetosphere or geostationary region (or the region of quasi-trapping). The first generally accepted stage of substorm onset is an auroral burst (breakup) and an increase in field-aligned electrons with energies of 0.5–5 keV that caused this burst. The appearance of field-aligned fluxes of low-energy electrons and related auroral brightening is a frequent phenomenon, especially during the substorm growth phase. Based on the CRRES data, Abel et al. [2002] analyzed and classified observed field-aligned fluxes. According this classification, many events do not cause substorm breakup. However, one of such bursts can trigger substorm onset at successful time and in successful region. The second chain element shifted in time is (local) dipolarization of the magnetic field and related injection: repeated acceleration of high-energy (20–300 keV) electrons.

Substorm with one activation is a rare phenomenon: substorms with multiple onsets and with a chain of three-five activations lasting several minutes are most often (almost always) observed [Rostoker et al., 1980]. It has long been assumed that previous activation prepares the next one, as a result of which a disturbed region expands (substorm expansion). Finally, the third substorm onset element is the appearance of accelerated ions before injection of energetic electrons. Certainly, ions are also accelerated during dipolarization but appear earlier, when field lines are stretched tailward, and the appearance of ions causes the so-called effect of explosive growth phase [Ohtani et al., 1992]: a rapid stretch of field lines before dipolarization onset.

We relate ion increases before dipolarization to the first substorm element: field-aligned electron fluxes or the so-called substorm current wedge. In our scheme electrons play the role of drivers of the next activation step: particle pressure rises, and the probability of a local explosive instability increases as a result of acceleration of energetic ions. It is quite probable that breakup begins with precisely such activation, which gives a sufficiently large flux of ions for the chain to be continued. Since ions drift westward, the region of subsequent activations gradually shifts toward the dusk sector.

Substorm develops in such a way, and all listed elements are found in two substorms considered above. We now consider what substorm elements are observed during the considered two PBs and what elements are absent or differ from typical substorm elements. First of all, PBs followed a developed growth phase, magnetic field lines stretched tailward, and the energy stored in the magnetic field was not lower than during the next substorms. The intensity of dipolarization and acceleration of energetic electrons was also comparable with that of similar breakup substorm elements. A similarity between these elements indicates that these two PBs cannot be called weak substorm, which is first of all characterized by a low accumulated energy and by a decreased intensity of the following energy release. (Note that such a gradation is absent for substorms in contrast to global storms with the generally accepted gradation of events with respect to intensity.)

We now consider differences between PB and substorm breakup. An auroral burst that triggers substorm was weaker during PB, the flux of low-energy electrons exciting a luminosity burst was an order of magnitude smaller, and the average electron energy was twice as low as during substorm breakup. The second singularity consists in the low energy range and intensity of an increase in energetic protons.

As was established in [Lazutin and Kozelova, 2004], the flux and energy of accelerated ions increase at each next activation during substorm; as a result, the conditions for the following activation are prepared. Precisely such a situation was also observed during the considered substorm of January 24, 1991. Figure 10 presents the ion energy spectrum (on the assumption that only protons are registered) measured before the substorm and during two breakup activations. Protons with energies of 70–250 keV are accelerated during the first activation, and the energy of accelerated particles substantially increases during the second activation (250–600 keV). It is clear (Fig. 10, dashed line) that an increase, as compared to the undisturbed spectrum of ions, is observed only in to low-energy channels (not higher than 60–80 keV) during PB.

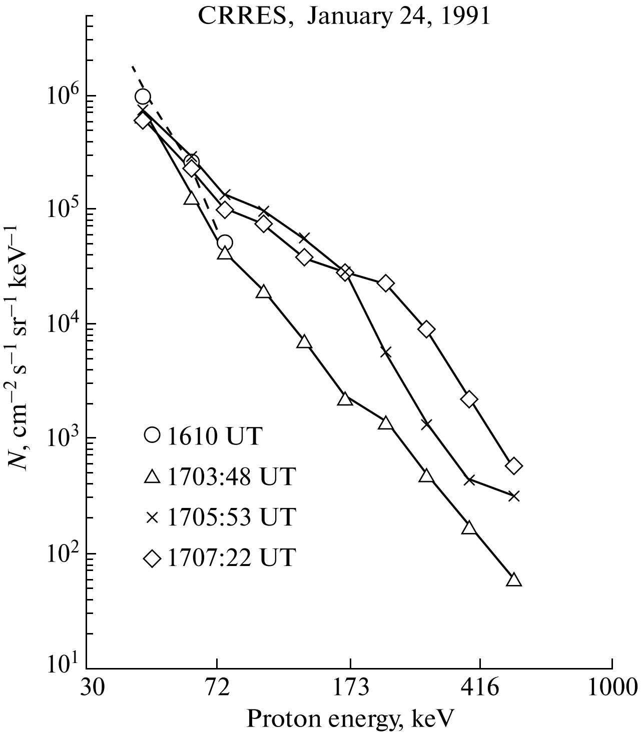

Fig. 10. Spectra of auroral protons during PB (1610 UT), before substorm (1703 UT), and during two substorm activations.

The mechanism of preparation of the following activation is apparently related to a change in the plasma pressure during activation due to an increase in the flux of energetic ions. Such a change in the pressure results in a variation in the pressure radial gradient and in the cross-field current in the plasma. As a result, the magnetic reconfiguration takes place, and the parameters of the plasma domains distant from the activation region can approach the instability development threshold [Lui, 2004; Ohtani et al., 1993; Antonova and Ovchinnikov, 2002]. On the other hand, an increased flux of ions is also a stabilizing factor, which hinders rapid development of dipolarization in this sector by restoring partially local tailward stretching of field lines. These two factors—deceleration of local activation and preparation of the next activation—apparently not operate during PB since the flux and average energy of accelerated ions measured on CRRES are two small. (Certainly, reliable quantitative criteria cannot replace the term “two small” based on one event.) As a result, PB is followed by a rapid single-stage reconfiguration of the magnetosphere in contrast to breakup, when the first activation stage is followed by the reconfiguration of the field lines stretched toward the magnetotail, and the conditions for the following activations are conserved (i.e., the energy accumulated in the magnetic field during the growth phase is not released at once). Koskinen et al. [1993] and Ohtani et al. [2993] noted that the growth phase takes place again after PB, and substorm activations are absent at this longitude during at least 20 min. This fact confirms our assumption that PB spends accumulated energy, i.e., resulting in reconfiguration of the magnetosphere into a relatively stable state.

We should note that the number of elaborated activation models is small. Probably, our data best of all correspond to the scheme of auroral activation proposed by Antonova [2006] and Stepanova et al. [2002], who assumed that the role of the local magnetosphere–ionosphere coupling is important. According to this scheme, auroral arc brightens as a result of a local increase in the electric field during the development of the quasi-electrostatic instability and transfer of cold ionospheric particles into the previously existed region of longitudinal acceleration. One prediction of this scheme of importance for us consists in that accelerated energetic electrons should appear before dipolarization, which is observed experimentally. At the same time, the observed regularities are still fragmentary and schematic, and good agreement between the theoretical concepts and experiment cannot be reached.

4. CONCLUSIONS

The PB singularity consists in that the intensities of an initial auroral burst and the flux of low-energy electrons along magnetic field line, which caused this burst, were low. The field-aligned flux of these electrons was an order of magnitude as small as such a flux during substorm breakup that occurred an hour later, and the energy of these electrons was twice lower than during breakup. The flux and energy of energetic ions accelerated before dipolarization were also substantially smaller during PB. We assume that, during PB, these ions ineffectively create conditions for the following activation. At the same time, the flux of energetic electrons is large, and the dipolarization degree is high, as a result of which the release of the energy accumulated in this sector is considerable.

A performed analysis indicates that further progress in understanding the physics of PB and other substorm activations is impossible without direct measurements of particles in a wider range of energies with a high (several seconds) time resolution. Our conclusions, drawn based on one–two events, are considered to be preliminary and require confirmation based on the larger number of events.

ACKNOWLEDGMENTS

We are grateful to N.P. Meredit (British Arctic Service) and A. Korth (Max Planck Institute, Lindau) for the presented CRRES data, G. Reeves (Los Alamos) for the LANL data, and the members of the geophysical observatories who presented us their data. We thank E.E. Antonova for valuable remarks.

This work was partially supported by the Russian Foundation for Basic Research (project nos. 06-05-64225, 06-05-65044), Presidium of the Russian Academy of Sciences, program "Solar Activity and Physical Processes in the Sun–Earth System," and Department of Physics of the Russian Academy of Sciences, program "Plasma Processes in the Solar System."

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