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The Structure of Substorm Activations in the Quasi-Trapping Region

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Abstract *Based on a large number of measurements of the magnetic field and energetic particles onboard the CRRES satellite and on ground-based measurements we describe the fine structure of the first several minutes of the expansion activation of a substorm. The main result is that we have found a fast enhancement of the flux of energetic ions immediately before the beginning of substorm dipolization of the magnetic field. This effect was not known earlier, and the enhancement is invisible from the ground during auroras. We suggest that the appearance of an excess flux of energetic ions has a triggering effect on the local expansion activation of a substorm. The model of a current meander is put forward, which explains the generation of an inductance electric field, current wedge, and other effects of the expansion commencement of a substrorm.*

1. INTRODUCTION

The basic sequence of events in a magnetospheric substorm is well established and described in many papers (see, for example, [1-8]). The zones of development of a disturbance in projection onto the ionosphere are determined, and the models of a substorm in the magnetotail [9, 10] and in the quasi-trapping region [11-15] are elaborated.

At the same time, the explosive commencement of activation (one of the main processes of a substorm) is studied insufficiently well. The problem is that the time resolution of order of one minute is commonly used in measurements. When the duration of a process is several minutes, it is impossible to reveal its detailed structure.

The **CRRES** satellite was one of rare satellites with telemetry that allowed one to have a second time resolution and had the trajectory crossing the quasi-trapping region. Several papers, in which the fine structure of substorm processes was revealed, used the measurements of this satellite [16-20].

This paper is a continuation and generalization of our earlier papers [21-27]. Based on a larger number of measurements of the magnetic field [28] and energetic particles by the EPAS detector system onboard the CRRES satellite, as well as on the data of ground-based measurements, we describe the fine structure of substorm onset, the first several minutes of the expansion phase of a substorm. We consider the discovery of a fast enhancement of the flux of energetic ions (protons) before the very beginning of a substorm dipolization od the magnetic field as the main result of this work. This enhancement, though unknown earlier and unobserved from the ground, probably serves as a trigger for the explosive instability of substorms. The enhancements of auroral electrons and protons known as particle injections are one of the main elements of explosive instability of a substorm.

Starting from the first works by McIlwain [30] devoted to determination of the position of injection boundaries, it was clear that they were located on closed shells in the zones of trapping or quasi-trapping. In the process of acceleration a part of energetic electrons immediately precipitates into the atmosphere. The bursts of bremsstrahlung X-ray emission generated in this case were repeatedly detected on balloons, simultaneously with the break-up of aurora and in the same place

[31, 32]. At the same time, the Pi2 pulsations, magnetic bays, and many other manifestations of the sudden commencement of the expansion phase of a substorm are also detected. It is known that dispersionless injections of energetic particles observed on satellites in the geosynchronous region are uniquely related to the substorm commencement in the auroral zone [24, 33].

Studying injection characteristics, we can hope to reveal the mechanisms of development of the substorm explosive instability. One can postulate the simultaneity of injections for electrons and protons only if the data are essentially averaged. However, if the time resolution on the second scale is available, one can found that there is a fine structure of the enhancement, with a complex dependence of the time structure of the bursts upon the charge and energy of particles, on the pitch-angle distribution and the satellite position relative to the center of instability.

The fine structure of the injections is studied insufficiently for understanding the processes that lead to the explosive instability of substorms, though some success was achieved. For example, in [34] the authors established that an extension of field lines into the magnetotail had been observed before the beginning of the expansion phase and dipolization of the magnetic field. This effect is similar to that taking place at the growth phase, but it is faster and sharper. They called this effect the Explosive Growth Phase (EGP). Later, it was demonstrated that EGP is observed after the beginning of the global expansion phase, but when the expansion has not reached the point of observation. Due to this reason, EGP should be classified among the local effects of propagation of repeated activations. In papers [18, 21] based on the measurements of particles and magnetic field onboard the CRRES satellite it was shown that such an extension of field lines resulted from the appearance of enhanced flux of energetic ions with energies of tens and hundreds of keV.

The existing theories of substorms in the inner magnetosphere on the closed quasi-dipole field lines ascribe the leading role to energetic particles. In [11-13], the substorm commencement is explained by a discontinuity of the evening-directed drift current that flows near the equator plane on the plasma sheet boundary nearest to the Earth. Energetic ions serve as predominant carriers of this current, and their distribution and dynamics determine both the stability approaching instability in a given region of the night magnetosphere. The balloon instability and its modifications [14, 15] also depend critically on the intensity and geometry of the fluxes of trapped and quasi-trapped ions of the plasma sheet and radiation belt. The energy density of ions often exceeds that of the magnetic field, which creates favorable conditions for instability development. At the same time, there are many unclear points in the behavior of ion fluxes during disturbances.

Both theoretical and experimental studies deal with global, large-scale development of a substorm. At the same time, substorm expansion consists of separate localized activations following one after another. The activity develops quickly so that considerable changes take a few seconds. In principle, one can use television records of aurorae in order to follow the break-up development in great detail. However, the analysis of these records shows that there is a considerable variety of scenarios of active auroral onset [35, 36]. One can suggest the existence of some important agent which is unseen by us in the aurora pattern. Most probably, the fluxes of energetic ions serve as such an agent. Their enhancements, as will be demonstrated below, are observed before the beginning of dipolization, and their acceleration proceeds mainly in the equatorial plane. As a result, this process does not manifest itself in the particle dynamics inside theloss cone or near the loss cone, and thus it is not observed in aurora and on low-orbit satellites.

Therefore, it is necessary to analyze the measurements in the equatorial plane, and one needs in this case the second time resolution. It is worthwhile to note that the expansion phase begins in a limited area, and the probability for one satellite to be exactly in this region is small. More frequently, the satellite turns out to be in the zone of disturbance expansion, in one of activations delayed with respect to the substorm commencement. Truly, there are no grounds to assume that revealed activations along the path of disturbance expansion differ considerably from the 'main' primary activation. They are identical in their consequences: particle acceleration, dipolization of the magnetic field (and again acceleration of particles). Therefore, to find the details of the fine structure of preparation and development of a next activation means to make a step to understanding the mechanism of expansion instability of a substorm.

In this paper we consider in great detail the time structure of ion fluxes a few minutes before and a few minutes after the local beginning of injection of electrons and dipolization of the magnetic field with an emphasis on time characteristics, energy spectrum, and pitch-angle distribution of protons (ions). Special attention is given to ion enhancements with a fast (several seconds) growth of intensity, which change the local structure of the magnetic field. It is probable that they serve as a first triggering element of expansion activation.

2. MEASUREMENTS

We consider in this paper the measurements of energetic particles and magnetic field during six passages of the CRRES satellite through the night sector of the disturbed auroral magnetosphere. The publications using ground-based observations and the CRRES data were devoted to practically all substorms under consideration. So, there is no necessity to make detailed descriptions of the substorm activity. Our analysis differs from others by maximum possible resolution (1-2 s) used for particle detectors. The magnetic field data have the period of averaging equal to 2 s.

Table 1 presents the energy thresholds of differential channels of the EPAS detector that are used in this paper. The detector of positively charged particles makes measurements of protons and heavier nuclei; therefore, when presenting these experimental data we use (to be precise) the word ions. However, when discussing results we can (taking into account the dominance of protons in the flux of charged particles) say about acceleration and injection of protons, as it is generally done in the literature.

2.1. Orbit 445 on January 24, 1991

Figure 1 presents the plots of variation of the H-component of the magnetic field at several magnetic stations of the auroral zone. One can isolate four intensifications of a substorm and negative bays corresponding to them: a weak one takes place at 16:50--16:55 UT, then follow one

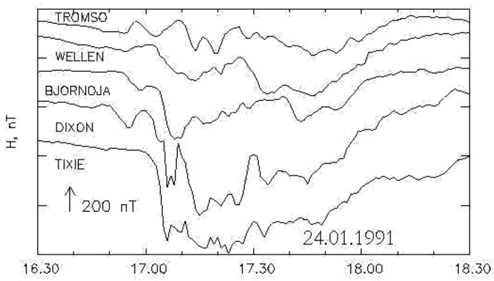


Fig. 1. The H-component of magnetograms of ground stations during a passage of the CRRES satellite over the northern auroral zone, orbit 445 on January 24, 1991. From top to bottom: Tromso, Uellen, Bjornoeya, Dickson, and Tiksi.

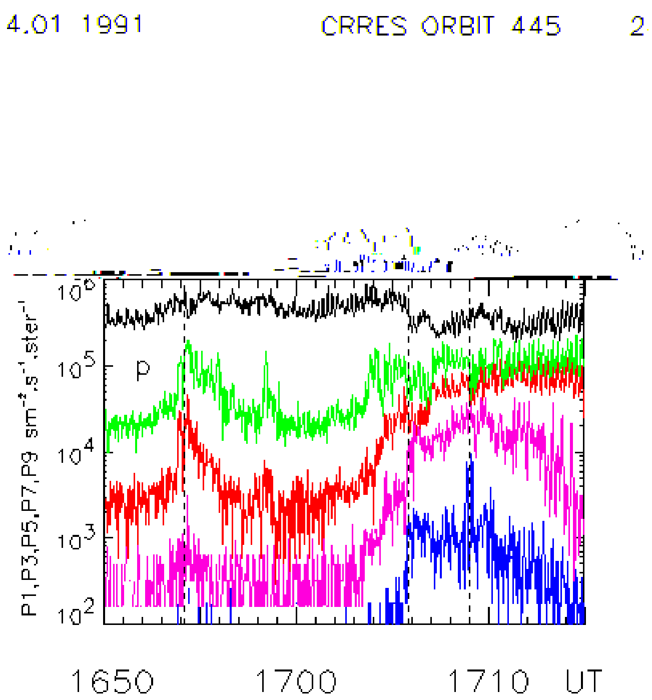


Fig. 2. Variations of the magnetic field, differential flux of electrons (cm2.s.sr)-1 in the energy channels E 1, 4, and 9 (see Table 1) and ions (P 1, 3, 5, 7, 9), orbit 445 on January 24, 1991. The regular oscillations of the counting rate with a period of 30 s are due to rotation of a satellite about its axis in the periods of anisotropic pitch-angle distribution of particles. Vertical dashed lines mark the moments of ion burst onsets.

after another the strongest bays beginning at 17:02 UT and 17:05 UT (they can be considered as two steps of one and the same disturbance, however, the Dickson data clearly demonstrate them to be two different activations). The fourth bay was observed at 17:09-17:14 UT.

Figure 2 presents the variation plots for the particle flux and Bz-component of the magnetic field as measured by the CRRES satellite at this stage of expansion of substorm activity. The dashed lines mark the instants of enhancements of the flux of energetic ions. Our attention is immediately drawn to the coincidence with the instants of buildup of the magnetic bays. Let us consider the variations of ion fluxes and the phenomena accompanying them in more detail.

First enhancement of ion fluxes and local break-up.

The first sharp burst of electrons accompanied by dipolization of the magnetic field was observed at 16:54:10 UT. This is a clear indicator of the commencement of a local activation. In this particular case it is delayed by 5 min with respect to the global commencement, which, according to [20], took place at 16:49 UT. Note also that the growth of ion intensity in channels 1-3 (below 80 keV) begins already 10-15 min before the local dipolization against the background of decaying flux of trapped particles. This growth is probably evidence that the near-Earth boundary of the plasma sheet is crossed, or it belongs to the effect of a growth phase. After the first burst of electrons no irreversible change of the magnetic field structure takes place: field lines are stretched again, and the flux of electrons drops down to the undisturbed level. But then the second activation follows, with a strong effect of acceleration of electrons, and after that dipolization is established. The third activation occurs, apparently, apart from the satellite, the magnetic field jump is smoother, and the effect in particle fluxes is small.

The intensity of ions with energies from 54 to 400 keV sharply increases 20 s before the first activation (there is no increase in the first channel, E = 37-54 keV). The ion burst is observed at all pitch angles from 40 to 170 measured at that instant. The enhancement begins simultaneously for all energies, a small delay of the maximum intensity in lower channels can be explained by the different velocities of magnetic drift from the eastern boundary of the region of acceleration. The duration of this burst is 2-3 min, it covers both the first and the second local activations.

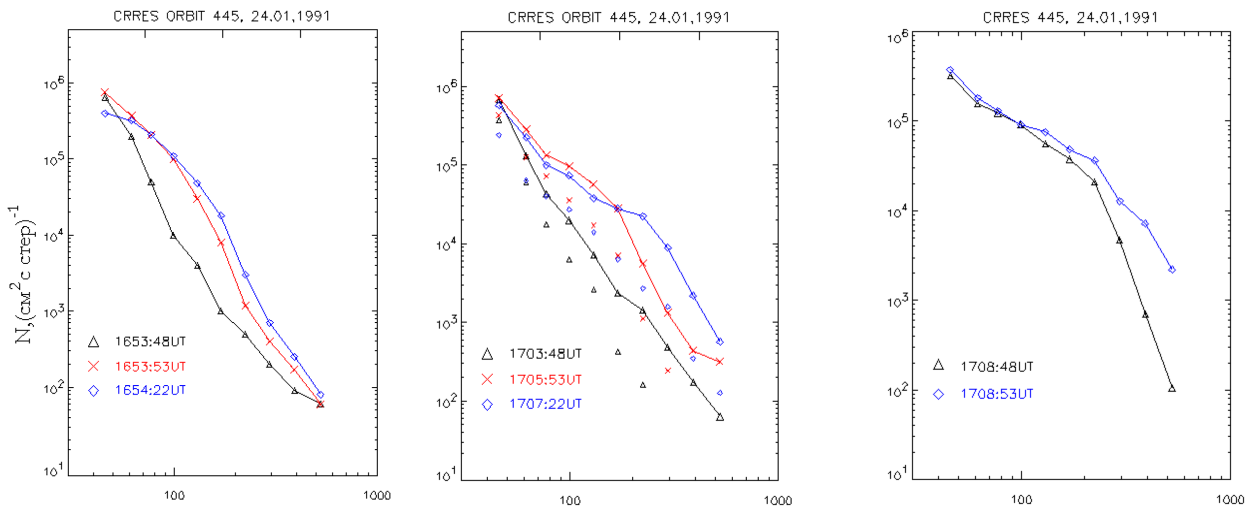


Fig. 3. Variations of the differential spectrum of trapped ions in three enhancements, CRRES orbit no. 445. The energy of ions is given in keV.

Figure 3a presents the energy spectra of ions before the enhancement, 5 s after the beginning of growth, and in a short (10 s) additional hard pulse observed half a minute after the burst commencement. Maximum acceleration takes place for ions in the energy range 100--200 keV (main burst) and > 150--300 keV (short pulse). The spectrum has an inflection point approximately at E = 75 keV. Finally, it should be noted that at the leading edge the enhancement of the ion flux causes additional stretching of the filed lines, the so-called effect of expansion growth phase [37]. Then, approximately near the maximum of the flux, dipolization begins.

After the first enhancement the ion intensity drops down, beginning from the highest channels (newly accelerated particles are swept away by the magnetic drift); all channels except the first one virtually regenerate the undisturbed level of intensity.

The second and the third enhancements of ion fluxes.

The next two-step enhancement of the ion flux is observed at 17:03:38 UT, this enhancement is impulsive in channels 1-3 and smooth in the higher channels. The second step at 17:05:40 UT revealed itself only in channels 7-10 (> 200 keV). The satellite projection along the field lines is located between Tiksi and Dickson, where at this time two strongest intensifications of the substorm are detected, the first one is extended in longitude, while the second one is observed in a narrow longitude sector. A more detailed consideration (Fig. 4) shows that, after the intensification at 17:02 UT, the scenario of the activation commencement is repeated on the satellite: dipolization and the increase of the flux of electrons follows in 12 s after the increase of the ion flux. A jump in Bz is small as well as the amplitude of electron injection. The small increase in electron fluxes (only by a factor of 2 in the first channel) is probably associated with the fact that the level of fluxes was already high before this activation.

The intensification at 17:05 UT was very local: the ground burst in **H** is observed only at Dikcson. The satellite located 20° to the east responded by a burst of energetic ions that has occurred at 17:05:50 UT and by an intensity drop in the lower channels.

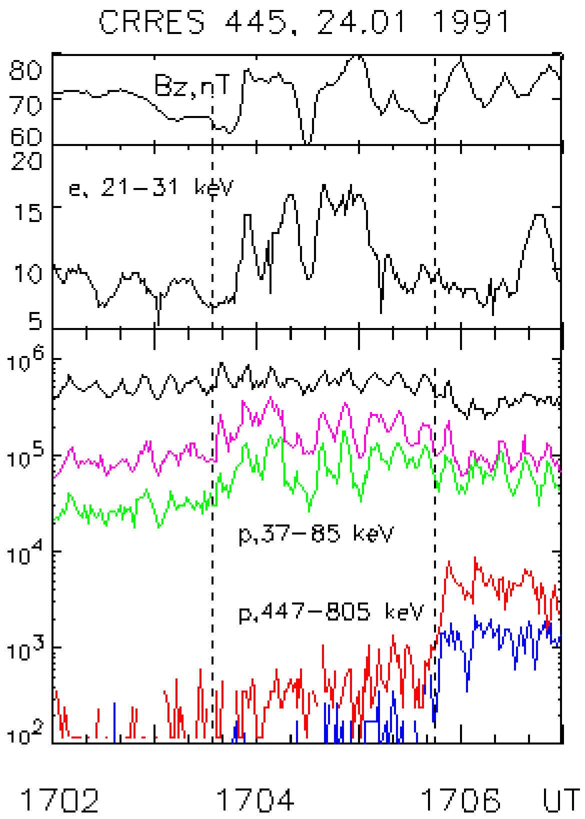


Fig. 4. The second and third bursts of the flux of ions (bottom panel, channels P 1, 2, 3, 9, and 11), and variations of the vertical component of magnetic field and of the electron flux in the E 1 channel, CRRES, orbit 445.

Localization of the disturbance resulted in the fact that there was no clear effect of dipolization onboard the CRRES, and a drop instead of enhancement was observed in the flux of energetic electrons, as well as a change in the pitch-angle distribution in higher channels, from a flat distribution to the trapped one, as is well seen in Fig. 2.

The character of changes in the energy spectrum of ions in this two-step enhancement is illustrated by Fig. 3b. At the first stage a substantial growth of the particle flux is observed in a limited range with the maximum relative amplitude of increase at 175 keV. This energy E* can be called critical in a sense, since in the future (at the second stage) it turns out to be a certain boundary above and below which the fluxes increase and decrease, respectively.

The fourth burst of the ion flux. The last burst of ions in this orbit has a duration of 25 s and is observed only in 8--10 channels (E > 250 keV) at 17:08:50 UT (Fig. 5). It is evidently related to the subsequent (in 10 s) sharp increase of the magnetic field strength (Bz component) and growing flux of electrons. One can see that the front of buildup of the ion burst is very steep, 1 s or less (the interval between two neighboring measurements), and that only particles with pitch-angles near 90° are accelerated (if one looks at the dip at 17:09:00 UT). In general, this is an episode of transient type: a train of waves or soliton passes near the satellite generating a short-lived substorm or a local activation with all its basic features (dipolization of the magnetic field and injection of energetic electrons).

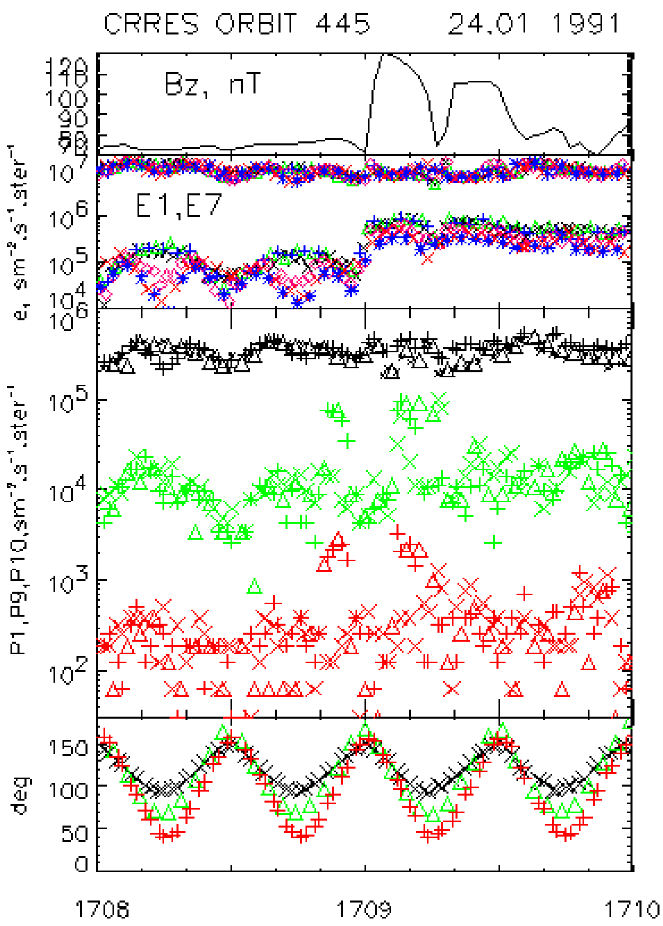


Fig. 5. The third burst of energetic ions, orbit 445, for electrons (channels E 5, 9) and ions (channels P 7, 9, 10). The bottom panel presents the acceptance pitch angles of the detector of ions.

The energy spectrum of this enhancement shown in Fig. 3c belongs to the second type; with an increase above the inflection point at E* = 220 keV.

Thus, in the course of development of a substorm the critical energy at the inflection point changes from 75 to 220 keV, reflecting either the gradual increase of the effective energy or acceleration of ions with the intensification of the magnetic field as a whole, i.e., in connection with a large-scale dipolization.

2.2. Orbit 553 on March 10, 1991

One more example of the fast (2--3 s) increase of ion fluxes is shown in Fig. 6. It is detected at the peak of the substorm, 30 min after its commencement and in 10 min after the second intensification, when the flux of newly accelerated electrons near the CRRES orbit has already reached its maximum. A drop of intensity is seen in the first three channels immediately after the maximum following a fast increase

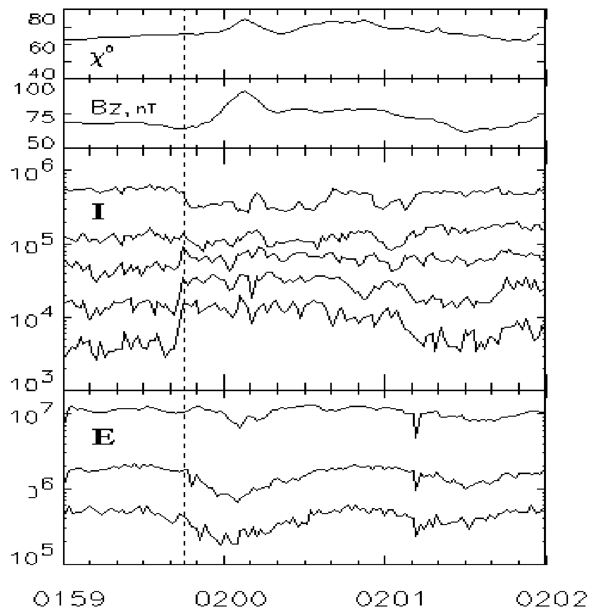


Fig. 6. The ion burst on March 10, 1991, orbit 553. From top to bottom: changing slope of field lines, Z-component of the magnetic field, the intensity of energetic ions in the first five channels, and variations of the flux of electrons (E1, E4, E6).

of ion fluxes in channels from third to eighth. This effect is observed nearly in all cases considered; therefore, it deserves a detailed analysis. In actual fact the detector measures two populations of ions (protons): trapped particles of the radiation belt and ions of the central plasma sheet, which prevail in the lower energy channels. These two populations have different radial profiles: when the satellite moves away from the Earth, the flux of trapped ions decreases, while the flux of ions of the plasma sheet increases after crossing the Alfven layer. Different signs of the radial gradient lead to the fact that during contraction or expansion of field lines of the night magnetosphere the variations of the fluxes of ions in energy ranges 20-50 keV and, say, 100-300 keV will be opposite in phase. This effect seems to be responsible for observed decreases of ion fluxes in lower channels. It should be only emphasized that in our events this decrease was observed not simultaneously with the increase of energetic particles (as was our previous opinion), but with a certain delay. For example, both an enhancement and a drop are observed sequentially in the third channel. Thus, the intensity drop in low-energy channels is the next stage in activation development.

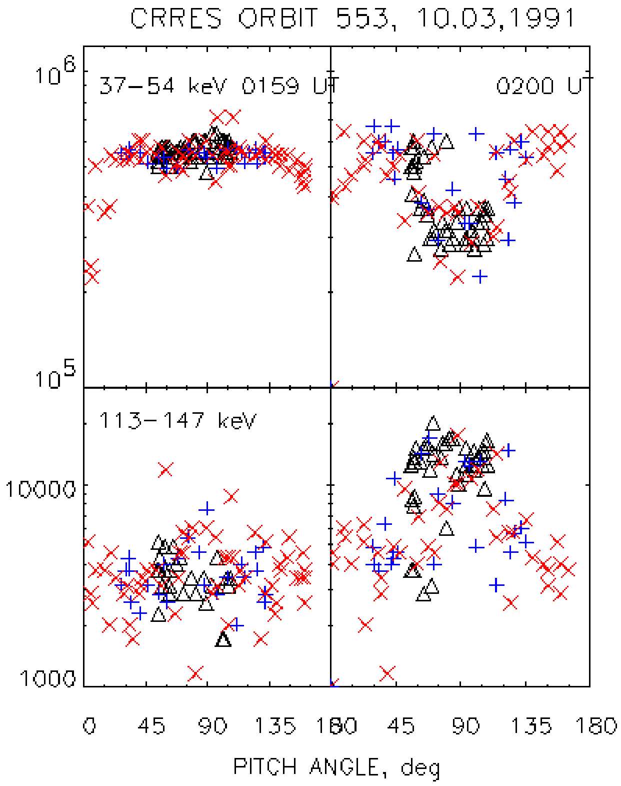


Fig. 7. Variation of the pitch-angle distribution of ions in the first and fifth channels on March 10, 1991, orbit 553. Three types of symbols correspond to three detectors of ions.

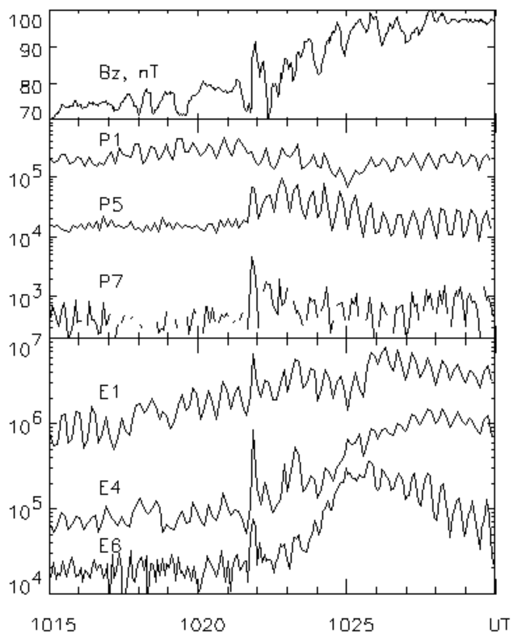


Fig. 8. Orbit 527 on February 27, 1991. A jump of local dipolization at 10:21:50 UT against the background of slower dipolization during the substorm expansion phase. Ions (channels P 3, 5, and 7) and electrons (channels E 1, 4, and 6).

Dipolization of the magnetic field begins in 15 s after the onset of the burst. The duration of the magnetic field jump is rather small, about 20 s, however, no enhancement of electrons occurs, may be because of the fact that the fluxes were already sufficiently high, or such was the geometry of the activation region. Figure 7 presents for two energy channels the pattern of ion distribution in pitch-angles before and after the burst maximum. It is seen that the intensity of particles with pitch-angles from 0 to 45 varies insignificantly, and the main changes are related to the particle flux near the equatorial plane. Trapped ions with energies above 80 keV are accelerated, while the intensity of low-energy particles decreases. In the second channel (54-69 keV) the tendencies of decrease and increase of intensity are balanced so that the counting rate is virtually invariable.

2.3. Orbit 527 on February 27, 1991

A moderate isolated substorm with a gradual commencement was observed on February 27, 1991. The bay-like disturbance begins at the magnetometer of the Simpson station at 10:05 UT and in Tiksi at 10:15 UT, the maximum was observed at 10:30--10:40 UT. For 20 min a smooth increase of the flux of electrons and ions in low-energy channels and a slow growth of Bz occur onboard the CRRES satellite (Fig. 8). It is probable that local activations of the type of pseudo-break-up take place before 10:20 UT. They do not cause the substorm expansion, but provide for a gradual smooth increase of the flux of particles, including precipitating particles. As a result, the electrojet grows. The onset of local activation can be precisely specified by a sharp jump in dipolization at Tc = 10:21:47 UT, the injection of energetic particles starts simultaneously. After the first activation, one or two more were observed, but the center of the disturbance was displaced to the west from the satellite judging from the dispersion of enhancement of electron fluxes.

Now let us consider the fine structure of the enhancement. Figure 9 presents the data in a 20-s interval near Tc. The flux of particles (both electrons and ions) increases by an order of magnitude in a few seconds; therefore, in order to trace the succession of events, one needs the maximum possible time resolution to be used. Let us first of all notice that in this case the burst of energetic ions begins earlier than that of electrons. Out of all cases considered, here the delay is minimal, only a few seconds. Nevertheless, the ion flux has already reached its maximum at the moment when the increase of electrons is yet to begin. As for the process of decrease of low-energy ions, the situation is unclear. It occurs either simultaneously or with a small delay with respect to the increase of the flux of energetic ions. Notice that, as in preceding cases, a transition to trapped pitch-angle distribution of ions is observed in higher channels, and this distribution is conserved also after the instant when the ion flux drops down to its undisturbed level.

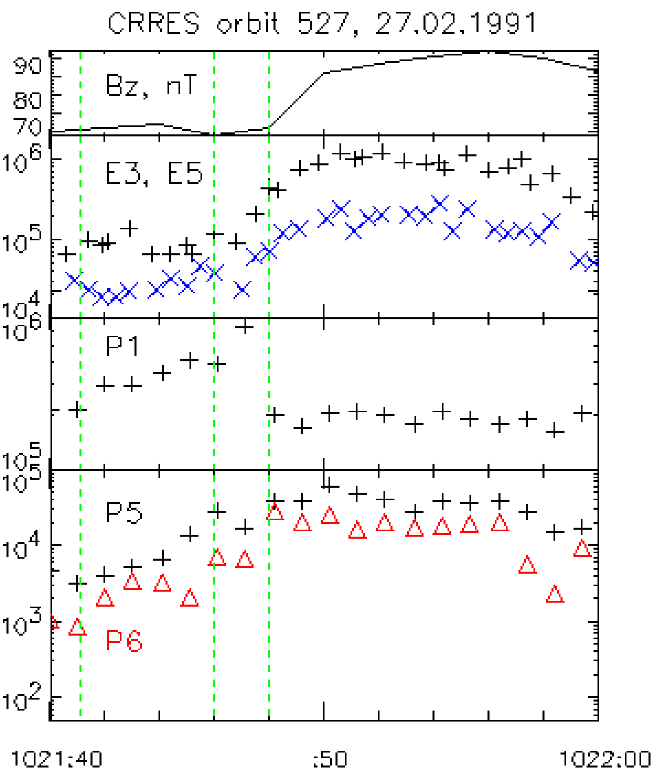


Fig. 9. Orbit 527, the beginning of local activation, maximum time resolution. Vertical dashed lines mark the beginning of the flux growth for ions and electron, and of magnetic field dipolization.

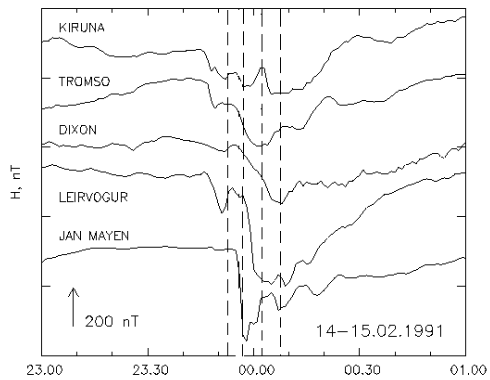
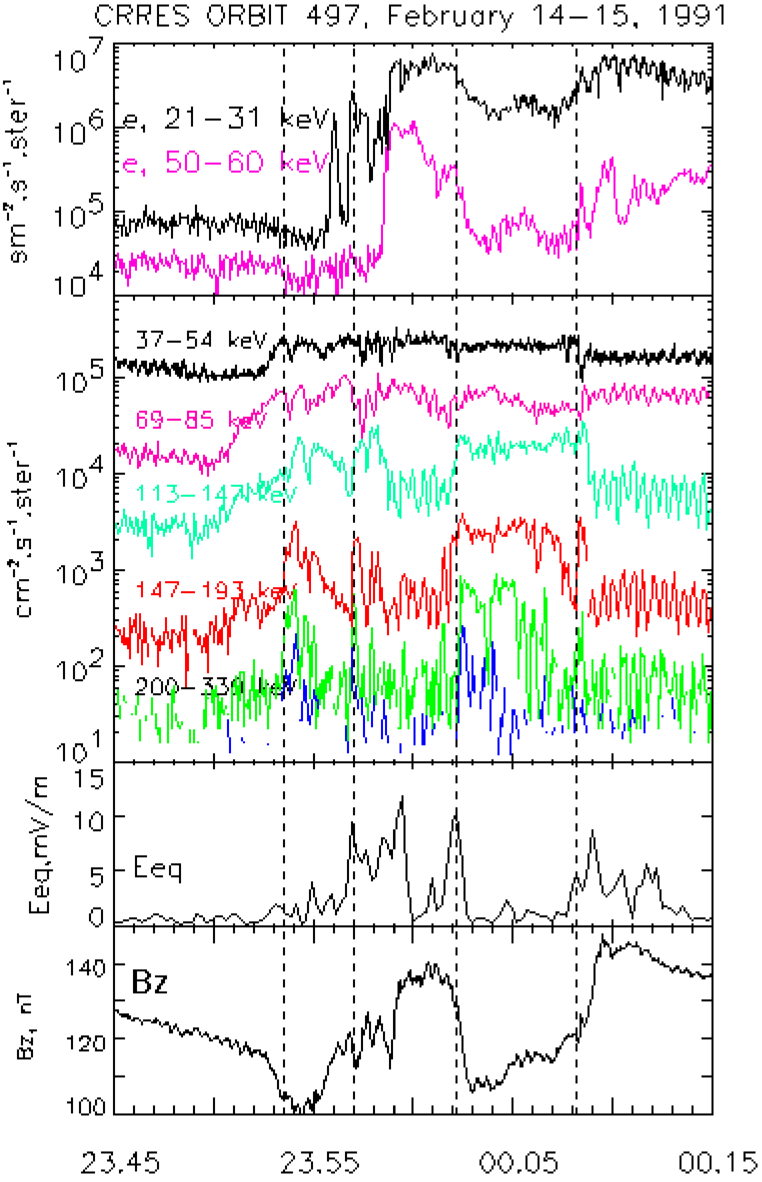


Fig. 10. The H-components of ground-based magnetometers during the substorm on February 14--15, 1991.

2.4. Orbit 497 on February 14--15, 1991

Having considered several disturbances with simple structure, let now pass to a complicated though short event. The substorm on February 14--15 has a three-step character: the first weak bay begins



at Tromso, Kiruna, and Leirvogur around 23:48 UT, later several more bays follow marked by dashed vertical lines (Fig. 10). Onboard the satellite an increase of the ion flux is observed since 23:50 UT. However, judging from the absence of disturbances of the magnetic field and in the electron flux, the local growth phase still continues here (Fig. 11). Dipolization of the magnetic field and the second substorm intensification begin at 23:55 UT and last about 6 min. As usual, the sharpest jump of Bz coincides with injection of electrons in a wide energy range. This moment (23:59 UT) is related to a local activation of the substorm. The electron bursts observed before this are detected only in the first (low-energy) channels - rather rare phenomenon if the satellite is not located near the outer boundary of quasi-trapping zone. In the given case, it is probably due to the features of the spatial structure of inductive field and, accordingly, of the region of particle acceleration.

The third intensification at 00:08 UT is traced against the strongly disturbed background both in ground magnetograms and

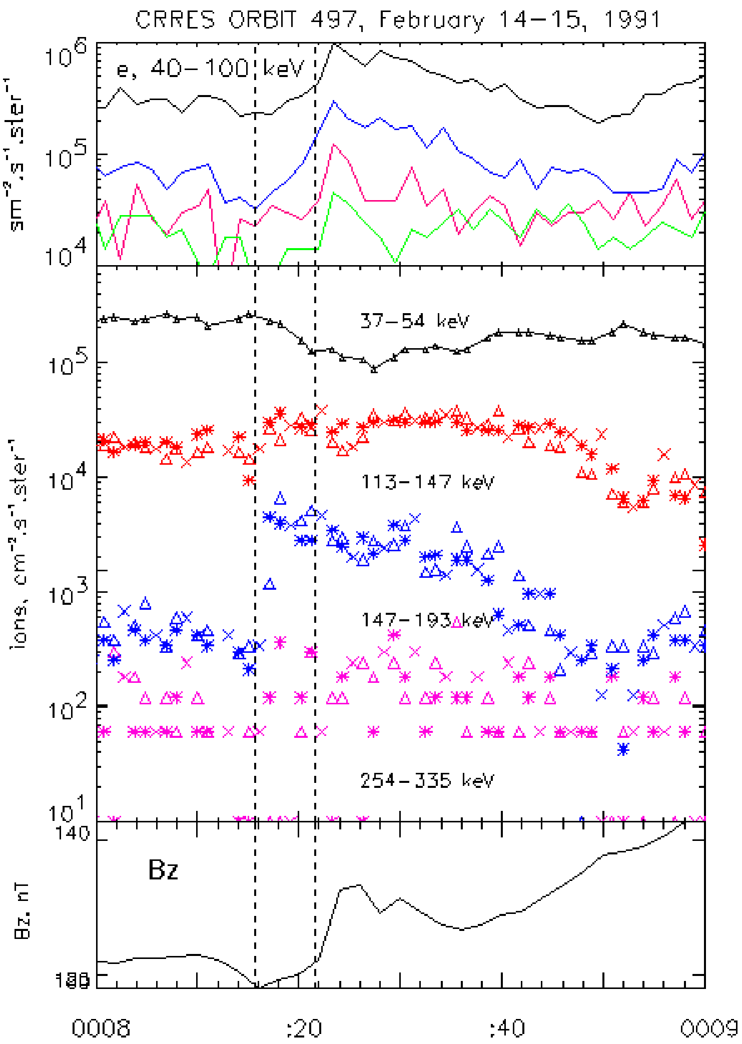
Fig. 11. Orbit 497. Mesurements of energetic electrons (E 1 and 4, the upper panel), ions (P 1, 3, 6, 8), and electric and magnetic fields during the substorm on March 14-15, 1991. Vertical dashed lines mark the instants of bursts of high-energy ions.

according to measurements of energetic electrons and magnetic field onboard the CRRES satellite.

The complicated pattern of the disturbance reveals itself in a strong variability of the flux of energetic ions (or, possibly, it is determined by it). We marked by vertical dashed lines in Fig. 11 four enhancements of energetic ions with sharp leading edges. Each enhancement is accompanied by extension of field lines into the magnetotail and by a decrease of the vertical component. These bursts do not differ in this from those considered earlier. At the same time, for the first three bursts one does not observe a fast (within a minute) reaction in the form of local dipolization and injection of electrons.

In addition, dispersion in energies (not shown in the figure) is observed in the first two bursts, ions drift from the east.

The third enhancement of ions resulted in a six-minute decrease of the electron flux and in return of the magnetic field structure to that more stretched into the tail. There is already no drift dispersion



here, and the satellite is closer to the center of the enhancement. Two peculiarities engage our attention. Firstly, the enhancement goes in two steps: first in middle and the in high energies. Such a structure was also observed by us earlier. The second peculiarity of this enhancement is the transition of the pitch-angle distribution of particles from trapped the flat one in the energies below 200 keV (we do not see the loss cone; therefore, one cannot speak about the isotropic distribution).

Let us take a notice that the pitch-angle distributions of ions with energies of 100--200 keV are very similar before the third burst (24:00--24:01 UT) and after the fourth one (00:10--00:15 UT), as if the satellite had moved for a time into another region behind a certain boundary and then returned back. The

Fig. 12. Enhancements of the fluxes of electrons (E 3, 5, 7) and ions (P 1, 5, 6, 8), and dipolization of the magnetic field, the fourth intensification at 00:08 UT on February 15, 1991.

projection of near-the-pole edge of the auroral bulge or WTC could serve as such a boundary. Based on the measurements of the GEOS-2 satellite, it was concluded long ago that the fluxes of energetic particles to the west of the bulge boundary are higher than inside it, while the fluxes of electrons are higher inside the bulge [15, 38]. It well may be that the unusual time behavior of electrons with low-energy bursts can be explained by the proximity of this boundary. Upon reaching its maximum in the third burst the intensity goes down starting from the higher channels (see Fig. 11), which can be explained by sweeping due to magnetic drift. If this is really the case, and a five-minute delay of 150 keV ions relative to 300 keV ions is due to the difference in the time of

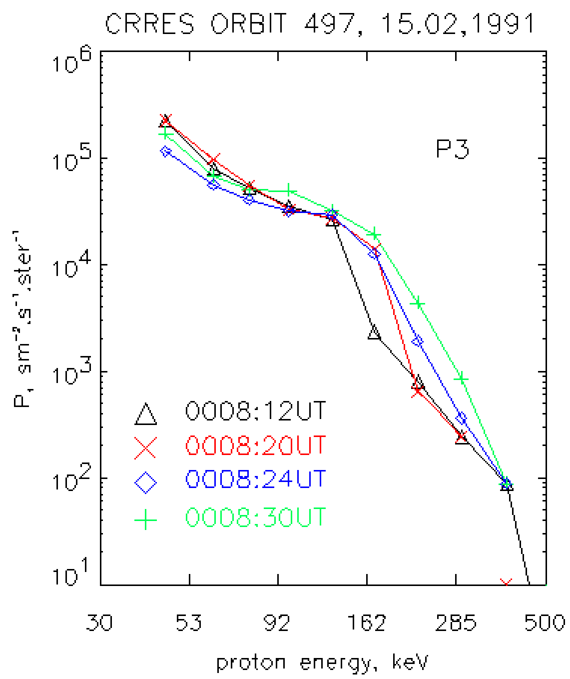


Fig. 13. The character of changes in the energy spectrum of ions during the fourth intensification on February 15, 1991, orbit 497.

drift from the farther boundary of the acceleration region, then the estimated azimuth size of the region is impressive (35˚). Take a notice that ion bursts are accompanied by generation of the electric field with an amplitude of up to 15 mV/m. However, since the time resolution of electric field measurements is not high, no far-reaching conclusions can be made.

In the fourth (last) enhancement of ions the complete scenario of activation is observed: in a few seconds after the ion burst an increase of Bz begins, being accompanied by the injection of electrons (Fig. 12). The energy spectrum of this burst is presented in Fig. 13. Again we can see the enhancement in a limited energy range, which extends to the region of high energies. Let us note the important property: the spectrum becomes flatter at a certain energy interval. Usually, a plateau on the distribution function of particles appears in the region of wave absorption [39].

2.5. Orbit 486 on February 10, 1991

We would like to emphasize one event from the measurements in orbit 486. This is a short (10 s) burst in the energy interval above 150 keV before the main ion burst (Fig. 14). The dip in the intensity between the short and main bursts is not an effect of pitch-angle modulation. This follows from the data on orientation of three ion detectors presented in the lower panel. In addition, using the amplitude difference of the burst in the first and third detectors, one can conclude that the short burst was observed in the fluxes of protons whose gyrocenters were located in the tail direction from the satellite, i.e., the displacement to the Earth took place.

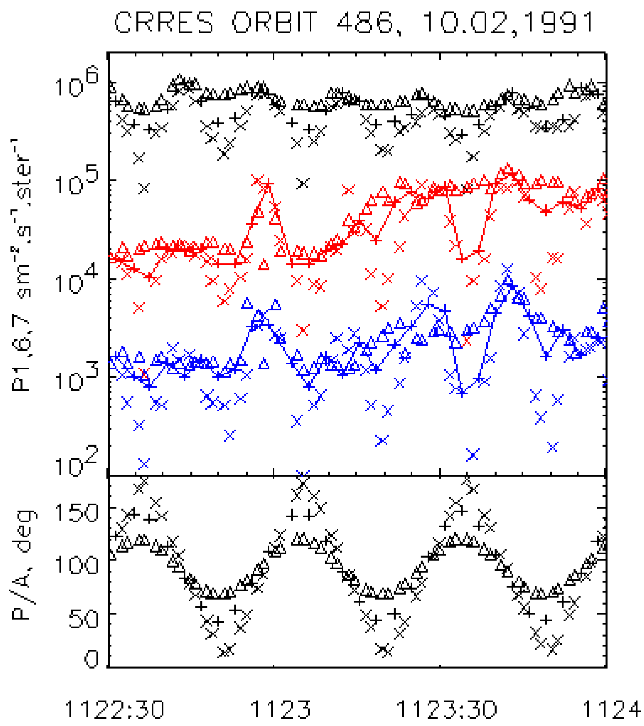
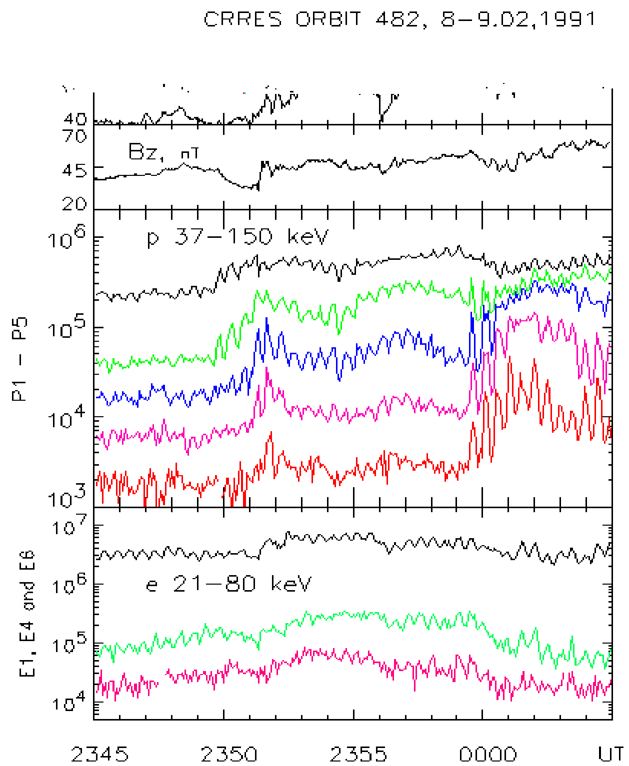


Fig. 14. A short burst and the main enhancement of the ion flux on February 10, 1991, channels P 1, 6, 7 (orbit 486).



2.6. Orbit 482 on February 8, 1991

In Fig. 15 where the variations of particle fluxes and magnetic fields are plotted for February 8, 1991 we emphasize two enhancements of ion fluxes: at 23:51 and 23:59 UT. The former is associated with a local activation, while the latter is not. In the first event we again have a two-step enhancement of the ion flux: in the beginning in the first two channels (this is probably due to entering the current sheet), and then in more energetic channels. A drop of ion intensity in the first channel follows after this burst of energetic ions: the delay is clearly seen in this case in

Fig. 15. Two bursts of energetic ion fluxes on February 8--9, 1991 (P 1, 3, 4, 5, and E 1, 6), CRRES orbit 482.

Fig. 16. Again we can see that only particles with a pitch-angle of 90° are subject to acceleration. Later on, the field-aligned fluxes also increase, though this can be already not the acceleration effect but a result of dipolization: the satellite turns out to be at deeper level of the radiation belt, where both the fluxes are higher and the pitch-angle distribution is more anisotropic. Dipolization of the magnetic field follows after the onset of the ion burst with a delay of about 7 s. The measurements of three ion detectors having different viewing angles are presented in Fig. 16 by different symbols (the lower panel of the figure). Using different counting rates of detectors one can determine the gradient of fluxes of accelerated ions: 30 s before Tdip the maximum is located tailward from the satellite. The time resolution of satellite detectors is insufficient for detailed investigation of this effect.

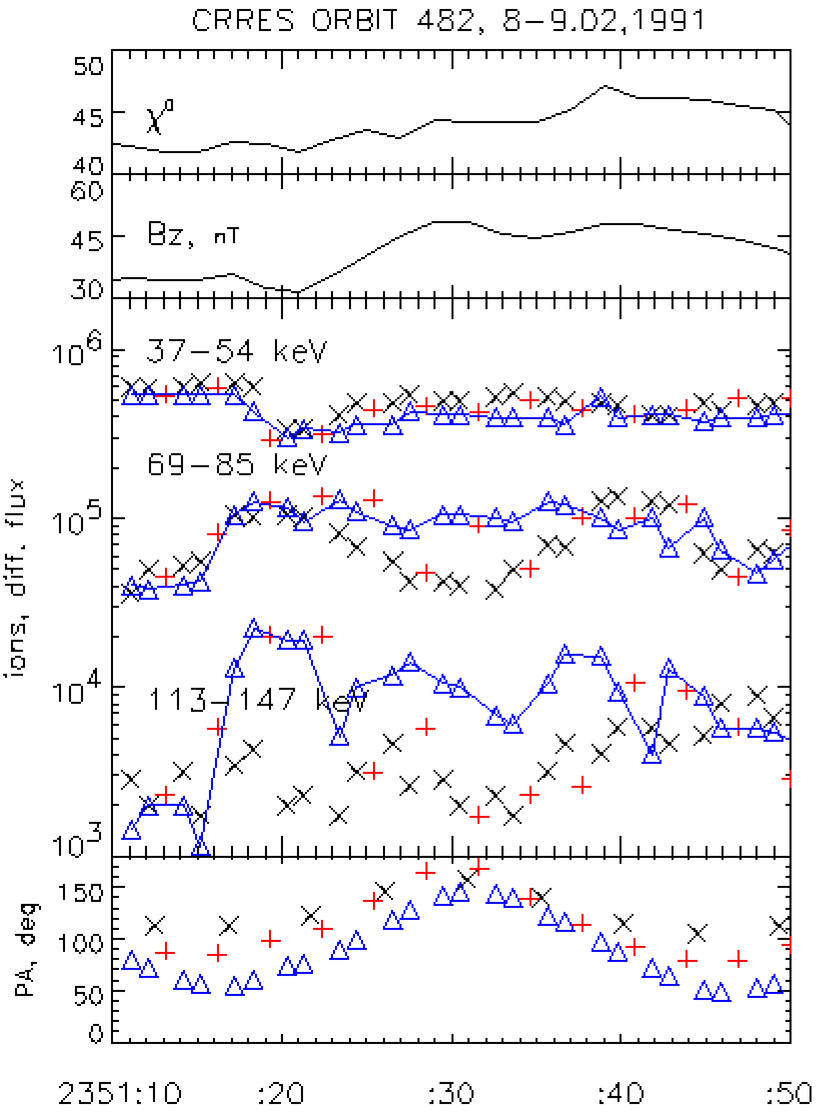


Fig. 16. The burst of ions on February 8, 1991 measured with maximum time resolution (P 1, 3, 5). The data of measurements by the detectors p1, p2, and p3 are denoted by skew crosses, pluses, and triangles, respectively.

So far we can only state the existence of a sharp boundary and fast displacements of the region of acceleration of energetic ions immediately in the process of growth of the particle intensity.

Figure 17 presents the plots of variations of the energy spectra of ions separately for the first and third detectors. Again we see the initial acceleration in a limited energy range with a subsequent displacement to the region of higher energies. The difference in measurements by the first and third detectors is clearly seen if one compares the character of variation of the energy spectrum of ions. The sharp boundary of the acceleration region had been located near the satellite at first seconds of acceleration, and then it reached the satellite.

The second enhancement of ions at 23:59 UT has the characteristics that have been noticed in several preceding cases: the initial acceleration is observed in a limited energy range, and then more energetic particles come into play. At first the acceleration of trapped ions prevails. The increase of particles with high longitudinal velocities is delayed by approximately a minute. In the energy channels from the second to fourth one can see in the maximum of enhancement a transition from trapped to a flat pitch-angle distribution. This effect does not exist for energies above 100 keV. The drop of intensity in the first channel accompanies this enhancement, and it has a smooth

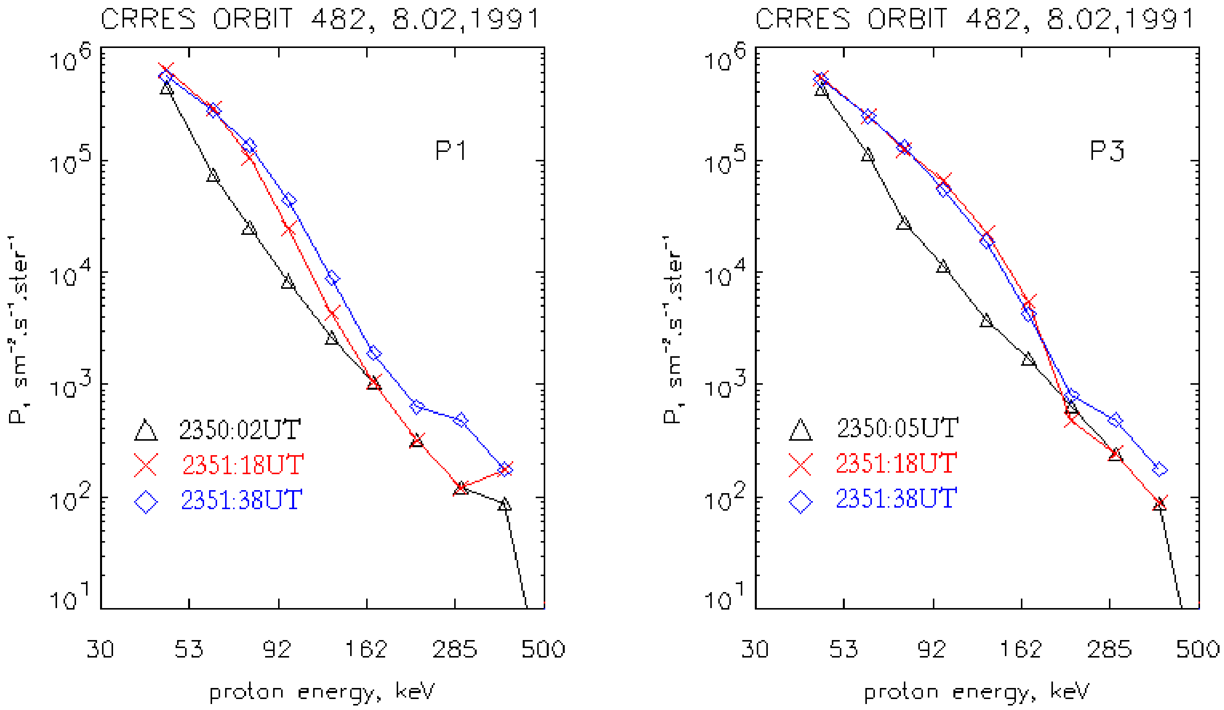


Fig. 17. Transformation of the energy spectrum of ions as measured by the first and third detectors, orbit 482 on February 8, 1991.

character. The magnetic field behave itself as is usual when the ion flux increases (Bz decreases, and field lines are stretched into the magnetotail), but subsequent dipolization is rather smooth, and the effect in electron fluxes is insignificant.

3. DISCUSSION OF RESULTS

3.1. A Short Summary of the Results of Measurements

Thus, we have considered 15 events of enhancements of the flux of energetic ions near the beginning of the substorm expansion phase. The sharp front of intensity rise (< 10 s from the beginning to the enhancement maximum) served as a criterion of selection of these events. Characteristics of the bursts of fast ions are summarized in Table 2.

The first column presents the orbit number and the number of an event in this orbit, the second column gives the delay of the beginning of dipolization with respect to the beginning of ion flux enhancement. One can see that all events can be divided in two groups according to the value of this parameter: the events with a delay less than 15 s and those with delays from 80 to 120 s. The sign '+' in the third and fourth columns means that the local dipolization and the increase (injection) of electrons are clearly identified. Then follow the approximate duration of the ion burst (it depends on energy, and this is why it is approximate) and the delay of the beginning of a burst of energetic ions relative to the preceding burst of ions of lower energies. Two columns that characterize the energy spectrum of ion bursts present the minimum energy (or energy range) of accelerated ions and the spectrum type. The type 1 spectra have a limited energy range (both from above and from below) and the maximum amplitude in the middle of it. The spectra of the second type have a clear cut lower limit of energy, while the upper limit usually cannot be determined because of low statistics. Notice that in all cases considered the enhanced slowly varying fluxes of auroral particles have already existed at the moment of detection of fast ion bursts. There is an obvious correlation

Table 2. Characteristics of fast ion bursts

1	2	3	4	5	6	7	8
Орб	dTs	Bz	e	T,s	DT2	Em	S
445.1	20	+	+	200	70	50	1
445.2	12	+	+	120		<100	1
445.3		~	-	120	120	200	1-2
445.4	10	+	+	25		>300	2
553	15	+	-	80		70-200	2
527	5	+	+	250		60-250	
497.1	100	+	~	100	240	>150	1-2
497.2	120	+	+	120		>150	
497.3		-	-	360	30	>100	1
497.4	6	+	+	30		>150	1
486	80	+	-	180		>150	
482.1	7	+	+	120	100	>70	1
482.2	100	+	-	300		>50	2
553s	-20			5		>120	
486s	-10			10		>150	
445s	+35			~10		>150	

of such low increase with the increase of the magnetic field strength. Most cases are associated with local activations of substorms, though there are exceptions that will be discussed separately. The typical sequence of events is as follows.

1. A gradual increase of the fluxes of electrons and protons in the lower channels (20--50 keV).
2. A fast burst of energetic ions, sometimes in two--three steps, the energy is higher in the second step.
3. Then, a drop of the ion fluxes in the lower channels (< 50 keV) follows (or proceeds almost simultaneously).
4. Dipolization of the magnetic field and injection of energetic electrons.
5. Activation continues, and an expansion of the disturbance is observed.

Sufficiently quick dipolization (seconds) and almost dispersionless injection of electrons that accompanies it are the evidence of a local activation. The slower dipolization (1-3 min) and less definite injection of particles (or the absence of one of these two features) can evidence that the satellite is located outside the local active region. One can see from the Table that ion bursts with duration of 25-250 s are related to local activation of substorms (type 1, the basic one). During three bursts that last 300-600 s there are no activations (type 2). And, finally, three very short bursts (< 15 s) at the end of the Table are also not accompanied by any manifestation of activations according to the data available for us (type 3). It well may be that these three very short bursts are precursors of future activations, being by their nature intimately related to subsequent main bursts of ions. According to the delay between the beginning of an ion burst and the onset of dipolization the basic events can be divided in two approximately equal groups: in one the delay is equal to 5-15 s, while another has delays of one-two minutes. It is not clear whether this distinction is sufficient that one could speak about different origin of these bursts (other their features are identical). Both of these groups have a sharp leading edge, and their typical duration is 2--3 min so that they terminate already after the end of local activations.

The majority of bursts are preceded by an enhancement due to the satellite entrance into the plasma sheet or as a consequence of a general increase of activity in the magnetosphere. Sometimes, before the main burst of intensity of high-energy ions an impulsive enhancement of less energetic ions is observed. As a result, the energy of particles involved in the enhancement gradually increases. (Let us remind that for enhancements with dispersion due to the drift arrival of ions from a source located to the east of the satellite the particle spectrum becomes softer in the course of time.)

We accentuate two types of events according to the character of their energy spectra. In the first type the energy range is limited, and the amplitude of enhancements decreases both for lower and for higher energies. The typical energy of the maximum enhancement is 150 keV, though in one case it was higher than 300 keV. Usually, such a character of the spectrum is observed on the front of the intensity increase. The second type demonstrates enhancements primarily in higher channels, one can clearly see in Fig. 13 how more energetic particles gradually move up. The second type frequently follows after the first one. It is not always possible to classify an event definitely as the first or the second type, since most commonly the counting rate in higher channels is small, and it is difficult to distinguish an enhancement from the background. Basically, it is possible that we deal in the case of the second type with dynamics of the radiation belt rather than with acceleration. This will be discussed somewhat later, let us first analyze the pitch-angle distribution.

The pitch-angle distribution of energetic particles on the slope of the radiation belt when the satellite moves from the Earth into the tail changes from trapped to the flat distribution, then to a butterfly-type distribution, and finally to isotropic one near the background boundary of trapping. In the cases under analysis the distribution remained either trapped or flat. The complete pitch-angle distribution of particles onboard the CRRES satellite can be measured only with averaging over longer intervals than the period of satellite rotation equal to 30 s, therefore, one rarely succeeds in getting information on transformations at the growth front. Though an event was observed when the flat distribution measured before the burst conserved also at the burst peak, apparently, the example shown in Fig. 7 of preferential acceleration of the particles dwelling near the equatorial plane is the most typical.

Once the initial acceleration of trapped particles has stopped, the flux of field-aligned ions also increases, and this increase can be caused by dipolization of the magnetic field: the satellite turns out to be deeper, nearer to the maximum of the radiation belt. This means that a two-minute burst of ions should be divided in two parts: before the maximum and after the maximum and the beginning of dipolization, physics of acceleration being different in these two parts. The increase of field-aligned particle, as well as the second-type increase of intensity of energetic ions, can be essentially the effect of transformation of the local structure of the magnetosphere, with additional acceleration of the betatron type.

As a rule, the appearance of an additional flux of ions causes a decrease of the Bz component of the magnetic field and a stretching of field lines into the magnetotail. As has been demonstrated earlier [21], before the beginning of activation the energy density of ions becomes equal or exceeds the energy density of the magnetic field, which increases the local instability. In this case, it is precisely the burst of energetic ions that gives the last (and, probably, critical) contribution to this excess.

3.2. Ion Fluxes and Waves in the Magnetosphere

First of all, we should understand the origin of strong variability of the fluxes, energy spectrum, and pitch-angle distribution of ions (protons) in the zone of quasi-trapping in the disturbed magnetosphere. We also must try to answer the question about the mechanism of acceleration in the triggering bursts of ions. The following scenario seems to be most adequate for the characteristics described above. At the end of the preparatory phase and later, in the first minutes of activation expansion, the enhanced flux and nonuniform distribution of particles make up favorable conditions for driving waves or formation of folds on the aurora arc. Resonance interaction with these waves or irregularities generates a series of local bursts of the intensity of ions (protons) in a narrow energy range. Thus the inhomogeneous pattern of variations of energetic ions which we frequently observe comes into being. Some of these bursts are sufficiently strong in order to change the local structure of the magnetic field and to trigger the irreversible process of substorm instability development.

During magnetospheric substorms and, in particular, in the very beginning of a disturbance various types of magnetic pulsations are observed, their frequencies being close to the gyrofrequency of protons. First of all, the pulsations PiB or SIP (Short Irregular Pulsations) are worthy of notice. The SIP events on the ground strongly correlate with electron precipitation events identified using the data of photometers, rhiometers, and balloon measurements of X-ray emission. Pulsations IPDP have a maximum of their frequency of occurrence near 22 h LT. The mechanism of gyroresonance interaction between waves and particles is usually considered to explain the origin of micropulsations. For irregular pulsations of SIP and AIP types the interaction with electrons is essential, while interactions with protons generate IPDPs. It was shown by Shepherd et al. [40] who studied particle measurements onboard the GEOS-2 satellite simultaneously with the aurora intensities that dipolization coincided with a short amplification of E field up to 15 mV/m and a short ULF burst in the SIP range 0-1.5 Hz. The authors concluded that these waves were generated in the equatorial plane and that they were associated with induction fields. In [41] it was demonstrated that strong SIP events observed in the very beginning of substorms coincided with a sharp dipolization of the magnetic field at the satellite. In addition, very intense spikes in E field (3-25 mV/m) had been observed 10--20 s earlier than SIP. In authors' opinion, in addition to manifestations of electromagnetic turbulence, the SIP events can include the magnetic field effects related to filed-aligned currents flowing near the satellite with a high velocity. Roux [38] studied the variations of particle fluxes and magnetic field onboard the geosynchronous GEOS-2 satellite simultaneously with ground-based observations of aurorae during substorms. The WTS was shown to be an ionospheric manifestation of a large-scale instability on the border between the field lines stretched into the tail and more dipole field lines. The gradient of particle pressure and azimuth (to the west) drift of energetic ions are a source of energy for this instability of the Rayleigh--Taylor type. In this case, a system of field-aligned currents is formed which later cascades to smaller scales. The appearance of a high-frequency component with a quasi-period of 1 s (approximately corresponds to the local gyroperiod of ions) coincided to WTS passage near the satellite projection onto the ionosphere. The development of large-scale bends, shear flows, and wortexes, as well as relations of these instabilities to pressure gradients, was studied in [42--43] and other papers.

Thus, the above suggested explanation of bursts and variations of energetic ions as produced due to interaction with enhanced activity of waves and spatial irregularities has sufficiently convincing experimental and theoretical support.

3.3. Injection of Particles and a Scenario of Expansion Instability of Substorms

The bursts of energetic protons and electrons in the magnetosphere during the substorm expansion were detected long ago and by many authors. McIlwain [30] interpreted these bursts as simultaneous 'throwing-in', injection of electrons and ions in a wide energy range, and he has determined the position of the injection boundary depending on a magnetic activity level. At the same time, detailed analysis with improved time resolution shows that injections of electrons and protons are far from being simultaneous. A certain natural effect of delay of the particles of one type can be obtained at a statistical analysis due to different directions of drift for ions and electrons. However, even at correct accounting for drift effects an anisotropy of the fluxes of protons and electrons was noted [44], and the existence of a very local induction field was hypothesized to explain it. In [23, 26] the appearance of ion bursts before the beginning of electron increase and magnetic field dipolization was observed. In [27] it was obtained that electron bursts

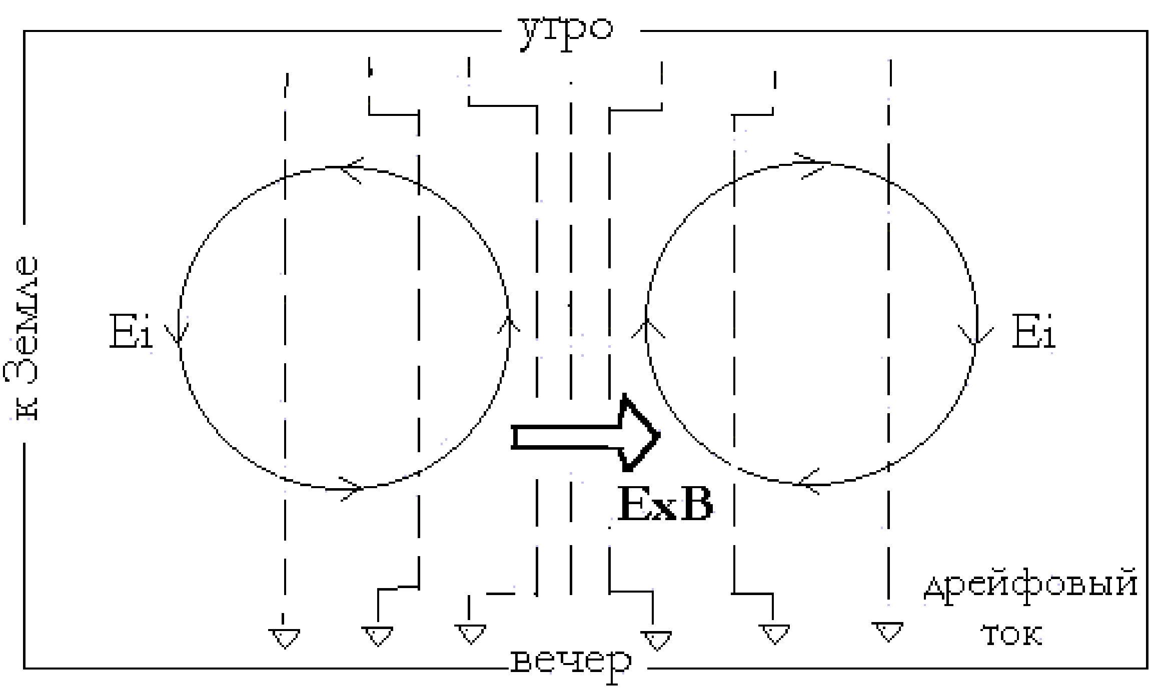


Fig. 18. A scheme of the induction field generated at a local increase of the flux of energetic ions.

on CRRES could also appear before the main injection of a substorm. In this case, they also correlated with bursts of dBd/t. Using the data of a spectrophotometer of aurora the hydrogen glow was revealed in [45] on average 4 min before the beginning of a break-up.

If the induction field is localized and its action is limited in time, one cannot expect a homogeneous response of particles of different sign and energy. Even for ions of a fixed energy the effect of acceleration by the induction field will essentially depend on the initial coordinates and the phase of cyclotron rotation. In the model suggested by Heikkila and Pellinen [46-48] a small local reduction of the flux of drifting ions will be supported and amplified because of the action of the induction electric field. Two wortexes of electric field generated in this case lead to the appearance of polarization fields that have a longitudinal component necessary for development of a substorm current wedge. The calculations of acceleration of energetic particles made by Heikkila and Pellinen for a negative meander, which in author's opinion is the most efficient for particle acceleration, confirm the complicated spatial pattern of acceleration, different for electrons and protons.

(i) Proton bursts occur mainly beyond the current loop to the west of it. Some protons can remain confined inside the loop (this depends on the initial position of particles).
(ii) Energetic electrons appear on both the east and west sides of the loop.
A local reduction of current was considered in the model by Heikkila and Pellinen as the initial disturbance. The initial disturbance in the form of a local amplification of the drift current will also result in the appearance of two wortexes of the induction field, but in the different modification shown in Fig. 18. The induction field is directed so that the current increase would be reduced. As a result, the radial drift of ions from the Earth to the tail arises, which will amplify the local increase of current, since the gradient of density of the particles of the radiation belt is directed to the Earth. At the same time on the inner edge of the plasma sheet the density gradient is directed from the

Earth, and one can expect a drop of intensity in the low energy channels at radial drift away from the Earth.
As opposed to the scheme of Heikkila and Pellinen, here the inner rather than outer meander will be the main one (but also negative), and all arguments of these authors concerning the generation of the longitudinal field, current wedge, and acceleration of energetic particles are quite applicable. Obviously, the pattern described above is rather simplified. At present, instead of simple schemes, computer modeling of the substorm processes [13, 49] is developing quickly. The proper choice of reference experimental data plays an important role for its successful application.

CONCLUSIONS

In spite of a great variety in development of individual transitions from the growth phase of a substorm to its expansion phase (local activations detected by satellites), one can describe the following chain of events: gradual increase of the flux of particles, ions and electrons with energies of tens of keV, at the end of global or local growth phase; then (in a quick sequence) a sharp growth of the flux of energetic ions, a drop of intensity of ions with moderate energies, dipolization of the magnetic field, and an increase of intensity of energetic electrons. When the analysis was made using the data with insufficient time resolution, these events frequently were not decomposed in a chain. They were assumed to occur simultaneously. Even the time resolution available for us (1-2 s) is often insufficient in order to reveal the details of this process, since the beginning of ions acceleration is sometimes ahead of the beginning of dipolization by a few seconds and, as a rule, by no more than 15-20 s.
In this sequence of substorm instability a quick (several seconds) acceleration of energetic ions (protons) is the initial event preceding the dipolization. If we continue to believe that reduction of the convection electric field is, most likely, the global factor triggering the expansion phase of substorms, we can assume that a fast increase of the flux of energetic ions can serve as a local trigger of substorm activation.
One can isolate the following characteristic features of ion dynamics.
1. Incoherent behavior, lack of coordination in variations of energetic ions in close limited parts of their energy spectrum is, as was demonstrated above, a common property of the disturbed auroral magnetosphere. Quick bursts are a separate class of these variations causing significant consequences in the development of substorms.
2. The rise time of ion intensity varies from one second to a few seconds.
3. The absence of dispersion in energy is testimony to local acceleration of particles.
4. The acceleration of ions on the front of an increase proceeds in a limited energy range, the average energy being from 50 to 300 keV.
5. Upon termination of the intensity growth (and after the beginning of dipolization) the flux of more energetic particles increases, while that of less energetic particles decreases.
6. The bursts are divided in two groups with duration of 10-15 s and 100-200 s. The first type does not result in activation. The second type triggers the substorm instability with local dipolization and acceleration of energetic electrons.
7. The drop of ion intensity at the end of a burst has dispersion in energies: particles of higher energies are swept away by magnetic drift more quickly. The dispersion allows one to estimate the azimuthal dimension of the acceleration region as 1-2 degrees for short bursts (for 6 ER this equals about 700-1400 km). The azimuth extension of long bursts can be substantially larger.
8. At first the particles with pitch angles of about 90˚ are preferentially accelerated. Then the dynamic changes caused by dipolization begin to control intensity variations and the pitch-angle distribution. Transformation of the energy spectrum in time leads to an increasing number of particles with higher energies (the second type of acceleration).

9. The effects observed can be explained by the following chain of events of local explosive instability: excitation of waves - a burst of energetic ions - a current meander - a current discontinuity and formation of a substorm current wedge. The initial stage of this chain can correspond to ballooning or drift-ballooning instability, while the next stage is closer to instability of the current discontinuity type.

Table 1 EPAS / CRRES energy channels.

№	1	2	3	4	5	6	7	8	9	10
Electrons, KeV	21.5 - 31.5	31,5 -40	40-49.5	49.5-59	59-69	69-81	81-94.5	94.5-112	112-129.5	129.5-151
Protons, keV	37-54	54-69	69-85	85-113	113-147	147-193	193-254	254-335	335-447	447-602

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