Fast Bursts of High Energy Protons and Their Role in Triggering of the Substorm Onset Instability

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Abstract. Several seconds prior to the local substorm onset (beginning of the dipolarization) the fast increases of a high energy ion flux were observed by CRRES particle detector within energy range restricted from the bellow at 50-200 keV level. It is possible that these bursts are responsible for the triggering of onset instability. The absence of simultaneous increase of the electrons and the middle energy ions suggests a resonant acceleration of the trigger bursts.

1. Introduction

Increase of the flux of auroral electrons and ions in the geosynchronous region known as particle injections stay as one of the basic elements of the substorm explosive instability. Since the first papers on injection boundaries by *McIlwain* [1974] it was clear, that injections occur on the closed field lines in a trapping or quasi-trapping zone. That directly follows from the measured spatial and pitch-angle distributions of energetic particles described in a number of case studies.
During the acceleration, part of energetic electrons precipitates into the atmosphere and associated bremstrahlung X-ray bursts were registered on balloon experiments simultaneously with an auroral breakup [*Winckler et al.*, 1958, *Barcus*, 1965] Thus, dispersionless injections of energetic particles registered on satellites in geosynchronous area are unambiguously connected, conjugate to explosive onset of a auroral substorms. The study of the fine structure of injections helps to reveal mechanisms of development of explosive instability of a substorm.

Injections of electrons and ions can be described as simultaneous only at the poor temporary resolution. Improvement of the temporal resolution to few seconds shows that injections are a mosaic of localized short flux enhancements with complicated dependence of a bursts structures on the type, energy and pitch-angle distribution of particles. It is clear that microscale processes are important if not predominant in substorm activity expansion as compared with macroscale one. But the substorm models including microscale structure are not arrived jet.

The most complicated temporal structure exhibit ions (protons) fluxes. Ion dynamics deserve special attention because of their importance as a current carriers and critical role on energy density balance. The arrival of the energetic ions several minutes before the local onset of the substorm creates the enhanced growth phase effect (EGP) described by *Ohtani et al.* [1994]. The "taillike" extension of magnetic field lines during EGP was explained by diamagnetic effect and local strengthening of a partial ring current which prepare local substorm instability [*Lazutin et al.*, 1998].

In the present work we examine the details of energetic ions dynamics before the local electron injection and magnetic field dipolarization. We found that high energy ion bursts with fast growth of intensity are the first and probably triggering element of the explosive substorm activation.

2. Measurements

In a short paper we only can present several examples of typical energetic proton behavior during substorm onset. All examples belong to the CRRES substorm events already examined and described in several publications. That releases us from necessity to provide the detailed descriptions of substorm activity. We use the best possible resolution of particle detector which is between 1 and 2 s. The data on a magnetic field have 2s resolution.

It is necessary to indicate, that the substorm explosive phase starts in the limited area, and the probability that our satellite happens to be in this area, is small. More often satellites detect one of the repetitive activations in a region of poleward (tailward) expansion with some temporary delay to the beginning of a substorm. As a result, the effects observed by CRRES may be divided into two parts - fast events of the local onset and slow changes related both to the continuation of the growth phase and distant effects of the active phase started in another place. The satellite might be located at some distance from the region of the particle acceleration which causes an energy dispersion. For our study we chose events with small or negligible dispersion, which suggests that satellite was near or inside the active region.

We regard the beginning of magnetic field dipolarization and energetic electron injection as a starting moment of the local explosive instability.

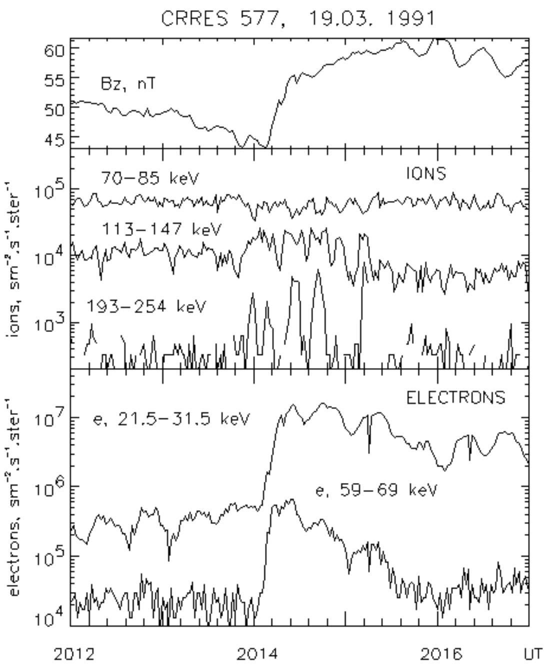


Figure 1. CRRES orbit 577, 19.03.1991. From top to bottom: Magnetic field Bz component, ion differential channels 3,5 and 7 (69-85 keV, 113-147 keV, 193-254 keV), and electron 21.5-31.5 keV and 59-69 kev channels. 30s periodicity reveals pitch angle asymmetry.

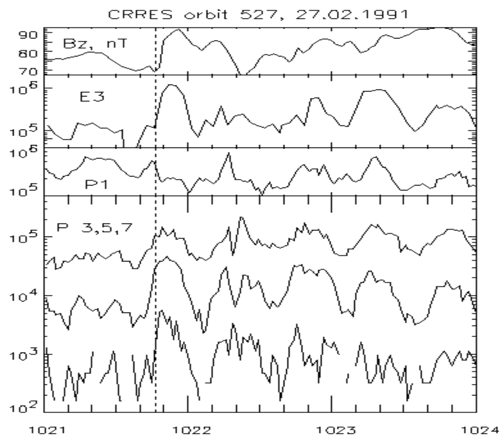


Figure 2. CRRES orbit 527, 27.02.1991. E3 and P1 channel registers electrons 40-49.5 keV, and ions 37-54 keV accordingly. Three other ion channels are the same as on figure 1.

Figure 1 gives a typical picture of local substorm onset identified by fast increase of the auroral electron intensity and magnetic field dipolarization. About 20s prior to the onset sharp increase of the ion intensity was registered. The total duration of the ion burst was 80s and the deep modulation of particle flux indicates on pitch angle anisotropy. The energy range of the accelerated ions was restricted from the bellow at 100 keV level, and the maximum increase was registered at 200 keV. In low energy channels decrease of the ion intensity was observed simultaneously with high energy particle increase.

Figure 2 shows another example of the local onset with dispersionless ion and electron injection. When the most possible resolution was applied, it was found that there is several second delay between ion and electron increase. Ion intensity reached maximum when electron increase and magnetic field dipolarization barely started. Again intensity decrease was registered in low energy channels simultaneously with dipolarization and electron increase.

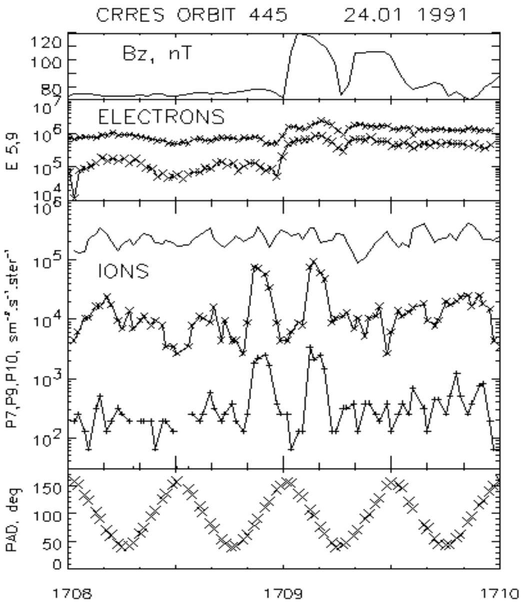


Figure 3. CRRES orbit 445, 24.01.1991. Magnetic field Bz component. Electrons 59-69 keV and 112-129.5 keV. Ions 193-254 keV, 337-447 keV and 447-602 keV. Bottom section shows pitch-angle view of the ion detector.

Figure 3 presents an example of short activation with the same features as in the above two cases. Let us note, that field-aligned ion flux remains at unadisturbed level and that the low energy threshold was unusually high, about 300 keV. The increase of the ion intensity in the burst is very sharp, usually lasts only several seconds

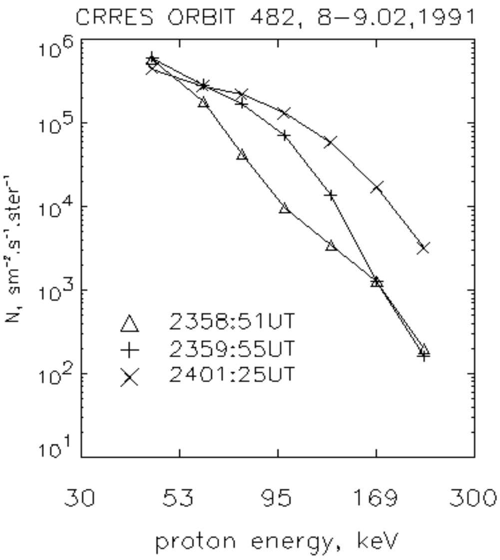


Figure 4. Evolution of the ion energy spectrum before, after the beginning and at the end of the fast ion burst, 8-9.02.1991, CRRES orbit 482.

and in some cases equal or less than one second (at the limit of the resolution). Energy dispersion in analyzed cases was absent or negligible.

Figure 4 presents typical dynamics of the ion energy spectrum before the burst, at the maximum and two minutes later. One can see the acceleration in the restricted energy range during the first seconds followed by the flux decrease in low energies and delayed increase at the high energy part of the spectrum.

On a figure 5 pitch angle distributions of ions on prior to the beginning of increase and in a maximum of burst for two energy channels are given. Three different sighs corresponds to three ion detectors with different direction of the field of view. The ion variations in these two channels are so dissimilar that it is possible to state that there are two different populations of particles. The energetic ions are accelerated, while intensity of low-energy ones decreases. Only trapped near to the equatorial plane particles change intensity, whereas particles with pitch angles from 0º up to 45º of degrees does not vary.

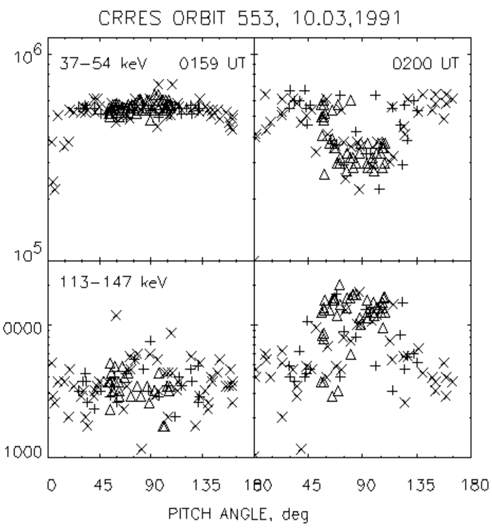


Figure 5. Changes of the pitch angle distribution of 37-54 keV and 113-147 keV ions intesity, 10.03.91, CRRES orbit 553

3. Discussion

In this section we will summarize characteristics of fast bursts of energetic ions and discuss possible mechanisms of acceleration and role of energetic ions in triggering of explosive instability of a substorm.

3.1 Fast Bursts of Energetic Ions

It is important to note, that fast bursts of ions and following local substorm onset occurs on the background which differs from the quiet time one. As a consequence of the growth phase and/or a distant effects of global substorm onset, the electron and ion fluxes gradually grow and magnetic field fluctuates. The effect of the dipolarization caused by distant local onsets is small and may be interrupted by taillike stretching (EGP - effect).

On a background of slow variations of particles flux and magnetic field, immediately before the beginning of a local explosive activation, we found fast bursts of energetic ions originating without any visible accompanied effects. It is the first, leading event of an instability. Let's summarize the main characteristics of fast bursts.

Duration of the bursts vary from 10-15s to several minutes. Shortest bursts are not followed by the instability, as opposite to the bursts with typical duration of 2 minutes. Its start up before and ended after the beginning of local activation. The front of intensity increase vary from less than 1s up to 10-15s. There are no doubts that the energetic ions are accelerated on a point of measurement or close to it, because energy dispersion is insignificant.

The energy range of accelerated ions is limited from the below. The smallest energy of the accelerated ions varies from 50 keV up to 300 keV, the upper limit can be above 500 keV. The maximum relative amplitude of the increase registers in the middle of the energy range, at 100-200 keV.

Dynamics of the ions of smaller energies is opposite to the high energy ones, decrease of the intensity is registered simultaneously with the magnetic field dipolarization. The difference may be explained as follows: low energy ions are magnetized and moving with the conservation of the adiabatic invariants, while the energetic ions are not moving adiabatically.

The pancake or trapped pitch-angle distribution of the freshly accelerated particles is observed. Ions with pitch-angle of 90˚ are preferentially accelerated. Later on an enhanced particle flux may appear on smaller pitch-angles, but that occurs after the local substorm onset.

3.2 On the Mechanism of Acceleration of Fast Bursts of the Ions

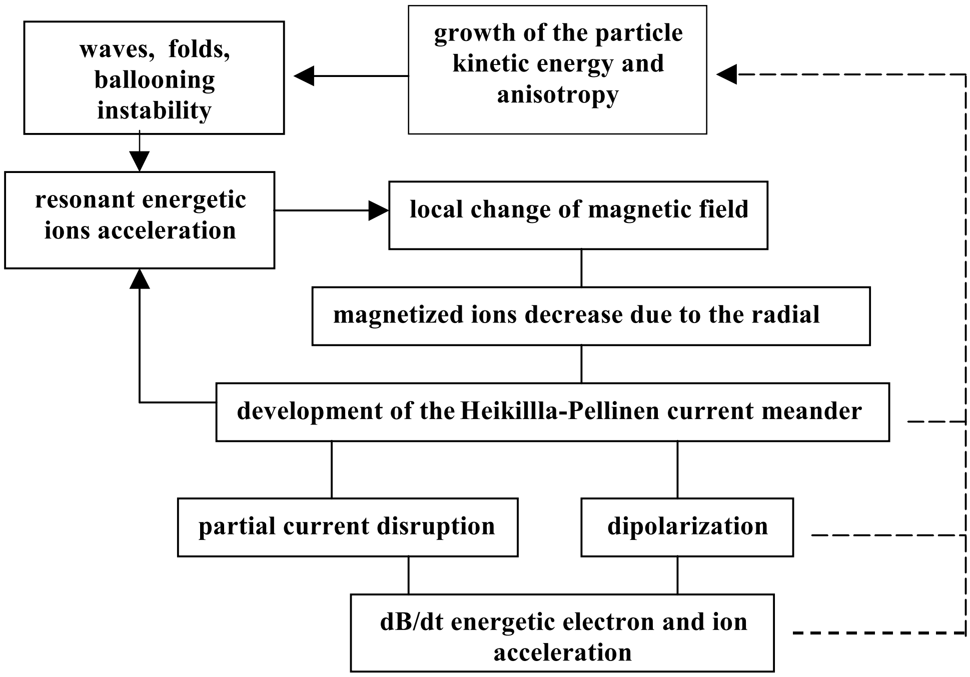
The above mentioned characteristics of hard ion bursts allows to limit the choice of possible mechanism of acceleration of ions. Main criteria for selection are following: the mechanism should be fast and selective (the electrons and ions of middle energies are not accelerated). It should be effective predominantly in the equatorial plane and must increase perpendicular component of particle energy.

By the first criterion such slow mechanisms, as stochastic or drift-resonant acceleration should be rejected. By the second criterion the combined drift in an electrical and magnetic field could not be considered also because it should also accelerate electrons and ions of all energies. Should be rejected also the mechanism of acceleration by inductive electric field, as the magnetic field at the first seconds of acceleration varies weakly and because the electrons must be also accelerated by the inductive electric field.

Only certain resonant mechanism of acceleration, selectively operating on ions (protons) in the restricted range of energies can satisfy to all listed above conditions. The dimension of the resonant structures and the frequency range must be close to the gyroradius and gyrofrequency of the energetic ions. For example the kinetic ballooning instability discussed by *Cheng and Lui*, [1998] may create the resonant structures with geometry comparable to energetic ion gyroradius. Protons with an energy 100 keV have hyroradius about 1000 km in a field 50 nT, in a projection to an ionosphere it make about 100 km. Curving and folds of auroral arcs are approximately of the same size. Tre resonant wave frequency ought to be about 5-10 Hz, Among the magnetic pulsations observed by the magnetometers in auroral zone possibly the best are PiB bursts which last some minutes and well coincide with Pi2 pulse , i.e. with activations of a substorm.

It is necessary to note, that resonant ion acceleration may explain also frequently observed ion flux variations during the substorm active phase with considerable difference between nearest energy channels.

Table 1. Substorm onset scheme



3.3 On the Geometry of Explosive Instability

Current disruption and development of a substorm current wedge are important elements of the inner magnetosphere substorm models. Disruption does not mean disappearance of a current carriers, energetic protons of a partial ring current. Even in the strong diffusion mode the noticeable decrease of ion flux by precipitation requires minutes, while we need seconds. Suggestion that disruption is a result of the chaotization of ions motion needs experimental support. From the energetic ion data we do not see any indications of such chaotization. The process, which can produce fast local weakening of a drift current was proposed by Lazutin [2000], it is the the radial shift of drift trajectories of ions at the region of a strong radial gradient. The resulting structure similar to the meander described by Heikilla and Pellinen [1974], is capable to explain selective acceleration of ions, local dipolarization, and derivation of a current wedge of a substorm.

The sequence of events might be illustrated by scheme presented by Table 1 and described as following.

At the end of a growth phase and further first minutes of expansion of activity the increase of the flux and spatial inhomogeneous of particles creates favorable conditions for the development of the macroscale instability (for example, the kinetic ballooning instability) . Fragmentation or folds on an auroral arcs are the visible sequence of this process. The resonant interaction with these waves or folds creates a series of localized intensity increases of ions (protons) in a narrow range of energies. Some of these bursts are intense enough to change the local structure of a magnetic field and to cause radial shift of drift orbits of magnetized ions of smaller energies. Decrease of the ion flux will create the meander described in Heikilla - Pellinen model providing the positive feedback necessary for support strengthening of a current disruption, current wedge and dipolarization of a magnetic field with acceleration of energetic electrons by induced electric field.

Repetition of such microscale structures will create complicated mosaic of development of auroral substorm active phase or substorm superposition.

4. Conclusion

The fast bursts of energetic ions in the limited range of energies are the widespread phenomenon in the disturbed auroral magnetosphere. The absence of an energy dispersion testifies to local acceleration of particles. The lower boundary energy of ions in bursts - from 50 up to 200 keV. The particles with pitch angles close to 90˚ are primarily accelerated.

Ion bursts duration vary from 10-15s to 100-200s. Short bursts either do not initiate an activation, or cause an activation not passing into the substorm. Long type cause substorm instability with a local dipolarization and acceleration of energetic electrons.

The growth of intensity is very fast - from less than one second to about several seconds. The decline of intensity has a dispersion on energies - particle of the large energies are faster taken out by magnetic drift. The dispersion allows to estimate azimuthal area of acceleration about 1-2 degrees.

Fast growth of the auroral electrons flux, decrease of the ion intensity in the low -energy channels and dipolarization of the local magnetic field are observed with delay of 5-20s after the beginning of the ion bursts.

We propose to explain observable effects by a resonant mechanism of energetic ion acceleration. The increase of the energetic ion flux may trigger local explosive instability with creation of a Heikilla-Pellinen meander and current wedge of a substorm.

Acknowledgments
The work of TK was supported by grant RFBR-01-05-64827.

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