ON RADIATION BELT DYNAMICS DURING MAGNETIC STORMS

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Abstract

Temporal variations of the radiation belt particle during the magnetic storms are investigated using measurements by the low altitude satellite spectrometer. Along with several known effects, such as the outer radiation belt intensity decrease at the main phase, the radial diffusion with the particle acceleration and the recovery of the radiation belt during the recovery phase, some less known features were investigated, such as the dawn-dusk asymmetry of the radiation belt. During the main phase in the dusk sector an extension of the outer magnetic field lines into magnetotail occurs, the electron flux previously measured in the outer radiation belt maximum decreases to the polar cap level. All three adiabatic invariants remain conserved during this transformation and as a consequence the radiation belt became adiabatically shifted to the lower latitudes with addition of the nonadiabatic radial displacement.

During the main phase in the dawn sector the chain of the substorm dipolarizations is acting against the tailward magnetic field line extension produced by the ring current and satellite registers an enhanced particle flux in the quasitrapping region.

The adiabatic recovery of the radiation belt take place at the end of the magnetic storm again with the addition of the nonadiabatic effects caused by the substorm activity.

It seems that a essential part of the radiation belt temporal dynamics during magnetic storms may be explained by the change of the magnetic field configuration and the adiabatic effects. Together with the nonadiabatic radial diffusion it results in the radial displacement of the outer radiation belt rather than the large losses or total disappearance of the outer radiation belt.

1. Introduction

The relativistic electron dynamics in the radiation belts during magnetic storms have been measured nearly continuously in space for more than four decades. The problems of the radiation belt transformation, particle acceleration and losses are studied intensively, especially for electrons, because of the dramatic consequences of the relativistic electron enhancements for space weather. All possible acceleration and loss mechanisms are described, theories for each of these processes are well developed (see reviews by Friedel et al. 2002, Antonova et al., 2009, Sprits et al., 2008, 2008a and references therein), but relative contributions on different phases of the magnetic storm are not well known. As a result, after the storms both flux decrease and losses may be registered (Reeves et al., 2003), Progress in understanding of the variability of the effects requires more experimental studies of the particle dynamics during individual storms.

The decrease of the energetic electron fluxes, may be caused by ionization losses, pitch-angle diffusion into the loss cone and magnetopause shadowing effect (See review by Milan and Thorne, 2007). Pitch-angle diffusion for the relativistic electrons is driven by the parasitic resonance with plasmaspheric hiss and whistlers and also with electromagnetic ion-cyclotron (EMIC) waves created by the ring current protons during magnetic storms (Meredith et al., 2003, Summers and Thorne, 2003).

The resonant interaction of the energetic electron with whistler-mode chorus waves is not only responsible for the losses, but is capable to accelerate electrons to relativistic energies (Chen et al., 2007, Horne et al., 2007, Meredith et al., 2002). Another and possibly the most important mechanism of the radiation belt electrons enhancement is the inward radial diffusion with magnetic moment conservation through magnetic drift resonance with enhanced ULF waves (Lanzerotti et al., 1970, Elkington et al., 1999, Loto'aniu et al., 2006, Fei et al., 2006, Sarris and Temerin, 2006, Thorne et al., 2007, Spritz et al., 2008), or other radial transport mechanisms. Energetic protons are usually more stable, but during strong magnetic storms they are also affected by magnetosphere dynamics. Acceleration can be the result of the earthward radial diffusion which equally affects electrons and protons. Additional changes of the proton radiation belt are created by the solar cosmic rays. During strong storms solar protons penetrate into the inner magnetosphere down to L~3 and can be trapped on the closed drift shells (Li et al., 1993, Lorentzen et al., 2002, Lazutin et al., 2007, Kuznetsov et al., 2008).

Particle intensity decrease (or increase) can often be measured by the satellites just because of the change of magnetic field configuration and radial shift of the magnetic drift shells. One of the known effects of this category is so called Dst-effect based on the conservation of the all three adiabatic invariants (McIlwain, 1966, Kim and Chan, 1997, Li et al., 1997). If the third adiabatic invariant is conserved, which can be the case during the main phase of the magnetic storm, the Dst effect will bring energetic particle to the new drift shell shifted outward in order to conserve the magnetic flux through the surface inside the magnetic drift orbit. If the new magnetic field line is longer than the previous one, conservation of the second adiabatic invariant will lead to the upward shift of the particle mirror point and consequently to decrease of the particle energy. This shift and cooling will result in decrease of the particle flux measured by satellite. The Dst effect during the recovery phase must adiabatically return particle population to the pre-storm condition, if there will not be other forces changing particle energy and position during the magnetic storm.

The present work is a case study of energetic electron dynamics during several magnetic storms based on a single low altitude satellite particle measurements. It is an attempt to show that even such restricted data analyzed with possible available temporal resolution may be useful for the understanding of the radiation belt dynamics during the magnetic storms. Some effects, such as a wave-particle interaction can not be studied here, but many other papers were concentrated on these subjects. Other effects, namely the influence of the magnetosphere configuration and drift shell motion on observed particle flux variations will be clearly seen in this study giving some new results.

The case studies based on the measurements of a single satellite have obvious restrictions. The addition of the other satellite data, especially in the equatorial plane, can provide more information, but that will be a different study. The interpretations of the measurements reflect the opinion of the author and not always will coincide with opinion of some other researchers.

2. Observations

The present work is based on the energetic electron and proton measurements made by the low-altitude polar orbiter SERVIS-1 (Space Environment Reliability Verification Integrated System). SERVIS-1 was developed by the Institute for Unmanned Space Experiment Free Flyer (USEF), Japan, and launched from Plesetsk Cosmodrome in Russia on October 30, 2003 on the Sun synchronous orbit in dawn-dusk plane, with the altitude of 1000 km and the inclination of 99.5°. Light Particle Detector (LPD) is a charged particle spectrometer which combines 0.5mm thick SSD and 24mm thick plastic scintillator. It has 60° field of view and oriented in the anti solar direction. The dawn-dusk orientation means that satellite orbits were located in a 06-18 local time meridian plane. Magnetic local time, which is more important for this study, was changing in the 2-8 and 15-20 MLT range accordingly.

We will use data of proton channel (1.2-12.5 MeV) and three electron channels (0.3-1.5 , 1.7-3.4 and 3.4-6.6 MeV) from the database provided by Prof. N. Hasebe from Waseda University, Japan.

In a text and figures only lower energies of the channel will be indicated.

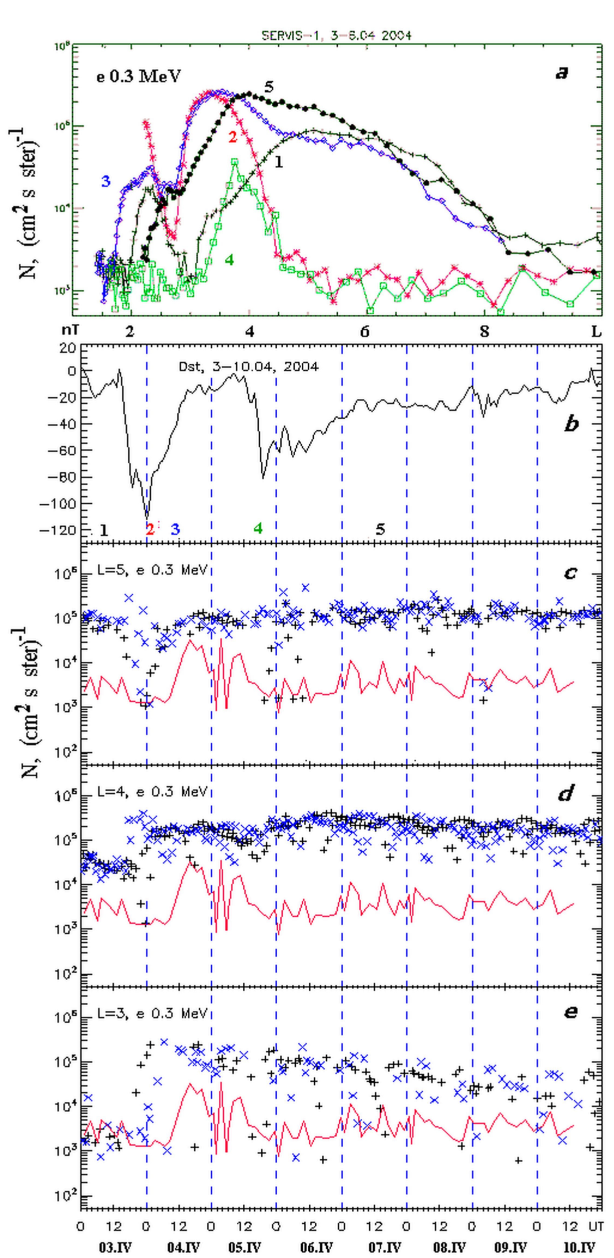

Fig 1. The April 3-5, 2004 magnetic storm. From top to the bottom: (a) several latitudinal profiles of the 0.3 MeV electrons at the moments indicated at Dst box (b), plots of the 0.3 MeV electron intensity at a fixed L during the April magnetic storm. Crosses and tilted crosses means the dawn and the dusk orbits accordingly. By the red solid line the electron intensity in the polar cap is shown (L=10).

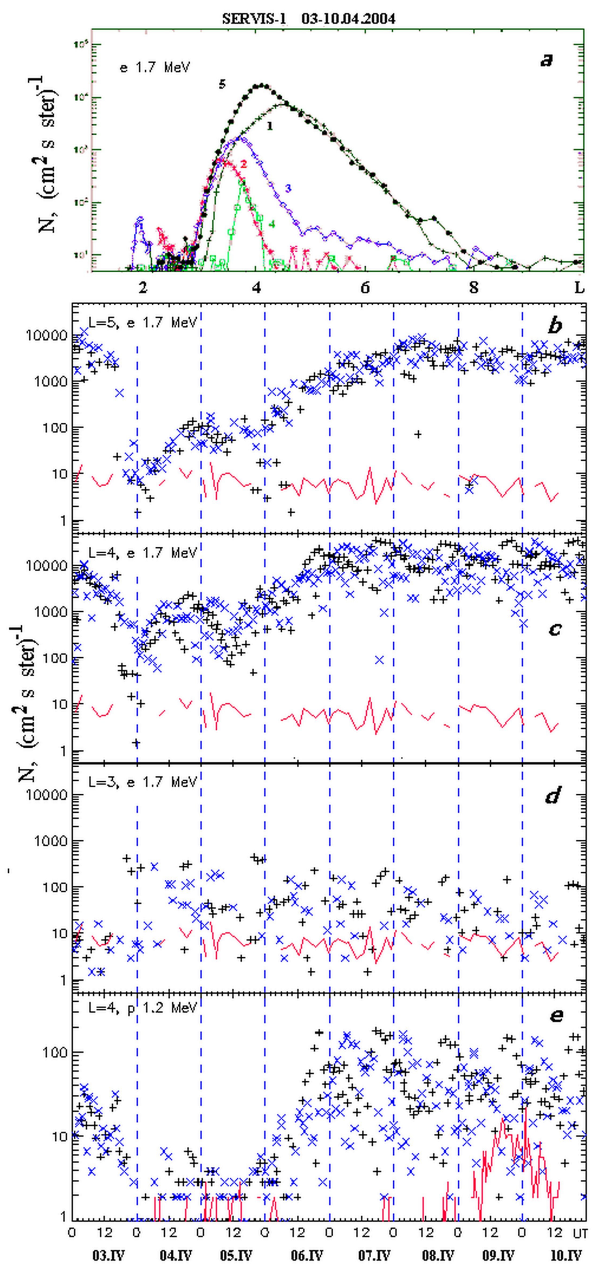

Fig 2. The plots of the 1.7 MeV electron latitudinal profiles and the intensity variations at a fixed L during April 3-5, 2004 magnetic storm similar to Fig 1. At the bottom box (e) the 1.2 MeV proton flux variation is presented.

The particle counting rates were taken every 4 s. Maximum counting rate was 200000 per second. The geometric factor 0.2 cm^2 ster. allows to measure electron flux up to 10^6 particles/ cm^2 s ster. In some figures the data of CORONAS-F polar orbiter, which have altitude 500 km, were used.

During 18 months from January 2004 to June 2005 28 magnetic storms with Dst < -45 nT occurred. The satellite data during all those storms were analyzed for the intensity changes. The detailed analysis of the energetic particle dynamics during three storms is presented below.

All particle data will be presented in two forms. In the first form several latitudinal profiles are given for each case study. During 90 minutes of the orbit period four latitudinal profiles of particle intensity were measured at the local evening or the local morning hours, which gives 64 profiles per day. As a rule we present profiles taken during the flights over Brazilian (South Atlantic) Magnetic Anomaly (BMA) which reflects particle profiles in the radiation belt before, after and in the middle of the storm.

The second type of figures presents electron or proton intensity measured at every orbits during this storm in some of the L positions (5, 4, 3.5 and 3) with deviations less than 1%. At some specific moments there is a difference between the dawn and dusk profiles due to the asymmetry of the magnetosphere, therefore we are using different signs for them.

In our study McIlwain L-coordinates calculated for the undisturbed conditions (IGRF field model) were used to indicate the satellite position. During the storm it does not necessarily correspond to the particle magnetic drift shells, it is just the analog of the corrected magnetic latitude (55, 58, 60 and 64 degrees for L=3, 3.5, 4 and 5). Coordinate system with L calculated for specific storm moments demand to introduce one of the existing magnetic field models, which are not perfect for the magnetic storms, especially for the strong ones. Roederer L* (L-star) might be better to use for the inner magnetosphere, but it demand a lot of computer time for the calculation and also reliable magnetic field model. L-star is directly proportional to the integral of the magnetic flux outlined by a charged particle drift orbit, which means that L-star cannot be calculated for quasitrapping region, where magnetic drift orbits are not closed, and where considerable part of our measurements was taken.

SERVIS-1 measured both trapped particle over BMA and precipitating flux in other longitudes.

The difference between them is clearly seen during the undisturbed conditions, for example on August 29 (Figure 10 b,c) , where at 06 UT in the morning passes over BMA (tilted crosses) registered flux exceeds the evening one (direct crosses). On 18 UT reverse relation was observed. Difference became smaller with the increase of intensity, and despite of the considerable point dispersion, it allows to study temporal variations of the intensity of the electron flux. In the following case studies we will mention possible explanation of the observed effects, but more extended discussion will be given in the last chapter.

2.1 April 3-5, 2004 Magnetic Storm

It was a double structured magnetic storm with Dst minimum -110 and -80 nT.
In the upper box (**a**) of Figures 1 and 2 several latitudinal profiles of the 0.3 MeV and 1.7 MeV electrons are shown. Plots 1and 3 were taken during the dawn part of the satellite orbits, the others during the dusk parts. Dst variation and times of the measurements are shown in Figure 1 (b). The remaining boxes of Figures 1 and 2 give temporal particle flux variations at three latitude levels. In that figures one can see considerable erosion of the electron intensity at the end of the main phase, followed by intensity increase in the inner magnetosphere. Let us consider some details of the temporal variation of the particle flux.

1.The first effect is a deep dropout of the 1.7 MeV particle flux during the main phase in the outer L where before the storm was the intensity maximum. As it was said in the introduction particles

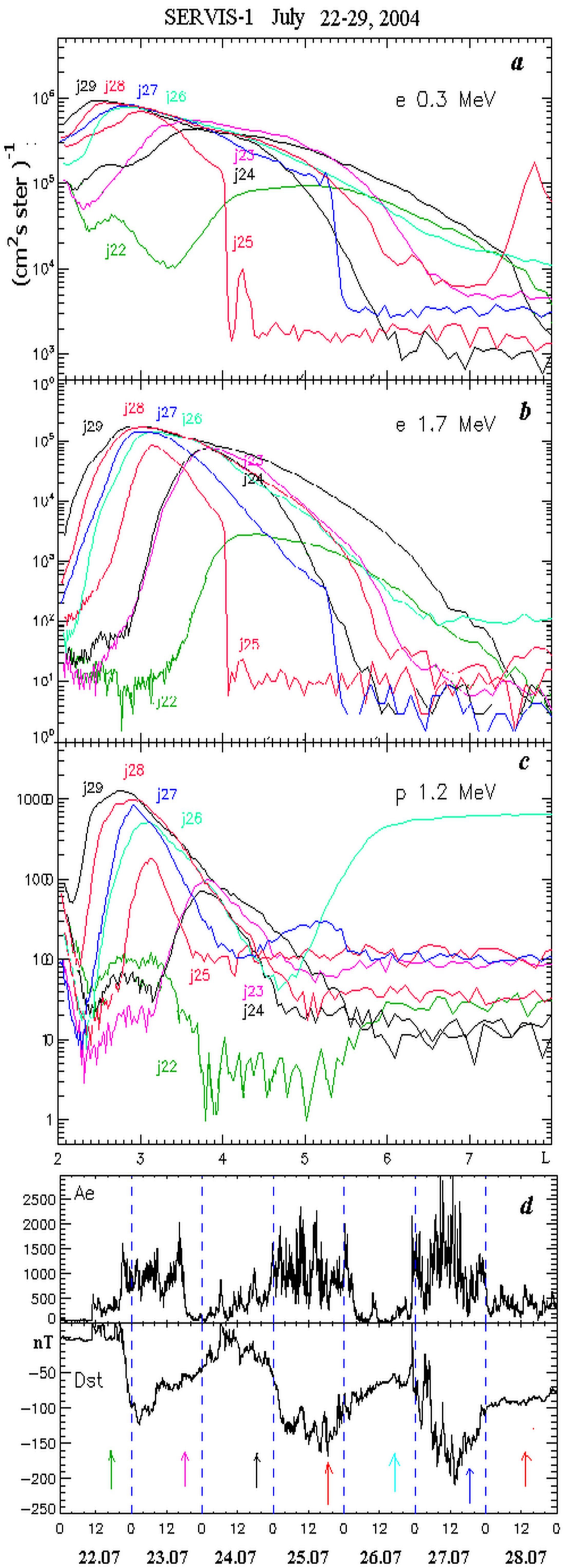

Fig 3 The July 22-28, 2004 multiple magnetic storm. The latitudinal profiles of the 0.3 (a) and 1.7 (b) MeV electrons, the 1.2 MeV proton (c) and Ae and Dst indexes (d) are shown. All profiles were measured over BMA in the evening sector (at the moments indicated by the arrows at the bottom box).

may be lost because of the pitch-angle diffusion or magnetopause shadowing or they may be transported to the other drift shells. In the 0.3 MeV channel the decrease was short, down to the polar cap level seen in the evening profiles at L= 4 and 5 during the first storm and at L=5 during the second storm. The intensity in the 1.7 MeV electron channel at L=5, 4 (Figure 2 ***a, b***) behave quite differently from the 0.3 MeV one. Similar deep decrease with a slow recovery one can see in the 1.2 MeV proton channel L=4 (Figure 2 ***e***). At the end of April 6 particle intensity in both channels at L=4 exceeds the pre-storm level.

2. Large and sharp increase of the electron intensity was registered before the end of the storm main phase at L =3 and 4 in the 0.3 MeV channel and at L=3 in the 1.7 MeV channel. If a fast earthward injection is behind this effect, then the intensity gradient in the initial L-profiles is important and the difference of the 0.3 and the 1.7 MeV profiles may explain absence of the effect at the L=4 in the 1.7 MeV channel. The fast intensity increase was observed during a short interruption of the ring current development, suggesting substorm association.

3. A large difference between the 0.3 and the 1.7 MeV fluxes at L=5 may also be explained by the

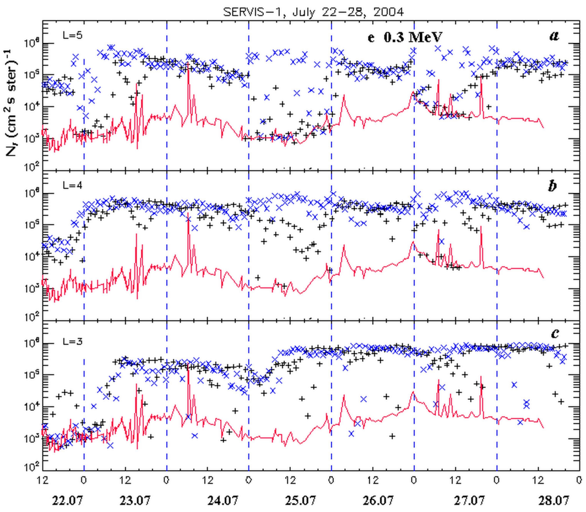

Fig 4 The same as Figure 2 for the July 22-28, 2004 magnetic storm for the 0.3 MeV electrons.

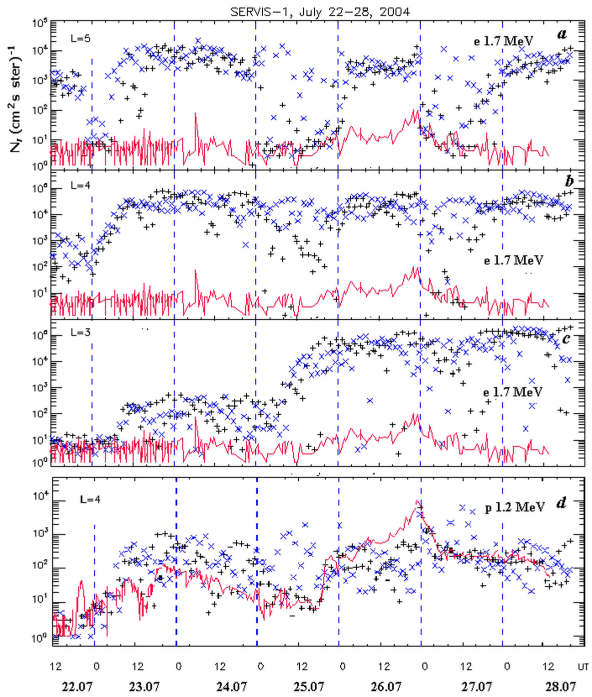

Fig 5 The same as on Figure 4 for the 1.7 MeV electrons (a,b,c) and 1.2 MeV protons (d).

substorm activity, because the known process of the auroral electron acceleration usually do not exceeds the 200-300 keV level [Lazutin,1986].

4. In the outer L-shells radiation belt recovers with remarkable coincidence of the pre-storm and after-storm shape of the outer radiation belt slope.

2.2. July 22-27, 2004 chain of the strong magnetic storms.

It was a chain of three magnetic storms with Dst -120, -150 and -200 nT. All the three storms were accompanied by a substorm activity. Figure 3 shows Ae and Dst indexes of the magnetic activity and the 0.3 and the 1.7 MeV electron and the 1.2 MeV proton radial profiles measured every day from July 21 to 29, 2004 during the evening pass over BMA.

Dst minimum of the first magnetic storm was registered at 03 UT, but the ring current remains strong until 06 UT. The 22.07 profile is typical for a low magnetic activity day with the maximum of the electron outer radiation belt at L= 4-5 and proton one at L=3. The next electron profile taken at the end of the recovery phase of the first storm shows an intensity increase and an earthward shift of the radiation belt maximum. The new proton profile maximum was shifted away from the Earth, but it was not a real shift of the proton belt particles, but the result of a solar proton capture (Kuznetsov et al., 2008).

The next Figures 4 and 5 present the plots of the particle intensity temporal development during the storm in the manner used in the previous case study. Most of the effects described earlier, can also be seen during the July magnetic storm.

1. The intensity dropouts were registered during the all three storms in both electron channels at L=5 and sometimes at L=4 during the second and the third storms. Dropouts were registered during the main phase and the early stage of the recovery, when the ring current was still strong. Only in the selected profiles dropouts were registered in the dawn sector, the majority were observed at the dusk ones. The energetic electron flux in the polar cap was changing with time and the dropout intensity repeats these variations, strongly indicating that the magnetic field lines from L=5 and

occasionally from L=4 at the dusk sector were extended to the magnetotail.

2. During the first magnetic storm an energetic electron increase was observed at L=3-5 in the 0.3, 1.7 and 3.4 MeV energy channels. It was registered first in the 0.3 MeV channel and proceeds with a time delay at the lower L and in the higher energy channels. Therefore the second profile which we registered over BMA at the end of the recovery phase (Figure 3) was created much earlier, before the beginning of the recovery phase. In L=3 the intensity increase was registered at the beginning of the first recovery phase and additionally during the second magnetic storm. At L=4 and 5 the second and third magnetic storms does not produce an intensity increase in both channels.

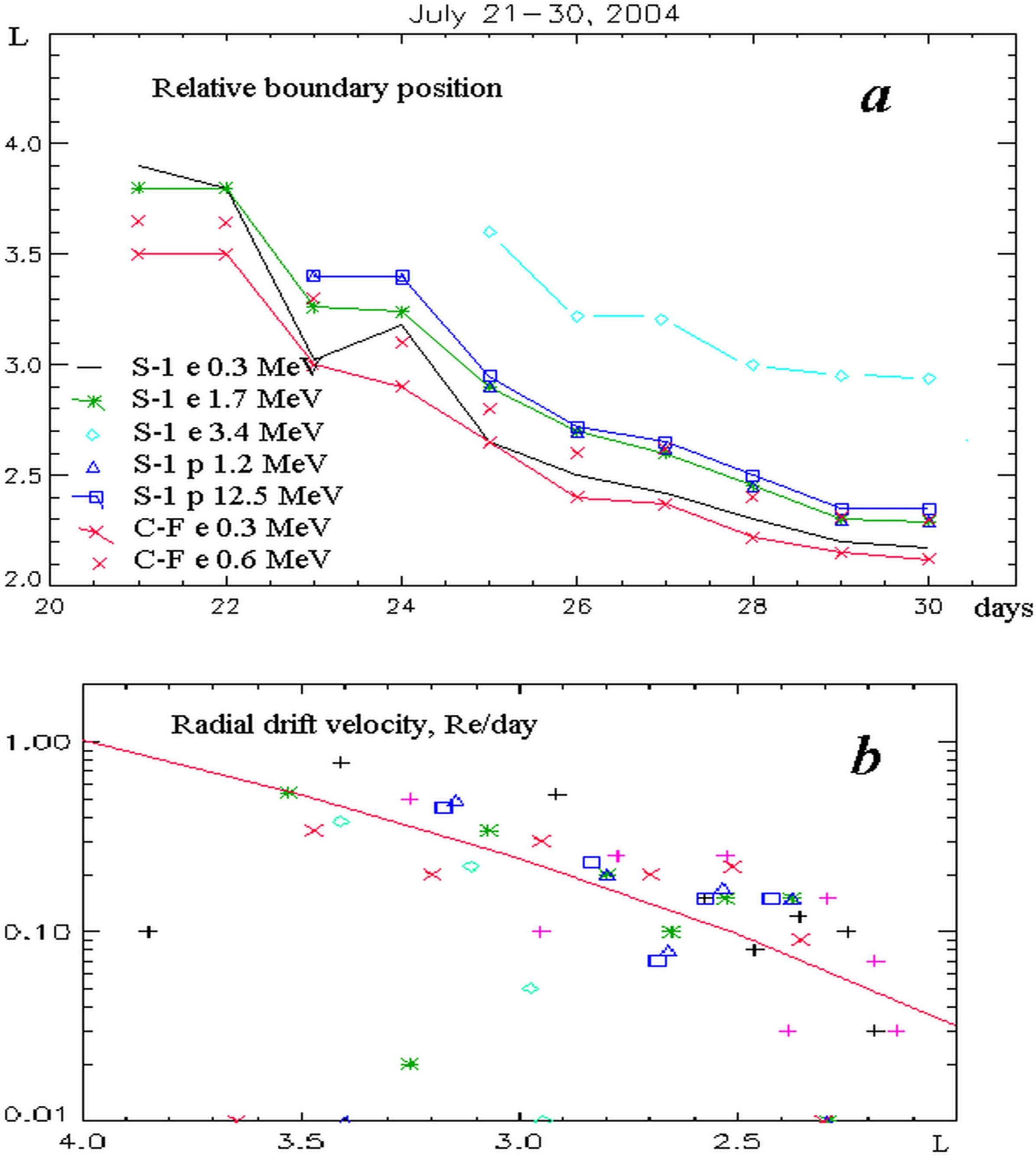

Fig 6 The relative position of the inner boundary of the radiation belts during the July 21-30, 2004 magnetic storm. S-1 – SERVIS-1 C-F - CORONAS-F data (a) and the radial drift velocity calculated from Figure 9 data (b).

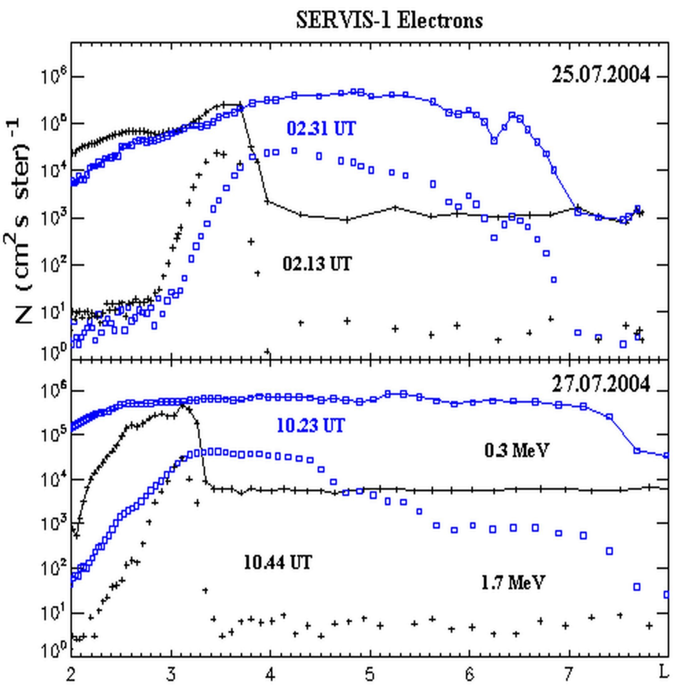

Fig 7 Two examples of the dawn-dusk asymmetry during the main phase of the 22-28.07.2004 magnetic storms. The solid lines show the 0.3MeV profiles, the separate signs show the 1.7 MeV profiles. The blue and black colors means dawn and dusk profiles accordingly.

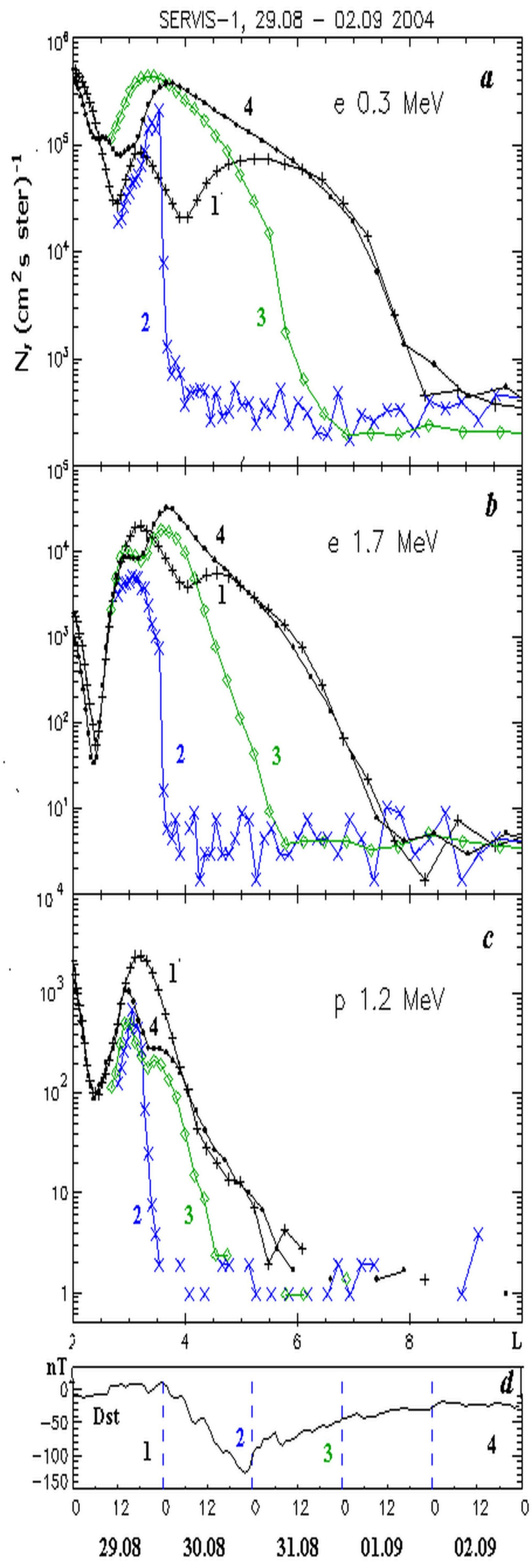

Fig 8. The August 29-September 02, 2004 magnetic storm. The latitudinal profiles of the 0.3 (a) and 1.7 (b) MeV electrons, the 1.2 MeV proton (c) and Dst index (d) are shown. All the profiles were measured over BMA in the evening sector (numbers at the bottom box indicate the time of the measurements).

The driving forces of the intensity increase in the inner magnetosphere is quite clear, it is radial injection and additional radial drift during the following hours and days. In Figure 3 one can see a gradual earthward shift of the both proton and electron radiation belt inner boundaries. The rate of the shift, measured every day at the middle of the slope and the calculated radial drift velocity are shown in Figures 6. The signs are the same for both figures. Solid line presents approximation $Vf/day = 10^{-3} L^5$.

This moderate diffusion is faster than the slow radial diffusion caused by magnetic pulses, $Vf/day = 10^{-7} L^9$ (Tverskoy, 1965).

3. The July 2004 case study presents more examples of the dawn side electron intensity increase while the dusk side intensity in the same magnetic latitude decreased to the polar cap level. Figure 7 presents two examples of the dawn-dusk asymmetry observed during the July 2004 magnetic storm both in the 0.3 MeV and the 1.7 MeV channels. It is obvious that an equal L does not mean an equal magnetic drift shells, but indicates on the strong dawn-dusk magnetic field asymmetry.

4. Outer radiation belt boundary became shifted toward the Earth in the main phases of all three magnetic storms and back after the recovery phase. During the next several days after the last storm the inner boundaries moves outside with the final intensities higher than before the beginning of the first storm. Recovery of the magnetic field configuration with Dst effect together with substorm acceleration may be responsible for that.

2.3. August 30, 2004 Magnetic Storm

Magnetic storm on August 30, 2004 differs from the other by a long main phase and by the radiation belts being still enhanced from the previous July 22-30 magnetic storm.

Fig 8 shows several latitudinal profiles of the 0.3 and the 1.7MeV electron and the 1.2 MeV proton fluxes measured over BMA during the different magnetic storm moments indicated in the Dst box below. Before the the beginning of the storm the latitudinal profiles of the electron intensity have an additional maximum at L~3 which remains after the July 2004 magnetic storm. The regular maximum at the 1.7 MeV channel was at L=5 while at the 0.3 MeV one it was extended from L =4.5 to L=7. At the end of the main phase the polar cap boundary was shifted to L=3.5-3.7 as measured both in the electron and proton channels (profiles 2). Detailed temporal development of the electron intensity is given in Figures 9 and 10.

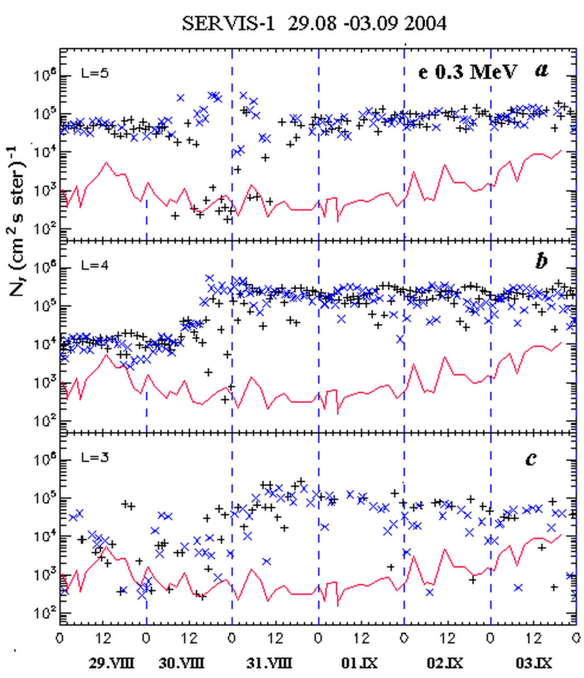

Fig 9. The same as Figure 2 for the August 30, 2004 magnetic storm and the 0.3 MeV electron channel.

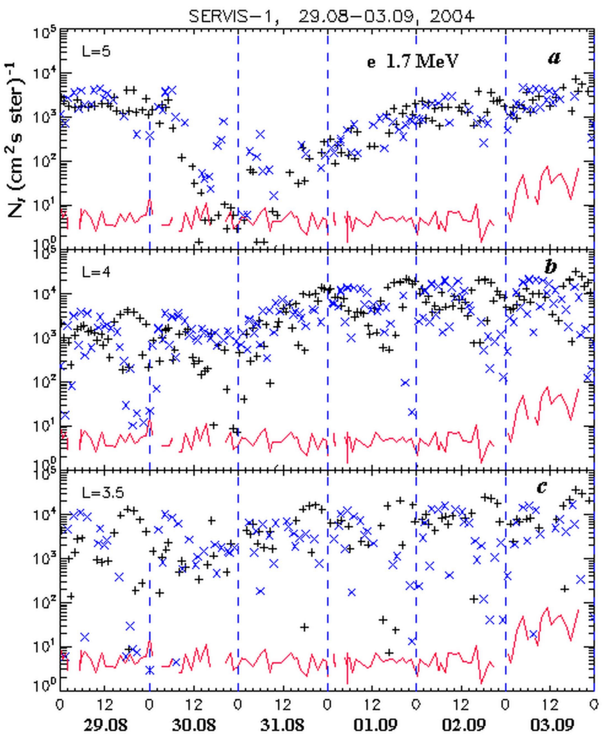

Fig 10. The same as on Figure 9 for the 1.7 MeV electron channel.

In the August case study one can find nearly all the effects as in the previously analyzed storms.

1. Deep intensity decrease down to the polar cap value was registered during the main phase at L= 4 and 5 only in the evening sector. Dawn-dusk asymmetry is evident from Figures 9 and 10 and from the comparison of the individual latitudinal profiles which we did not show here, because they are similar to these presented earlier.

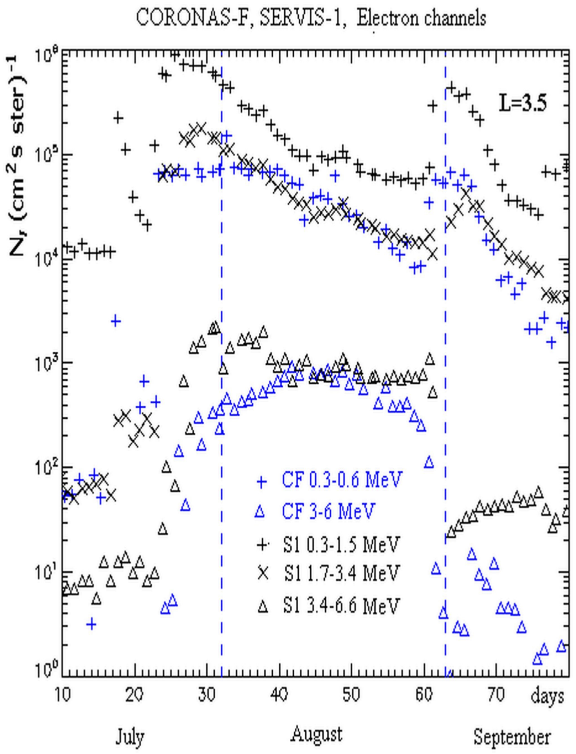

Fig 11. The energetic electron intensity variations during the July-September 2004 at L=3.5 measured over BMA by SERVIS-1 (S1) and CORONAS-F (CF) satellites.

2. Intensity increase was not as fast as in the previous case studies, but two steps are clearly seen (Figure 9, b) with a time delay between L= 4 and 3. Both steps coincide with the interruptions in the ring current development and high level of the substorm activity.

3. Comparison of the profiles 1 and 4, Figure 8, shows that again after the recovery phase the intensity profiles coincide with the pre-storm profiles of the outer belt slope in all three channels including the 1.2 MeV proton one.

4. Figure 11 shows the difference between the electron intensity variations in a different energy ranges. Each point represent daily maximum counting rate at L=3.5. Along with SERVIS-1 data we additionally used the data of the low altitude polar orbiter CORONAS-F satellite operating at the altitude of 500 km (Lazutin et al, 2010). In a contrast with the increase of the lower energy electrons, the decrease of the higher energy ones was registered, namely in the 3.4 MeV SERVIS-1 and in the 3-6 MeV CORONAS-F electron channels. It is very possible that these intensity decreases are the result of the electron resonance with the EMIC waves.

3. Discussion

The information from one satellite cannot allow to make unconditional conclusions on the physical mechanisms of the observed effects, but it presents interesting opportunity to guess, and to imagine, what is going on in the storm distorted magnetosphere. Besides, the main processes are known, well studied and modeled, there were many previously made direct particle measurements, therefore our attempt to understand what is going on may be justified.

3.1 Particle dropouts and the dawn-dusk asymmetry

<u>Dropouts.</u> Deep decreases of the electron intensities registered in all case studies may be explained by particle losses. Particle precipitation into the atmosphere is quite possible and usually is regarded as one of the main effect of particle dynamics during magnetic storms. There is an opinion (see for example Tverskaya et al., 2003) that the outer radiation belt totally disappears and new “storm injected belt” emerges.

The difference of the evening and morning latitudinal profiles therefore may be explained in the following way: electrons are accelerated in midnight-early morning sector by substorms and during magnetic drift to the evening side are precipitating into the atmosphere or lost in the magnetopause. The lifetime of the energetic electrons at L=5 for the strong pitch angle diffusion regime is only from tens to several hundreds of seconds (Kennel and Petschek, 1966) , therefore electron intensity might be decreased down to the cosmic ray background.

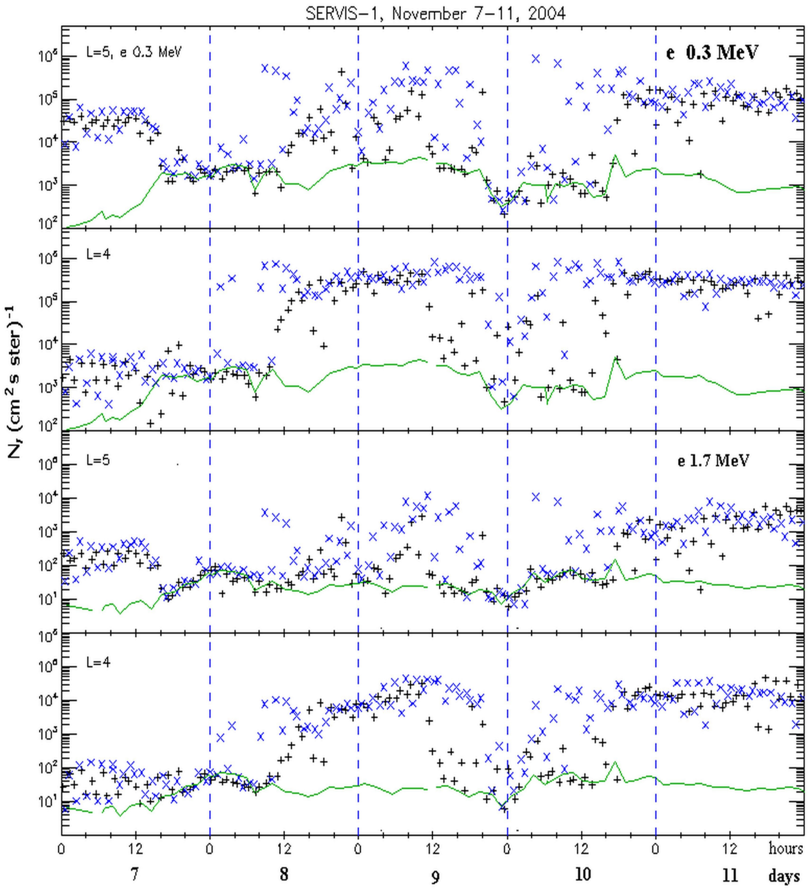

Fig 12. The plots of the 0.3 and 1.7 MeV electron intensity at a fixed L during the November 7-11, 2004 magnetic storm. Green line shows the polar cap intensity.

But there is one question which allows to exclude the precipitation model: why particle flux decrease only to the polar cap level which in several cases was higher than the background one? The minimum flux registered in the 0.3 and 1.7 MeV channels are 300-600 and 2-4 per cm^2 s ster accordingly, which can be regarded as a cosmic ray background level. Figure 12 presents one more example of the electron intensity variation at L=4 and 5 during the most intense magnetic storm of November 7, 2004 where the electron flux in the polar cap was enhanced due to the presence of solar cosmic ray electrons, and the electron intensities at L=5 and L=4 decreased exactly to the polar cap level. For hours they precisely follow the polar cap intensity variations. The only possible explanation is the change of the magnetic field line configuration: during magnetic disturbances the magnetic field line which in normal conditions went in the equatorial plane to the middle of the outer radiation belt now is extended into the magnetotail.

Dawn-dusk asymmetry. Local inflation of the magnetic field may explain why the evening sector have taillike field line configuration more often than the morning one. The high dusk side ion pressure associated with a partial ring current leads to the asymmetric inflation of the magnetic field in the dusk side that is registered by satellite magnetometers (Frank, 1970, Roelof, 1987, Brandt et al., 2002). Modeling of the storm-time magnetosphere (Tsyganenko,et al., 2002, 2002a, 2003) revealed an enormous distortion and the dawn-dusk asymmetry of the inner magnetosphere during the peak of the storm's main phase, which is caused by the combined effect of the symmetric and partial ring currents, the cross-tail current, and Birkeland currents. Ground-based magnetometers also registered asymmetry of the low-latitude H component during magnetic storms (Akasofu and Chapman, 1964; Crooker and Siscoe, 1971), as a consequence of the asymmetric change of magnetosphere-ionosphere current systems.

In a case study Onsager et al. (2002) found that the flux depletion was not symmetrical, it began in the dusk-to-midnight sector. They also came to the conclusion that the observed local-time development of the flux dropout was not consistent with the global diffusive loss or with the Dst effect.

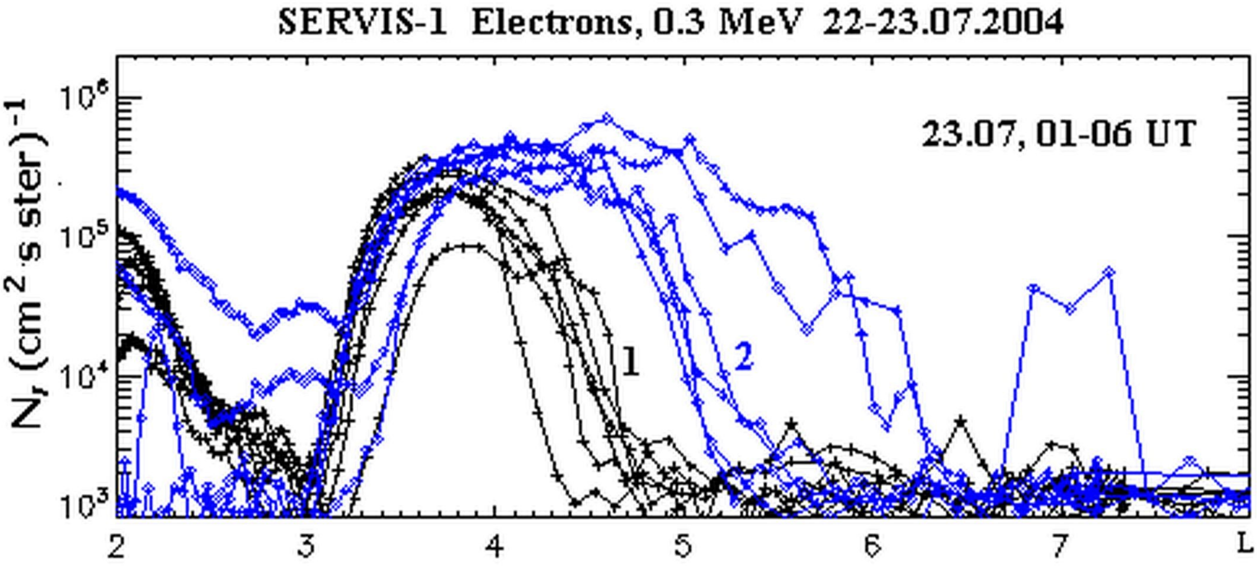

Fig 13. Several dusk (black) and dawn (navy) latitudinal profiles during the stably strong ring current interval of the first July 2004 magnetic storm.

What is happening with the energetic electrons during magnetic field taillike transformation? There is no reason to suppose that the particles should remain at the same field line while the magnetic field is slowly changing. The particles may be regarded as a fixed to the magnetic field line while the movements are caused by the potential electric field. In a case of a slowly changing magnetic field it is necessary to consider the radiation belt dynamics based on the adiabatic invariants. The characteristic time of the particle motion, including the magnetic drift is much shorter than that of the magnetic field reconfiguration, therefore the adiabatic invariants will be conserved, the magnetic drift shells will be progressively shifting earthward, following the shift of the stable trapping region. The magnetopause shadowing effect therefore cannot be regarded as an important loss mechanism because the radiation belt electrons will remain in the stable trapping region. From our data wave-particle interaction can not be excluded, both the acceleration and losses may take place during the main phase but without severe consequences. Our data show that the outer radiation belt does not disappear and the new shifted profiles intensity may decrease at the end of the storm main phase, possibly because of the Dst-effect, but also may come with enhanced intensity.

The dawn-dusk asymmetry remains after the end of the main phase as well. During the July 23, 2004 magnetic storm after the end of the main phase there were 5 hours before the beginning of the recovery phase and the ring current decrease. In Figure 13 two groups of the L-profiles are shown, the dusk (1) and dawn (2)ones plotted with different color. There are two dawn substorm influenced profiles, all other have similar stable forms of 1 and 2 with the coincidence of the inner flux boundary and with the polar cap boundary position for the dusk sector located at L = 4.5-4.8 and at 5.2-5.5 for the dawn sector.

3.2 Radial injection and diffusion

The radial diffusion or radial injection can be regarded as the most possible driving force for the electron acceleration. There is a difference between those two processes. The radial diffusion means numerous interaction and a gradual radial displacement of the energetic particles with time scale from tens hours to several days. The injection means a single radial particle shift. An example of the particle acceleration by the injection was registered by CRRES satellite during SC of the March 24, 1991 magnetic storm (Li et al., 1993).

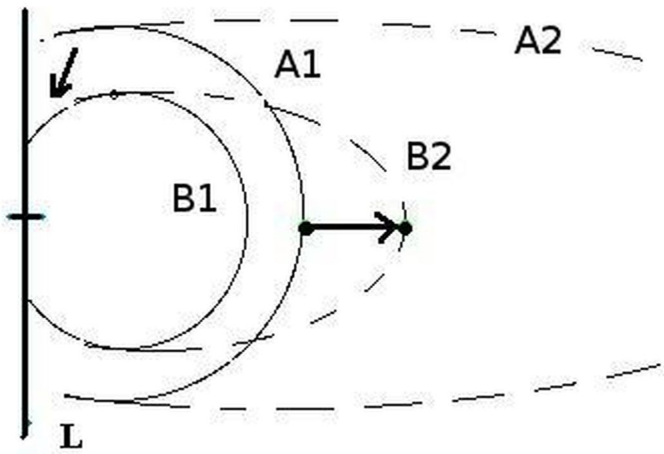

Fig 14. The schematic illustration of the magnetic drift shell dynamic caused by the Dst effect during the main storm phase. The solid lines (A1, B1) show magnetic field lines dipole shape before the storm, the broken lines (A2, B2) show the same lines tailward extended at the end of the main phase.

Radial injection can explain the electron flux increases during 1-2 hours which were registered several times by SERVIS-1. Figures 1d,e 2d and 9b give examples of the fast injections; all occurs during the main phase where SC can not be regarded as a driving force. We explain this effect as a result of the substorm activations, but this effect will be investigated a separate study.

The earthward radial diffusion may be caused by the resonance with the Pc3-5 magnetic pulsations (often referred as ULF waves). This type of acceleration was widely discussed before (McAdams et al., 2001, Elkington et al., 2003, Kuznetsov and Tverskaya, 2008, Lanzerotti et al., 1970, Elkington et al., 1999, 2003, Loto'aniu et al., 2006, Sarris and Temerin, 2006, Thorne et al., 2007). Our input to the previous studies is an estimation the drift velocity during gradual radial shift of the inner slope of the radiation belt observed several days of July 2004 chain of the magnetic storms (Fig 6).

A moderate diffusion creates enhanced particle flux in the electron and proton radiation belts which returns to the normal level only after several weeks or months (Hasebe et al., 2008).

Radial transport of the energetic particles occurs simultaneously with the magnetic field effects and can cause essential increase of the particle flux due to the conservation of the magnetic moment. But that is possible if the radial gradient of the electrons is positive. If the radial gradient is negative, the decrease of the particle intensity may be observed despite of the betatron acceleration.

The nonadiabatic and adiabatic effects together during the main phase are acting in one direction, namely shifting the radiation belt toward the lower latitudes. Dst effect which shifts the equatorial position of the magnetic drift shells away from the Earth, will simultaneously shift the low-altitude part of the magnetic field lines to the lower latitudes, as illustrated by Figure 14.

As a result the main phases of the different magnetic storms will emerge with the variety of the radial profiles of the earthward shifted radiation belts.

3.3 Dawn side electron enhancements.

The dawn-dusk asymmetry was registered practically in all analyzed magnetic storms during the main and early recovery phase. When most of the evening profiles suggest the magnetotail field line stretching, the morning profiles at the same time show that an intense particle flux appears in a wide latitude region including the traditional auroral zone location. Not only electrons, but protons as well were registered during the morning profiles at the expanded latitudes (Figure 5d). To see this particles, satellite magnetic field line must be extended to the trapping or quasitrapping region, not to the magnetotail. We can understand this phenomena as a result of the concurrence between the influence of the ring current and substorm auroral region currents on the magnetic fields configuration. While ring current causes magnetic field line stretching, substorm activations opposedby creation of the magnetic field dipolarizations and therefore sometimes satellite registers polar cap intensities, and at other times –an enhanced flux in the quasitrapping region.

The equatorial boundary of the auroral oval during the storms is shifted deeply to the subauroral latitudes while the polar boundary between the auroral oval and the polar cap shifts in average much less (Feldstein and Starkov,1968). The boundary movements during the individual substorms depend on the substorm phases: the field line stretching during the substorm growth phase shifts the boundary toward the Earth while the magnetic field dipolarization moves it back away tailward. It corresponds to the decrease and the increase of the field line projection latitude.

Especially large flux enhancements were registered in the 0.3 MeV electron channel, which suggests direct acceleration of those particles during the substorm activations (Lazutin et al, 2007). It is possible that the 1.7 MeV electrons also can be accelerated directly in one substorm activation or in a chain of several activations. Therefore during the morning flights we often see energetic electron enhancements as a consequence of the substorm acceleration.

3.4 Particle dynamics during the recovery phase

While the electron intensities at the lower L-shells L< 4-5 basically became established during the main and the early recovery phase (usually higher than before the storm), the electrons in the outer L-shells began to recovery configuration later, during the recovery phase and returned to the prestorm shape with certain deviations, which depends on the substorm activity.

Among the 28 magnetic storms with Dst <-45 nT observed from January 2004 to July 2005, one has an indefinite signature of a particle dynamic, the rest show the following statistics. At L=4 we register 15 cases with the post-storm intensity increase both of the 1.2 MeV protons and the 1.7 MeV electrons and 12 cases have the intensity decrease in those two channels. The 0.3 MeV electrons behave similarly, only in two cases there was an increase of the counting rate instead of the decrease. For all storms with intensity increases and decreases at L=4, we calculate daily sum of 3-hour Kp index for 24 hours before the end of the storm main phase, during the first 24 hours of the storm recovery and during the next 24 hours. Results are shown in the Table.

Average Σ Kp	main phase	first recovery day	second recovery day
increase	29.3	32.0	26.5
decrease	30.0	24.0	19.0

It seems that the substorm activity during the main phase of the magnetic storm does not influence the final intensity, while the first recovery day is the most important: when the daily sum was high (32), the resulting increase of the particle flux was observed, while the lower sum (24) leads to the particle decrease. The correlation of the intensity variation in electron and proton channels is not surprising because the protons are also being accelerated during the substorms at least to the several hundreds keV. Substorms rise pulsations level, therefore our conclusion agrees with the results of (O'Brien et al., 2001) who found a high level correlation of the energetic electron flux with Pc-5 magnetic field pulsations during the recovery phase of the magnetic storms. In 80% of all cases with a high level of Pc-5 pulsations during 24 hours after the storm, higher increases of the electron flux were observed.

4. Conclusions

Analysis of the energetic electron dynamics during several magnetic storms by the low altitude satellite allows to present following description of the process.

<u>During the main phase in the dusk sector</u> an extension of the outer magnetic field lines into magnetotail occurs, the electron flux previously measured at the outer radiation belt maximum decreases to the polar cap level. Magnetic field transformation in all analyzed cases was slow enough to conserve all the three adiabatic invariants and as a consequence the radiation belt

became shifted to the lower latitudes.

During the main phase in the dawn sector the chain of the substorm dipolarizations is acting against the tailward magnetic field line extension produced by the ring current. As a result the dawn-dusk asymmetry of the radiation belt configuration was registered in all analyzed cases. The tailward extension dominates when the substorm activity was low or the magnetic storm was very strong.

The fast inward injection of the electrons was registered in two occasions possibly related to the substorm activations, but this effect needs separate study.

The adiabatic radial shift can be enforced by the radial drift with the particle acceleration caused by the magnetic drift resonance with ULF waves. The pitch-angle diffusion at the same time can reduce the particle flux. As a combined action of all three factors both the increase and decrease of the electron intensity can be registered. In the inner drift shell the radial diffusion and consequently particle intensity increase are prevailing.

During the recovery phase the adiabatic recovery of the radiation belt must take place but again with the addition of the nonadiabatic effects. With the decrease of the ring current the magnetic field lines returns to the quasi-dipole configuration, the dawn-dusk asymmetry disappears. The recovered radiation belt may be equal, higher or lower by the intensity than the prestorm radiation belt. If the substorm activity was low and substorm number reduced during the recovery phase, the intensity decrease was registered as a rule, when the substorms follow one after another the intensity increase was registered. After the strong and superstrong magnetic storms the intensity increase both in the inner and outer drift shells was observed.

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