Dedicated to the memory of
S. N. Kuznetsov

Regular and turbulent mechanisms of relativistic electron acceleration in the magnetosphere of the Earth: Theoretical treatment and results of experimental observations

Elizaveta E. Antonova,

Margarita F. Bahareva, Igor P. Kirpichev, Irina N. Myagkova., Ilya L. Ovchinnikov,

Ksenia G. Orlova, Marina V. Stepanova, Maria O. Riazantseva, Vadim V. Vovchenko

***Abstract*—The problem of the appearance of extremely large fluxes of relativistic electrons ("satellite killers") is analyzed taking into account the action of both regular and turbulent mechanisms of particle acceleration. The configuration of storm time magnetospheric current systems is discussed. The dynamics of magnetospheric current systems including ring current and its high latitude continuation – cut ring current, partial ring current is considered as a reason for magnetospheric topology changes. Storm time decrease of magnetospheric field and its restore during storm recovery phase produce adiabatic acceleration of seed population of electrons injected into the region of weaken magnetic field. High level of storm time turbulence in wide frequency range leads to turbulent particle acceleration. The possibility to clarify the contribution of different mechanisms of the formation of relativistic electron spectra is discussed.**

1. Introduction

THE problem of the acceleration of relativistic electrons continues to be one of the main unsolved problems of the physics of the magnetosphere. Relativistic electrons are called ‘‘satellite killers" due to effects leading to satellite anomalies and even loss of spacecrafts. Large fluxes of relativistic electrons appear, as a rule, during the recovery phase of geomagnetic storm. Clarification of the mechanisms of the acceleration of relativistic electrons is considered as one of the major aspects of Space Weather problem. It is also very important for understanding of the processes of cosmic ray acceleration. Generally, the magnetosphere of the Earth is a giant plasma laboratory in which different mechanisms of particle acceleration can be tested.

In this paper we discuss regular and turbulent mechanisms of relativistic electron acceleration and try to show that the solution of the problem of the nature of relativistic electrons in the magnetosphere of the Earth is deeply connected to the study of the topology of magnetosphere.

E. E. Antonova, I.P. Kirpichev, M.O. Riazantseva are with Skobeltsyn Institute of Nuclear Physics Moscow State University Moscow, 119991Russia, and Space Research Institute RAS, Profsouyuznaya St., Moscow, 117997, Russia, (corresponding author to provide phone: +7-495-9392810; fax: +7-495-9390896; e-mail: antonovaa@orearm.msk.ru).

M.F. Bahareva, I.N. Mygkova, I.L. Ovchinnikov, K.G. Orlova are with Skobeltsyn Institute of Nuclear Physics Moscow State University, Moscow, 119991, Russia.

V.V. Vovchenko is with Space Research Institute RAS, Profsouyuznaya St., Moscow, 117997, Russia.

M.V.Stepanova, is with Physics Department, Universidad de Santiago de Chile, Casilla 347, Correo 2, Santiago, Chile.

2. Radiation belts of the Earth: regular and turbulent mechanisms of relativistic electron acceleration

Large fluxes of relativistic electrons in the magnetosphere of the Earth fill the outer radiation belt (ORB). ORB was discovered in 1958 by Vernov, Chudakov, Gorchakov, Logachev (discovery No 23 in the list of USSR discovery registration) in the Institute of Nuclear Physics Moscow State University (now SINP MSU) and was studied using the data of satellites Electron, SAMPEX, Polar, GPS, CRRES, LANL, GOES, HEO etc. Nevertheless, a significant progress in ORB study was achieved due to CORONAS-F satellite measurements. Fig. 1 demonstrates averaged meridional distribution of fluxes of electrons in the radiation belts of the Earth obtained due to data of early measurements (http://www.kosmofizika.ru).

Two main approaches of the solution for the problem of acceleration of relativistic electrons have been suggested:

stochastic acceleration by fluctuating electric fields and regular acceleration of "seed" population. Both mechanisms suggest that "seed" population of electrons with energies ~100 keV formed during storm main phase is accelerated till relativistic energies during storm recovery phase.

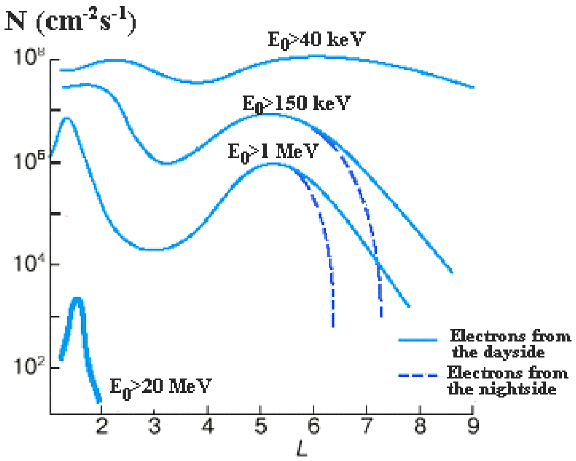

Fig. 1. Averaged meridional distribution of fluxes of electrons in the radiation belts of the Earth obtained due to data of early measurements (http://www.kosmofizika.ru)

Stochastic mechanisms of acceleration are the most popular now. Interactions with ULF [1]-[10] and whistler mode waves [11]-[21] are analyzed. It is not clear which wave mode is the most effective one. It is also necessary to stress that the effectiveness of stochastic mechanisms is possible to estimate only after exclusion of an action of regular mechanism.

Great increase of plasma pressure inside the magnetosphere during magnetic storms leads to decrease of magnetic field due to diamagnetic effect of plasma. The effect is especially pronounced in the asymmetric ring current regions. For example the decrease of B_z component of geomagnetic field till ~0 was observed at the geostationary orbit in [22] during magnetic storm 31 March 2001 with $|Dst|_{max}$ = 350 nT. This means that the restore of magnetic field during storm recovery phase can produce considerable regular betatron acceleration of particles. Therefore, it is necessary first of all to analyze the change of magnetic configuration. It is also necessary to analyze particle transport across drift shells and particle losses due to precipitations into the ionosphere and drift to the magnetopause. However, this problem is out of the scope of present review.

3. Topology of Magnetic Configuration

To evaluate the contribution of regular mechanism of relativistic electron acceleration it is necessary to have comparatively good model of the near Earth magnetic field. The majority of existing models of magnetic field suggest that the main sources of the magnetospheric magnetic field are magnetopause currents, tail current, ring current and partial ring current, field-aligned currents. Adequate selection of magnetospheric current system is rather important as neglecting the contribution of some comparatively powerful systems can produce significant discrepancies between the experimental data and the modeling. As an example it is possible to mention the difficulties of the latest Tsyganenko model – Tsyganenko-2004 [23] in reproducing the positions of the geomagnetic cutoffs as analyzed in [24].

Recently Tsyganenko and Sitnov [25], [26] developed a new empirical model of the magnetospheric magnetic field (TS07). In this model the magnetospheric equatorial currents is expanded into a sum of orthogonal basis functions with different scales, capable to reproduce various radial and azimuthal distributions of the field, including its noon-midnight and dawn-dusk asymmetries. The set of functions is built on the basis of the general solution of Ampere's equation for infinitely thin equatorial current layer. All the terms are separately shielded inside the model magnetopause and combined with the modules corresponding to Birkeland currents.

TS07 model reproduces many important features of magnetospheric structure and its changes during storms. However, it does not take into account that - as it was found in [27] - dayside part of inner magnetospheric transverse current flows at comparatively high latitudes far from the equatorial plane. Fig. 2 helps to understand this statement. It shows the results of calculation of isolines *B*=const (for *B*=100 nT, 90 nT, ets.) in accordance with Tsyganenko-2004 model for the following parameters: the solar wind dynamic pressure p_{din}=2 nPa, components of interplanetary magnetic field (IMF) *Bz*=-5нT, *By*= *Bx*=0 and zero inclination of Earth's magnetic dipole.

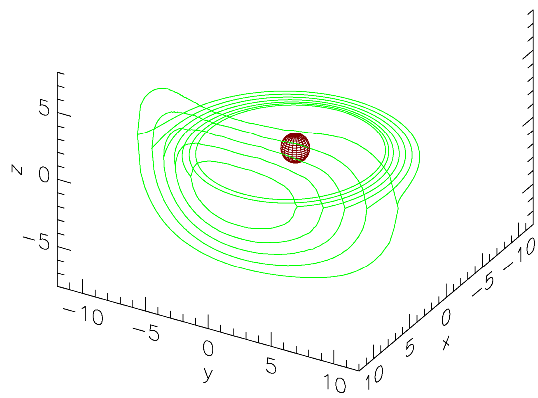

Fig. 2. Example of calculation of isolines *B*=const (for *B*=100 nT, 90 nT, ets.) in accordance with Tsyganenko-2004 model if p_{din}=2 nPa, and components of IMF *Bz*=-5нT, *By*= *Bx*=0

Magnetic field value in the internal ring on Fig. 2 corresponds to 100 nT. Next curve corresponds to 90 nT etc. till 40 nT at the external curve. The majority of existing models of the magnetospheric magnetic field reproduces the same topology of the field lines: The magnetic field minima are shifted from the equatorial plane near noon due to daytime magnetospheric compression. Minimal values of magnetic field take place far from the equatorial plane. Analysis of the configuration of

B=const isolines leads to the conclusion that most part of daytime transverse current can be concentrated far from the equatorial plane.

The distribution of transverse current along the dayside magnetic field lines was analyzed in [28]. Fig. 3 shows the configuration of magnetic field line at $Y = 0$ in GSM coordinate system calculated using Tsyganenko-01 model [29], [30] for solar wind magnetic field parameters B_z = -5 nT, B_y = 0, solar wind dynamic pressure equal to 1.6 nPa and Dst = -5 nT. It is possible to see the decrease of the value of minimal magnetic field with the growth of geocentric distance and the increase of Z coordinate of such minima.

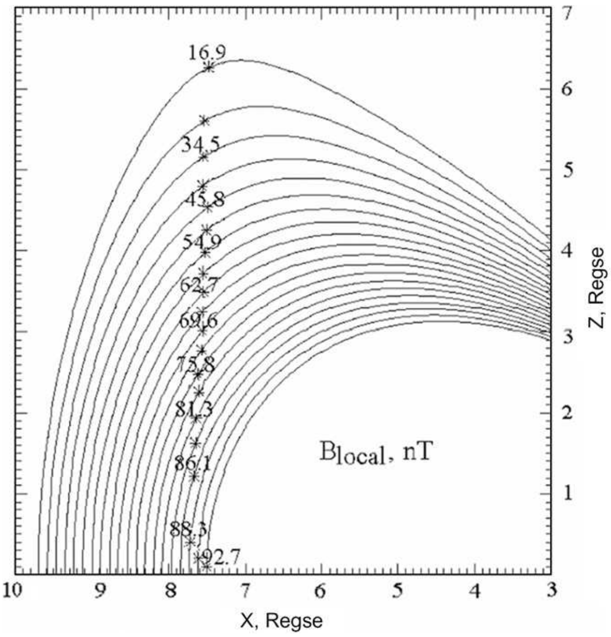

Fig. 3. The position of magnetic field minima at the daytime field lines in accordance with Tsyganenko-01 magnetic field model.

The density of transverse current **j** at the dayside field lines was evaluated taking into account weak anisotropy of plasma pressure at $L > 7$. In such a case, transverse current is equal

$$\mathbf{j}_{\perp} = \mathbf{B} \times \nabla p / B^2 \qquad (1)$$

where ∇p is the plasma pressure gradient. Results of AMPPTE/CCE plasma pressure measurements obtained in [31] are used for determination ∇p for geocentric distances till 9 R_E. The radial dependence of plasma pressure from 9 till 10 R_E was approximated using exponential dependence. Fig. 2 shows the results of transverse current density calculations.

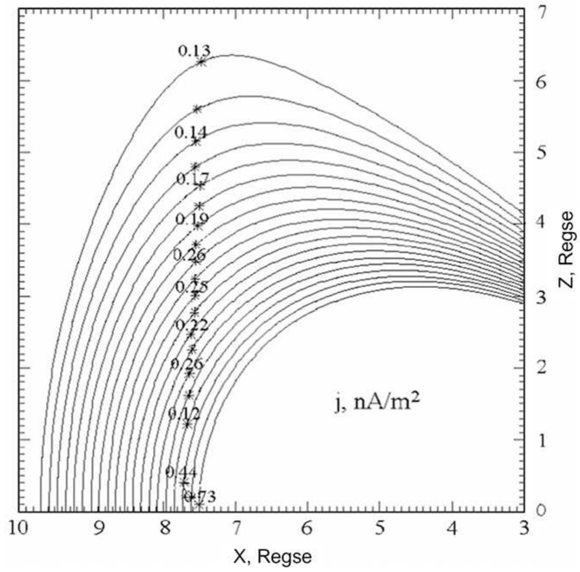

Fig. 4. Transverse current densities in the regions of daytime field lines.

The calculation of the integral current between 7.5 and 9.7R_E gives integral current $\sim 2 \cdot 10^5$ A in each hemisphere or the integral transverse current $4 \cdot 10^5$ A in both hemispheres during quite conditions. Simple estimations show that the same current value exists at the same geocentric distances in the region, which is ordinarily considered the near Earth tail. Fig. 5 schematically shows integral current configuration named in [27] cut ring current (CRC).

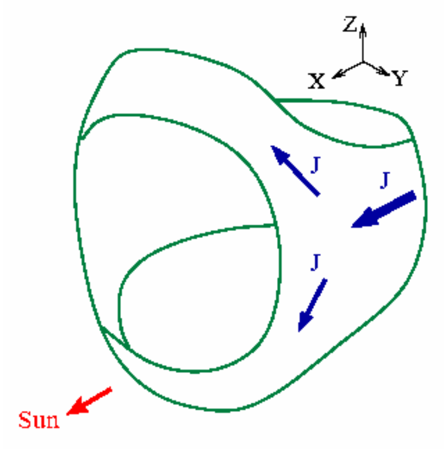

Fig. 5. Sketch illustrating the configuration of currents in CRC.

CRC is a high latitude continuation of ordinary ring current. It was shown in [32], [33] that most parts of auroral oval are mapped into the CRC region. CRC value is greatly increased during magnetic storm and makes considerable contribution to Dst value.

4. Localization of the Region of Relativistic Electron Appearanse

The inclusion of CRC into the analysis of relativistic electron acceleration is especially important in the context of the relation obtained in [34], [35]. It was shown that the position of the peak intensity of fluxes of relativistic electrons, which appear during storm recovery phase L_{max} is connected to the maximal value of Dst-variation $|Dst|_{max}$ by the following relation:

$$|Dst|_{max} = 2.75 \cdot 10^4 / L_{max}^4 \text{ nT} . \qquad (2)$$

L_{max} coincides with the lowest position of the westward electrojet center during the storm. Westward electrojet is localized inside the auroral oval. This means that the processes of the acceleration of auroral electrons are deeply connected to the equatorial regions mapped onto the auroral oval latitudes and correspondingly to CRC dynamics. Auroral oval moves to the equator during magnetic storm. The results of observations presented in [36] support this conclusion as sometimes it is possible to observe the increase of relativistic electrons at low L without increase at geostationary satellites.

TABLE I
Comparison of the Parameters of 22 Geomagnetic Storms with Obtained in [33],[34] Relation

Data and time of main phase beginning	$\|Dst\|_{max}$ nT	L_{max} exp/calc [R_E]
25.09.2001/02	-166	3.1/3.6
21.10.2001/19	-187	3.7/3.5
28.10.2001/05	-157	3.2/3.6
05.11.2001/21	-292	3.0/3.1
24.11.2001/18	-221	2.6/3.3
11.05.2002/01	-110	3.7/4.0
23.05.2002/13	-109	3.8/4.0
04.09.2002/01	-109	3.8/4.0
07.09.2002/16	-181	3.0/3.5
01.10.2002/05	-176	3.5/3.6
29.05.2003/20	-131	2.8/3.8
18.06.2003/03	-145	3.0/3.7
18.08.2003/16	-168	3.0/3.6
28.10.2003/17	-363	3.0/3.0
30.10/2003/19	-401	2.5/2.9
20.11.2003/04	-472	2.8/2.8
22.11.2004/06	-149	3.5/3.7
03.04.2004/16	-112	3.5/4.0
22.91.2004/06	-182	2.8/3.5
30.08.2004/02	-125	3.6/3.9
07.11.2004/22	-384	2.9/2.9
09.11.2004/12	-296	2.8/3.1

The dependence $|Dst|_{max} \sim L_{max}^{-4}$ nT was explained in the paper [37] and the value of the coefficient in the relation (2) in the paper [38] in the azimuthally symmetric case of quasidipole magnetic configuration. It was taken into account that upper limit of the inner magnetospheric particle feeling is determined by the stability of the distribution of the plasma pressure. This limit exists in spite of the action of different acceleration and transport mechanisms of plasma particles. Suggestions made in [27] with the introduction of CRC become more realistic and helps to understand the coincidence of the lowest position of the westward electrojet center with the position of the peak intensity of fluxes of relativistic electrons.

The relation (2) was checked in [39] using data of CORONAS-F observations. MKL-device on board KORONAS-F satellite [40] measured fluxes of precipitating electrons in the energy range 0.3-12 MeV at the altitude ~500 km in the nearly circular orbit with an inclination of ~82.5^o. Variations of electron fluxes with energies 0.6-1.5 MeV, during 22 strong magnetic storms (Dst < ~100 nT) were analyzed in [39]. It was shown that the relation (2) is consistent with observations. Table 1 obtained in accordance with [39] shows the results of such comparison. However, analyzing Table 1 it is possible to see that sometimes a significant discrepancy between L_{max} values measured by CORONAS-F and described by relation (2) is observed. Therefore, the relation (2) requires the additional checking.

One of the main predictions of theory developed in [37], [38] is the storm time dependence of radial plasma pressure distribution. Theory predicts the dependence $p \propto L^{-7}$.

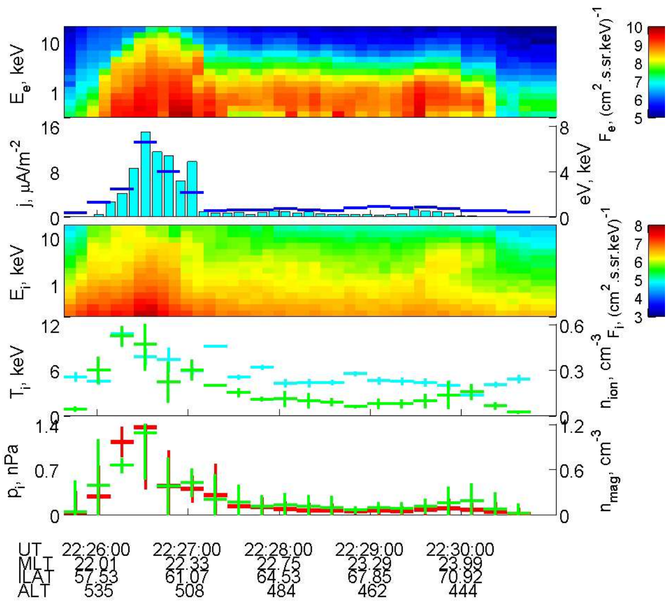

Fig. 6. The electron precipitating fluxes (a), the field-aligned current densities and field-aligned potential drops (b), the ion precipitating fluxes (c), the ion concentration at the ionospheric altitudes and the ion temperature (d), the ion concentration in the magnetosphere and the plasma pressure (e), obtained during the March 2, 1982 auroral oval crossing.

Such dependence was found experimentally in the paper [36] using data of high apogee Polar satellite observations for magnetic storm 10.01.1997 with $|Dst|_{max}$=300 nT and in [41] using data of auroral Aureol-3 satellite for the magnetic storm March 1-8, 1982 with $|Dst|_{max}$=211 nT. Fig. 6 shows the results of Aureol-3 observations near the end of storm main phase. Fig. 7 shows the results of plasma pressure profile fitting by the dependence $p\propto L^{-s}$ with s=6.3±0.5. Analyzing Fig. 7 it is possible to see that in spite of not very good accuracy of observations real plasma pressure profile has the theoretically predicted dependence.

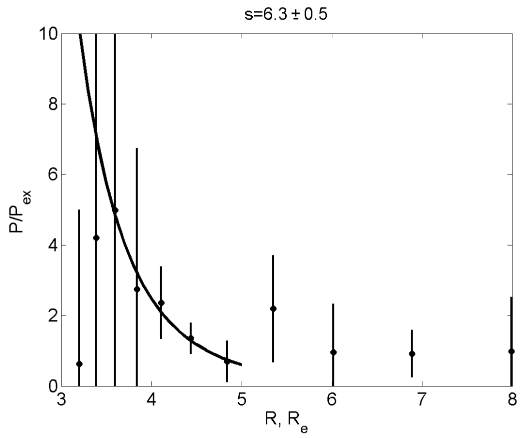

Fig. 7. Fitting of the radial plasma pressure distribution by the dependence $p\propto L^{-s}$.

It is necessary to stress, that the events reported in [36], [41] are the unique radial plasma pressure profiles obtained to date during magnetic storms, and it is necessary to continue working in this direction to obtain a significant statistic to make final conclusions.

3. Stochastic acceleration and losses

The acceleration of relativistic electrons in the region mapped onto the auroral oval produces the real limitations in the action of stochastic mechanisms of acceleration. Such mechanisms must be connected to the properties of turbulent fluctuations at the auroral field lines. The most popular mechanisms of electron interaction with whistler mode waves have no such feature. It is necessary to mention also that discussed mechanisms of stochastic relativistic electron acceleration have definite problems connected to the time of acceleration, as amplitudes of observed waves are comparatively small. Very large amplitude of whistler-mode waves ~240 mV/m in Earth's radiation belts were observed in STEREO experiment (see [42]). This observation can really change obtained estimations. However, such large amplitudes are not typically observed. At the same time plasma, electric and magnetic field parameters significantly fluctuate at the auroral field line even during quite conditions in a very wide frequency range (see review [43]). This means that there exists a possibility of stochastic relativistic electron acceleration by different waves. Some features of such acceleration can be studied using formalism described in [44].

Nonstationary diffusion equation with losses for averaged over pitch angle distribution function $f(p,t)$**.**was analyzed in [44]. It has the form

$$\frac{\partial f}{\partial t}=\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D(p)\frac{\partial f}{\partial p}\right]-\frac{f}{t_{esc}}, \tag{3}$$

where $p=\varepsilon v/c$ is dimensionless momentum, $\varepsilon=\sqrt{1+p^2}$ is dimensionless full energy, $D(p)$ is the diffusion coefficient in the momentum space, t_{esc} is the averaged time of losses. The coefficient of diffusion determines time of acceleration $t_{ac}=p^2/D(p)$. Power low spectrum of turbulence leads to power low dependence of the coefficient of diffusion for the momentum

$$D(p)=D_0 p^q, \tag{4}$$

where the quantity q depends on the power low of the spectra of the turbulence, the constant D_0 reflects the rate of the acceleration and depends on the spectrum of turbulence, plasma density and magnetic field. Introduction of dimensionless variables

$$\tau=D_0 t,\quad a=(D_0 t_{esc})^{-1}$$

(5)

leads to the expression

$$\frac{\partial f}{\partial t}=\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^{2+q}\frac{\partial f}{\partial p}\right]-af\ . \tag{6}$$

Analytical solution of the equation (6) in the case when particle injection has the form of delta-function and q<2 has the form

$$f(p,q)=f_0\tau^{-\frac{3}{2-q}}\exp\left[-\frac{p^{2-q}}{(2-q)^2\tau}-a\tau\right]. \tag{7}$$

If the source of accelerated particles acts during the time interval t_0 and the power of the source $Q(t)=Q_0$=const when $t<t_0$ and $Q(t)=0$ when $t>t_0$ the distribution function $f(p,\tau)$ is transformed into $F(p,\tau)$, where

$$F(p,\tau)=\frac{Q_0}{D_0}\int_0^\tau f(p,y)dy \quad \text{if } \tau<\tau_0, \tag{8}$$

where $\tau_0=D_0t_0$. The lower limit in the integral (8) is changed from 0 on $(\tau-\tau_0)$ if $\tau>\tau_0$. If $\tau>>\tau_0$

$$F(p,\tau)=\frac{Q_0}{D_0}\int_{\tau-\tau_0}^{\tau} f(p,y)dy\approx\frac{Q_0}{D_0}\tau_0 f(p,\tau). \tag{9}$$

Differential flux dJ/dE is connected to f by the expression

$$dJ/dE=(4\pi mc)^{-1}p^2 f, \qquad (10)$$

where m is the electron mass, c is the speed of light. The developed in [44] theory gives the possibility to study relative roles of acceleration and losses in the formation of measured particle spectra and their dynamics. Fig. 8 shows the form of the solution obtained. Here $A_0=Q_0(4\pi mcD_0)^{-1}$.

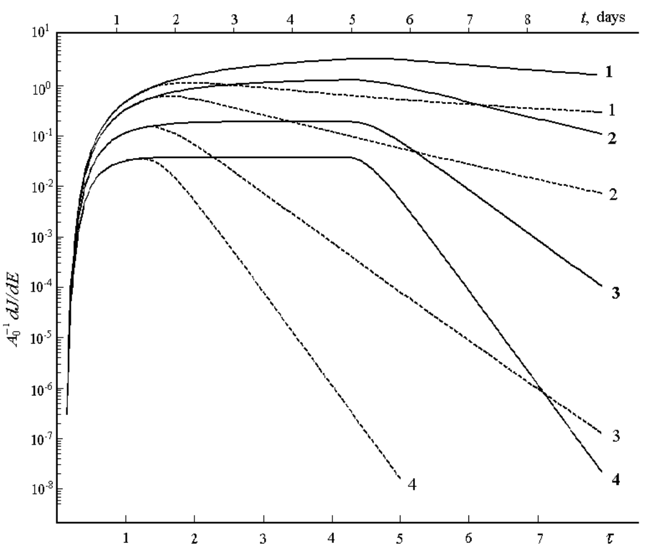

Fig. 8. The dependence of differential fluxes dJ/dE of electrons with energy 1 MeV on dimensionless time τ and fixed D_0 in the case of instantaneous injection of seed population if $\tau_0=D_0t_0=4$ (firm lines) and τ_0 =1 (dotted lines) and $a=(D_0\ t_{esc})^{-1}$ =0, 0.5, 2 and 4. Dotted line is the flux of electrons with energy 0.5 MeV if a=4. Upper horizontal axes is real $t=\tau/D_0$ if $D_0=10^{-5}$ c^{-1}.

The developed theory was especially effective for the analysis of the formation of the plateau in electron particle fluxes observed by the geostationary EXPRESS-A2 satellite.

It is necessary to mention that developed theory describe wide class of events and is applicable to different types of turbulence.

3. Local radiation belts

The most interesting latest findings in the study of electron radiation belts are KORONAS-F observations of the increase of electron flux to the pole of the outer radiation belt (ORB) boundary [45]. Fig. 9 shows variations of electron fluxes with energies 300-600 keV and 0.6-1.5 MeV along the satellite orbit September 15, 2003. 412 crossings of polar region at altitude 400-450 km were analyzed using low altitude polar orbiting Russian satellite CORONAS-F data. CORONAS-F measured fluxes of relativistic electrons at the altitude ~500 km. Increases of fluxes of precipitating relativistic electrons at L>8 were observed in 248 cases.

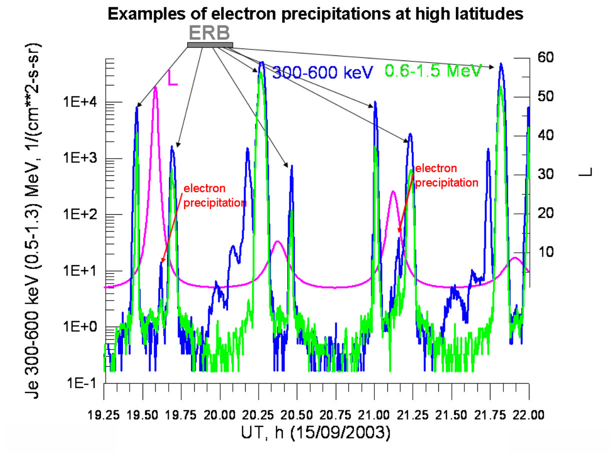

Fig. 9. Results of CORONAS-F observations 15 September 2003.

84 polar crossings with electron precipitations observed during December 2003 and January 2004 were compared with near simultaneous Meteor-3M satellite observations to identify the location of studied regions in comparison with the position of auroral oval. Meteor-3M satellite measures electron fluxes with energies in the energy range from 0.1 to 20 keV, which gives the possibility to identify the position of the auroral oval. The time of observations, coordinates and MLT- sectors were available for 32 events, identified by KORONAS-F. The position of only one event could be identified as localized in the polar cap. Other 31 events are situated inside the auroral oval. Fig. 10 shows an example of nearly simultaneous CORONAS-F and Meteor-3M observations.

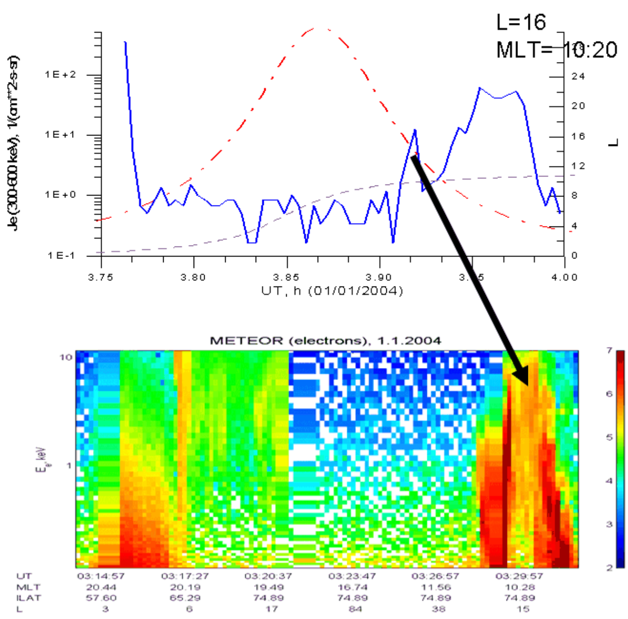

Fig. 10. Nearly simultaneous CORONAS-F and Meteor-3M observations for the event 01.01.2004.

Events of increased relativistic electron precipitations to the pole from the outer boundary of ORB can be identified as a result of local increase of pitch-angle diffusion or as a result of local acceleration of electrons in the plasma sheet by induction electric fields. Nevertheless, some features of observed phenomena require to find some other explanation. For example, Fig. 11 shows the results of CORONAS-F measurements during three consecutive crossings of the outer ORB boundary. It is possible to see that observed region of the increase of electron precipitations maintains practically at the same position for ~4.5 hours. This means that we deal with a quasi-stationary phenomenon.

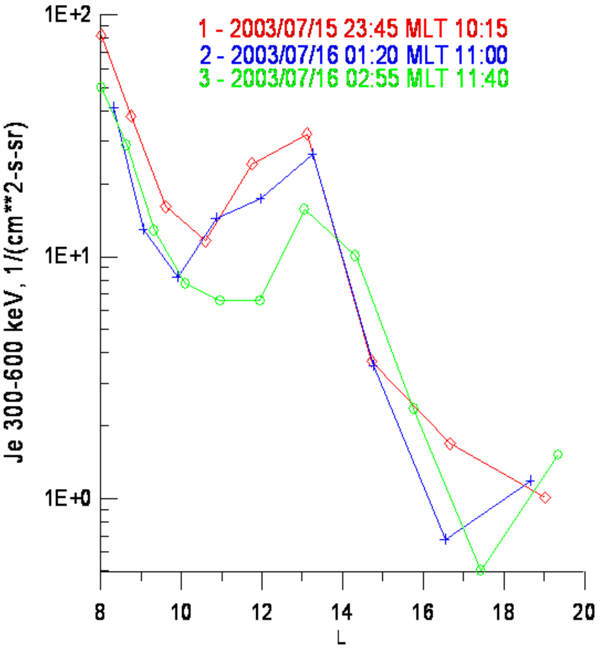

Fig. 11. Electron precipitations observed to the pole from the ORB outer boundary during 3 consecutive crossings (~4.5 hours) July 15-16, 2003.

Analysis of plasma pressure distribution along trajectories of high apogee satellite shows an inhomogeneity of radial profile of plasma pressure at the equatorial plane in a number of cases. Fig. 12 shows an example of the restore of the plasma pressure profile using data of Interball/Tail probe observations for the event November 17, 1995 [46]. It is possible to see that regions of increase of plasma pressure coincide with the regions of decrease of the magnetic field. It is possible to see the same features analyzing the results of CRESS satellite observations (see [47]). They show the presence of diamagnetic plasma cavities in the regions mapped onto the auroral oval latitudes. Such regions can be a source of local plasma traps. Isolines of constant magnetic field B=const in such traps do not surround the Earth and do not cross the magnetopause. Such traps in accordance with Fig. 12 have scales of ~1-2R_E. Energetic particles drift along isolines B=const. Therefore, local plasma traps can be formed due to pressure inhomogeneity. Energetic electrons can fill local plasma traps. They form local radiation belts.

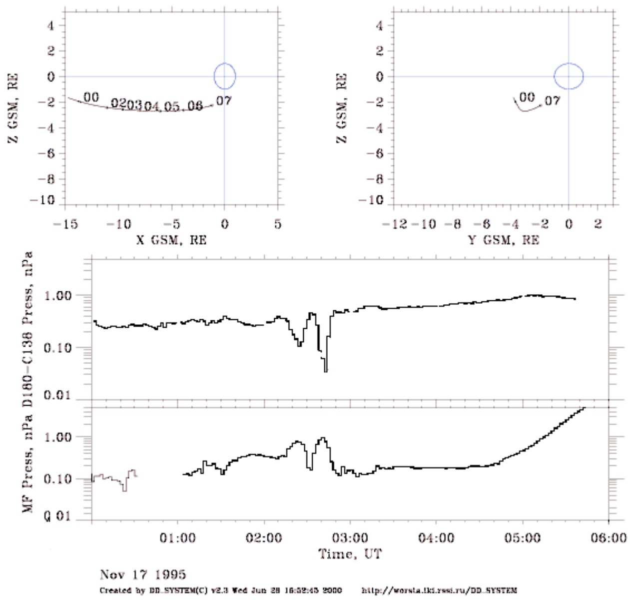

Fig. 12. Results of Interball/Tail probe observations November 17, 1995. Upper panes show satellite orbit position. Low panels show particle and magnetic pressure calculated along the satellite trajectory [46].

Partial ring current can be considered as the most pronounced diamagnetic cavity in the magnetosphere (see [22], [48], [49]).

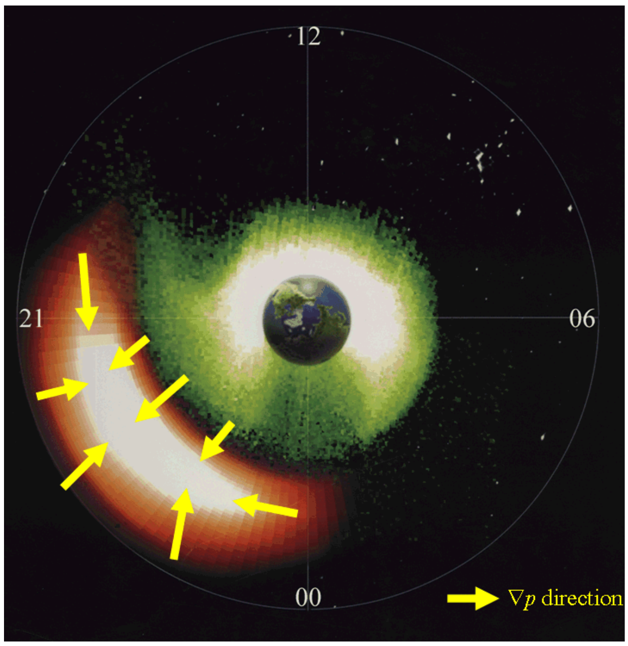

Fig. 13. Sketch, illustrating directions of plasma pressure gradients in the region of asymmetric ring current.

Fig. 13. Shows the averaged partial ring current (red) configuration (see [50]) obtained using data of IMAGE satellite and simultaneous plasmasphere location (green). Arrows show the direction of plasma pressure gradients.

Untiearthward directed plasma pressure gradients leads in accordance with (1) to the appearance of eastward transverse current (see the discussion in [51]). Simultaneous existence of azimuthally localized enhanced westward and eastward currents means the possibility of the formation of closed current loops. Such current loops decrease magnetic field inside the loop and increase the magnetic field outside the loop. Such magnetic field changes can lead to the formation of closed localized contours of *B*=const.

Results of modeling of changes of magnetic configuration due to changes of plasma pressure support the possibility of the formation of local contours with *B*=const in the high latitude magnetosphere. The modeling of the distribution of particle pressure, electric fields and field-aligned currents in the high latitude magnetosphere was made in accordance with scheme described in [52].

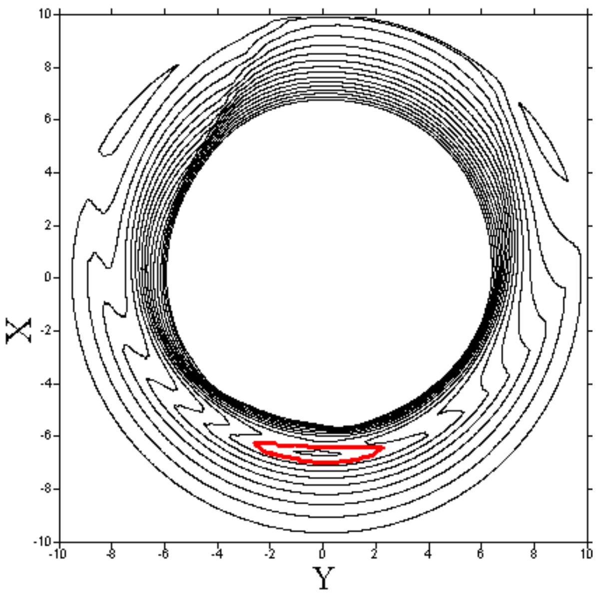

Fig. 14. Preliminary results of the modeling of the distortion of the Earth's dipole magnetic field by convecting tail plasma.

Modification of magnetic field by increased plasma pressure was taken into account suggesting the validity of the condition of magnetostatic equilibrium. Fig. 14 shows the preliminary results of such modeling. It was suggested that dawn-dusk potential drop is increased from 20 to 100 kV and plasma density is increased from 1 till 6 cm^{-3} for 10 min and then again decreased till 1 cm^{-3}. Middle energy was equal to 5 keV at the boundary of modeled region at $10R_E$. Initial magnetic field had dipole configuration. Red line in Fig. 14 shows formed closed loop *B*=const. Therefore the results of produced by the modeling support the suggestion about the possibility of the formation closed loops of *B*=const in the high latitude magnetosphere. It is interesting to mention that closed loops in Fig. 14 surround region of increased magnetic field.

Produced analysis shows the possibility of the formation of local plasma traps in high latitude magnetosphere. Filling such traps by energetic electrons will lead to the formation of local radiation belts to the pole from the outer boundary of ORB. The formation of such local radiation belts can explain shown on Fig. 10-11 results of CORONAS-F observations. It is necessary to stress that only preliminary results are presented. Future studies will help to clarify the situation.

6. DISCUSSION AND CONCLUSIONS

Presented analysis shows that:

- Regular and stochastic acceleration mechanisms can produce definite contribution to the acceleration of relativistic electrons. The contribution of stochastic mechanisms can be obtained only after extraction of the contribution of regular mechanisms.
- The solution of the problem of acceleration of relativistic electrons requires proper models of magnetic field taking into account the distribution of plasma pressure inside the magnetosphere.
- Dayside part of inner magnetosphere transverse currents flow at high latitudes. Such currents are closed inside the magnetosphere by nighttime transverse currents and constitute the high latitude continuation of ordinary ring current.
- Local plasma traps filled by relativistic electrons (local radiation belts) can be formed in the high latitude magnetosphere

The solution of the problem of the formation of high fluxes of relativistic electrons – "satellite killers" - unfortunately is not received till now in spite of 50-years history of its study. One of the major problems is the problem of proper description of the topology of magnetic configuration. Obtained results demonstrate the importance of some effects, which was not included into the existing magnetic field models. Penetration of solar cosmic rays into the magnetosphere (the position of the penetration boundary) gives now and will give in the future very important information about the magnetic field configuration. However, at the end, it is necessary to stress the importance of new experimental observations and theory development for better understanding of the phenomena leading to the relativistic electron acceleration.

ACKNOWLEDGMENTS

The work was supported by RFBR Grants and FONDECYT Grant 1070131.

REFERENCES

[1] M. Fujimoto, and A. Nishida, "Energization and anisotropization of energetic electrons in the Earth's radiation belt by the recirculation process", *J. Geophys. Res.*, 1990, vol. 95(A4), pp. 4265 -4270.

[2] W. W. Liu, G. Rostoker, and D. N. Baker, "Internal acceleration of relativistic electrons by large-amplitude ULF pulsations", *J. Geophys. Res.*, 1999, vol. 104(A8), pp. 17391-17407.

[3] M. K. Hudson, S. R. Elkington,; J. G. Lyon, and C. C.Goodrich, Increase in Relativistic Electron Flux in the Inner Magnetosphere: ULF Wave Mode Structure, *Adv. Space. Res.*, 2000, vol. 25(12), pp. 2327-2337.

[4] S. R. Elkington, M. K. Hudson, and A. A. Chan, "Acceleration of relativistic electrons via drift-resonant interaction with toroidal-mode Pc-5 ULF oscillations", *Geophys. Res. Lett.*, 1999, vol. 26(21), pp. 3273-3276.

[5] D. Summers, and Chun-ya Ma., "A model for generating relativistic electrons in Earth's inner magnetosphere based on gyroresonant wave-particle interactions", *J. Geophys. Res.*, 2000, vol. 105(A2), pp. 2625–2639.

[6] A. V. Dmitriev, M. F. Bakhareva, and Yu. S. Minaeva, "Electron acceleration by magnetic pumping on the tail magnetopause", *Adv. Space Res.*, 2001, vol. 28(5), pp. 807-812.

[7] M. F. Bakhareva, A. V. Dmitriev, "Statistical alfven acceleration of electrons in the external magnetosphere of the Earth", *Geomagnetism and Aeronomia*, 2002, vol. 2(1), pp. 21 – 31.

[8] O. Kozyreva, V. Pilipenko, M. J. Engebretson, K. Yumoto, J. Watermann, and N. Romanova, "In search of a new ULF index: Comparison of Pc5 power with dynamics of geostationary relativistic electrons", *Planet. Space Sci.*, 2007, 55(6), pp. 755-769 .

[9] A. W. Degeling, L. G. Ozeke, R. Rankin, I. R. Mann, and K. Kabin, "Drift resonant generation of peaked relativistic electron distributions by Pc 5 ULF waves", *J. Geophys. Res.*, 2008, vol. 113, A02208, doi:10.1029/2007JA012411.

[10] L. G. Ozeke, and I. R. Mann, "Energization of radiation belt electrons by ring current ion driven ULF waves", *J. Geophys. Res.*, 2008, vol. 113, A02201, doi:10.1029/2007JA012468.

[11] R. B. Horne, and R. M. Thorne, "Potential wave modes for electron scattering and stochastic acceleration to relativistic energies during magnetic storms", *Geophys. Res. Lett.*, 1998, vol. 25(15), pp. 3011-3014.

[12] D. Summers, R. M. Thorne, and F. Xiao, "Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the magnetosphere", *J. Geophys. Res.*, 1998, vol. 103(A9), pp. 20487-20500.

[13] D. Summers, C. Ma, N. P. Meredith, R. B. Horne, R. M. Thorne, D. Heynderickx, and R. R. Anderson, "Model of the energization of outer-zone electrons by whistler-mode chorus during the October 9, 1990 geomagnetic storm", *Geophys. Res. Lett.*, 2002, vol. 29(4), doi:10.1029/2002GL016039.

[14] D. Summers, C. Ma, and T. Mukai, "Competition between acceleration and loss mechanisms of relativistic electrons during geomagnetic storms", *J. Geophys. Res.*, 2004, vol. 109, A04221, doi:10.1029/2004JA010437.

[15] R. B. Horne, and R. M. Thorne, "Relativistic electron acceleration and precipitation during resonant interactions with whistler-mode chorus", *Geophys. Res. Lett.*, 2003, vol. 30(10), doi:10.1029/2003GL016973.

[16] R. B. Horne, R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R. Anderson, "Timescale for radiation belt electron acceleration by whistler mode chorus waves", *J. Geophys. Res.*, 2005, vol. 110, A03225, doi:10.1029/2004JA010811.

[17] A. Varotsou, D. Boscher, and S. Bourdarie, R. B. Horne, S.A. Glauert, and N. P. Meredith, "Simulation of the outer radiation belt electrons near geosynchronous orbit including both radial diffusion and resonant interaction with whistler-mode chorus waves", *Geophys. Res. Lett.*, 2005, vol. 32, L19106, doi:10.1029/2005GL023282,.

[18] A. G. Demekhov, V. Yu. Trakhtengerts, M. J. Rycroft, and D. Nunn, Electron acceleration in the magnetosphere by whistler-mode waves of varying frequency, Geomagnetism and Aeronomy, vol. 46(6), pp. 711-716.

[19] D. Summers, B. Ni, and N. P. Meredith, "Timescales for radiation belt electron acceleration and loss due to resonant wave-particle interactions: 2. Evaluation for VLF chorus, ELF hiss, and electromagnetic ion cyclotron waves", *J. Geophys. Res.*, 2007, vol. 112, A04207, doi:10.1029/2006JA011993.

[20] R. M. Thorne, Y. Y. Shprits, N. P. Meredith, R. B. Horne, W. Li, and L. R. Lyons, "Refilling of the slot region between the inner and outer electron radiation belts during geomagnetic storms", *J. Geophys. Res.*, 2007, vol. 112, A06203, doi:10.1029/2006JA012176.

[21] N. P. Meredith, R. B. Horne, S. A. Glauert, and R. R. Anderson, "Slot region electron loss timescales due to plasmaspheric hiss and lightning generated whistlers", *J. Geophys. Res.*, 2007, vol. 112, A08214, doi:10.1029/2007JA012413.

[22] R. M. Skoug, M. F. Thomsen, M. G. Henderson, H. O. Funsten, G. D. Reeves, C. J. Pollock, J.-M. Jahn, D. J. McComas, D. G. Mitchell, P. C. Brandt, B. R. Sandel, C. R. Clauer, and H. J. Singer, "Tail-dominated storm main phase: 31 March 2001", *J. Geophys. Res*, 2003, vol. 108 (A6), doi:10.1029/2002JA009705.

[23] N. A. Tsyganenko, and M. I. Sitnov, "Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms", *J. Geophys. Res*., 2005, vol. 110 (A3), doi:10.1029/2004JA010798.

[24] K. Kudela, and R. Bucik, "Low energy cosmic rays and disturbed magnetosphere". *Proceedings of the second international symposium Solar Extreme Events, Fundamental Science and Applied Aspects*, Nor Amberd, Armenia, 26–30 September 2005, 2006, pp. 57–62.

[25] N. A. Tsyganenko, and M. I. Sitnov, "Magnetospheric configurations from a high-resolution data-based magnetic field model", *J. Geophys. Res.*, 2007, vol. 112(A6), doi:10.1029/2007JA012260.

[26] M. I. Sitnov, N. A. Tsyganenko, A. Y. Ukhorskiy, and P. C. Brandt, Dynamical data-based modeling of the storm time geomagnetic field with enhanced spatial resolution, 2008, *J. Geophys. Res*., 2008, vol. 113, doi:10.1029/2007JA013003.

[27] E.E. Antonova, and N. Yu. Ganushkina, "Inner magnetospheric currents and their role in the magnetosphere dynamics", *Phys. Chem. Earth(C)*, 2000, vol. 25 (1–2), pp. 23–26.

[28] E. E. Antonova, I. P. Kirpichev, M. V. Stepanova, K. G. Orlova, I. L. Ovchinnikov, "Topology of the high latitude magnetosphere during large magnetic storms and the main mechanisms of relativistic electron acceleration", *Adv. Space Res.*, 2008, in press.

[29] N. A. Tsyganenko,"A model of the near magnetosphere with a dawn-dusk asymmetry: 1. Mathematical structure", *J. Geophys. Res*., 2002a, 107 (A8), doi:10.1029/2001JA000219.

[30] N. A. Tsyganenko, "A model of the near magnetosphere with a dawn-dusk asymmetry: 2 Parameterization and fitting to observations", *J. Geophys. Res*., 2002b, vol. 107 (A8), doi:10.1029/2001JA000220.

[31] A. T. Y. Lui, and D. C. Hamilton, "Radial profile of quite time magnetospheric parameters", *J. Geophys. Res.*, 1992, vol. 97 (A12), pp. 19325–19332.

[32] Antonova, E.E. "Investigation of the hot plasma pressure gradients and the configuration of magnetospheric currents from INTERBALL", *Adv. Space Res.*, 2003, vol. 31(5), 1157–1166.

[33] E. E. Antonova, "Magnetostatic equilibrium and current systems in the Earth's magnetosphere", *Adv. Space Res*, 2004, vol. 33, pp. 752–760.

[34] L. V. Tverskaya, "On the boundary of electron injection into the magnetosphere", *Geomagetism and. Aeroomia*, 1986, vol. 26 (5), pp. 864–865 (in Russian).

[35] L. V. Tverskaya, N. N. Pavlov, J. B. Blake, R. S. Selesnick, and J. F. Fennell, "Predicting the L-position of the storm-injected relativistic electron belt", *Adv. Space Res.*, 2003, vol. 31 (4), pp. 1039–1044.

[36] L. V. Tverskaya, T. A. Ivanova, N. N. Pavlov, S. Ya. Reizman, I. A. Rubinstein, E. N. Sosnovets, N. N. Veden'kin, "Storm-time formation of a relativistic electron belt and some relevant phenomena in other magnetosphere plasma domains, *Adv. Space Res*., 2005, vol. 36(12), pp. 2392-2400.

[37] B. A. Tverskoy, "Formation mechanism for the structure of the magnetic storm ring current", *Geomagnetism and Aeronomia*, 1997, vol. 37 (5), pp. 555–559 (in Russian).

[38] E. E. Antonova, "Magnetospheric substorms and the sources of inner magnetosphere particle acceleration", *The Inner Magnetosphere: Physics And Modeling*, *Geophysical Monograph Series 155*, 2005, Copyright 2005 by AGU, doi:10.1029/155GM12, pp. 105–111.

[39] M. Slivka, K. Kudela, S. N. Kuznetsov, "Some aspects of relativistic electron fluxes dynamics in the outer radiation belt during magnetic storms", *Acta physica slovaca*, 2006, vol. 56(2), pp. 103-107.

[40] S. N. Kuznetsov, K. Kudela, S. P. Ryumin, Y. V. Gotselyuk, "CORONAS-F satellite: Tasks for study of particle acceleration", *Adv. Space. Res.*, 2002, vol. 30, (7), pp. 1857-1863.

[41] M. Stepanova, E. E. Antonova, and J. M. Bosqued, "Radial distribution of the inner magnetosphere plasma pressure using low-altitude satellite data during geomagnetic storm: The March 1–8, 1982 event", *Adv. Space Res.*, 2008, vol. 41, pp. 1658–1665.

[42] C. Cattell, J. R. Wygant, K. Goetz, K. Kersten, P. J. Kellogg, T. von Rosenvinge, S. D. Bale, I. Roth, M. Temerin, M. K. Hudson, R. A. Mewaldt, M. Wiedenbeck, M. Maksimovic, R. Ergun, M. Acuna, and C. T. Russell, "Discovery of very large amplitude whistler-mode waves in Earth's radiation belts", *Geophys. Res. Lett.*, 2008, vol. 35, L01105, doi:10.1029/2007GL032009.

[43] E. E. Antonova, "Magnetostatic equilibrium and turbulent transport in Earth's magnetosphere: A review of experimental observation data and theoretical approach", *International Journal of Geom. and Aeronomy*, 2002, vol. 3(2), pp. 117-130.

[44] M.F. Bahareva, and K.G. Orlova, "The influence of the temps of acceleration and losses on the temporal dynamics of energetic electrons during geomagnetic disturbances", *Geomagnetism and Aeronomia*, 2008, in press (in Russian).

[45] I. N. Myagkova, M. O. Riazantseva, E. E. Antonova, S. N. Kuznetsov, Yu. I. Denisov, B. V. Marjin, "Sub-relativistic electron precipitation at high latitudes: Low latitude satellite observations", Proceedings of 7-th International Conference Problem of Geocosmos, St. Peterburg, Russia, 26-30 May, 2008, in press.

[46] E. E. Antonova, E. Yu. Budnik, I. P. Kirpichev, V. N. Lutsenko, and N. F. Pissarenko, "Magnetospheric plasma pressure and space weather", *Adv. Space Res.*, 2003, vol. 31(4), p. 1093-1098.

[47] T. V. Kozelova, L. L. Lazutin, and B. V. Kozelov, "Total ion pressure changes with L shell in the nightside inner magnetosphere", *J. Geophys. Res.*, vol. 113(A07), doi:10.1029/2007JA012799, 2008.

[48] C. J. Pollock, K. Asamura, M. M. Balkey, J. L. Burch, H. O. Funsten, M. Grande, M. Gruntman, M. Henderson, J.-M. Jahn, M. Lampton, M. W. Liemohn, D. J. McComas, T. Mukai, S. Ritzau, M. L. Schattenburg, E. Scime, R. Skoug, P. Valek, and M. Wüest. "First medium energy neutral atom (MENA) images of Earth's magnetosphere during substorm and storm-time", *Geophys. Res. Lett.*, 2001, vol. 28(6), pp. 1147-1150.

[49] D. G. Mitchell, K. C. Hsieh, C. C. Curtis, D. C. Hamilton, H. D. Voss, E. C. Roelof, and P. C:son-Brandt. "Imaging two geomagnetic storms in energetic neutral atoms", *Geophys. Res. Lett.*, 2001, vol. 28(6), pp. 1151-1154.

[50] The inner magnetosphere physics and modeling, ed. T. I. Pulkkinen, N. A. Tsygenenko, R. H. W. Friedel, Geophysical Monograph Series 155, 2005, Copyright 2005 by AGU, doi:10.1029/155GM12.

[51] E. E. Antonova, V. F. Bashkirov, and N. Yu. Ganyshkina, "Quite time plasma pressure distribution in the Earth's magnetospheric trap calculated on the basis of the existing models of trapped radiation", *Radiation measurements*, 1999, vol. 30, pp. 523-527.

[52] F. Tofoletto, S. Sazykin, R. Spiro, and R. Wolf, "Inner magnetospheric modeling with the Rice Convection Model", *Space Sci. Rev.*, 2003, vol. 107, pp. 175-196.