"Physics of Auroral Phenomena", Proc. XXXV Annual Seminar, Apatity, pp. 9 - 16, 2012

Polar Geophysical Institute

MAGNETOSPHERIC STORMS AND SUBSTORMS, NATURE AND TOPOLOGY OF HIGH LATITUDE CURRENT SYSTEMS

E.E. Antonova[1,2], I.P.Kirpichev[2,1], V.V. Vovchenko[2], M.O. Riazantseva [1,2], M.S. Pulinets[1], I.L. Ovchinnikov[1], S.S. Znatkova[1], M.V. Stepanova[3]

[1]*Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991, Russia, antonova@orearm.msk.ru*
[2]*Space Research Institute (IKI) Russian Academy of Science, Moscow, Russia*
[3]*Physics Department, Science Faculty, Universidad de Santiago de Chile, Chile*

Abstract. The nighttime region at geocentric distances ~7-10R_E is ordinarily considered as the near tail region. However the results of observations including latest THEMIS mission clearly demonstrate the existence of surrounding the Earth plasma ring at these geocentric distances. The distribution of plasma pressure in the ring is near to azimuthally symmetric. Daytime compression of magnetic field lines and shift of minimal value of the magnetic field till high latitudes lead to splitting of daytime transverse currents in Z direction. As a result nighttime transverse currents in the surrounding the Earth plasma ring are concentrated near equator, daytime transverse currents are spread along compressed by solar wind field lines forming the cut ring current (CRC) which is the high latitude continuation of the ordinary ring current. CRC is supported by directed to the Earth plasma pressure gradients.

The role of CRC in the development of magnetic storm and the creation of the Dst variation is analyzed. We stress that the development of partial ring current, which is one of the well-known features of magnetic storm, in the CRC region helps to eliminate paradox, appeared when it was suggested that tail current could have the considerable role in the Dst formation. The contribution CRC in the process of Dst formation during magnetic storms is evaluated for selected magnetic storms with known radial profile of plasma pressure.

The magnetospheric substorm is one of the most extensively stydied magnetospheric phenomena for the most than 50 latest years. However the mechanism of observed energy explosion and localization of substorm onset continue to be widely discussed. We summarize the results of observations demonstrating the isolated substorm onset at geosentric distances smaller than 10R_E. It is suggested that isolated substorm onset is localized in CRC.

Introduction

More than fifty years period of auroral researches reveal the main features of auroral dynamics (see Feldstein et al. [2010]). However, the main processes of auroral formation continue to be extensively debated. Later findings (see the review [Antonova et al., 2011]) show that even the wide-spread opinion about auroral oval mapping on the plasma sheet of the magnetosphere of the Earth requires more careful analysis.

First results of particle observations in the magnetosphere of the Earth (see Vernov et al. [1969]) reviled the existence of the region from the geostationary orbit till ~10R_E named the region of quasitrapping. Trajectories of energetic particle in this region cross the magnetopause when the particle pitch angle is equal to 90° and the drift shell splitting effect is observed for particles with smaller pitch angles [Shabansky and Antonova, 1968]. Drift trajectories of such particles are closed inside the magnetosphere. Effect of drift echo is observed till ~13R_E near midnight [Hori et al., 2003]. This means that the external boundary of the region of quasitrapping can be localized at such distances.

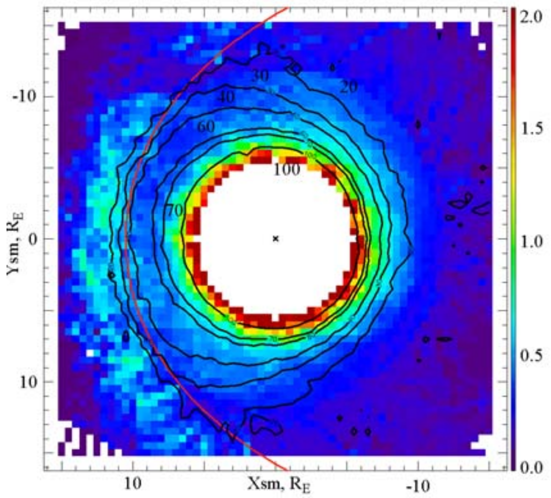
Characteristics of plasma population in the region of quasitrapping are near to plasma sheet plasma (see discussion in Antonova [2007], Antonova et al. [2009a, 2011]). This statement is supported by results of low altitude and near equatorial observations. Newell and Meng [1992] using DMSP satellite data showed that plasma sheet-like particle precipitations near noon come from a region situated at the equator from the low latitude boundary layer. Created models of auroal particle precipitations (see [Vorobjev and Yagodkina, 2008; Newell et al., 2009] and ref. in these papers) demonstrate the existence of closed near noon ring of plasma sheet-like particle precipitations. Particle observations of THEMIS mission (see [Angelopoulos, 2008]) show the presence of plasma sheet-like plasma near noon at every crossing of the magnetopause to the equator from the low latitude boundary layer (LLBL). Analyzing statistical picture of Geotail observations obtained by Nagata et al. [2008] at X_{GSW}<0 (where *GSW* is Geocentric Solar Wind coordinate system) it is also possible to select the ring-type distribution of plasma around the Earth.

The existence of the surrounding the Earth plasma ring with quasitapped energetic particle population selects this ring as the magnetospheric domain, the study of which can be important for understanding of storm and substorm dynamics. In this paper, we shall try to analyze the distribution of plasma pressure in the ring and structure of transverse currents. We try to demonstrate that symmetric part of the transverse current in the ring during magnetic storms create the main contribution in the azimuthally symmetric part of magnetic disturbance at the Earth producing Dst variation. We also discuss the localization of isolated substorm onset.

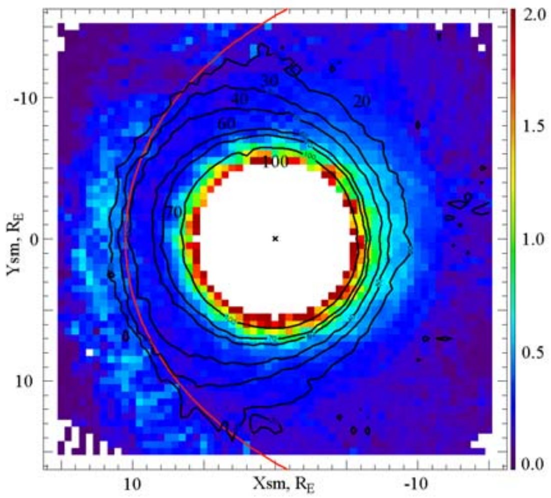
Distribution of pressure in the ring in accordance with THEMIS data

Plasma pressure is among the main parameters responsible for the current distribution in plasma systems and plasma stability. Determining plasma pressure within the magnetosphere can also be of a direct practical importance in connection with the problem of predicting space weather [Antonova et al., 2003]. The obtaining of plasma distribution requires measurements of all plasma particles in a wide energy range. That is why comparatively limited information was obtained about plasma pressure distribution. Tsyganenko and Mukai [2003] created a magnetotail plasma pressure model based on the GEOTAIL satellite data at geocentric distances larger than $10R_E$. The global distribution of plasma pressure in the night sector using Geotail data was obtained by Wang et al. [2009]. The global pressure distribution in the inner regions of the Earth's magnetosphere at geocentric distances < $8.8R_E$ was obtained from the AMPTE/CCE equatorial satellite by DeMichells et al. [1997, 1999], Lui [1992, 2003]. The region of transition from dipole to tailward stretched field lines has been studied relatively poorly. Some pressure profiles in this region were obtained onboard the Interball/Tail probe in [Antonova et al., 2002; Kirpichev et al., 2005].

Data obtained in the process of realization of THEMIS mission (Angelopoulos [2008], http://themis.ssl.berkeley.edu/, http://cdaweb.gsfc.nasa,gov/) give the possibility to obtain the global picture of pressure distribution inside the magnetosphere till the dayside magnetopause. First results of the analysis were obtained by Kirpichev and Antonova [2011]. The moments of ion and electron distribution functions were obtained using two different instruments: ESA, which is an electrostatic analyzer of ions in the energy range from 1.6 eV to 25 keV and electrons with energies from 2 eV to 32 keV, and SST, which is a solid state telescope measured ions with energies from 25 keV to 6 MeV and electrons with energies from 25 to ~900 keV. The period of satellite rotation about its axis made it possible to calculate the distribution function moments at an interval of 3 s. A local magnetic field with the same time resolution (3 s) was obtained from the FGM magnetometer data. The ion composition was not determined in this experiment; therefore, we subsequently assume that protons make the main contribution, which is a good approximation during magnetically quiet periods [Daglis et al., 1999]. Solar minimum was observed during analyzed period and *Dst* was mainly larger than –40 nT. The minimal *Dst* value was about –80 nT. The equatorial plane (*XY*) was divided into $0.5R_E$ bins in the solar–magnetospheric (SM) coordinate system. The measurements on all five satellites were accumulated and averaged in each bin. When a satellite crossed each bin in the (*XY*) plane, we averaged the pressure over a 5 min interval in each considered bin. When approaching the Earth (closer than $6R_E$), the penetrating radiation results in a distortion in ESA readings [McFadden et al., 2008] which can be the source of uncertainty of pressure at $R<6R_E$.



a

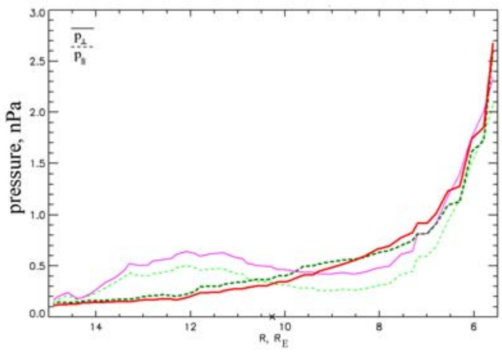


b

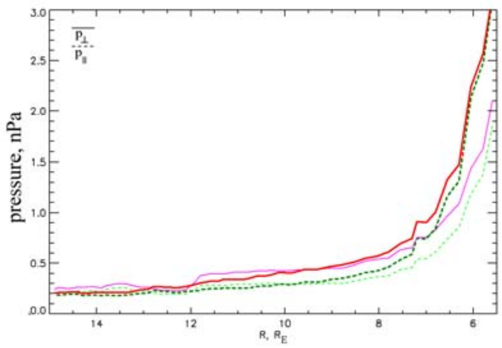
Fig. 1. **(a)** Distribution of the average value of the pressure perpendicular to the magnetic field ($p_\perp$) and **(b)** parallel to the magnetic field ($p_{||}$) obtained using ESA and SST THEMIS measurements. The thick line shows the magnetopause position in accordance with Shue et al. [1998] model at $10R_E$, thin lines show the local magnetic field constant value (in nT) contours obtained in accordance with FGM THEMIS measurements.

Fig. 1a,b shows the averaged picture of the diagonal components of the pressure tensor in a coordinate system attached to a local magnetic field, i.e., the pressure components aligned with the magnetic field

($p_{||}$) and perpendicular to this field ($p_{\perp}$). The results are presented without smoothing. The contours of the average value of the local magnetic field magnitude measured on the satellites and the magnetopause position according to the model of Shue et al. [1998] when the subsolar point was at $10R_E$ are additionally drawn. White bins correspond to region with low statistics. The pressure values outside the magnetopause correspond to the averaged plasma pressure values in the magnetosheath. Near the subsolar point, such a pressure can almost completely balance the magnetic field pressure inside the magnetosphere (see [Znatkova et al., 2010) and references therein].



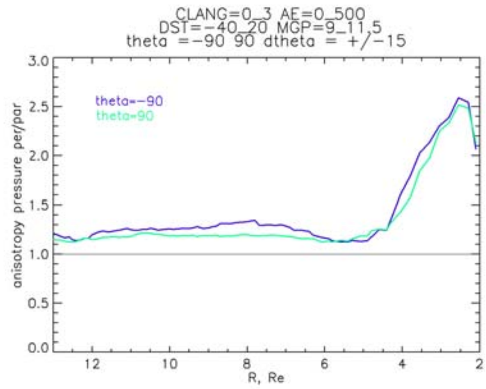
a

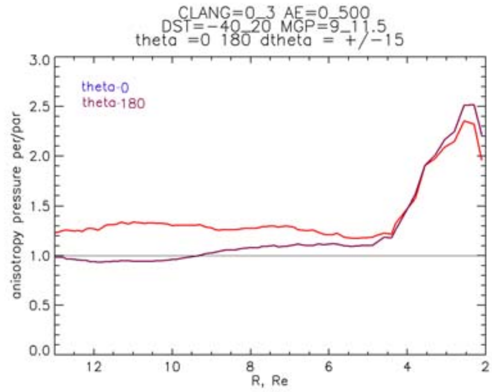


b

Fig. 2. Radial profiles of the perpendicular and parallel pressure component at **(a)** the noon – midnight and **(b)** dawn - dusk meridians for IMF Bz>0 and Bz <0. Night pressure is shown by solid thin line for IMF Bz>0 and solid thick line for IMF Bz <0. Noon pressure is shown by dashed thin line for IMF Bz>0 and dashed thick line for IMF Bz <0. Dawn pressure is shown by solid thin line for IMF Bz>0 and solid thick line for IMF Bz <0. Dusk pressure is shown by dashed thin line for IMF Bz>0 and dashed thick line for IMF Bz <0.

Fig. 2a,b demonstrates the radial profiles of the parallel and perpendicular pressure components at the day–night and dawn-dusk meridians, which make it possible to analyze the pressure distribution asymmetry. We constructed Figs. 2 when averaging was performed in a certain direction in the ±15° azimuthal sector. The asterisk on the abscissa of Fig. 2a shows the magnetopause position according to the model of Shue et al. [1998]. It is possible to see, that the pressure in the dusk sector is higher than that in the dawn sector. However, we should note that the dawn-dusk asymmetry is only observed beginning from a distance of $\sim 7R_E$ and increases towards the Earth.





a

b

Fig. 3. Pressure anisotropy at **(a)** the noon–midnight and **(b)** dawn-dusk meridians for IMF Bz>0 and Bz <0. Night pressure anisotropy is shown by solid thin line for IMF Bz>0 and solid thick line for IMF Bz <0. Noon pressure anisotropy is shown by dashed thin line for IMF Bz>0 and dashed thick line for IMF Bz <0. Dawn pressure anisotropy is shown by solid thin line for IMF Bz>0 and solid thick line for IMF Bz <0. Dusk pressure anisotropy is shown by dashed thin line for IMF Bz>0 and dashed thick line for IMF Bz <0.

Fig. 3 shows the pressure anisotropy ($p_{\perp}$- $p_{||}$)/ $p_{||}$ in %. The pressure anisotropy depends on the geocentric distance but is insignificant at geocentric distances larger than $7.5R_E$. Such result is in agreement with the latest finding of Wang et al. [2011]. This means that the approximation of isotropic pressure can be used with comparatively high accuracy. The statistical errors resulting from the determination of the pressure values are not shown on Fig. 2,3. However, produced analysis shows that the differences in the perpendicular and parallel pressure components and the pressure azimuthal asymmetry are inside the statistical errors. This means that in the first approximation surrounding the Earth plasma ring has near to azimuthally symmetric isotropic pressure distribution during quite time.

Transverse currents in the plasma ring

In the conditions of magnetostatic equilibrium and isotropic plasma pressure transverse current $j_\perp$ is determined in accordance with the relation:

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

where ∇p is the plasma pressure gradient, **B** is the magnetic field. Equation (1) indicates that surrounding the Earth plasma ring till the dayside magnetopause with plasma pressure gradient directed to the Earth (see Fig. 2) contains westward directed transverse current. Simultaneous measurements of pressure gradients and magnetic field give the possibility to determine current density. However, only nighttime current densities give the information about integral current. The shift of minimal value of magnetic field on the daytime field lines leads to current spreading along field line (see Antonova et al. [1999b,c]). Taking into consideration that the plasma pressure has a constant value along magnetic field line it is possible to evaluate current density at any point of the field line, if plasma pressure distribution at the equatorial plane is known, using one of the magnetic field models. Although such approach is not self consistent, it makes it possible to estimate current densities far from the equatorial plane. The calculations produced by Antonova et al. [1999b,c] using Tsyganenko-2001 model show that integral current at geocentric distances from 7.5 to $10R_E$ is comparable with the nighttime current at the same geocentric distances. The centre of the averaged transverse current in these calculations was shift on Z_{eff}=±$2.7R_E$ from the equator. Such finding can mean, that surrounding the Earth plasma ring is the ring current domain, in which region till ~$7R_E$ is the region of ordinary ring current and the region at greater distances till magnetopause near noon is the region of high latitude continuation of this current named by Antonova [2003, 2004] the cut ring current (CRC). Transverse current splits into two branches in the dayside magnetosphere. The daytime part of CRC is situated comparatively close to the magnetopause and is located far from the equatorial plane. This could be the reason why it was not included into the traditional versions of Tsyganenko models and overstretching of these models. It is interesting to mention that current lines corresponding to CRC appear in the results MHD modelling (see Liemohn et al. [2011]).

Plasma pressure gradients in the surrounding the Earth plasma ring as the source of Dst variation

Numerous studies have been published on the relative contributions of different terrestrial and magnetospheric currents to the Dst index. Ring current was considered as the main source of negative values of Dst variation at the first stages. This point of view was later criticized (see the discussion in [Greenspan and Hamilton, 2000; Antonova, 2001] as some features of Dst dynamics (for example, the decrease of |Dst| index after substorm onset or effect of Iyemori and Rao [1996]) was difficult to explain using traditional ring current description. This leads to the suggestion that tail current produce large contribution in Dst formation. However many scientist (see Roeder et al. [1996]; Jordanova et al. [1998]; Greenspan and Hamilton [2000]) continued to support the traditional point of view.

The existence of the surrounding the Earth plasma with earthward directed plasma pressure gradient at geocentric distances till the Earth magnetopause activate the attention to the problem of the sources of currents producing the Dst variation during magnetic storms. Greenspan and Hamilton [2000] chose $L = 7$ (L is considered as only the distance at the equatorial plane) as an outer boundary for the ring current because they consider that during disturbed times the nightside inner edge of the plasma sheet typically is located near that L value [Parks, 1991]. The existence of the surrounding the Earth plasma ring and CRC shifts the inner edge of the plasma sheet and tail current at larger L. That is why it is necessary try to evaluate the contribution of the ring current including its high latitude continuation in the Dst formation.

The direct way of the clarification of the role of CRC in the Dst formation is the creation of the magnetic field model in which CRC is included. It was not possible until now to obtain the analytical expression for CRC magnetic field and create the corresponding model. However, it is possible to obtain the simplified estimation of the role of the whole ring current in the Dst formation if the radial distribution of the magnetospheric plasma pressure is measured. The value of the magnetic pressure in the external parts of the magnetic trap is comparable with plasma pressure. That is why instead of the Dessler-Parker-Sckopke relation (DPS), which predicts a linear dependence of the perturbation magnetic field at the surface of the Earth ΔB on the total ring current kinetic energy U_p, it is necessary to use expression, obtained by Carovillano and Maguire [1968]:

$$\Delta B / B_s = (2U_p + U_b) / 3U_s , \qquad (2)$$

where B_s is the field on Earth's equator, U_s is the energy of the dipole field outside the Earth's surface, U_b is the self-energy of ring current field. Expression (2) gives the possibility to calculate the effect of neglecting in DPS the fact that the magnetic field in which the ring current particles move includes the field that these particles produce. The ring current kinetic energy U_p in DPS in accordance with (2) should be replaced by $U_p + U_b /2$, where U_b is the self-energy of the ring current magnetic field. Calculation of U_b if the radial distribution of isotropic plasma pressure $p(r)$ is known requires the solution using the sequential iteration method of the equation (see Vovchenko and Antonova [2010, 2012] and ref. therein):

$$\left\{\frac{1}{r\cdot\cos\theta}\cdot\frac{\partial^2\Phi}{\partial r^2}+\frac{1}{r^3}\cdot\frac{\partial}{\partial\theta}\left(\frac{1}{\cos\theta}\cdot\frac{\partial\Phi}{\partial\theta}\right)\right\}= -4\cdot\pi\cdot r\cdot\cos\theta\cdot\frac{\partial p}{\partial\Phi}, \quad (3)$$

where $\Phi = r\cdot\cos\theta\cdot A_\varphi$, A_φ is the azimuthal component of the vector potential of the magnetic field (**B**=*rot***A**) in the spherical system of coordinates (r, θ, φ). The initial magnetic field not distorted by currents flowing in the plasma is considered the dipole field.

Distribution of plasma pressure during the main phase of the magnetic storm is very asymmetric with maximum near midnight and evening. Plasma pressure is near to isotropic during the magnetic storm (see Greenspan and Hamilton [2000]). That is why to analyze the symmetric part of the ring current it is necessary to use $p(r)$ measured during daytime or dawn hours. The obtaining of $p(r)$ requires the crossings of the region of radial plasma pressure gradient for the time, which is much smaller than the time of pressure changes. It is quite difficult using high orbiting satellites. For example, AMPTE CCE passes through the ring current required 3 hours (see Greenspan and Hamilton [2000]). That is why the analysis can be based only on rather random observations for comparatively large magnetic storms. We analyze the pressure profiles published by Hamilton et al. [1988] for great magnetic storm of February 1986, Williams and Sugiura [1985] and Krimigis et al. [1985] for the magnetic storm of September 4–7, 1984, and Greenspan and Hamilton [2000] for the magnetic storm November 30, 1988. Fig. 4a,b,c shows the comparison of measured Dst with the results of calculations. Calculated Dst was multiplied on the coefficient of 3/2 related to induction currents in the Earth. Fig. 4 demonstrates comparatively good coincidence of the results of calculations and measured Dst in spite of the rather simple used model.

Comparatively good coincidence of measured and calculated Dst for the great magnetic storm February 1986 is connected with the position of pressure maxima at comparatively small L where the distortions of the magnetic field by currents in plasma are not very large. It is necessary to mentioned that the discussion of the contribution of tail current in the Dst started with the analysis of this storm when the contribution of Earth currents to Dst was not included (see Greenspan and Hamilton [2000], Feldstein [1992]).

Greenspan and Hamilton [2000] tested the DPS relation during maximum phase of 80 magnetic storms and found the strong linear correlation between ring current energy estimated from nightside ion measurements and the Dst index. In contrast, dayside measurements of the ring current energy do not yield a robust correlation with Dst. It seems to us that this result is mainly connected with large distortion of daytime flux tubes and limiting of ring current energy calculations at geocentric distances smaller than $7R_E$. Taking into account the existence of the high latitude part of the plasma pressure at geocentric distances $>7R_E$ it may be possible to restore the whole pressure profile using data of low orbiting satellites as it was done, for example, by Stepanova et al. [2008]. It is possible to mention also that the introduction of CRC removes the difficulties connected with Iyemori and Rao [1996] effect as near Earth part of tail current becomes the part of the whole ring current.

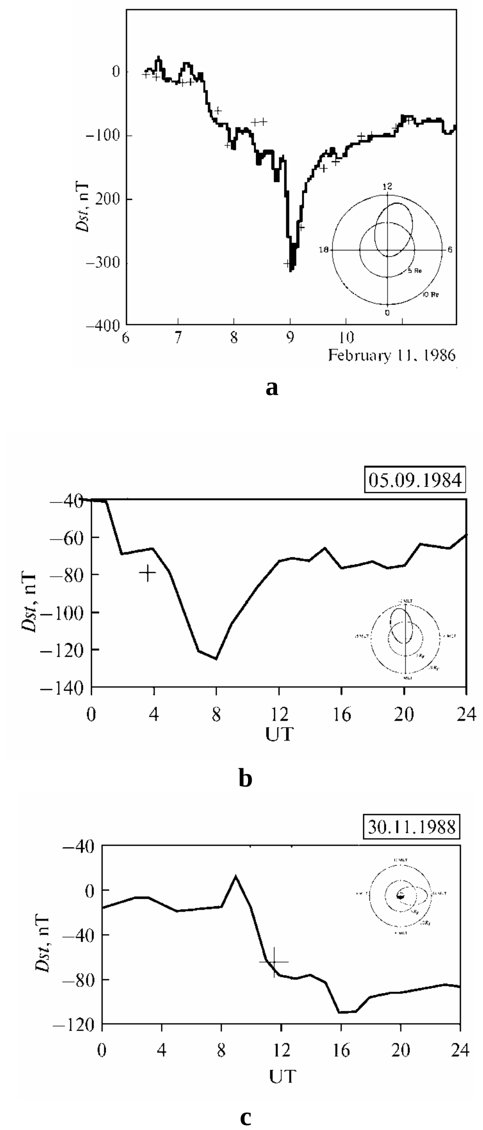


Fig. 4. The results of the comparison of the value of measured (thick line) and calculated Dst (crosses) for three magnetic storms **(a)** February 1986, **(b)** September 4 –7, 1984, **(c)** November 30, 1988. Parts of the figures show satellite orbit positions.

The produced analysis demonstrates the possibility to restore the traditional interpretation of Dst as mainly the result of ring current (including CRC) development. It is necessary to stress that the suggestion about great role of tail current in Dst formation mitts with definite difficulties discussed by Antonova [2001]. Partial ring current must be localized in the same region near midnight as the tail current, which leads to difficulties with evolution of partial ring current leading to symmetric ring current during storm recovery phase. Pressure disbalance at the flank magnetopause is also appeared. CRC is closed inside the magnetosphere and its development does not lead to problems with magnetopause pressure balance and partial ring current evolution.

Isolated magnetospheric substorm onset

The introduction of CRC removes some problems of magnetospheric substorm. Multiple results of observations demonstrate the position of substorm injection boundary not very far from the geostationary orbit (see Lopez et al. [1990]). It is well known that substorm injections lead to the effect of drift echo. Substorm injections are frequently considered as the source of the asymmetric ring current. Produced analysis show that substorm particle injections during magnetic storm are localized inside ring current or its high latitude continuation CRC.

It is interesting to mention also that the introduction of CRC can lead also to definite changes of the analysis of the processes during isolated magnetospheric substorm. Isolated substorm onset in accordance with Akasofu [1964] is localized at the equatorial boundary of the auroral oval, which is ordinarily identified as the inner plasma sheet boundary. This boundary in accordance with the results of multiple observations (see, for example, [Parks, 1991]) is localized at ~7R_E. It is greatly shifted to the Earth during magnetic storms. Isolated substorm onset in accordance with (see, Lui [2011] and references therein, Yahnin et al. [2002], Dubyagin et al. [2003]) is localized at geocentric distances smaller than 10R_E. This means that it is localized in the CRC region, which can be important for the analysis of the process of current disruption and field line dipolarization during substorm.

Discussion and conclusions

We summarize the data of observations demonstrating the existence of plasma ring at geocentric distances from ~7R_E till ~10R_E-13R_E with the same as in the plasma sheet plasma characteristics. The discussed region is the region of quasitrapping for energetic particles. The nighttime part of the ring is ordinarily selected as the near Earth plasma sheet.

The distribution of plasma pressure in the ring is obtained using data of THEMIS mission. It is shown, that quite time averaged plasma pressure profile is near to azimuthally symmetric and plasma pressure is near to isotropic. Radial gradient of plasma pressure has the earthward direction.

Earthward direction of plasma pressure gradients in the conditions of magnetostatic equilibrium means the existence of transverse westward current. The value of dayside part of these current was previously underestimated, as it was not taken into account the compression of daytime field lines and the shifts of minima of the magnetic field at the field line at high latitudes. Estimations of daytime transverse currents taking into account that these currents are not concentrated at the equatorial plane leads to comparatively high values of daytime transverse currents comparable with nighttime transverse currents at the same geocentric distances. Such feature gives the possibility to analyze the region of surrounding the Earth plasma ring as the high latitude continuation of the ordinary ring current.

The existence of the high latitude continuation of the ordinary ring current requires the analysis of role of this current in the Dst formation during geomagnetic storm. We try to show that it is necessary to include the contribution of this current in the azimuthally symmetric part of the near Earth disturbance of magnetic field producing decrease of Dst during magnetic storms. Taking into account the existence of CRC it is possible to overcome problems of the hypothesis of comparatively large role of tail current in the Dst formation and location of isolated substorm onset.

The produced simple analysis can be considered only as one of the first steps in the analysis of the role of the surrounding the Earth plasma ring in the magnetospheric dynamics. We hope that future studies will reveal this role more clearly.

Acknowledgements. We are grateful to the THEMIS team for the mission data. The work was partially supported by the Russian Foundation for Basic Research by grants 10-05-00247, 12-05-01030, 12-02-00217, and FONDECYT grant 1110729.

References

Akasofu, S.-I. (1964). The development of the auroral substorm, *Planet. Space Sci.*, *12*(4), 273-282.

Angelopoulos, V. (2008), The THEMIS mission. *Space Science Rev., 141*, 5–34, doi:10.1007/s11214-008-9336-1.

Antonova, E.E. (2001), Radial plasma pressure gradients in the earth's magnetosphere and the Dst variation, *Geomagnetizm and aeronomia, 41*(2), 142-149.

Antonova, E.E., E.Yu. Budnik, V.N. Lutsenko, and N.F. Pissarenko (2001), Interball/Tail observations of high latitude pressure distribution. *Adv. Space Res., 30*(10), 2289-2293.

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

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

Antonova, E.E. (2004), Magnetostatic equilibrium and current systems in the Earth’s magnetosphere. *Adv. Space Res., 33*, 752-760.

Antonova, E.E. (2007), Topology of high latitude magnetosphere and the main features of auroral phenomena, “Physics of Auroral Phenomena”, *Proc. XXX Annual Seminar*, Apatity, 2007, Kola Science Centre, Russian Academy of Science, pp. 9 – 12.

Antonova E.E., I.P. Kirpichev, I.A. Kornilov, T.A. Kornilova, K.G. Orlova, I.L. Ovchinnikov, S.S. Pulinets, S.S. Rossolenko, M.V. Stepanova, and V.V. Vovchenko (2009a), Features of high latitude magnetospheric topology and magnetospheric substorms, *Proceedings of the 32th annual seminar*, 3-6 марта 2009 г., Apatitu, Russia, 9-16.

Antonova, E.E., I.P. Kirpichev, M.V. Stepanova, K.G. Orlova, and I.L. Ovchinnikov (2009b), Topology of the high latitude magnetosphere during large magnetic storms and the main mechanisms of relativistic electron acceleration. *Adv. Space Res., 43*, 628–633.

Antonova, E.E., I.P. Kirpichev, I.L. Ovchinnikov, K.G. Orlova, and M.V. Stepanova (2009c), High latitude magnetospheric topology and magnetospheric substorm. *Annales Geophysicae, 27*(10), 4069–4073.

Antonova, E.E., I.P. Kirpichev, I.L. Ovchinnikov, M.S. Pulinets, S.S. Znatkova, K.G. Orlova, and M.V. Stepanova (2011), Topology of high-latitude magnetospheric currents, *IAGA Special Sopron Book Series, Volume 3*, The Dynamic Magnetosphere, Editors William Liu and Masaki Fujimoto, Springer, 201-210.

Carovillano, R.L., and J.J. Maguire (1968), Magnetic energy relationships in the magnetosphere. *Physics of the magnetosphere*, ed. Carovillano R. L., and McClay J.F.. D. Reidel publishing company, Dordrecht, Holland, 290-300.

Daglis, J.A., R.M. Thorne, W. Baumjohann, and S. Orsini (1999), The terrestrial ring current: Origin, formation, and decay. *Reviews of Geophysics, 37*, 407–438.

Greenspan M.E., and D.C. Hamilton (2000), A test of the Dessler-Parker-Sckopke relation during magnetic storms, *J. Geophys. Res., 105*(3), 5419-5430.

DeMichelis, P., I.A. Daglis, and G. Consolini (1997), Average terrestrial ring current derived from AMPTE/CCE-CHEM measurements, *J. Geophys. Res. 102*(A7), 14103-14111.

DeMichelis, P., I.A. Daglis, and G. Consolini (1999), An average image of proton plasma pressure and of current systems in the equatorial plane derived from AMPTE/CCE-CHEM measurements, *J. Geophys. Res. 104*(A12), 28615-28624.

Dubyagin, S.V., V.A. Sergeev, C.W. Carlson, S.R. Marple, T.I. Pulkkinen, and A.G. Yahnin (2003), Evidence of near-Earth breakup location, *Geophys. Res. Lett. 30*(6), 1282, doi:10.1029/ 2002GL016569,

Feldstein, Ya. I., Modelling of the magnetic field of magnetospheric ring current as a function of interplanetary medium parameters, *Space Sci. Rev., 59*(1/2), 83-166, 1992.

Feldstein, Ya.I., V.G. Vorobjev, and V.L. Zverev (2010), Planetary features of aurorae: Results of the IGY (a review), *Geomagnetism and Aeronomy, 50*(4), 413-435.

Hamilton, D.C., G. Gloeckler, F.M. Ipavich, W. Stüdemann, B. Wilken, and G. Kremser (1988), Ring current development during the great geomagnetic storm of February 1986, *J. Geophys. Res. 93*(A12), 14343-14355.

Hori, T., S. Ohtani, A.T.Y. Lui, R.W. McEntire, K. Maezawa, Y. Sato, and T. Mukai (2003), A substorm associated drift echo of energetic protons observed by Geotail: Radial density gradient structure, *Geophys. Res. Lett. 30*(6), doi:10.1029/20002GL016137.

Iyemori, T., and D.K.K. Rao (1996), Decay of the Dst field of geomagnetic disturbance after substorm onset and its implications to storm-substorm relation, *Annales Geophysicae, 14*, 608-618.

Jordanova, V.K., C.J. Farrugia, J.M. Quinn, R.M. Thone, K.W. Ogilvie, R.P., Lu, G. Lepping, A.J. Lazarus, M.F. Thomsen, and R.D. Belian (1998), Effect of wave-particle interactions on ring current evolution for January 10– 11, 1997: Initial results, *Geophys. Res. Lett., 25*, 2971–2974.

Kirpichev, I.P., E.E. Antonova, N.L. Borodkova, E.Yu. Budnik, V.N. Lutsenko, E.I. Morozova, N.F. Pisarenko, and Yu.I. Yermolaev (2005), The features of the ion plasma pressure distributions in the near Earth plasma sheet, *Planet. Space Sci. 53*, 209–215.

Kirpichev, I.P., and E.E. Antonova (2011), Plasma pressure distribution in the equatorial plane of the Earth’s magnetosphere at geocentric distances of 6–10R_E according to the international THEMIS mission data, *Geomagnetism and aeronomy, 51*(4), 450–455.

Krimigis, S.M., G. Gloeckler, R.W. McEntire, T.A. Potemra, F.L. Scarf, and E.G. Shelley (1985), Magnetic storm of September 4, 1984: A synthesis of ring current spectra and energy densities measured with AMPTE/CCE, *Geophys, Res. Lett. 12*(5), 329-332.

Liemohn, M.W., and M. Jazowski (2008), Ring current simulations of the 90 intense storms during solar cycle 23, *J. Geophys. Res. 113*, A00A17, doi:10.1029/2008JA013466.

Liemohn, M.W., D. L. De Zeeuw, R. Ilie, N.Y. Ganushkina (2011), Deciphering magnetospheric cross-field currents, *Geophys. Res. Lett., 38*, L20106, doi:10.1029/2011GL049611.

Lopez, R.E., D.G. Sibeck, R.W. McEntire, S.M. Krimigis (1990), The energetic ion substorm injection boundar, *J. Geophys. Res. 95*(A1), 109-117.

Lui, A.T.Y., and D.C. Hamilton (1992), Radial profile of quite time magnetospheric parameters, *J. Geophys. Res., 97*(A12), 19325-19332.

Lui, A.T.Y. (2003), Inner magnetospheric plasma pressure distribution and its local time asymmetry, *Geophys. Res. Lett., 30*(16), doi:10.1029/ 2003GL017596.

Lui, A.T.Y. (2011), Physical processes for magnetospheric substorm expansion onsets. *IAGA*

Special Sopron Book Series, Volume 3, The Dynamic Magnetosphere, Editors William Liu and Masaki Fujimoto, Springer, 65-116.

McFadden, J.P., C.W. Carlson, D. Larson, M. Ludlam, R. Abiad, B. Elliott, P. Turin, M. Marckwordt, and V. Angelopoulos (2008), The THEMIS ESA plasma instrument and inflight calibration, *Space Science Rev., 141*, 277–302, doi:10.1007/s11214-008-9440-2.

Nagata, D., S. Machida, S. Ohtani, Y. Saito, and T. Mukai (2008), Solar wind control of plasma number density in the near-Earth plasma sheet: three-dimensional structure. *Annales Geophysicae, 26*, 4031–4049.

Newell, P.T., and C.-I. Meng (1992), Mapping the dayside ionosphere to the magnetosphere according to particle precipitation characteristics, *Geophys. Res. Lett., 19*(6), 609-612.

Newell, P.T, T. Sotirelis, S. Wing (2009), Diffuse, monoenergetic, and broadband aurora: the global precipitation budget, *J. Geophys. Res., 114*(A9), A09207, doi:10.1029/2009JA014326.

Parks, G. K. (1991), *Physics of Space Plasmas*, Addison-Wesley, Reading, Mass, p. 236.

Roeder, J.L., J.F. Fennell, M.W. Chen, M. Schultz, M. Grande, S. Livi (1996), CRRES observations of the composition of ring current populations, *Adv. Space Res., 17*(10), 17– 24.

Shabansky V.P, and A.E. Antonova (1968), Topology of particle drift shells in the Earth's magnetosphere, *Geomagnetizm and Aeronomia (in Russian), 8*, 993–997.

Shue, J.-H., P. Song, C.T. Russell, J .T. Steinberg et al. (1998), Magnetopause location under extreme solar wind conditions, *J. Geophys. Res. 103*(A8), doi:10.1029/98JA01103.

Stepanova, M., E.E. Antonova, and J.M. Bosqued, (2008), 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. 41*, 1658–1665.

Tsyganenko, N.A., and T. Mukai (2003), Tail plasma sheet models derived from Geotail data, *J. Geophys. Res. 108*(A3), 10.1029/2002JA009707.

Vernov, S.N., E. V. Gorchakov, S.N, Kuznetsov, Yu. I. Logachev, E.N. Sosnovets, and V.G.. Stolpovsky (1969), Particle fluxes in the outer geomagnetic field, *Reviews of Geophysics, 7*(1-2), 258-279.

Vorobjev, V.G., O. I. Yagodkina (2008), Empirical model of auroral precipitation power during substorms, *Journal of Atmospheric and Solar-Terrestrial Physics, 70*(2-4), 654-662.

Vovchenko, V.V., and E.E. Antonova (2010), Nonlinear dipole field disturbance by axially symmetric plasma distribution, *Geomagnetism and aeronomia, 50*(6), 768–777.

Vovchenko, V.V., and E.E. Antonova (2012), Dependence of volumes of magnetic flux tubes on plasma pressure and disturbance in the magnetic field in the axially symmetric case, *Geomagnetism and aeronomia, 52*(1), 53–63.

Wang, C.-P., L.R. Lyons, R.A. Wolf, T. Nagai, J.M. Weygand, and A.T.Y. Lui (2009), The plasma sheet $PV^{5/3}$ and nV and associated plasma and energy transport for different convection strengths and AE levels, *J. Geophys. Res., 114*, A00D02, doi:10.1029/2008JA013849.

Wang, C.-P., M. Gkioulidou, L.R. Lyons, R.A. Wolf, V. Angelopoulos, T. Nagai, J.M. Weygand, and A.T.Y. Lui (2011), Spatial distributions of ions and electrons from the plasma sheet to the inner magnetosphere: Comparisons between THEMIS-Geotail statistical results and the Rice convection model, *J. Geophys. Res., 116*, A11216, doi:10.1029/2011JA016809.

Williams D.J., and M. Sugiura (1985), The AMPTE charge composition explorer and 4–7 September 1984 geomagnetic storm, *Geophys. Res. Lett., 12*(5), 305–308.

Yahnin, A.G., V.A. Sergeev, M.V. Kubyshkina, T.I. Pulkkinen, K. Liou, C.-I. Meng, V. Angelopoulos, N.L. Borodkova, T. Mukai, and S. Kokubun (2002), Timing and location of phenomena during auroral breakup: A case study, *Adv. Space Res., 30*(7), 1775-1778.

Znatkova S.S., E.E. Antonova, G.N. Zastenker, I.P. Kirpichev (2011), Pressure balance on the magnetopause near the subsolar point according to observational data of the THEMIS project satellites, *Cosmic Research, 49*(1), 3–20.