Available online at www.sciencedirect.com

SCIENCE DIRECT®

Advances in Space Research 33 (2004) 723–728

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Ring current ion motion in the disturbed magnetosphere with non-equipotential magnetic field lines

G.I. Pugacheva [a,*], U.B. Jayanthi [b], N.G. Schuch [a], A.A. Gusev [b,d], W.N. Spjeldvik [c]

[a] Southern Regional Space Research Center/INPE, Santa Maria, RE, Brazil
[b] National Institute for Space Research, INPE, Av. Astronautas, 1758, São José dos Campos, SP, Brazil
[c] Weber State University, Ogden, UT, USA
[d] Space Research Institute (IKI), Russian Academy of Sciences, Moscow, Russia

Abstract

Transport of ring current ions during the main phase of the geomagnetic storm is modeled. Particle trajectories are simulated by the Lorentz equation for dipole and Tsyganenko magnetic field models. The convection electric field is described by variations on the K_p dependent Volland–Stern model structure in the equatorial plane. Out of that plane the electric field is assumed to be the same as in the equatorial plane at least at the low latitudes. This consideration implies the possibility of non-equipotentiality of geomagnetic field lines at least for $L \geqslant 6$ during strong magnetic storms. In our modeling energetic protons, typically of several tens of keV, start on the night side at $L = 4$ or at $L = 7$, and move initially under gradient magnetospheric drift largely confined to the equatorial plane. However, soon after crossing the noon–night meridian, the protons rather abruptly depart from the equatorial plane and deviate towards high latitude regions. This latter motion is essentially confined to a plane perpendicular to the equator, and it is characterized by finite periodic motion. The calculations indicate a slow violation of the first adiabatic invariant at the point of ion departure from the equatorial region, with slower non-adiabatic variation later along the orbit. The greater the convection electric field, the higher is the energy of the protons participating in this off equatorial divergent flow. The more energetic ions, of hundreds of keV and higher, however, rather continue their magnetic drift around the Earth uninterruptedly and these ions form the symmetric ring current ion population. The numerical calculations described herein explicitly indicate that the perpendicular divergent ion flow can contribute to the morning–evening component of the magnetic field perturbation during magnetic storm conditions, and can result in populating the high latitude and tail regions by the energetic protons.

Keywords: Magnetosphere; Drift; Proton

1. Introduction

An appearance in the Earth's vicinity of a substantial negative IMF B_z component coupled to increased velocity of solar wind, leads to an increase in the magnitude of the large-scale magnetospheric convection electric field. Its strength is $\boldsymbol{E}_{\text{conv}} = -[\boldsymbol{V}_{\text{sw}} \times \boldsymbol{B}_{\text{IMF}}]$. In the idealized case, the convection electric field vector located in the equatorial plane is directed along the morning to evening sectors. For quiet times, the geoelectric field strength is of the order of 0.1 mV/m, and is enhanced up to 10–20 mV/m during the main phase of great magnetic storms. Drift trajectories of the charged particles (energetic ions and electrons of about 3–300 keV energy) trapped in the magnetosphere can change dramatically due to the convection fields. Strong convection electric fields drive hot plasma particles from the tail region into the inner magnetosphere where their trajectories typically approach the Earth to distances of about 2–4 earth radii, depending on the magnitude of the *E*-field produced (e.g., Roederer, 1970).

The flow of this hot plasma from the magnetotail is so strong that it creates a significant geoelectrical solenoid located at $L > 3$, which induces an almost-uniform perturbation magnetic field that is directed anti-parallel to the Earth's magnetic dipole axis at $L < 3$. During strong magnetic storms this current-generated magnetic field

---

[*] Corresponding author.
E-mail address: galina@das.inpe.br (G.I. Pugacheva).

0273-1177/$30 © 2003 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/S0273-1177(03)00640-9

sometimes reaches several hundreds of γ ($1\gamma = 10^{-5}$ nT) as shown by measurements of the azimuthally symmetric component of the geomagnetic field, an effect which is associated with the $D_{\rm st}$ index. Ring current ion transport, confined and divergent, in the disturbed magnetosphere is the subject of the present investigation.

2. Particle motion in geomagnetic and geoelectric fields

2.1. The two-dimensional case

Traditionally, the transport of ring current charged particles is simulated by the guiding center motion of equatorially mirroring particles (Nishida, 1971) with the second adiabatic invariant vanishing (i.e., $J = 0$). In this work the particle trajectorie are simulated basing on the full Lorentz force equation for a particle motion in geomagnetic and geoelectric fields (i.e., Gusev and Pugacheva, 1982) instead of the guiding center approximation. The charged particle motion in magnetic field of strength B and in an electric field of strength E is described as

$$\frac{{\rm d}(mV)}{{\rm d}t} = q\left(E + \frac{1}{c}V \times B\right), \qquad (1)$$

where q, m, and V are particle charge, relativistic mass, and velocity and c is the light velocity. In a simple dipolar geomagnetic field, and in the absence of any electric fields, particles drift around the Earth due to the geomagnetic field gradient. Their leading center trajectories in a purely dipolar B-field are concentric circles around the dipole center. But in the presence of even small electric fields in the magnetospheric morning–evening direction, charged particles drift in $[\boldsymbol{E} \times \boldsymbol{B}]$ direction from the night side towards noon independent of the sign of their electric charge.

Eq. (1), is solved numerically applying the Runge–Kutta–Guills method. A corresponding Fortran code uses double and where necessary quadruple precision. The solution of the equation for the dipolar and for the IGRF model magnetic fields has a form of auto control whereby charged particles drift around the Earth with conservation of the L-shell parameter, and after one drift period approximately return to the initial starting point, i.e., performs a finite motion. In this case it is not necessary to check the solution by computing the reversed trajectory as is always made for infinite particle trajectories as, for example, this is most often carried out of vertical and directional cosmic ray cutoff rigidities for neutron monitors.

Examples of trajectories of protons of 13.5–100 keV energy with $J = 0$ in a dipolar geomagnetic field with superposed dawn–dusk directed electric fields are shown in Fig. 1(a,b). These figures show particle orbits in the Earth's equatorial plane without any off-equator bounce oscillations (i.e., $V_z = 0$).

For modeling the proton orbits we used a combination of the corrotation and convection electric fields. The former is defined by the potential $U_{\rm cor} - k(R_{\rm e})^2/R$, and the latter is described in the equatorial plane by the model of Volland–Stern with dependence on geomagnetic activity in the interpretation of Nishida (1971). Thus $U_{\rm V\text{–}S} = AR^2 \sin a$, where a is the angle between the direction of the field vector and the direction towards the sun (our X axis), R is the radial distance from magnetic dipole center, and with A as the magnetic activity-dependent strength coefficient taken to be: $A = 0.0449/(1 - 0.159K_{\rm P} + 0.009K_{\rm P}^2)^3$, in units of $kV/R_{\rm e}^2$.

During a geomagnetic disturbance with $K_{\rm P} = 8$, the values of $E_{\rm V\text{–}S}$ on the morning side at $L = 7$ is 2.9 and at $L = 4$ is 1.67 mV/m. In a quiet magnetosphere with $K_{\rm P} = 1$, the field values at these points are of 0.159 and 0.0917 mV/m. The same corrotation and convection

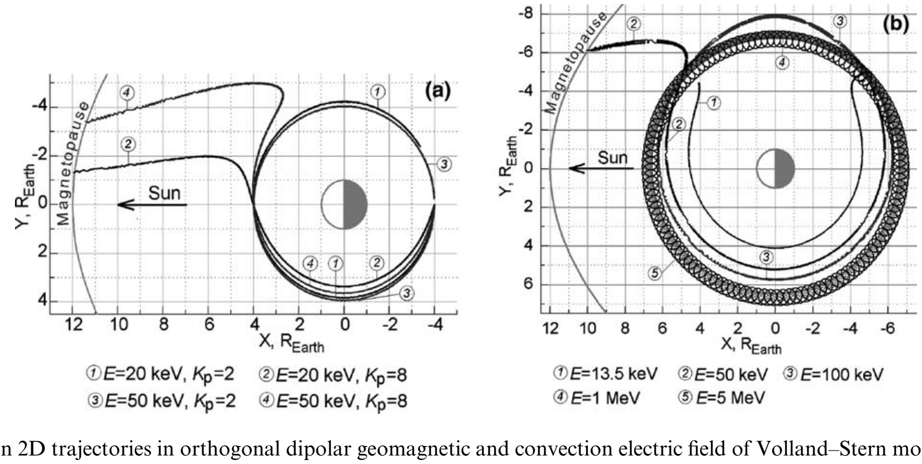

Fig. 1. Energetic proton 2D trajectories in orthogonal dipolar geomagnetic and convection electric field of Volland–Stern model: (a) starting point at $L = 4$ ($X = -4R_{\rm Earth}$, $Y = 0$); (b) starting point at $L = 7$ ($X = -7R_{\rm Earth}$, $Y = 0$). At higher energies, the Larmor rotation of the drifting ions is distinguishable because its gyration radius is comparable to the spatial scale sizes involved.

electric field models were earlier used in the works of Liemohn et al. (2001), Delcourt and Sauvaud (1998) and Öztürk et al. (2001). In this regard, we found comparable proton trajectories as shown herein as in Liemohn et al. (2001). These are quite similar in purely two-dimensional approximations.

The magnetospheric convection electric field is defined as $\boldsymbol{E}_{\text{conv}} = -[\boldsymbol{V}_{\text{SW}} \times \boldsymbol{B}_{\text{IMF}}]$ where $\boldsymbol{V}_{\text{SW}}$ is the solar wind velocity and $\boldsymbol{B}_{\text{IMF}}$ is the near-Earth interplanetary magnetic field (IMF). For idealized conditions when $V_{\text{SW}} \equiv V_X$ and $\boldsymbol{B}_{\text{IMF}} \equiv B_Z$ one gets $E_Y = V_X B_Z$, i.e., the resulting magnetospheric electric field has only a dawn–dusk component. During an intense geomagnetic storm, such as the so-called "Bastilian Day" one of 14–15 July 2001, B_Z is of ~ -50 nT, V_{sw} is of ~ 1000 km/s, and $E_Y = 50$ mV/m (source: http://nssdc.gsfc.nasa.gov.omniweb), i.e., the electric field strength is here substantially greater than that implied by the Volland–Stern model even for $K_{\text{P}} = 8$.

The orbits of 20–50 keV protons starting on the night side at $L = 4$ (Fig. 1(a)) remain inside the inner magnetosphere during relatively low activity ($K_{\text{P}} = 2$), this is as expected. However, for disturbed times ($K_{\text{P}} = 8$) they are forced out from inner zone towards the dayside magnetopause. Fig. 1(b) shows the drift orbits of protons starting at $L = 7$ (practically from the magnetotail). Protons with energies higher than ≈ 50 keV are well confined to the inner magnetosphere even during strong geomagnetic storms, and they form a roughly symmetric component of the magnetospheric ring current. However, protons below 50 keV move from the geomagnetic tail towards the magnetopause, and so leave the inner magnetosphere after residing and drifting there for about 3 h, creating the partial asymmetric component of the magnetospheric ring current. This part of the ion flow is mainly responsible for the geomagnetic storm manifestation in the Earth's magnetic field, as D_{st} index.

2.2. The three dimensional case

The electric field structure away from the Earth's equatorial plane is much less well known. In 3D modeling, we assume that the electric field would be the same as in the equatorial plane. It is clear that this implies non-equipotentiality of the geomagnetic field lines at magnetospheric off-equatorial locations, and we suppose that this is indeed possible for $L > 6$ in a highly disturbed magnetosphere. Indeed, there is no compelling reason to suppose that field-aligned equipotentiality is fully maintained during geomagnetic storms at all times in the outer magnetosphere and the following computations of an electric field at $L > 6$ during Bastilian Day geomagnetic storm of 15 July 2000 made for us by the Community Coordinated Modeling Center (CMCC) showed that we were enough right in this assumption.

Adiabatic drift paths of equatorially mirroring low-energy protons in a dipolar magnetic field were described a long time ago, in 70s by Chen (1970). However, most of the ring current ions have a small non-zero second adiabatic invariant, i.e., they have a component of velocity perpendicular to equatorial plane different of zero, $V_Z \neq 0$, $J \neq 0$. To investigate the full 3D proton trajectories in the storm time case, we use the same Eq. (1) with the same initial conditions as in Fig. 1, but with one crucial difference: the protons have a small initial V_Z components of magnitude approximately 10^{-4}–10^{-5} V. This makes a dramatic difference in the drift-flow of these particles.

We traced various ion trajectories in the inner magnetosphere, utilizing both the purely dipolar and the Tsyganenko (1990) field models. The larger E_{conv} values compared to those of the traditional Volland–Stern model (even with $K_{\text{P}} = 8$) are necessary in order to obtain the appropriately larger E-fields corresponding to geomagnetic storm main phase conditions. We calculated the structure of the E-fields due to Volland–Stern model for $K_{\text{P}} = 8$ to keep proper topology of the field, and multiplied those magnitudes by a factors of 2–5 to approximate the typically observed electric field magnitude values during intense geomagnetic storms.

In Fig. 2, the 3D view of a characteristic energetic proton orbit in the dipolar magnetic field is shown. Similar to the 2D case, the ion travels westward from the night side of towards the dayside while remaining confined to the equatorial plane. The geoelectric field energizes the protons up in the motion against the electric field when approaching the local noon position. Also, this energy loss continues after the crosses magnetic local noon, and consequently the velocity of magnetic drift around the Earth is decreased.

At the point where the magnetic drift velocity is approximately equal to zero, the particle abruptly leaves the equatorial plane, and it travels upwards towards

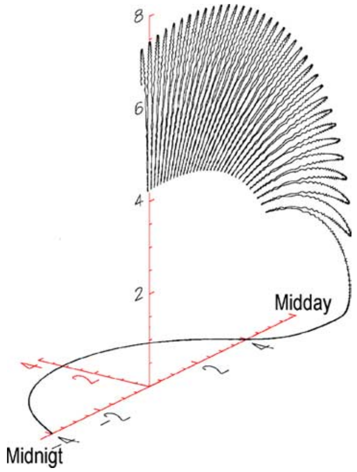

Fig. 2. 3D view of 50 keV proton orbit.

middle and high geomagnetic latitudes. There is a reason, in our model, why a particle leaves the equatorial plane on the morning side of magnetosphere after crossing the noon–night line (see Fig. 3): The dawn–dusk electric field E_Y focuses particles onto the equatorial plane on the evening side due to the existence of a component E_t tangential to magnetic field line. It is directed towards the equatorial plane on the evening side and away from it on the morning side. It presses the particles to the equatorial plane on the evening side decreasing their bounce oscillations and increases these motions on the morning side. An ion leaving the equatorial plane essentially remains on a plane that is perpendicular to the Earth's equator plane, and its motion is effectively being scattered by the defocusing action of this off-equatorial electric field. Drifting further in noon–midnight direction the proton crosses the midnight meridian and enter the area of the focusing electric field returning to the equatorial plane and thus closing its drift trajectory around the Earth.

The nature of the upper and the lower mirror points limiting bounce oscillations in the morning hemisphere are different. The mechanism of reflection from the upper mirror point is the same as in the case of the absence of the electric field, i.e., the increase of the geomagnetic field module ("magnetic line density") along a geomagnetic field line. In spite of the acceleration of the proton by the tangential component of the electric field the increase of the magnetic field is enough to stop further proton motion towards the dipole center. Different from the case of the absence of the electric field the lower mirror point located in the same semi-sphere as the upper one. It is simply due to the fact that the parallel impulse of the proton is zeroed by the tangential component of the electric field directed in this case opposite to the proton velocity. Thus the nature of the lower mirror point is essentially related with the presence of the electric field and has nothing to do with the dipole character of the geomagnetic field.

The particle motion in the geomagnetic field with the presence of electric field is not exactly adiabatic, and even the magnetic moment could well be slowly varied (if do not say, violated) by the processes herein described. Its instantaneous magnitude ($\mu = E_{\perp}/B$) for a 50 keV proton is shown in Fig. 4. One can see that the magnetic moment is practically conserved along the path until it reaches $X \approx 4R_e$ (blue lines). The moment undergoes little variations around $\mu = 10.25$ MeV/Gauss, caused by ion gyration in the presence of electric fields. The strong variation of the invariant begins at $X > 4R_{\mathrm{Earth}}$ and continues up to $X = 7R_{\mathrm{Earth}}$, but the average value of the invariant still doesn't change much (blue lines). In the crucial moment of the particle's departure from the equatorial plane, its first adiabatic invariant is violated, decreasing to ≈6.0 MeV/Gauss (Fig. 4, black lines).

The numerical solution of Eq. (1) is done with a double precision algorithm, and the solution was checked with 4-fold precision. A proton orbit was also traced back in time to the starting point shown in Fig. 2, confirming the quality of the mathematical solution. The

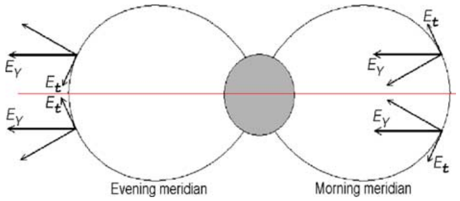

Fig. 3. The perpendicular and tangential (E_t) components of morning–evening electric field (E_Y) projected on magnetic field lines in morning and evening meridians.

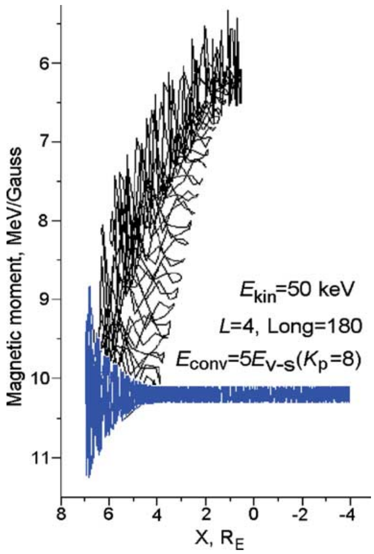

Fig. 4. The variation of the proton magnetic moment along the trajectory when it moves in (blue) and out off (black) equatorial plane.

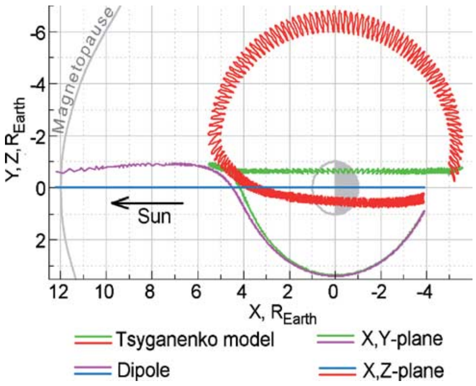

Fig. 5. Projections of the simulated trajectories for proton of 135 keV energy moving in Tsyganenko (3D) and dipolar (2D) magnetic fields and convectional electric field equal to 5-fold of that for K_P of Volland–Stern model.

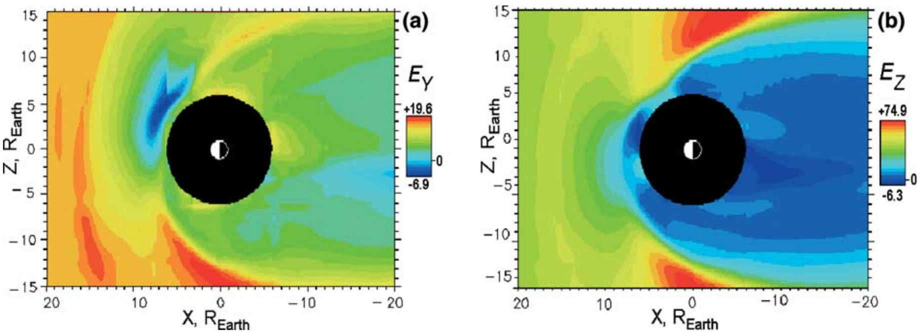

Fig. 6. The E_Y (a) and E_Z (b) electric field components (mV/m) in X, Z-plane simulated in NASA Community Coordinated Modeling Center (http://ccmc.gsfc.nasa.gov) for the 15.07.2000 event (UT22:36:00). X axis is directed towards the Sun, Y is in dawn–dusk direction, Z is toward the North.

simulations were also made using the Tsyganenko (1990) magnetic field model. The results are illustrated in Fig. 5 which shows the 3D 135 keV proton orbit with convection electric field 5 times larger than the Volland–Stern model at $K_P = 8$. The orbit tracing starting point is at $L = 4$ (longitude 166.67°). For comparison, the magnet and blue lines in this figure are the corresponding 2D projections of a corresponding proton orbit for a purely dipolar magnetic field with the proton's second invariant $J = 0$. All these particle trajectory examinations confirm the main result we have obtained: in the presence of an electric field, a significant part of the asymmetric ring current leaves the Earth's equatorial plane on the dayside magnetosphere. Consequently, energetic ions flow into the middle and high latitudes populating the tail plasma. This motion remains finite and even periodic, as seen in Figs. 2 and 5 if we remain strictly limited by the relatively stable magnetospheric and electric fields. The modeling conducted here corresponds specifically to the $L = 4 - 7$ region. Recently, similar results were obtained for ions in the higher L-shell region at $L \geqslant 8$ (i.e., Delcourt and Sauvaud, 1998; Öztürk et al., 2001). The reason of a sudden shift of ring current ions from the equatorial plane on the dayside in that case is different from considered herein, namely that near the noon magnetopause near the equatorial plane the geomagnetic field has a small local maximum and two local minima in the adjacent regions both north and south of the equator on the same L-shell (i.e., Shabansky, 1971). Consequently, when a night-side particle which bounces symmetrically around the equator drifts toward noon and reach $L \approx 8$, it may shift out of the equatorial plane and so mirror about the northern and southern polar cusps with a violation of the second adiabatic invariant.

2.3. *MHD equation numerical solution by CCMC for the Bastille Day event*

The NASA Community Coordinated Modeling Center (CCMC, 2002) has, on our request, run their 3D numerical simulation software of the magnetospheric MHD equations for the "Bastille Day" (July 15, 2000) magnetic storm. The physical models that are the basis for the CCMC software are described in the CCMC Website. Using the time-dependent solar wind input data one obtains magnetospheric time-dependent convection electric fields at $L > 6$ as an MHD equation solution. The computed MHD parameters also include the magnetic field and the plasma flow velocity components.

In Fig. 6(a) and (b) we show the calculated E_Y and E_Z components of the magnetospheric electric field strength in the (Z, X) noon–night meridianal plane (X is directed towards the Sun; Y is the dawn–dusk direction, and Z is towards the North) at the time of the approximate maximum of the D_{st} development. We find that during several minutes near the geomagnetic storm maximum in the outer magnetosphere at L-shell between 6 and about $8R_{Earth}$ there exists definite conditions in the (X, Z)-plane with a strong, of several mV/m, dawn–dusk electric field in the absence of a significant E_Z-component, and also a very small E_X electric field component. As demonstrated in this paper, these conditions could cause and sustain an effective energetic particle outflow from equatorial plane when they occur on the noon-side magnetosphere during such events. This could be another mechanism causing consequential energetic particle appearance in the magnetospheric tail, and also in the middle and even high latitudes of the magnetosphere. These aspects suggest that further analysis of the electric field structures on the front-side magnetosphere during event periods can shed light and insight into energetic particle streaming and flows elsewhere in the Earth's magnetosphere.

3. Conclusion

The energetic particle orbital tracing conducted in this work was specially carried out for protons with energies as high as 50–135 keV, and with assumed geoelectric fields that for magnetic storm conditions are greater by factors of 2–5 compared to the Volland–Stern electric field model strength. As the CCMC modeling of 3D numerical solution of MHD equations shows, these stronger electric fields are, however, quite natural during intense magnetic storms when the Earth's magnetosphere is severely perturbed. The results described above show that even the very energetic part of the magnetospheric ring current ion spectrum can participate in this energetic charged particle flow out of the equatorial region during strong magnetic storms. In fact, the more negative the B_z component of the interplanetary magnetic field and the greater the solar wind velocity, the larger the magnitude of the dawn–dusk electric field. The natural consequence is that the more energetic ring current particles can leave the equatorial plane, thus contributing to the depletion of the ring current itself from ions flowing out into the mid-latitude and cusp regions of the magnetosphere. This is in addition to the well-understood depletion mechanism by collisional charge exchange losses of ring current ions.

The escaping energetic charged particle from the magnetospheric ring current could then populate the middle and high latitudes of the storm time magnetosphere, and possibly also some part of the geomagnetic tail region with tens of keV protons and heavier ions. The protons of the ring current that did not take part in this geoelectric field caused outflow continue to drift around the Earth forming the symmetric ring current component. The upward part of this ring current could conceivably create the morning–evening component of the magnetic field variation observed during geomagnetic storms, possibly with a comparable *B*-field perturbation magnitude to that of the horizontal D_{st} variation.

Our next step in this ongoing analysis will be to trace single particle orbit in the close-to-realistic magnetospheric electric and magnetic fields obtained by the CCMC MHD modeling to determine the spatial and energy distribution of the energetic particles outflow and its temporal evolution and duration during geomagnetic disturbed periods.

Acknowledgements

Drs. A. Gusev and G. Pugacheva thank the CNPq and FAPERGS for Brazilian grants to work at INPE.

References

CCMC group. Available from http://ccmc.gsfc.nasa.gov, 2002.

Chen, A.J. Penetration of low energy protons deep into the magnetosphere. J. Geophys. Res. 75 (A13), 2458–2467, 1970.

Delcourt, D.C., Sauvaud, J.-A. Recirculation of plasma sheet particles into high latitude boundary level. J. Geophys. Res. 103 (A11), 26521–26532, 1998.

Gusev, A.A., Pugacheva, G.I. About output of quasi-trapped electrons from the atmosphere. Geomagn. Aeron. 22, 487–489, 1982 (in Russian).

Liemohn, M.W., Kozira, J.U., Thomsen, M.F., et al. Dominant role of the asymmetric ring current in producing the storm time D_{st}. J. Geophys. Res. 106 (A6), 10883–10904, 2001.

Nishida, A., Geomagnetic Diagnosis of the Magnetosphere. Springer-Verlag, New York p. 180, 256, 1971.

Öztürk, M.K., Chan, A.A., Wolf, R.A. Violation of the Second Invariant in a Static Magnetic Field, (Abstract), International Workshop ISEC 2001: Radiation Belt Science and Technology. Queenstown, New Zealand, 2001.

Roederer, J. Dynamics of Geomagnetically Trapped Radiation. Springer-Verlag, Heidelberg, 1970.

Shabansky, V.P. Some processes in magnetosphere. Space Sci. Rev. 12 (3), 299–418, 1971.

Tsyganenko, N.A. Quantitative models of the magnetospheric magnetic field: methods and results. Space Sci. Rev. 54, 75–186, 1990.