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MAGNETIC FIELD DISTORTION IN THE PROCESS OF PLASMA CONVECTION IN THE MAGNETOSPHERE OF THE EARTH: PRELIMINARY RESULTS OF MODELING

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Abstract. The increase of plasma convection in the magnetosphere of the Earth leads to the increase of plasma pressure in the inner magnetospheric regions. The effect is especially pronounced during magnetic storms when ion distribution functions become nearly isotropic and plasma transport can have near adiabatic character. The distortion of the magnetic field by the increase of plasma pressure is modeled using self-consistent modified Wolf-like model. Model description is presented. Model describes the formation of asymmetric ring current, systems of transverse and field-aligned currents and electric fields of large-scale magnetospheric convection. It includes the effect of local magnetic field distortion due to the increase of plasma pressure in every point calculated in the suggestion of the validity of the condition of magnetostatic equilibrium. It is shown, that closed inside the magnetosphere isolines B=const at the equatorial plane which does not surround the Earth can appear due to magnetic field distortion.

1. Introduction

Multiple results of experimental observations demonstrate the appearance of magnetic field distortions due to the increase of magnetospheric convection. Diamagnetism of moving to the Earth plasma leads to the decrease of B_z component of the magnetic field and field line stretching. Such feature is connected with the increase of plasma pressure in the inner magnetospheric regions. The effect is especially pronounced during magnetic storms.

The coupling between plasma and fields is necessary and unresolved problem of inner magnetosphere physical models. The change of magnetic configuration in the process of magnetospheric convection was analyzed by Toffoletto et al. [2003] using Rice Convection Model of magnetospheric convection (see Wolf et al. [1982], Garner et al. [2004], Wang et al. [2001, 2003]) and by Zaharia et al. [2006, 2008] using the kinetic model of Jordanova et al. [1997] (RAM code). The real progress was achieved. However the main attention was concentrated on the large-scale effects and the changes of the structure of lines B=const at the equatorial plane was not analyzed.

In this paper we analyze local magnetic field distortions in the process of plasma convection using modified Rice Convection Model when such distortions are comparatively small. We shall try to show, that local regions in which lines B=const do not surround the Earth and do not cross the magnetopause are formed.

2. Model description

Drift motions of particles are analyzed. The isotropy of the distribution function and the absence of field-aligned potential drops are suggested. Bounce-averaged drift is described as

$$\left\langle \mathbf{v}_k^{drift} \right\rangle = -c \cdot \frac{2}{3} \cdot \frac{k}{q} \cdot \frac{1}{V} \cdot \frac{[\nabla V \times \mathbf{B}]}{B^2} + c \cdot \frac{[\mathbf{E} \times \mathbf{B}]}{B^2}, \qquad (1)$$

where c is the velocity of light, **B** is the magnetic field, **E** is the electric field, k and q are the kinetic energy and particle charge, V is the flux tube volume (V=∫dl/B, where dl is an element of the length of the magnetic field line and the integration takes place between the conjugate hemispheres).

The kinetic energy change of drifting particles is determined by the change in flux tube volume according to the relation

$$\varepsilon_k \cdot V^{\frac{2}{3}} = \lambda_k, \qquad (2)$$

where λ_k is constant along a particle's drift path and is called the energy invariant. Constant λ_k is calculated for the particle with fixed energy at the boundary of the model,

The change of the number of particles in the flux tube η_k is determined by the relation

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_k^{drift} \nabla \right) \eta_k = -\frac{\eta_k}{\tau_k}, \qquad (3)$$

where τ_k is the loss time. It is suggested, that τ_k is comparatively large and it is possible to neglect by losses at large L.

The relation which determining particle drift velocity at the ionospheric mapping has the form

$$\left\langle \mathbf{v}_k^{drift} \right\rangle = c \cdot \frac{\mathbf{B}_i(r,t) \times \nabla \left(\Phi + \frac{\lambda_k \cdot V^{-\frac{2}{3}}}{q} \right)}{B_i^2(r,t)} = \qquad (4)$$

$$= c \cdot \frac{\mathbf{B}_i(r,t) \times \nabla \Phi_0}{B_i^2(r,t)},$$

where $\Phi_0 = \Phi + \frac{\lambda_k \cdot V^{-\frac{2}{3}}}{q}$. Φ is the electrostatic potential, $\mathbf{B}_i$ is the magnetic field at ionospheric altitudes. Using geomagnetic longitude and latitude θ and φ we have

$$\left\langle v_{k,\theta}^{drift} \right\rangle = c \cdot \frac{1}{Sin(I)} \cdot \frac{B_i(r,t) \times \frac{1}{Sin(I)} \cdot \frac{\partial \Phi_0}{\partial \theta}}{B_i^2(r,t)},$$

$$\left\langle v_{k,\varphi}^{drift} \right\rangle = c \cdot \frac{1}{Cos(\theta)} \cdot \frac{B_i(r,t) \times \frac{\partial \Phi_0}{\partial \varphi}}{B_i^2(r,t)}, \qquad (5)$$

where, I is the dip angle of magnetic field line.

The temperature of electrons is much smaller than the temperature of ions. Therefore, the gradient drift of electrons is not taken into account. Electric drifts of particles do not produce current due to the condition of quasineutrality. Integral drift current of magnetospheric ions is

$$\mathbf{J}^m = q \cdot \sum_k \eta_k \cdot B \cdot \left\langle \mathbf{v}_k^{drift,gradV} \right\rangle = c \sum_k \eta_k \lambda_k \frac{B \times \nabla V^{-\frac{2}{3}}}{B}. \qquad (6)$$

The whole transverse current includes the magnetization current divergence of which is equal to zero.

Current at ionospheric altitudes is

$$\begin{pmatrix} J_i^\theta \\ J_i^\varphi \end{pmatrix} = \begin{pmatrix} \frac{\Sigma_P}{\sin(\mathrm{I})} & -\frac{\Sigma_H}{\sin(\mathrm{I})} \\ \Sigma_h & \Sigma_p \end{pmatrix} \cdot \begin{pmatrix} E_\theta \\ E_\varphi \end{pmatrix}, \qquad (7)$$

where *Div* is the two dimensional divergence, Σ_P, Σ_H integral Hall and Pedersen conductivities, , $J_i^\theta, J_\varphi^\theta$, E_θ, E_φ are the components of ionospheric current and electric field, $E_\theta = -\frac{1}{Sin(\mathrm{I})} \cdot \frac{\partial \Phi}{\partial \theta}$, $E_\varphi = -\frac{1}{Cos(\theta)} \cdot \frac{\partial \Phi}{\partial \varphi}$ in spherical coordinate system.

The equation of current continuity at the ionospheric altitudes has the form

$$div_i (J_i + J^m) = 0. \qquad (8)$$

Ionospheric conductivity consists from disturbed and not disturbed parts. IRI (International Reference Ionosphere [Rawer and Ramanamurty, 1986]), and MSIS models are used for the calculation of the first part. The second part is described in accordance with Jaggi and Wolf [1973] model

$$\Delta\Sigma_P = 4 \cdot \exp(-100 \cdot (\theta - 0.3)^2),$$
$$\Delta\Sigma_H = 8 \cdot \exp(-100 \cdot (\theta - 0.3)^2), \qquad (9)$$

where conductivities are measured in mhos.

The solution of the self-consistent problem of particle motion and magnetosphere-ionosphere interactions at fixed magnetic field gives the possibility to describes the formation of asymmetric ring current, systems of transverse and field-aligned currents and electric fields of large-scale magnetospheric convection.

The calculation of the magnetic configuration appearing in the process of plasma drift requires the analysis of drift and magnetization currents. The main contribution in the magnetic field distortion is connected with plasma diamagnetism. Therefore, the problem can be simplified suggesting the validity of the condition of magnetostatic equilibrium, which can be useful as the isotropy of ion distribution functions is suggested. In accordance with this condition the distortion of the magnetic field $\delta\mathbf{B}$ appearing due to particle pressure p is determined by the equation

$$\nabla \left(\frac{(\mathbf{B} + \delta\mathbf{B})^2}{8\pi} + p \right) = \frac{(\mathbf{B} + \delta\mathbf{B}) \nabla (\mathbf{B} + \delta\mathbf{B})}{4\pi}, \qquad (10)$$

where **B** is the undisturbed magnetic field. Modeling magnetic field disturbance by convecting plasma we start at the first approximation from dipole configuration and consider only comparatively week disturbances. In such a case $\mathbf{B} = \mathbf{B}^{dip}$, where $\mathbf{B}^{dip}$ is the dipole magnetic field. We also take into account that the magnetic disturbance near the equatorial plane produces the main contribution in the change of the form of the magnetic field line. The main contribution in $\delta\mathbf{B}$ can be evaluated using one dimensional approximation (see Tverskoy [1997]). The amplitude of magnetic field disturbance ($\delta B<0$) is calculated using the expression

$$2B^{dip}\delta B + \delta B^2 + 8\pi p \approx 0. \qquad (10)$$

Fig. 1 shows the scheme illustrating the disturbance of the dipole magnetic field line in the process of convection.

Flux tube volume disturbance is calculated in accordance with the relation $V \cong V^{dip} B^{dip} / (B^{dip} + \delta B)$, where $\delta B<0$ и $|\delta B| << B^{dip}$. Small changes of field line length are neglected. Flux tube volume disturbance leads to the change of the pressure p in accordance with adiabatic relation

$$p = p_0 \cdot \left(\frac{V_0}{V} \right)^{5/3} = p_0 \cdot \left(\frac{B_{dip}}{B_{dip} + \delta B} \right)^{5/3}, \qquad (11)$$

where p_0 is calculated using dipole magnetic field.

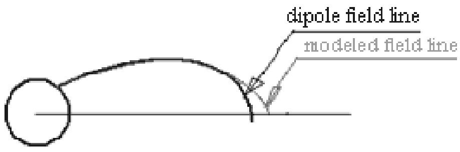

Fig. 1. Scheme illustrating the disturbance of dipole magnetic field line in the process of convection

The simulation region is the ring at the equatorial plane with the outside boundary at $8R_E$. The radius of the inner boundary is 1.1 R_E**.** Simulation boundaries are rings at the ionospheric altitudes with geomagnetic latitudes 17.5° and 69.3°. The condition $J_i^0 = 0$ is selected at the inner boundary. Potential distribution at the outer boundary is selected as $\Phi_{bound} = \Phi_0 \cdot \sin(\pi \mathrm{MLT}/12)$. An iterative approach is used for calculations of the particle motion and magnetosphere-ionosphere interactions in the disturbed magnetic field.

3. Results of modeling

At the first stage, the filling of the empty magnetospheric trap at low value of cross polar cap potential drop equal to 20 kV is calculated during 24 hours. It is suggested, that the distribution function at the boundary of the modeled region is Maxwellian with temperature 6 keV and plasma density equal to 0.5 cm^{-3}. We start our simulation (Time=0) for enhanced convection with this quiet time equilibrium. Then the cross polar cap potential drop is increased till 100 kV for 10 min and plasma density till 2 cm^{-3}. Plasma density has the same value next 10 min and then is decreased till the initial value. Fig. 2 demonstrate the configuration of isolines B=const at the equatorial plane at different steps of modeling. It is possible to see that closed lopes B=const are formed when Time=55 min. This effect disappears approximately ~ 30 min later. To verify the accuracy of numerical calculations the resolution is increased in eight times. The effect continues to exist.

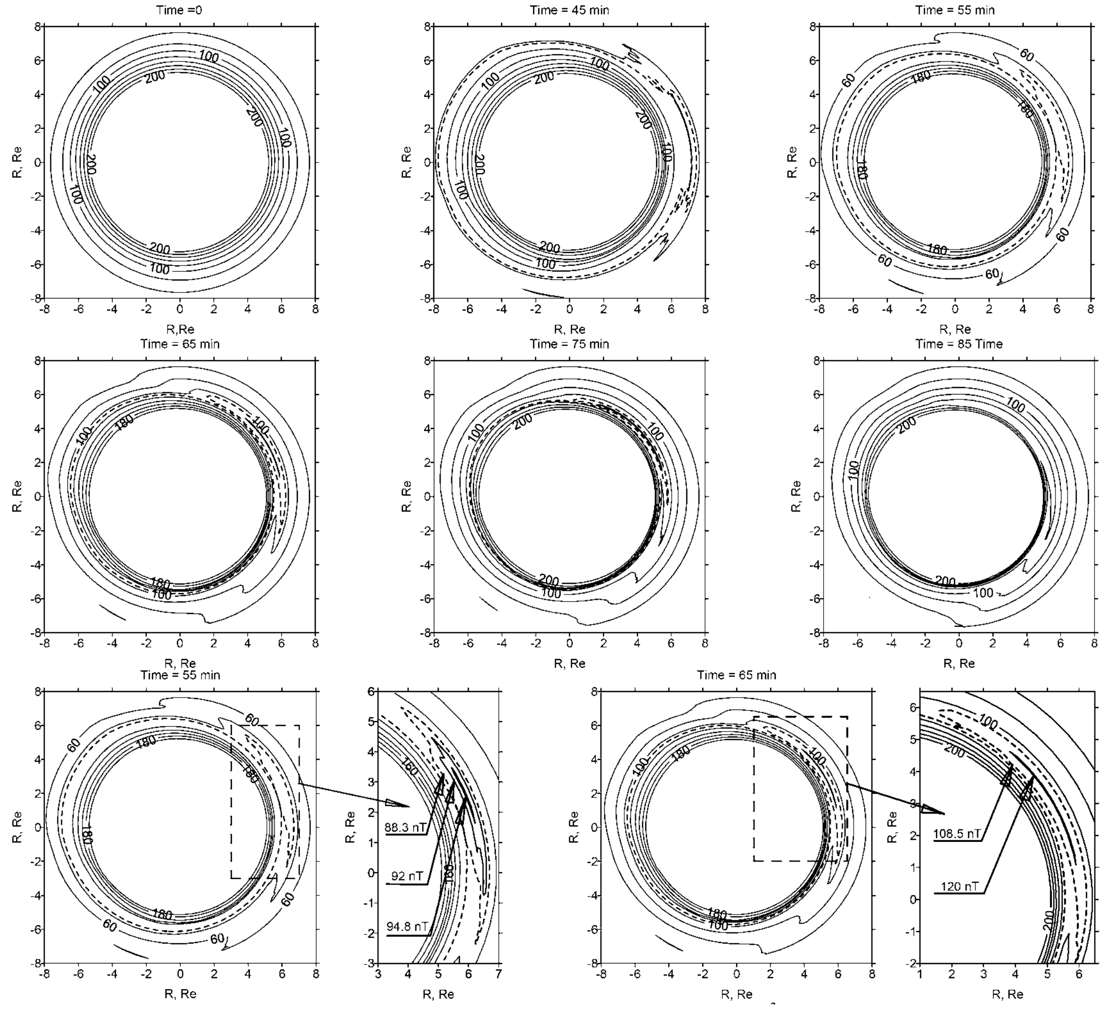

Fig. 2. Configuration B=const at the equatorial plane

4. Conclusions and discussion

Presented preliminary results of the analysis of the magnetic field distortion in the process of the magnetospheric convection are not fully self consistent. The adiabatic particle motion without losses is suggested. Such approximation can work only in the conditions of magnetic storms. Rather simplified scheme of magnetic field distortion is used. At the same time, the model can help to understand the process of change of the magnetic field in the inner magnetospheric regions by convecting plasma.

We model the plasma convection in the inner magnetospheric regions at fixed distribution of the potential, plasma density and temperature at the boundary and obtain the solution of the problem of magnetosphere-ionosphere interactions taking into account the magnetic field distortion by convecting plasma. The most interesting result obtained in such modeling is the demonstration of the possibility of the formation of local closed loops B=const at the equatorial plane which does not surround the Earth. Local structures B=const which does not surround the Earth appear in the case of the change of plasma density at the boundary of the modeled region.

The appearance of local not surrounding the Earth structures B=const at the equatorial plane can be very interesting feature as magnetic drift of particles is determined by isolines B=const. Such features can lead to the formation of local particle traps for energetic particles. The formation of such local traps to the pole of the external boundary of the external electron radiation belt can help for example to explain the results of the observations of the comparatively stable (existing more then 4.5 h) enhancements of subrelativistic particle fluxed examined by Myagkova et al. [2008].

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