

## THE DEPLETION AND DIPOLARIZATION OF THE MAGNETIC FLUX TUBES ABOVE AURORAL ARC

M.A. Volkov (Murmansk State Technical University, 13 Sportivnaya Str., Murmansk, 183010, e-mail: [volkovma@mstu.edu.ru](mailto:volkovma@mstu.edu.ru))

**Abstract.** The role of the hot magnetospheric particles (protons) in the formation of the electric fields and the field-aligned currents from the ionosphere to the magnetosphere have been studied. It has been shown that the gradient drift of the hot particles in these cases leads to the depletion of the magnetic flux tubes and increasing of the magnetic field in them. The induction electric field invoked of the magnetic field increasing leads to acceleration of the magnetospheric plasma which despite the energy spread begins to move as one unit. These phenomena occur above the auroral arcs and "inverted V" precipitations. The evaluations of the magnetic flux tube depletion and increasing the magnetic field in it have been made. The velocities of the magnetospheric plasma in the equatorial plane magnetosphere have been calculated at different distances from the Earth.

### Introduction

The expansion phase of the magnetospheric substorm is accompanied by increase of the  $B_z$  (Z-to the pole, X and Y axes are directed toward the Sun and on the morning side ) component of the magnetic field in the magnetosphere tail and decrease of the plasma pressure [Runov et al., 2009]. This process is called dipolarization of the magnetic field lines, it begins at the tail of the magnetosphere and in a few minutes covers the length of  $\sim 10 R_E$  (the Earth radius), approaching the Earth at the speed of  $\sim 300$  km / s. The velocity of the propagation of the magnetic field lines dipolarization is more than Alfvén speed, but noticeably less the magnetosonic one and is equal to the electric drift velocity of the plasma in the magnetosphere tail. These changes of the magnetic field and plasma may be result of the precipitation of charged particles in the ionosphere from the magnetic flux tube. This leads to the its cooling, reduce of pressure and increase of the magnetic field [Volkov, 2011]. However, the precipitating particles are mostly electrons whose pressure in the magnetosphere is negligible in comparison to the pressure of the ions. In this work we have been considered the possible mechanism of energy transfer from ions to electrons in the magnetic flux tube above the auroral arc. The most likely mechanism of the electrons acceleration over auroral arcs is appearance of the parallel electric field [Knight, 1973], the field-aligned electric field above the arc accelerates electrons, which precipitate into the ionosphere. Hot magnetospheric ions are also leaving the magnetic flux tube, moving across the magnetic field lines. As a result, the pressure and the magnetic moment of charged particles in the tube decreases, it leads to the increase of the magnetic field.

### Description of the main processes

Figure 1 shows possible distribution of electric potential and currents above the auroral arc. The ionospheric currents  $I_i$  flow towards the electric field, but the magnetospheric currents direct against the electric field. The magnetospheric current  $I_M$  is carried by hot ions and cold electrons move along the lines of the equal electric potential. The electric field makes negative work on the magnetospheric ions and the magnetic flux tube above the arc is cooled.

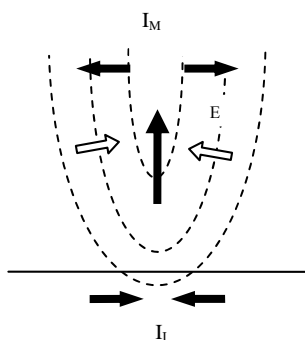


Fig. 1

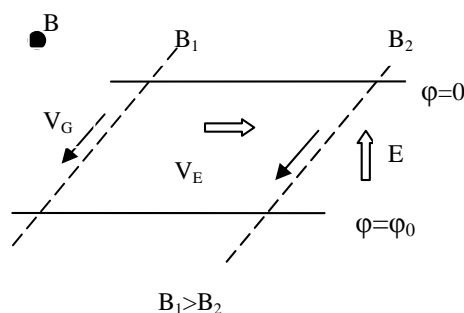


Fig. 2

We assume that the field-aligned current flowing from the ionosphere is carried by cold electrons. In the magnetic flux tube with the field-aligned current arc the condition of charge neutrality is performed everywhere, i.e.

the electron density is approximately equal to the ions density  $n_e \approx n_i$ . In this case, the precipitating electrons have to replace the other electrons, or the ions must leave the tube. The ionospheric electrons can not get to the magnetic flux tube from the ionosphere along magnetic field lines because the field-aligned electric field prevents them. The cold magnetospheric electrons move together with the tube with the speed of the magnetospheric convection. Thus the condition of charge neutrality can be provided only when the hot magnetospheric ions drift from the magnetic flux tube across the magnetic field lines. The ions are moving across the magnetic flux tube with the velocity of the gradient or diamagnetic drift. The direction of the magnetosphere current is shown in fig. 2, it coincides with the gradient drift  $V_G$  of the ions directed along the line of the equal magnetic field. Let the magnetic field be directed to us, then the electric drift of ions  $V_E$  is directed to the right in fig. 2. The ions will drift under the electric field in the region of the weaker magnetic field. Since the magnetic moment of ions is saved their energy will decrease. We shall consider this mechanism in more details. For simplicity, we assume that all of the magnetospheric ions have the magnetic moment  $\mu$ . The total energy of the ion is equal to:

$$E_i = \frac{mu_{\perp}^2}{2} + \mu B + e\phi, \quad (1)$$

where  $\mu B$ -the transverse ion energy,  $\phi$ -the potential electric field.

Let the induction inside the flux tube in the center of the arc be equal to  $B_1$ , the potential  $\phi_1 = -\phi_0$ , outside the arc  $B_2$ ,  $\phi_2 = 0$ . The total energy of the ion (1) conserves at any point of the particle trajectory. Assuming  $B_1 > B_2$ , the minimum value of this energy is equal to  $\mu B_2$ , the condition of the magnetic moment conservation is not satisfied for lower values energy. For the case  $B = B_2$  reflection points lie far from the equatorial plane of the magnetosphere and longitudinal velocities of the ions are small, this follows from the second adiabatic invariant  $I = \nu l$ , where  $\nu$ -the average speed,  $l$ -the length of the magnetic field line between the reflection points. The expression of the potential  $\phi_0$  can be obtained from (1):

$$j_0 = m(B_1 - B_2)/e + \frac{mu_{\perp}^2}{2e} \quad (2)$$

Accepting  $B_1/B_2 = 3$ ,  $\mu B_1/2 = mv_{\perp}^2/2 = 2.5 \text{ keV}$ , we shall receive value  $\phi_0 \approx 6 \text{ kV}$ , which is close to the observed values.

Let us estimate the change in concentration of the charged particles inside the magnetic flux tube above the auroral arc in this simple model. Assuming the magnetic moment of the electron being small, the relationship between the concentration and the magnetic field is given by the following expression:

$$(n_2 - n_1) = \frac{B_1 - B_2}{m_0 m}, \quad (3)$$

where  $n_{1,2}$ -the charged particle concentration inside and outside the magnetic flux tube,  $\mu_0$ -the magnetic permeability. For the situation described in [Runov et al., 2009], from the observations by satellite Themis (e) take the values of  $B_1 = 35 \text{ nT}$ ,  $B_2 = 10 \text{ nT}$ ,  $\mu B_1 = 4.5 \text{ keV}$ , the depletion of the concentration from the formula (3) will be equal  $(n_2 - n_1) = 0.97 \text{ cm}^{-3}$ . The observed value of changes in the concentration is equal  $\approx 0.9 \text{ cm}^{-3}$ . This good accordance with the experiment can be explained by the fact that the velocity of the dipolarization front is much smaller than the ion thermal and Alfen velocity and that the curvature of the magnetic field line is much larger than the ion gyroradius. The evaluation of the plasma velocity at the different distances from the Earth will be made further.

Thus in the magnetic flux tube with the intense current flowing from the ionosphere the density and the pressure of the magnetospheric particles decreases due to precipitation of energetic electrons. The decrease in the pressure leads to the increase in the magnetic field strength in the flux tube because the plasma is diamagnetic. The increase of the magnetic field in turn leads to compression of the magnetic flux tube and the particles in it. The pressure in the flux tube changes and a new configuration of the distribution of the pressure and the magnetic field in the magnetotail arise.

## Calculation results

Figure 3 shows the thermal energy distributions of charged particles  $3/2pV$  in the magnetic flux tube vers. the colatitude  $\theta$  (1) before and after dipolarization (2), it allows to track changes in these quantities in the magnetic flux tubes. The presented data have been obtained by solving the balance equation for the magnetic and plasma pressure with constant pressure along the magnetic field lines [Volkov, 2011] using the model of the magnetic field [Tsyganenko, 1995]. For the case of the preceding dipolarization the component of the IMF  $B_z$  is equal  $-5 \text{ nT}$ , after depolarization  $B_z = 0 \text{ nT}$ ,  $B_y = 0$  in both cases. The IMF components values correspond to the observed on the satellite ACE values of the IMF given in the dipolarization time. The solar wind pressure is equal  $2 \text{ nPa}$ ,  $Dst = 0$ . The pressure in the plasma sheet at  $X = -20R_E$  was set equal  $0.5 \text{ nPa}$  before and  $0.25 \text{ nPa}$  after dipolarization which is close to the values observed by the satellite Themis (b) [Runov et al., 2009]

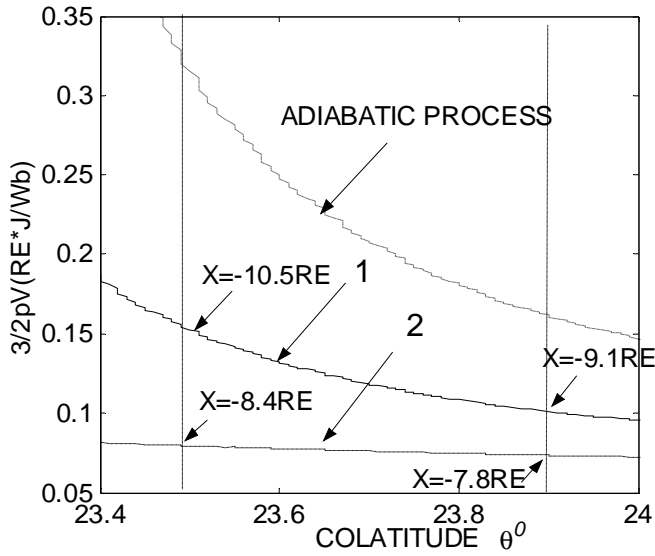


Fig.3

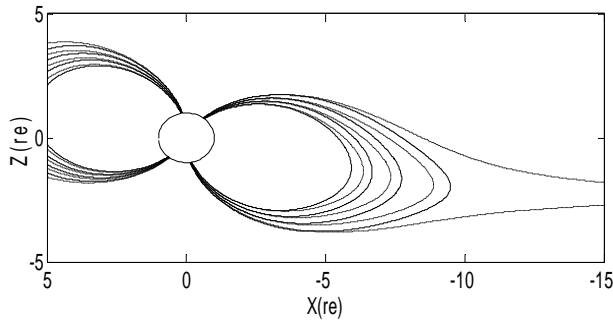


Fig.4

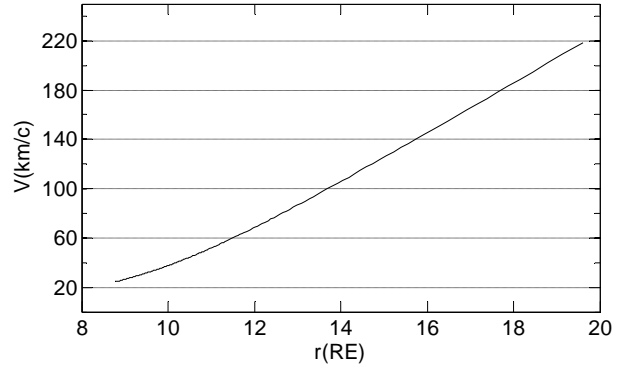


Fig.5

It is seen in fig.3 that the thermal energy of charged particles decreases significantly after dipolarization. The figure also shows the value of the thermal energy of particles in flux tubes in the case of the adiabatic process. The noticeable increase in the thermal energy with decreasing colatitude  $\theta$  is associated with the significant change of the magnetic flux tubes volume at large distances from the Earth in the magnetotail during dipolarization. The decrease of the magnetic flux tubes volume during the adiabatic process is produced by the work of external forces namely the operation of the electric field. The electric field in this case is solenoidal and is caused by the increase of the magnetic field. Considering the time dipolarization equal to 5 minutes we can estimate the plasma velocity at different distances from the Earth using the displacement of the magnetic field lines. Fig.4 shows the variation of the magnetic field lines before and after dipolarization (— before depolarization, - after) calculated with the magnetic field model [Tsyganenko, 1995]. Fig5. shows the change in the velocity of the magnetic field lines and plasma velocity vers. the distance from the Earth. The reducing the plasma velocity toward the Earth during dipolarization is a well established experimental fact. The velocities values obtained from the calculations coincide with observations also [Baumjohann et al., 1990; Angelopoulos et al 1994; Reeves et al., 1996, Shiokawa et al., 1997].

### Estimation of magnetic flux tubes cooling

Let us appreciate cooling of the magnetic field tubes due to the precipitation of the particles. The current in the arcs of the aurora can reach values of  $10 \text{ A/km}^2$ , the average energy of injected particles will be taken as  $5 \text{ keV}$ . The time of depolarization is 5 minutes. Then the amount of heat lost by a magnetic tube with a single magnetic flux is equal to  $0.05 R_E \text{ (J/ Wb)}$ . These losses should be added to the flow of the electromagnetic energy into the ionosphere, it can be estimated by the Joule losses in the auroral arc. Taking the electric field across the arc equal to  $20 \text{ mV/m}$  and the integrated Pedersen conductivity of the ionosphere in the auroral arc equal to  $40 \text{ Cm}$  [Marklund et al., 1982] we receive losses  $0.015 R_E \text{ (J/ Wb)}$  and total losses equal to  $0.065 R_E \text{ (J/ Wb)}$ . This value is sufficient to explain the cooling of the magnetic flux tubes at distances of up to  $10 R_E$ . At large distances the volume of the magnetic flux

tubes and their thermal energy are significantly increased. The thermal energy increases significantly as it is seen in fig.3 for the adiabatic process. This significant increase of the thermal energy in this model suggests that at large distances from the Earth the two-dimensional motion of the magnetospheric plasma perpendicular to the magnetic field lines should be considered.

## Conclusions

The precipitation of the charged particles effects the redistribution of plasma pressure and the  $B_z$  component of the magnetic field in the magnetosphere tail. This effect is manifested as the dipolarization of the magnetic field lines. This effect according to the results is essential for a distance not exceeding  $10 R_E$ . At larger distances the cooling of magnetic tubes is difficult to explain only by precipitation of the particles. It is estimated that the plasma velocity decreases towards the Earth from  $220 \text{ km/c}$  at the distance of  $20 R_E$  up to  $25 \text{ km/c}$  at the distance  $8 R_E$  during the dipolarization, that is consistent with observations.

## References

- Angelopoulos, V., Kennel, C., Coroniti, F., Pellat, R., Kivelson, M., Walker, R., Russell, C., Baumjohann, W., Feldman, W., and Gosling, J.: Statistical Characteristics of Bursty Bulk Flow Events, *J. Geophys. Res.*, 99(A11), 21257–21280, 1994.
- Baumjohann, W., G. Paschmann, and H. L. uhr (1990), Characteristics of high speed ion flows in the plasma sheet, *J. Geophys. Res.*, 95, 3801–3809.
- Knight, S., Parallel electric fields, *Planet. Space Sci.*, 21, 741, 1973.
- Marklund G., Sandahl I., and Opgenoorth H. A study of the dynamics of a discrete auroral arc. *Planet.Space.Sci.*, vol.30, p.179, 1982.
- Reeves, G. D., Henderson, M. G., McLachlan, P. S., Belian, R. D., Friedel, R. H.W., and Korth, A.: Radial propagation of substorm injections, in Proceedings of ICS-3, Versailles, France, 12–17 May 1996, ESA SP-389, 579–584, 1996.
- Runov, A., V. Angelopoulos, M.I. Sitnov, V.A. Sergeev, J. Bonnell, J.P. McFadden, D. Larson, K.- Glassmeier, and U. Auster, THEMIS observations of an earthward-propagating dipolarization front, *Geophysical Research Letters*, Vol.36, L14106, doi:10.1029/2009GL038980, 2009.
- Shiokawa, K., W. Baumjohann, and G. Haerendel. Breaking of high-speed flows in the near-Earth tail, *Geophys. Res. Lett.*, 24, 1179–1182. 1997.
- Tsyganenko N. A., Modeling the Earth's Magnetospheric Magnetic Field Confined Within a Realistic Magnetopause, *J.Geophys.Res.*, 100, 5599-5612, 1995.
- Volkov M.A. The influence of electric field increasing on the substorm currents formation. Proceedings of the 33<sup>rd</sup> Annual Seminar “Physics of auroral phenomena”, Apatity 2011, p.46-48.