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THE MAGNETOSTATIC EQUILIBRIUM IN THE MAGNETOSPHERE AND SUBSTORM PLASMA PROPERTIES

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Abstract. Main magnetospheric substorm properties are analyzed on the basis of developed theory of dawn-dusk electric field formation and magnetospheric turbulence development. It is suggested that the magnetostatic equilibrium condition controls inner magnetospheric processes in all the magnetospheric substorm phases except the expansive phase. The theory naturally explains dawn-dusk electric field growth during the growth phase, plasma sheet thinning, magnetic field line stretching. It can also explain the innermagnetosphere beginning of a substorm, field line depolarization and plasma heating. The plasma sheet thickenning at the recovery phase is explained by taking into consideration plasma turbulence growth. The theory does not require introduction of unmeasurable parameters. All theory predictions can be verified on the basis of multi-satellite observations.

Proof of the auroral oval projection on the inner plasma sheet regions [1, 2, 3] and substorm beginning near the equatorial boundary of the central plasma sheet at $L \sim 7-8$ (see [4]) require changes of the main theoretical approaches to the theories of dawn-dusk electric field creation and magnetospheric substorm nature. It became clear [5] that maximal dawn-dusk potential drop takes place in the inner magnetospheric regions which create real difficulty to reconnection or viscous interaction theories. In the work by Antonova and Tverskoy [6] it was suggested that the existence of dawn-dusk electric field is a result of Iidjima and Potemra Region I field-aligned currents closing in the ionospheric dynamo region. Existence of Region I field-aligned currents was explained as a result of plasma pressure gradient along the volume isosurfaces of magnetic flux tube (azimuthal hot plasma pressure gradients). This hypothesis was supported by Antonova and Ganushkina [5, 7, 8, 9, 10]. It became possible to show that high latitude magnetosphere has enough hot plasma pressure to support necessary to Region I field-aligned currents generation azimuthal hot plasma pressure gradients. It also became possible to show that geomagnetic trap geometry really corresponds to the case of magnetostatical equilibrium field-aligned currents existence the sign and deposition of which correspond to Region I currents picture [7], and suggested mechanism of Region I field-aligned currents generation can explain the Interplanetary Magnetic Field (IMF) control of magnetospheric activity [8]. The main features of this approach can be understood analyzing the magnetic flux tube volume ($W = \int dl/B$ where dl is the field line length element, B is the magnetic field value and the integration must be taken along magnetic field line between conjugate points) isolines and current lines positions in the equatorial plane (see Figure 1). In accordance with magnetostatic equilibrium condition

$$\nabla p = \frac{1}{c}[\mathbf{j}, \mathbf{B}] \tag{1}$$

where ∇p is hot plasma pressure gradient, $\mathbf{j}$ is current density, $\mathbf{B}$ is the magnetic field, plasma pressure gradient is perpendicular to the current line. The projection of the field-aligned current on the equatorial plane under the magnetostatical equilibrium condition [11] has the value

$$j_{\|} = -0.5\,\frac{B_i}{B_e}\,\frac{\mathbf{B}_e}{B_e}\,[[\mathbf{j}, \mathbf{B}], \nabla W] \tag{2}$$

where B_e is the equatorial magnetic field, B_i is the magnetic field at the ionospheric altitudes. So if current lines do not coincide with $W =$ const isolines plasma pressure gradient has the projection on $W =$ const isolines and field-aligned current must be generated. In the region of symmetrical ring current $W =$ const isolines and current lines are concentric circles, and there is no field-aligned current generation. In the geomagnetic tail current flows along Y-axis (GSM coordinate system), W isolines are straight lines, and there is no field-aligned current generation too. The generation of intense field-aligned currents under the magnetostatical equilibrium condition may be realized in the most asymmetric part of the magnetospheric trap and that trap part is the transition region from a quasidipole to the tail. The analysis of magnetic

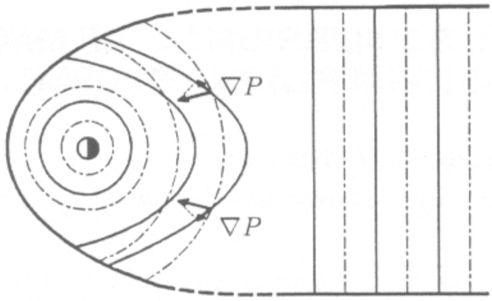

Figure 1: W = const isolines (thick lines) and current lines (stroke-dotted lines) positions in the equatorial plane of high latitude magnetosphere. The magnetopause equatorial plane projection is also shown.

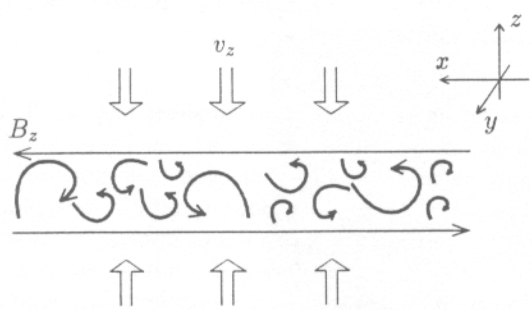

Figure 2: The schematic picture of one dimensional turbulent current sheet.

field configuration in Tsyganenko's magnetic field models gave qualitatively just the same picture. IMF control of Region I currents and so the dawn-dusk electric field and magnetospheric activity in the hot plasma pressure gradient theory is explained as a result of IMF control of magnetospheric currents. As plasma pressure redistribution is a much slower process (convection times) than magnetic field changes (Alfvén wave travel times) the condition of magnetostatic equilibrium in accordance with (1) requires transverse currents growth if magnetic field decreases ($B_z^{IMF} < 0$ penetration). Such growth may bring to much larger magnetic field change than addition of $B_z^{IMF} < 0$. The change of W = const and current line configuration was analyzed by Antonova and Ganushkina [8]. When $B_z^{IMF} > 0$ the stability of plasma sheet can be destroyed, plasma sheet bifurcation takes place and theta-aurora is formed.

At first sight, action of the azimuthal hot plasma gradient mechanism contradicts to the quasistationary convection picture. The problem which was formulated as "convection crisis problem" [12], as it is well known, arises in accordance with the suggestion of magnetic flux tube adiabatic compression. As it was shown in the work [13] for solution of the problem it is necessary to take into account that magnetic field lines can be nonequipotential and that apart from large-scale magnetospheric dawn-dusk electric field middle scale electric fields amplitudes which are one order larger are continuously observed in the plasma sheet (the characteristic example of such field is the electric field of "inverted V" structure). As a result effective plasma mixing take place and plasma compression by dawn-dusk electric field can be compensated by a diffusion flux. This point of view found additional support when Angelopoulos et al. [14, 15] showed that regular plasma sheet plasma velocity is one order smaller than the chaotic velocity.

The suggestion of convective flux compensation by diffusion flux allows to formulate the self-consistent theory of plasma sheet pressure distribution [16]. It was suggested in accordance with observational data that plasma sheet mixing brings to temperature equalizing across the plasma sheet. So the stationary equation of plasma continuity in the case of diffusion flux existence (see Figure 2)

$$-nv_z = D\nabla n \tag{3}$$

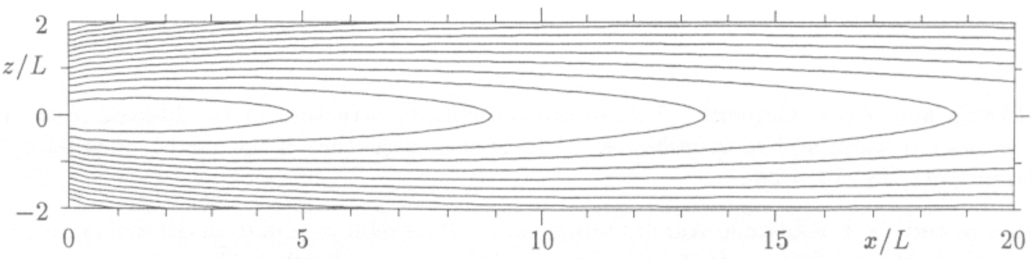

Figure 3: The magnetic field line configuration for $L/x_0 = 0.1$ and the case when D/v_z is independent from the magnetic field.

where n is the plasma concentration, v_z is the convective velocity, D is the diffusion coefficient, allows, if the dependence of regular velocity and diffusion coefficient on the magnetic field is known, to find plasma pressure dependence on the magnetic field. Magnetic field plasma pressure dependence in the two=dimensional case $p = p(A)$ (where $A(x, z)$ is the y component of vector-potential ($\mathbf{B} = [\mathrm{e}_y, \nabla A]$) allows to solve Grad-Shafranov equation

$$\Delta A + 4\pi \frac{dp}{dA} = 0 \tag{4}$$

and to find field line configuration in the tail approximation (when plasma sheet half thickness L is much larger than plasma sheet characteristic length x_0). Figure 3 shows the magnetic field line configuration when D/v_z is independent from the magnetic field. This can take place if, for example, the convection velocity is inversely proportional to the magnetic field (E/B drift) and diffusive coefficient is also inversely proportional to magnetic field (Bohm's diffusion) and also in the unmagnitised case. It was suggested that tail axis plasma pressure has the form $p_0(x) = p_0(x/x_0)^{-q}$. The characteristic plasma sheet half thickness $L = D^0/v_z^0$ where $D^0 = D|_{B=B_L}$, $v_z^0 = v_z|_{B=B_L}$ and B_L is the magnetic field in the tail lobes.

The developed approach gives the possibility to analyze the substorm development from the point of view of magnetospheric currents and plasma pressure redistribution. When B_z^{IMF} turns southward the corresponding Alfvén wave propagating in the magnetosphere from noon to midnight changes the magnetospheric magnetic field and so brings to transverse currents growth first of all in the near Earth tail region. As a result of transverse currents growth field line stretching take place. Region I field-aligned currents also grow creating dawn-dusk electric field growth and all phenomena connected with such growth including the growth of azimuthal plasma pressure gradients in the dipole magnetosphere region supporting Region 2 field-aligned currents and corresponding Region 2 currents growth. Development of equilibrium plasma turbulence requires some time ($\sim$ 1 hour), and the plasma sheet thinning must take place at this substorm phase. Growth of near Earth currents brings to inner magnetosphere magnetic field distortion which is much larger than B_z^{IMF}. It is also necessary to mention that magnetospheric currents growth brings to magnetopause motion to the Earth (see [17] for quantitative evaluations). At the definite stage of the process the magnetic field in the localized region can become near to zero. So the magnetostatic equilibrium can not be supported any longer and plasma instabilities can develop bringing to transverse current disruption and plasma heating. As a result most of transverse current is converges to the ionosphere, Birkeland current loop is formed and magnetic field lines are depolarized. Growth of plasma turbulence brings to plasma sheet thickening. Heated plasma volume not being in equilibrium with the magnetic field due to plasma diamagnetism moves tailward producing all effects characteristic for plasmoid.

So the suggested theory allows to explain most features of magnetospheric substorm including particle and field dynamics. It is preferable as it does not contain unmeasurable parameters. The theory can be verified during the multisatellite experiments such as the INTERBALL project.

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