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ON THE RE-DISTRIBUTION OF THE MAGNETIC FIELD AND PLASMA IN THE NEAR NIGHTSIDE MAGNETOSPHERE DURING A SUBSTORM GROWTH PHASE

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Abstract—There exists strong experimental evidence that drastic changes of the geomagnetic field configuration take place in the near nightside magnetosphere before the onset of explosive phase of a substorm. A study of adiabatic effects of this field re-structuring in the particle distribution anisotropies is done in this work. It is shown that an externally induced non-stationarity of the magnetic field (most likely, due to increasing tail lobe magnetic flux) plays an important role in developing a field-aligned plasma pressure anisotropy, which is necessary for formation of an intense and thin current sheet at $x_{GSM} \sim -8R_E$. Other sources of the anisotropy related to the pitch angle dependence of the drift velocities are also discussed.

1. INTRODUCTION

Experimental evidence indicates that considerable changes of the magnetic field configuration take place in the near region of the nightside magnetosphere at $R \sim 7$–$10R_E$ during the growth phase of a substorm (Kokubun and McPherron, 1981; Kaufmann, 1987). A significant decrease in the B_z component at low latitudes is observed on the time scale of several tens of minutes, while the westward current flowing in this region increases dramatically and concentrates into a very thin current sheet. As a result, the originally quasi-dipolar configuration evolves into a tail-like one even at relatively small geocentric distances. A statistical analysis carried out by Lin and Barfield (1984) using the data from two geosynchronous spacecraft showed that even at $R = 6.6R_E$ one frequently observes such stretched magnetic field line configurations during the periods with high disturbance levels.

Kaufmann (1987) showed in a wire-model simulation study that the measured magnetic field disturbances require a formation of a current sheet at $R \sim 7$–$8R_E$ with a total current flow intensity exceeding that observed under normal conditions by an order of magnitude. The most surprising and paradoxical fact discussed in that work is that the increase of the current is not accompanied by enhancement of the particle flux and energy; on the contrary, they usually show a gradual decrease up to the very moment of the explosive phase onset.

At present there exists no clear understanding of the observed evolution of the magnetic field and plasma in this region. Kaufmann (1987) proposed an explanation based on an idea of a positive feedback between the curvature drift current and the degree of the magnetic field line stretching. However, this hypothesis does not seem to be adequate, since, as shown in several works (Rich *et al.*, 1972; Pudovkin and Tsyganenko, 1973; Cowley, 1978), the total current in the sheet does not depend on the curvature of magnetic field lines in the equatorial region; rather, it is proportional to the difference between parallel and transversal pressures $p_\parallel - p_\perp$ outside the field reversal layer. A necessary condition for the existence of an equilibrium configuration with a thin current sheet is a field-aligned pitch-angle anisotropy satisfying an approximate stress balance condition $p_\parallel - p_\perp \approx B^2/4\pi$.

In the present paper possible mechanisms for formation of the anisotropic plasma distributions in the near nightside magnetosphere are considered. We shall analyze adiabatic evolution of pitch-angle anisotropies both for stationary and non-stationary plasma convection and estimate the associated current densities, with the aim to assess the degree of feedback between the magnetic field re-structuring and the induced re-distribution of particles.

2. FORMULATION OF THE PROBLEM AND THE MAGNETIC FIELD MODEL

A stationary earthward adiabatic convection in the extended tail region ($x_{GSM} \lesssim -10R_E$) should result in a compression and energization of the convecting plasma with a predominance of the Fermi acceleration mechanism over the betatron one, which could lead to formation of a field-aligned anisotropy with $p_\parallel > p_\perp$ in the tail plasma sheet (Tsyganenko, 1982a). However, there exists an effective mechanism of non-adiabatic pitch-angle scattering of particles in the current sheet, that destroys anisotropy at $x_{GSM} \lesssim -10R_E$ (Tsyganenko, 1982b).

At smaller geocentric distances with $x_{GSM} \sim -(6–9)R_E$ the opposite situation is present. The magnetic field in this region is nearly quasi-dipolar under quiet conditions and hence the non-adiabatic scattering effects are negligibly small for particles with $w \sim 1–10$ keV. At the same time, the quasi-dipolar field distribution with a much larger radial gradient of B than that in the tail, leads to a predominance of the transverse energization of particles over the field-aligned one. In a stationary earthward convection model this is manifested in a more rapid increase of $p_\perp$ than of $p_\parallel$ and hence to the development of an anisotropic particle distribution with $p_\perp > p_\parallel$ (Southwood and Kivelson, 1975), which rules out a possibility for formation of a thin current sheet.

It should be kept in mind, however, that for a substorm growth phase the magnetic field configuration cannot be treated as a static one.

The observed increase of the magnetotail flux accompanied by a deepening of the near-Earth magnetic field depression results in an induction electric field which modifies the pattern of plasma convection. Combined with the non-stationarity of the magnetic field, this can significantly change the rate of its variation in the convecting frame of reference and hence modify the relative rates of perpendicular and parallel particle energization, in comparison with those obtained in the stationary convection model. In order to clarify this question, let us carry out the following calculations.

The magnetic field distribution in the nightside region will be modeled as the sum of contributions from two sources, namely, the geodipole field $\mathbf{B}_D$ and the field of an axially symmetric current sheet of finite thickness $\mathbf{B}_T$ (Tsyganenko, 1989), so that

$$\mathbf{B} = \mathbf{B}_D + \mathbf{B}_T. \tag{1}$$

In a cylindrical coordinate system (ρ, φ, z) co-axial with the geodipole the second term in (1) has the components

$$B_{T_\rho} = 3C\rho z(a+\zeta)\zeta^{-1}[(a+\zeta)^2+\rho^2]^{-5/2}$$
$$B_{T_z} = C[2(a+\zeta)^2-\rho^2]\cdot[(a+\zeta)^2+\rho^2]^{-5/2} \tag{2}$$

where $\zeta = (z^2+D^2)^{1/2}$, D is a characteristic half-thickness of the sheet, a is a radial scale length of the current density distribution, and C is a coefficient defining the intensity of the current sheet contribution to the total magnetic field.

During the substorm growth phase a gradual increase of the magnetotail current takes place, which is controlled by the reconnection of the dayside geomagnetic field with IMF and accumulation of the reconnected magnetic flux within the tail lobes. It is supposed that the magnetic field configuration changes rather slowly and the temporal evolution of the plasma parameters can thus be calculated using the assumption that the first and second adiabatic invariants are conserved. In this case the final particle distribution can be uniquely determined, provided that the initial and final configurations of the magnetic field are defined by specifying the initial and final values of the coefficient C in (2).

Let us solve a problem to find the parallel and perpendicular pressure distributions along a magnetic force line tube lying at an axially symmetric shell, S_f (Fig. 1) corresponding to a final configuration. Assume that before the re-structuring of the magnetic field the particles were located at an initial force line shell S_i shown in Fig. 1 and with the isotropic pitch-angle distribution having a pressure p_0.

The initial force line shell S_i is assumed to be located arbitrarily with respect to the final one, S_f, which corresponds to arbitrariness in setting the intensity of the convection electrostatic field $\mathbf{E}_c$. In particular, if $\mathbf{E}_c = 0$, then the particles drift solely under the action of the induction electric field $\mathbf{E}_i = -(1/c)\ \partial\mathbf{A}/\partial t$, so that the shells S_i and S_f are linked with each other by the equation

$$\rho A_{\varphi_i}(\rho, z) = \rho A_{\varphi_f}(\rho, z) = \text{constant}.$$

This can be easily verified by taking the full derivative $\mathrm{d}/\mathrm{d}t = \partial/\partial t + (\mathbf{v}_D, \nabla)$ of ρA_φ, with $\mathbf{v}_D$ being the electric drift velocity corresponding to $\mathbf{E}_i$. In the case of growing tail lobe magnetic field the induction electric field is directed from dusk to dawn, so that the S_i shell lies within S_f, i.e. the particles and the frozen-in field lines are stretched tailwards.

In the opposite case of a sufficiently strong dawn–dusk electrostatic field the plasma drifts towards the Earth, so that the initial shell lies at larger distances than the final one, as is shown in Fig. 1.

3. CALCULATION OF THE PRESSURE DISTRIBUTIONS IN THE ADIABATIC APPROXIMATION

Following Tsyganenko (1982a), the parallel pressure at a cross-section K_f of a force line tube at the shell S_f (Fig. 1) can be written as

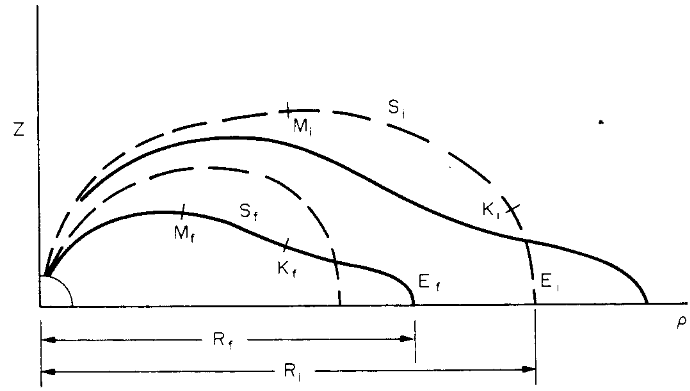

FIG. 1. ILLUSTRATING THE DERIVATION OF THE PARALLEL AND PERPENDICULAR PRESSURES AT THE FINAL MAGNETIC FIELD LINE SHELL S_f (SOLID LINES), PROVIDED THE INITIAL MAGNETIC FIELD CONFIGURATION (BROKEN LINES) WITH ISOTROPIC PARTICLE DISTRIBUTION IS KNOWN.

$$p_f = 2\pi \int_0^\infty \mathrm{d}w_f \int_0^\pi \mathrm{d}\theta_f (2w_f/m)^{3/2} f(w_f, \theta_f) \sin\theta_f \cos^2\theta_f \quad (3)$$

where w_f and θ_f are, respectively, the energy and pitch-angle of particles having at this location the velocity distribution function $f(w_f, \theta_f)$. Denoting the magnetic field magnitude at K_f as B_{K_f}, let a group of particles with $w = w_f$ and $\theta = \theta_f$ at K_f have $w = w_i$ and $\theta = \theta_i$ at a cross-section K_i with $B = B_{K_i}$ of an initial field line tube at the shell S_i. The magnetic field intensities in the corresponding mirror points M_f and M_i are

$$B_{M_f} = B_{K_f}/\sin^2\theta_f \quad \text{and} \quad B_{M_i} = B_{K_i}/\sin^2\theta_i. \quad (4)$$

Note that particles with different final energies w_f and pitch angles θ_f have different azimuthal drift velocities and hence originate from different field line tubes of the initial shell S_i. However, the assumed axial symmetry within a sufficiently large range of longitude around the midnight meridian plane makes it possible to describe the initial isotropic plasma distribution by means of a single function $F(w_i)$, which does not depend on longitude and pitch-angle.

Conservation of the second adiabatic invariant provides the equation

$$\int_{E_f}^{M_f} \sqrt{B_{M_f} - B_f(s)}\,\mathrm{d}s = \int_{E_i}^{M_i} \sqrt{B_{M_i} - B_i(s)}\,\mathrm{d}s \quad (5)$$

yielding the relationship between the mirror point magnetic fields as a function $B_{M_f} = G(B_{M_i})$, which can be calculated numerically, once the initial and final magnetic field distributions and force lines defining integration paths in (5) are given.

Adding to these equations the condition of the first invariant conservation

$$w_f/B_{M_f} = w_i/B_{M_i} \quad (6)$$

we express the integration variables w_f and θ_f in (3) through the initial quantities w_i and θ_i

$$w_f(w_i, \theta_i) = (w_i/B_{K_i}) G(B_{K_i}/\sin^2\theta_i) \sin^2\theta_i \quad (7)$$

$$\sin^2\theta_f(w_i, \theta_i) = B_{K_f}/G(B_{K_i}/\sin^2\theta_i). \quad (8)$$

Using equations (6–8) and the Liouville's theorem

$$f(w_f(w_i, \theta_i), \theta_f(w_i, \theta_i)) = F(w_i),$$

let us replace integration variables (w_f, θ_f) in (3) by (w_i, θ_i). In general, the limits of integration over the pitch angle should be changed; however, this can be avoided by a special choice of the cross-section K_i at the initial shell S_i so that $G(B_{K_i}) = B_{K_f}$. In this case $\theta_f = \pi/2$ corresponds to $\theta_i = \pi/2$, and we obtain

$$p_\parallel = 2\pi \int_0^\infty \mathrm{d}w_i \int_0^\pi \mathrm{d}\theta_i (2w_f/m)^{3/2} \times F(w_i) \sin\theta_f \cos^2\theta_f \frac{D(w_f, \theta_f)}{D(w_i, \theta_i)} \quad (9)$$

where w_f and θ_f are expressed in terms of w_i and θ_i using (7) and (8). Actually, θ_f does not depend on w_i, and the Jacobian in (9) reads

$$\frac{D(w_f, \theta_f)}{D(w_i, \theta_i)} = \frac{\partial w_f}{\partial w_i} \cdot \frac{\partial \theta_f}{\partial \theta_i} = G'(B_{K_i}/\sin^2\theta_i) \cot\theta_i/\cot\theta_f. \quad (10)$$

Substituting (10) in (9) and separating the integration over w_i into a factor proportional to the initial isotropic pressure p_0, we obtain the normalized parallel pressure at K_f as

$$p_\parallel/p_0 = 3\int_0^{\pi/2} [G(B_{M_i})/B_{M_i}]^{3/2} \times G'(B_{M_i}) \frac{\cot\theta_i}{\cot\theta_f} \sin\theta_f \cos^2\theta_f \, d\theta_i \quad (11)$$

where $B_{M_i} = B_{K_i}/\sin^2\theta_i$.

Similarly, the perpendicular pressure reads

$$p_\perp/p_0 = (3/2)\int_0^{\pi/2} [G(B_{M_i})/B_{M_i}]^{3/2} \times G'(B_{M_i}) \frac{\cot\theta_i}{\cot\theta_f} \sin^3\theta_f \, d\theta_i. \quad (12)$$

4. RESULTS

According to Kaufmann (1987), the main part of the current responsible for the observed deformation of the nightside magnetic field configuration during the substorm growth phase concentrates within a thin sheet with the maximal intensity near $x_{GSM} \sim -8R_E$. On this ground the final distributions of $p_\parallel$ and $p_\perp$ and the corresponding current densities have been computed in all cases for the same field line crossing the equatorial plane at $R_f = 8R_E$. As for the initial field line shell, its location depends on the relative intensities of the electrostatic and induction electric field during the magnetic field restructuring. Semenov and Sergeev (1981) showed that $\mathbf{E}_c$ and $\mathbf{E}_i$ approximately cancel each other in the tail plasma sheet during the substorm growth phase. Judging from the experimental results discussed in the paper by Kaufmann (1987), this is also the case in the nearer nightside magnetosphere, because the increase of the current is accompanied by a decrease of the particle fluxes and characteristic energies, i.e. the Joule dissipation rate $(\mathbf{E}\cdot\mathbf{j})$ seems to be negative. Therefore, we cannot rule out a possibility that the induction field $\mathbf{E}_i$ prevails over the electrostatic one at this stage and, hence, the current sheet developing at $x_{GSM} \sim -8R_E$ is fed by the tailward particle inflow from the inner nightside magnetosphere. Because of an incomplete understanding in this question, the calculations have been done for several cases, including (i) plasma convection from inside ($R_i < R_f$, i.e. the induction electric field predominating over the electrostatic one), (ii) nearly no convection ($R_i = R_f$, i.e. an approximate balance between $\mathbf{E}_c$ and $\mathbf{E}_i$), and (iii) a pronounced earthward convection ($R_i > R_f$) due to a rather strong dawn–dusk electrostatic field.

Figure 2 shows the final distributions of $p_\perp/p_0$ (crosses) and $p_\parallel/p_0$ (solid dots) along the magnetic field line with $R_f = 8R_E$ for four initial values of $R_i = 6, 8, 10$ and $12R_E$. Plasma which was originally isotropic is convected from the initial to the final shell, while the field B_T is gradually growing, so that initially $C_i = -6\times10^4$ and finally $C_f = -1.4\times10^5$. In the bottom of Fig. 2 the initial (dotted lines) and the final (solid lines) magnetic field configurations are shown; the open circles on the force line with $R_f = 8R_E$ correspond to the points where the pressures were computed. The magnitudes of the current in the sheet for both configurations were chosen so that the obtained magnetic field distributions approximately correspond to the observed ones.

As is readily apparent from the plots, anisotropic particle distributions with $p_\parallel > p_\perp$ develop in the final field line tube in all cases considered. Both $p_\parallel$ and $p_\perp$ increase with distance S along the field line from its equatorial crossing point, in agreement with expectations based on simple considerations of particle mirroring. It can also be seen that both pressures are progressively larger for greater radii R_i of the initial field line shell; thus, in the first case (convection from $R_i = 6$ to $R_f = 8$ with adiabatic cooling of the plasma) both $p_\parallel$ and $p_\perp$ have the smallest values on the order of $(0.1\text{–}0.3)p_0$, while in the case with $R_i = 12$ a strong compression and energization is observed with $p_\parallel$, $p_\perp \sim (5\text{–}10)p_0$.

To assess the role of non-stationarity of the magnetic field in producing the anisotropic field-aligned particle distributions, a similar computation was done for static configurations of the magnetic field, namely, for the cases of (i) a purely dipolar field, (ii) a weakly stretched configuration (1) with $C = -6\times10^4$ nearly corresponding to the average observed field distributions during quiet conditions, and (iii) a strongly deformed tail-like magnetic field with $C = -1.4\times10^5$. The results are displayed in Figs 3, 4 and 5, respectively, in the same format as in Fig. 2. From Figs 3 and 4 it is evident that the stationary convection in the dipolar and weakly stretched magnetic configurations is accompanied by the development of a transverse anisotropy with $p_\perp > p_\parallel$. Accordingly, both pressures show a slight decrease along the field line tube towards its ionospheric ends, in contrast with the non-stationary case represented by Fig. 2.

The convection in the tail-like static magnetic field, as can be seen from Fig. 5, provides an example of a more complex situation, where the field-aligned anisotropy develops only in case of sufficiently large values of R_i, i.e. if the convection of initially isotropic plasma is assumed to start at relatively large distances. However, such an extremely distorted configuration is unlikely to exist before the beginning of the growth phase. Rather, it corresponds to the moment just before the break-up phase and implies that the process

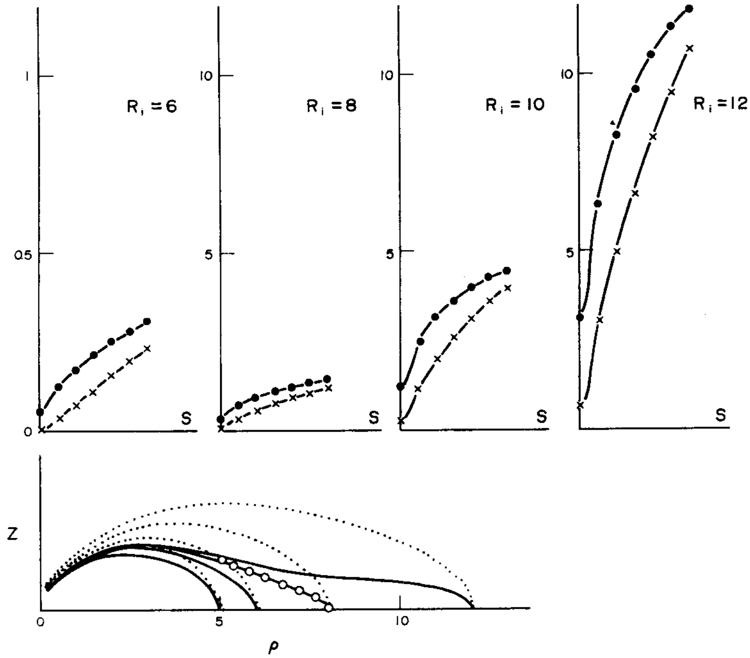

FIG. 2. PLOTS OF THE PARALLEL (SOLID CIRCLES) AND PERPENDICULAR (CROSSES) PRESSURES NORMALIZED BY THE INITIAL ISOTROPIC PRESSURE VALUE p_0 VS THE DISTANCE S ALONG THE FINAL MAGNETIC FIELD LINE TUBE WITH $R_f = 8R_E$, MEASURED FROM ITS EQUATORIAL CROSSING POINT, FOR FOUR STARTING SHELLS WITH $R_i = 6$, 8, 10, AND $12R_E$.

Note a different vertical scale in the first plot. Initial (dotted lines) and final (solid lines) model magnetic field configurations are shown in the bottom. Open circles along the field line with $R_f = 8$ correspond to the points, where the pressure values for the upper plots had been computed.

of the formation of the intense current sheet had already begun long before.

It is also worthy to note that the case of a purely dipolar field was studied by Southwood and Kivelson (1975), who obtained the following approximate analytic expressions for $p_\perp/p_0$ and $p_\parallel/p_0$ in the equatorial plane

$$p_\perp/p_0 = (R_i/R_f)^{7.275}\{1-0.14[1-(R_f/R_i)^{0.45}]\}$$
$$p_\parallel/p_0 = (R_i/R_f)^{6.825}\{1-0.56[1-(R_f/R_i)^{0.45}]\}. \quad (13)$$

These expressions were used in the present work as a test for checking the accuracy of our numerical results, which were found to deviate from (13) by not more than $\sim 0.5\%$.

The obtained results may be considered as an indication that the changes in the magnetic field structure around $X_{SM} \sim -(6\text{–}10)R_E$ are initiated by a gradual increase of the plasma sheet current with the corresponding decrease of B_z in the nightside magnetosphere caused by enhanced dayside reconnection and accumulation of the magnetic flux in the tail lobes. This process has been quantitatively studied by Erickson (1984), who showed that a deep minimum in B_z develops near $X \sim -10R_E$ as a consequence of a non-stationary convection in a 2-D MHD model.

It should be realized, of course, that a serious limitation of the present study consists in that the magnetic field distribution in the modeling region is considered as a given function of coordinates, and its temporal change is also imposed by varying the value of a single coefficient C in (2). In reality the evolution of the current sheet during the substorm growth phase is a complicated self-regulating process, which seems to be only partly controlled by external solar-wind-related factors. The field-aligned anisotropy which develops in the course of the magnetic field re-structuring leads to a further increase of the current and an earthward shift of the thinning current sheet. This problem should be treated self-consistently using a kinetic description of plasma behaviour, the solar wind control being incorporated by properly setting the non-stationary boundary conditions. However, even in the framework of the simple approach adopted in this work we can evaluate the degree of a positive feedback between the magnetic structure changes and tension in the anisotropic plasma by calculating the

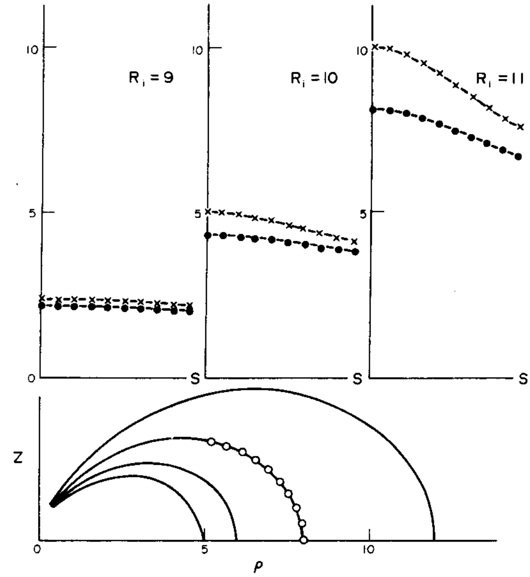

FIG. 3. ILLUSTRATING THE PARALLEL AND PERPENDICULAR PRESSURE DISTRIBUTIONS ALONG THE FIELD LINE TUBE WITH $R_f = 8R_E$ IN THE CASE OF THE EARTHWARD CONVECTION IN A PURELY DIPOLAR STATIC MAGNETIC FIELD.

The results are displayed in the same format as in Fig. 2.

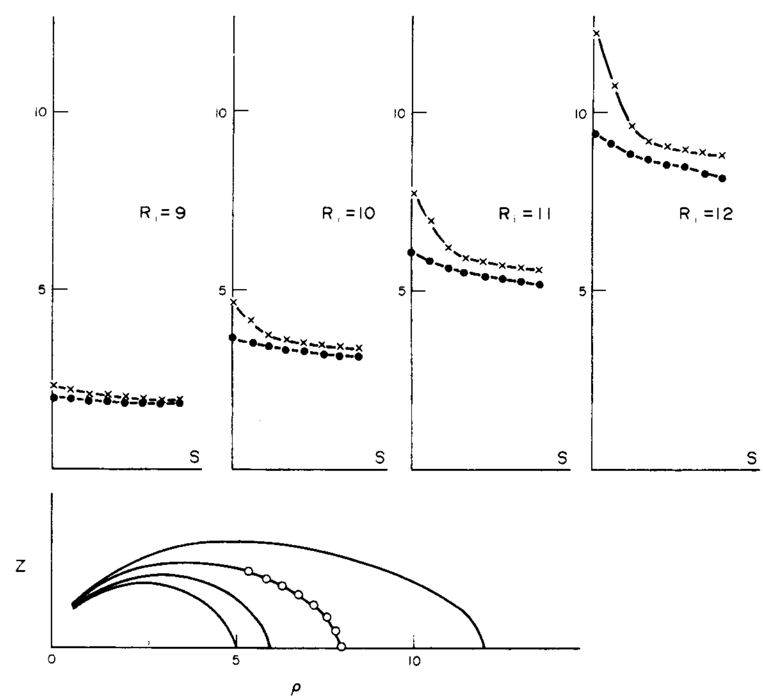

FIG. 4. SIMILAR TO FIG. 3, EXCEPT THAT THE STATIC MAGNETIC FIELD CONFIGURATION IS WEAKLY STRETCHED BY THE EQUATORIAL CURRENT DISC CONTRIBUTION (2) WITH $C = -6\times10^4\,\mathrm{nT}\cdot R_E^3$.

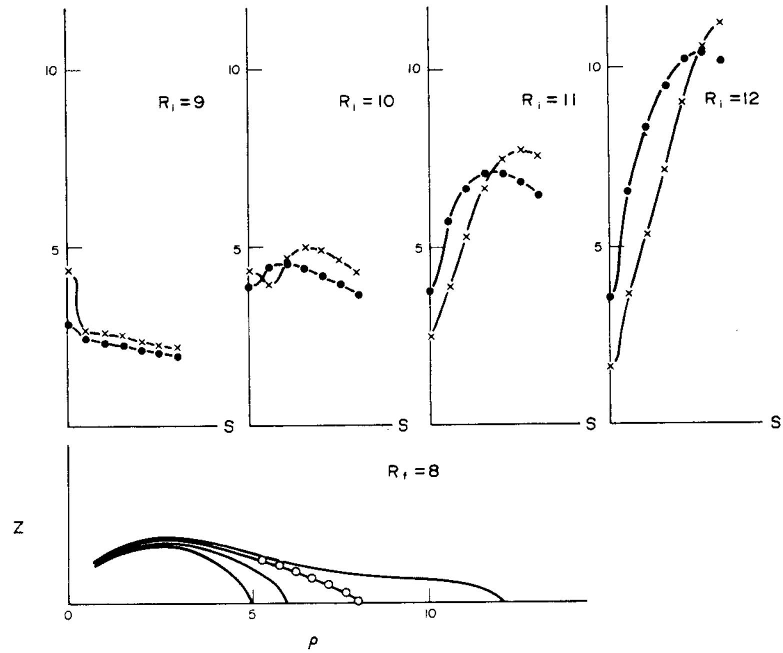

FIG. 5. SIMILAR TO FIG. 4, EXCEPT THAT A SIGNIFICANTLY MORE INTENSE CURRENT FLOWS IN THE EQUATORIAL DISC ($C = -1.4 \times 10^5$ nT $\cdot R_E^3$).
Note that the opposite type of anisotropy arises for $R_i \geq 11$, in comparison with cases shown in Figs 3 and 4.

current density corresponding to the obtained distribution of $p_{\parallel}$ and $p_{\perp}$ and the assumed configuration of the magnetic field given by (2).

The electric current density in the anisotropic plasma is given by the well-known relationship (Parker, 1957)

$$\mathbf{j} = (c/B^2)\mathbf{B} \times \left\{ \nabla p_{\perp} + (p_{\parallel} - p_{\perp}) \frac{\mathbf{e}_n}{\rho_c} \right\} \quad (14)$$

where the second term in the brackets containing the curvature of the magnetic field line $\mathbf{e}_n/\rho_c$ plays a dominant role in configurations with thin current sheets. Specifying a value of isotropic plasma pressure in the initial field line shell by $p_0 = 20$ keV cm^{-3}, which corresponds to the typical observed energy densities at distances $R \sim 8R_E$ (Kaufmann, 1987), and using the obtained distributions of $p_{\parallel}$ and $p_{\perp}$ together with the magnetic field model (1–2), we can evaluate the distribution of the electric current density given by the second term in (14). Calculations show that in the case corresponding to the magnetic field re-distribution displayed in Fig. 2 with $R_i = 8R_E$ (no bulk transport of plasma during the growth phase period) this current is concentrated within a layer with a characteristic thickness of $\sim 0.2R_E$ and has the volume density on the order of $\sim 10^{-7}$ A $\cdot$ m^{-2}. Therefore, the net dawn to dusk sheet current density, integrated across the layer is ~ 0.1 A $\cdot$ m^{-1}, which is of the same order of magnitude as the estimates given by Kaufmann (1987), as well as the value obtained directly from taking the curl of our model magnetic field (2). It should thus be concluded that the feedback effect is essential and should be taken into account in a more accurate physical model.

5. THE ROLE OF AZIMUTHAL PARTICLE DRIFTS

In the above calculations the model magnetic field was assumed to be axially symmetric. The real magnetospheric field is asymmetric in the Sun–Earth direction, as well as confined by the magnetopause at dawn and dusk flanks. This leads to additional effects which give rise to anisotropic pitch angle distributions. One such effect is the well-known drift shell splitting (Roederer, 1969), also discussed in a context of the observed particle pitch angle distributions in the recent paper by Sibeck *et al.* (1987). Pudovkin and Tsyganenko (1973) pointed out that this effect may be responsible for formation of thin tail current sheet in the near nightside magnetosphere due to a leakage of particles with $\theta \sim 90°$ outside the magnetosphere and increasing the relative concentration of particles with smaller pitch angles. This mechanism becomes more and more effective, while the tail lobe magnetic field and hence the plasma sheet current increase in the course of the substorm growth phase, because the day–night asymmetry of the magnetosphere is growing and the region of unclosed lines of constant B shifts closer to the Earth at the nightside. Therefore, a positive feedback is also inherent in this mechanism, though a considerable time delay on the order of tens of minutes must be present, which corresponds to the time necessary for particles with energies $w \sim 10$ keV to drift from the midnight meridian to the magnetopause.

Besides that, there exists one more possible mechanism, which operates in a distorted magnetic field of a type intermediate between the dipolar and strongly tail-like configuration. Its essence consists in that the particles with near-90° pitch-angles spend the most time in the near-equatorial region with a depressed magnetic field also having a relatively large radial gradient. Therefore, their bounce-averaged drift velocity $\tilde{v}$ must be significantly larger than that for particles with lower pitch angles, and this will result in a more rapid ejection of the particles with $\theta \sim 90°$, leading to a relative increase of $p_{\parallel}$ over $p_{\perp}$. In the more distant tail region this effect should be much less, because the field gradients rapidly decrease tailwards and the particle motion tends to the drift-free one described by Stern and Palmadesso (1975). At closer geocentric distances with a quasi-dipolar magnetic field geometry this drift velocity separation effect also weakens, since $\tilde{v}$ shows only a slight dependence on the pitch angle in the purely dipolar magnetic field (Hamlin *et al.*, 1961).

These qualitative arguments can be illustrated by model calculations. Figure 6 shows the plots of the bounce-averaged drift velocity $\tilde{v}$ normalized by its value for equatorial particles $\tilde{v}_e = \tilde{v}_{\theta=90°}$, vs the pitch angle, for several drift shells with different equatorial radii R_e. Computations have been done for the midnight meridian plane using a simple magnetic field model similar to (1), where the tail current sheet contribution was given by expressions (5) from the work by Tsyganenko and Usmanov (1982) with the half-thickness $D = 0.7R_E$ and the inner edge located at $X_N = -7R_E$. The intensity of the current was set by taking $B_N = 80$ nT and $\Delta B = 110$ nT, so that the resultant magnetic field distribution be typical of that observed just before the onset of a substorm (at the X_{GSM} axis, by $X = -6, -7$, and $-8R_E$, this model yields the total field magnitude $B = 81$, 16, and 3 nT, respectively). A considerable difference in the drift speed for particles with $\theta \sim 0°$ and $\theta \sim 90°$ is evident from the plots, the effect being more pronounced for

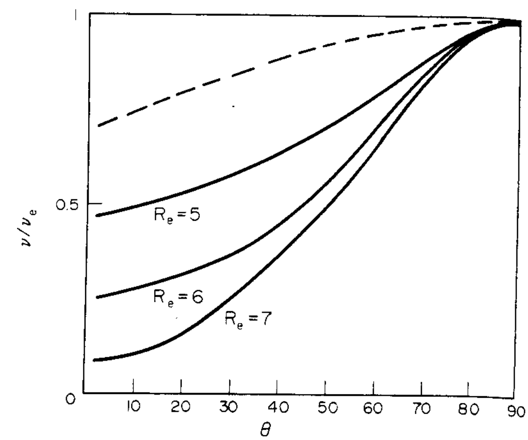

Fig. 6. Plots of the bounce-averaged drift speed of particles normalized to its value for $\theta = 90°$, as a function of the equatorial pitch angle, for three shells with different equatorial radius, R_e. The corresponding result for the purely dipolar field is shown by the broken line.

larger shell radii R_e. The curve for a purely dipolar field is given also for comparison, showing only a $\sim 30\%$ variation of $\tilde{v}$ between $\theta = 0°$ and $\theta = 90°$.

6. DISCUSSION AND CONCLUSIONS

It should be noted once again that the above results were obtained under the assumption of the adiabatic regime of the particle motion. The validity of this assumption can be checked by evaluating the dimensionless parameter $k = R_c/\rho_L = R_c B_z/G$ (e.g. Sergeev *et al.*, 1983), where B_z and R_c are the equatorial values of the magnetic field and its force line curvature radius, respectively, and $G = mvc/e$ is the particle's rigidity. Adiabaticity holds for $k \gtrsim 10$, so that for protons we obtain the threshold energy in kiloelectronvolt units as $w_c \approx 2 \times 10^{-2} R_c^2 B_z^2$, where R_c and B_z should be substituted in Earth radii and nanoteslas, respectively. During quiet conditions $B_z \sim 40$ nT at $R = 8R_E$. Taking $R_c = 0.5R_E$ (a purely dipolar value is $R_c = R/3 \sim 3R_E$ in this region), we still obtain $w_c \sim 10$ keV. Particles with $w \gtrsim w_c$ will move adiabatically, and those with $w \lesssim w_c$ will pitch angle scatter on traversing the current sheet. These estimates show that the spatial limit of the validity of the adiabatic treatment for the bulk of the nightside thermal plasma population is unlikely to extend further than 8–10R_E.

The threshold energy, w_c is very sensitive to the magnetic field configuration, since decreases in B_z during the growth phases are accompanied by a decrease in R_c. This suggests some qualitative considerations concerning such a question of paramount importance as the mechanism for the onset of the explosive phase.

Namely, at a certain stage of the growth phase the current sheet thickness can become so small that for a major part of the ions a transition to the non-adiabatic motion with an intense pitch-angle scattering will occur. This will cause a decrease of the current and a transverse expansion of the current sheet. Due to a positive feedback the process will develop in an explosive disruption of the current. It is important that, due to initial local inhomogeneities of the current sheet thickness, the expansions will also appear within spatially limited regions, located with a maximal probability near the midnight meridian, where the magnetic field line stretching is the largest. These features are typical for the observed distribution of the substorm explosive reconfiguration regions (Lopez *et al.*, 1988). It can be therefore proposed that the outlined mechanism can play a significant role in initiating the substorm explosions.

There exists strong experimental evidence in favour of the crucial role of the field-aligned particle anisotropies in the nightside magnetosphere dynamics during the substorm growth phase. Baker *et al.* (1978, 1981) made an extensive study of electrons in the 30–300 keV energy range at geosynchronous orbit, which shows that for periods 1–2 h prior to the onset of substorm highly cigarlike (field-aligned) pitch angle distributions develop typically near the midnight sector, accompanied by a stretching of the magnetic field into a tail-like configuration. The onset of explosive phase with a collapse of the field lines towards a dipolar shape is manifested by an abrupt transition of electron distributions to isotropic or pancaked ones. As for the ions, a similar behaviour of parallel and perpendicular fluxes can be also observed at geostationary distances during the growth phase (*GEOS-2* unpublished data, Sergeev, private communication, 1988).

To summarize, we have studied the development of the pressure anisotropy in the near nightside magnetosphere during the period of the magnetic field re-distribution pertaining to the growth phase of a substorm. The computations based on assumption of conservation of the first two adiabatic invariants and a given model of the magnetic field showed that an externally induced non-stationarity of the overall **B** distribution plays an important role in developing a field-aligned pressure anisotropy, which is necessary for formation of an intense and thin current sheet at $x_{GSM} \sim -8R_E$. A gradual decrease of B_z component in the near equatorial region at the nightside seems to be initiated by enhancement of the tail lobe magnetic flux due to the reconnection of the magnetospheric field with IMF. It appears also quite likely that a positive feedback exists between the magnetic field restructuring and the particle pitch-angle re-distribution, which must be incorporated in future physical models. Some other sources of the pressure anisotropy in the near tail region have been discussed briefly.

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