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Calculation of the Shape and Position of the Last Closed Field Line Boundary and the Coordinates of the Magnetopause Neutral Points in a Theoretical Magnetospheric Field Model

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Abstract. Variations of the shape and position of the last closed field line boundary, the location of the magnetopause neutral points, and the topology of the polar cusp have been calculated in a „closed" model magnetosphere with respect to substorm growth phase effects and the earth's dipole tilt angle. It was found that the dayside part of the last closed field line boundary depends on the stand-off distance and the dipole tilted in summer direction, whereas the nightside part is determined by the neutral sheet's magnetic field and position, and the dipole tilted in winter direction. Thus the geomagnetic conjugate points of the last closed field line boundary vary sensitively with the dipole tilt angle and pre-substorm related variations of the model parameters.

The position of the polar cusp, and the boundary depend, with decreasing influence, on (1) the stand-off distance to the subsolar point, (2) the tilt angle of the earth's dipole, (3) the neutral sheet field, and (4) the distance of the neutral sheet's inner edge. A compression of the dayside magnetosphere and an increase of the tail field caused by a substorm growth phase result in an equatorward displacement of the polar cusp and the last closed field line boundary as whole.

The magnetopause of the field model is a tangential discontinuity with given geometry. Thus no B-field component normal to the surface and no interconnection with the interplanetary magnetic field can be considered. The field configuration inside the magnetospheric cavity results from a 3-dim. solution of the Chapman-Ferraro problem.

Key words: Closed Field Lines — Magnetopause — Magnetosphere — Magnetospheric Model — Neutral Points.

Introduction

The boundary of last closed field lines can be observed at geomagnetic high latitudes by changes of electron flux profiles which are closely associated with the different behavior of charged particles in open and closed field line regions. Eather (1973) and Feldstein (1973) argued that the equatorial edge of the auroral oval represented by this boundary could be regarded as a "natural" coordinate system for geophysical phenomena being related with the polar cap.

Feldstein (1973) and other authors pointed out that the dayside of the polar oval is connected with the polar cusp, whereas the nightside part is connected with the inner edge of the plasma sheet in the tail. Thus it is evident that the equatorward boundary of the oval is a function of magnetic local time and changes with magnetic activity (Winningham, 1972). The tilt angle of the geomagnetic dipole axis results in a seasonal variation of the boundary (McDiarmid and Wilson, 1968; Burch, 1972). Superimposed are daily variations due to the 11° angle between the geographic and geomagnetic axes of the earth (Maehlum, 1968; Feldstein und Starkov, 1970).

Thus it is the purpose of this paper to calculate variations of (1) the shape and position of the last closed field line boundary, (2) the location of the magnetopause neutral points, and (3) the topology of the polar cusp in a model magnetosphere with respect to a pre-substorm related magnetic disturbance and the dipole tilt angle.

The following symbols are used throughout this paper in order to describe the high latitude quantities:

ϑ_D = polar distance of the neutral point measured from the dipole axis in [°],

r_N = radial distance to the magnetopause neutral point in [Re],

Λ_D, Λ_N = geomagnetic latitude of the last closed field line at local noon (D) and local midnight (N).

Experimental Results from Particle Observations

The boundary of last closed field lines has been identified as the poleward trapping boundary of electrons with energies $E > 35$—40 kev. Alouette-2 data (McDiarmid and Burrows, 1968) indicated this boundary to be coincident with the region where the counting rate of electrons falls into the cosmic ray background level. This became evident also by a sharp decrease in the dayside flux of electrons with energies $E \sim 10$ kev (Heikkila and Winningham, 1971). Detailed analyses of the high latitude boundaries have been given by Feldstein and Starkov (1970), Fritz (1970), and Burrows and McDiarmid (1972).

Gurnett and Frank (1973) found the last closed field line to be coincident with the convection electric field reversal and the trapping boundary of 45 kev electrons. This boundary coincides with the equatorward edge of the polar cusp which intersects the ionosphere at $\Lambda_D = 79 \pm 1°$ (Frank, 1971).

Along with measurements of OGO-4 (Evans and Stone, 1972) and ISIS-1 (Winningham, 1972), the geomagnetic latitude of the last closed field lines at local noon Λ_D and local midnight Λ_N can be stated as

$$\begin{aligned}\Lambda_D &= 77.6 \pm 1.6^\circ \\ \Lambda_N &= 70.5 \pm 2.5^\circ\end{aligned}$$

with a noon-midnight asymmetry of about 7° for magnetically quiet conditions. These values are averages of the available published experimental data.

Magnetospheric Field Model

The magnetospheric field model is a "closed" model in the sense that the magnetopause is a tangential discontinuity with given geometry. The magnetopause is an infinite thin current sheet covering the whole magnetospheric field. Thus no B-field component normal to the surface exists, and interconnection of field lines between magnetosheath and magnetosphere cannot be described by the model.

The magnetic field inside the magnetospheric cavity is based on the "classical" Chapman-Ferraro problem which can be solved by a 3-dimensional solution of Neumann's boundary value problem of potential theory with respect to the magnetopause geometry (Voigt, 1972). The magnetospheric field $\underline{H}(\underline{x})$ results from a scalar potential $u(\underline{x})$ which consists of the earth's dipole potential u_d, the potential of the tail field u_s, and the potential u_{bc} due to the magnetic field of the Chapman-Ferraro currents on the magnetopause shielding the fields of the dipole and the tail current system. Thus,

$$u(\underline{x}) = u_d + u_s + u_{bc} \tag{1}$$

where $\underline{H}(\underline{x}) = -\nabla u(\underline{x})$. The total magnetic field normal to the magnetopause H_n must vanish exactly on the boundary since it is a tangential discontinuity. Thus,

$$H_n = -\frac{\partial}{\partial n} u(\underline{x}) = 0 \Big|_{\text{magnetopause}} \tag{2}$$

Together with the singularities of the problem $\underline{H}_d$ and $\underline{H}_s$ given by

$$\begin{aligned}\underline{H}_d &= -\nabla u_d \\ \underline{H}_s &= -\nabla u_s\end{aligned} \tag{3}$$

Neumann's boundary conditions on the magnetopause can be given for the unknown potential u_{bc} by

$$\frac{\partial}{\partial n} u_{bc} = +\underline{\hat{n}} \cdot (\underline{H}_d + \underline{H}_s) \tag{4}$$

where $\underline{\hat{n}}$ denotes the direction normal to the magnetopause, and $\underline{H}_d$ and $\underline{H}_s$ are the magnetic field of the earth's dipole and the field of a closed tail current system. Moreover, the potential u_{bc} must obey Laplace's equation

$$\Delta u_{bc} = 0 \tag{5}$$

inside the magnetospheric cavity. The formalism is valid in the same way if one adds a possible ring current field $\underline{H}_r$ as an additional singularity. Eqs. (4) and (5) show clearly that the boundary currents depend on the singularities inside the magnetosphere and the magnetopause geometry. For mathematical discussion of the problem and analytical expressions of the results, see Voigt (1972).

The last closed field line in the model is defined by the last field line with both ends in the ionosphere on the dayside, and on the nightside by the last field line which hits the neutral sheet with an acute angle of incidence and returns to the earth (see, for example, the 72° nightside field line in Fig. 1b). This last point of impact depends on the neutral sheet field H_0 and is located between 15 Re and 20 Re down the tail where the field component normal to the neutral sheet changes sign. The open field lines in the model are those being swept back into the tail which touch neither the neutral sheet nor the magnetopause. The physical parameters of the model are:

1. the radius of the magnetosphere R,
2. the stand-off distance to the subsolar point A,
3. the distance to the neutral sheet's inner edge B,
4. the magnetic field of the neutral sheet H_0,
5. an arbitrary tilt angle of the earth's dipole Ψ which is the angle between the dipole axis and the direction normal to the solar ecliptic plane.

Magnetic variations, and shifting of the last closed field line boundary and the neutral points discussed in this paper are due to a pre-substorm related compression and tail field increase in an "closed" magnetosphere caused by a successive variation of the model parameters. The magnetopause neutral points are of a Chapman-Ferraro type in the sense that the interplanetary magnetic field (IMF) is assumed to be zero.

The change of the neutral points into a more realistic Dungey type has been taken into account by Forbes and Speiser (1971). The authors superimposed the IMF with arbitrary direction on a closed model. The effect

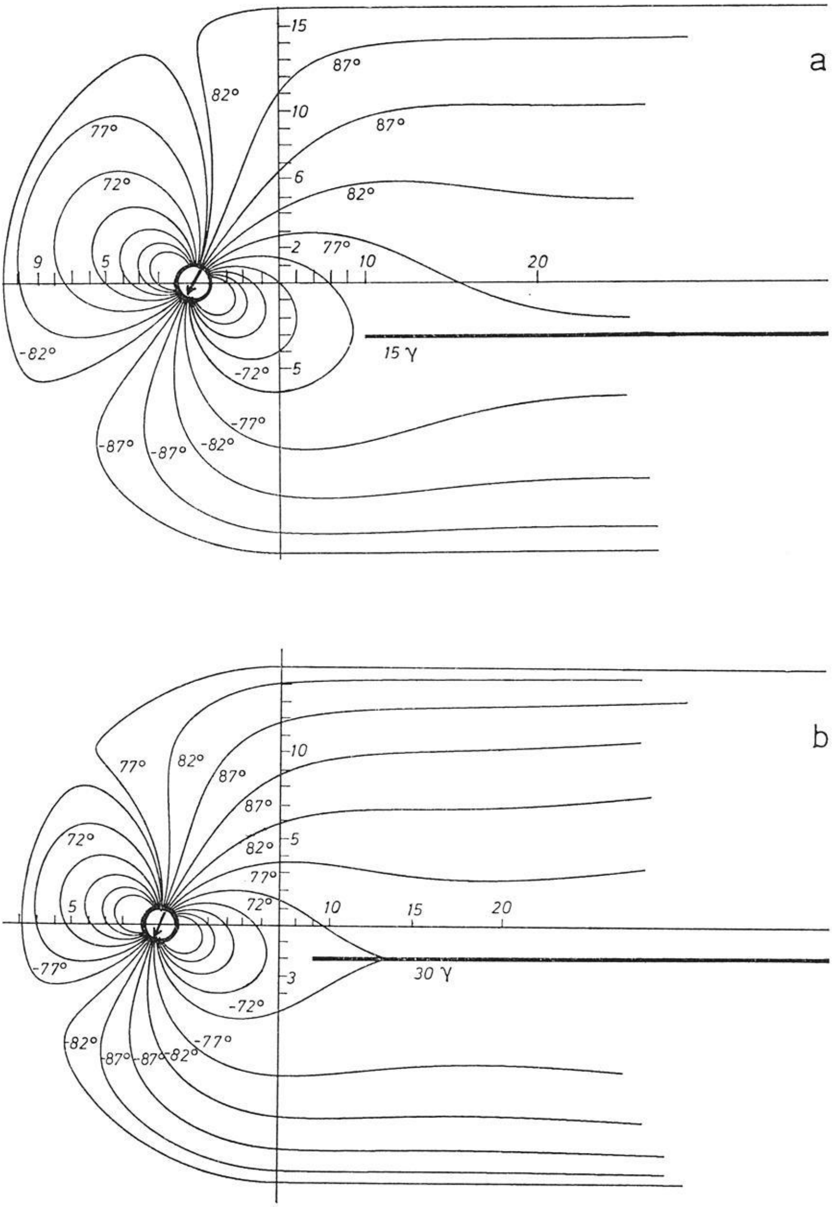

Fig. 1. Computed field line configuration of the 3-dim. analytical magnetospheric field model in the noon-midnight meridian plane, (a) undisturbed magnetosphere: stand-off distance = 11 Re, neutral sheet field = 15 γ, dipole tilt angle = 30°; (b) pre-substorm magnetosphere: stand-off distance = 8 Re, neutral sheet field = 30 γ, dipole tilt angle = 24°

of the IMF on magnetospheric field topology, as discussed by Forbes and Speiser (1971) and Speiser (1971) in the context of an open magnetosphere, would violate the validity of the mathematical boundary value problem and the resulting magnetic field of the model which is based on the formalism noted above. On the other hand it became more and more evident that field line erosion on the dayside magnetosphere plays an important role in the early phase of a substorm. For discussion of the controversy of whether the magnetosphere is open or closed see Vasyliunas and Wolf (1973).

Figs. 1a and 1b show the computed field line configuration of the model for an undisturbed and a pre-substorm magnetosphere based on the model parameters which are listed in Table 1. A comparison of both figures shows the pre-substorm related compression of the dayside magnetosphere in Fig. 1b which is mainly due to a decrease of the stand-off distance from 11 Re to 8 Re. The difference of the tilt angles in both figures is insignificant in this context.

Table 1. Model parameters for field line computations shown in Fig. 1: radius of the magnetosphere (R), stand-off distance (A), neutral sheet field (H_0) and distance to the inner edge (B), and the dipole tilt angle (Ψ)

parameters	R [Re]	A [Re]	B [Re]	H_0 [γ]	Ψ (winter) [°]
undisturbed	16	11	10	15γ	$+30°$
pre-substorm	15	8	9	30γ	$+24°$

Effects of the Dipole Tilt Angle

Seasonal and diurnal variations of the last closed field line boundary and the neutral points on the magnetopause are caused by a change of the dipole tilt angle Ψ. Model calculations have been made for a maximum seasonal variation of $-30°$ (northern summer) $<\Psi[°]<+30°$ (northern winter).

The resulting tilt-dependent shifts of the last closed field line boundary at local noon and local midnight are plotted in Fig. 2 for a magnetically quiet and a pre-substorm magnetosphere. The corresponding displacement of the neutral points on the magnetopause are shown in Fig. 3. Note that the labels "summer" and "winter" indicate the tilt direction for the northern hemisphere, and that the angles are measured relative to a dipole fixed coordinate system.

Table 2a contains the values of Figs. 2 and 3 for the untilted dipole ($\Psi=0°$) and for the maximum summer and winter tilts ($\Psi=\pm 30°$).

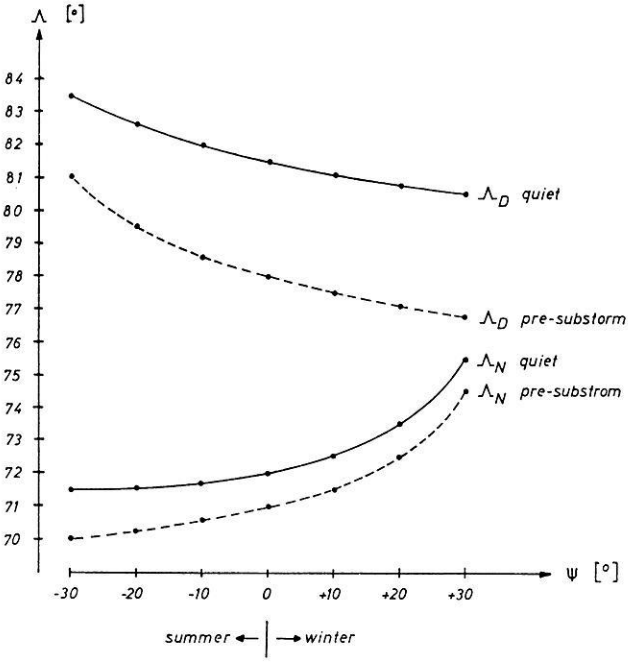

Fig. 2. Geomagnetic latitude Λ of the last closed field line at local noon (D) and local midnight (N) depending on the dipole tilt angle Ψ for an undisturbed (solid line) and a pre-substorm (dashed line) magnetosphere

Table 2a. High latitude quantities in [°] for three different dipole tilt angles Ψ. The magnetic conjugate points of the last closed field lines are situated at different latitudes Λ_D and Λ_N in the northern and southern hemisphere in case of $\Psi \neq 0°$. Values for other tilt angles Ψ can be obtained from Figs. 2 and 3

Ψ	$-30°$	$0°$	$+30°$	magnetosphere-configuration
ϑ_D	22.6	30.2	34.1	undisturbed
Λ_D	83.5	81.5	80.5	
Λ_N	71.5	72.0	75.5	
ϑ_D	28.2	39.2	46.7	pre-substrom
Λ_D	81.0	78.0	76.8	
Λ_N	70.0	71.0	74.5	

Table 2b shows the variation of the high latitude quantities, $\delta\vartheta_D$, $\delta\Lambda_D$, and $\delta\Lambda_N$ due to a change of the tilt angle $\delta\Psi = \pm 30°$ compared with total seasonal variation. A look at Fig. 2 and Table 2b indicates that the night-side shift of the last closed field line boundary exceeds the dayside shift

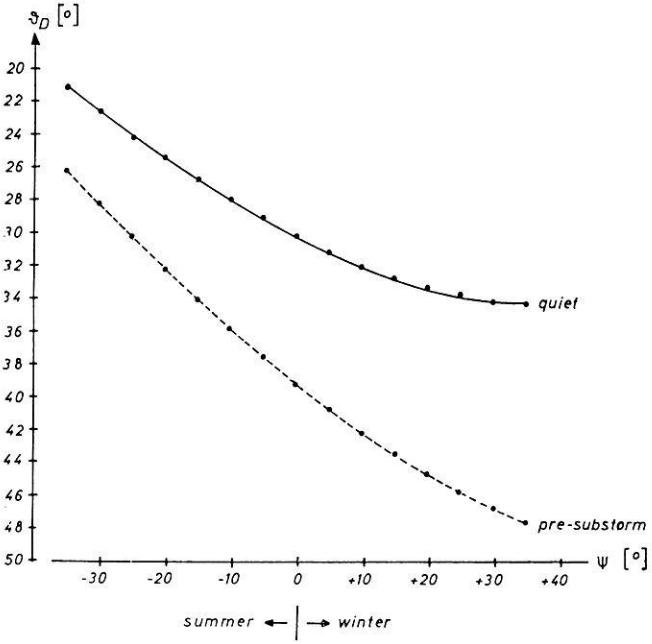

Fig. 3. Polar distance ϑ_D of the northern neutral point depending on the dipole tilt angle Ψ for an undisturbed (solid line) and a pre-substorm (dashed line) magnetosphere. The neutral points on the magnetopause are of the Chapman-Ferraro type. Note that ϑ_D is measured from the dipole axis

Table 2b. Variation of the high latitude quantities in [°] for an undisturbed and a pre-substorm magnetosphere depending on a change of the dipole tilt $\delta\Psi$ [°]. The shift $\delta\Lambda_D$ exceeds $\delta\Lambda_N$ for the dipole tilted in summer direction ($\delta\Psi = -30°$). The reverse results for the tilt in winter direction ($\delta\Psi = +30°$). The differences, δ, are obtained from Table 2a

$\delta\Psi$	$0° \rightarrow -30°$	$0° \rightarrow +30°$	$-30° \rightarrow +30°$	magnetosphere-configuration
$\delta\vartheta_D$	− 7.6	+3.9	+11.5	
$\delta\Lambda_D$	+ 2.0	−1.0	− 3.0	undisturbed
$\delta\Lambda_N$	− 0.5	+3.5	+ 4.0	
$\delta\vartheta_D$	−11.0	+7.5	+18.5	
$\delta\Lambda_D$	+ 3.0	−1.2	− 4.2	pre-substorm
$\delta\Lambda_N$	− 1.0	+3.5	+ 4.5	

for the boundary in the winter hemisphere, whereas the opposite occurs for the boundary in the summer hemisphere. Thus the northern and the southern hemisphere (i.e. the winter and the summer hemisphere) show a different behavior of the tilt-dependent boundary variations.

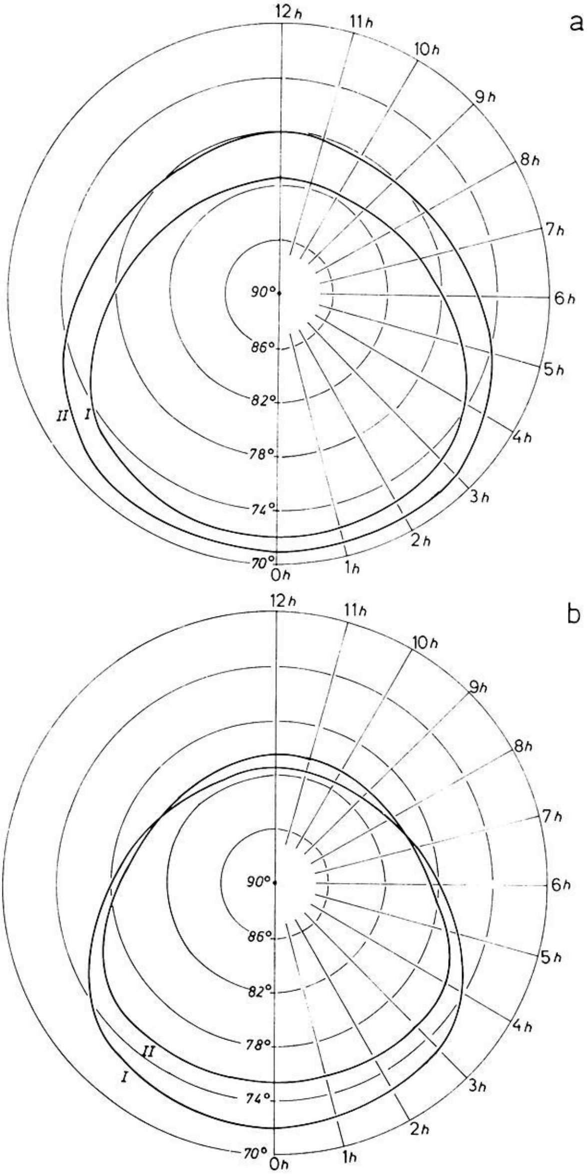

Fig. 4. Shape of the last closed field line boundary for (a) the untilted earth's dipole. Curve I is the boundary for an undisturbed magnetosphere and curve II for a pre-substorm magnetosphere. The dayside shift exceeds the nightside shift due to the predominant effect of the pre-substorm related inward motion of the subsolar point. (b) magnetic quiet conditions. Curve I is the boundary for $\Psi = 0^\circ$, curve II for $\Psi = +30^\circ$ (winter). Note that the coordinate system is fixed on the dipole axis. The nightside shift exceeds the dayside shift for the dipole tilt in winter direction. The reverse results for the tilt in summer direction (compare with Fig. 2)

An example is given in Fig. 4b which shows the northern last closed field line boundary of the undisturbed model magnetosphere due to the untilted earth's dipole (boundary I) and due to the geomagnetic axis tilted by $\Psi = +30°$ in winter direction (boundary II). In this case the nightside shift exceeds the dayside shift.

The model calculations can be summarized as follows:

1. Fig. 2 and Table 2a indicate clearly that the position of geomagnetic conjugate points vary with the tilt angle. They are situated at different geomagnetic latitudes in the northern and southern hemisphere in case of the tilted geomagnetic axis. See for example the undisturbed magnetosphere configuration in Table 2a: The conjugate points of the last closed field lines are situated at Λ_D (north) $= 80.5°$, Λ_D (south) $= 83.5°$ at local noon, and Λ_N (north) $= 75.5°$, Λ_N (south) $= 71.5°$ at local midnight. Fig. 1a gives another example: The 82° dayside field line in the northern hemisphere is swept back into the tail, whereas the corresponding $-82°$ field line in the southern hemisphere is closed on the dayside; it's magnetic conjugate point is located at $\Lambda = 81°$ in the northern hemisphere. The same occurs analogously in case of the pre-substorm magnetosphere in Fig. 1b. The southern $-77°$ dayside field line intersects the earth at $\Lambda = 76.2°$ in the northern hemisphere.

The neutral points belonging to Figs. 1a and 1b can be obtained from Fig. 3. For the magnetically quiet field configuration ($\Psi = +30°$), we find ϑ_D (north) $= 34.0°$, ϑ_D (south) $= 22.6°$. The values for the pre-substorm magnetosphere ($\Psi = +24°$) are ϑ_D (north) $= 45.7°$, ϑ_D (south) $= 30.2°$. The position of the neutral points depends strongly on the dipole tilt angle.

2. For a change of the dipole tilt from northern summer to northern winter, the dayside part of the northern last closed field line boundary and the northern neutral point move equatorward, whereas the nightside part of the boundary tends to move poleward (see Figs. 2 and 3). The opposite occurs in the southern hemisphere. Table 2b shows in detail that the absolute value of the shift $\delta\Lambda_D$ in the northern hemisphere exceeds the nightside shift $\delta\Lambda_N$ in both magnetospheric field configurations, if the northern hemisphere will be tilted in summer direction ($\delta\Psi = -30°$). The reverse results for the tilt into winter direction ($\delta\Psi = +30°$).

One can conclude that magnetic variations related to the dayside magnetosphere will affect the dayside part of the polar oval and the cusp in the summer hemisphere more than in the winter hemisphere. In contrast, the nightside part of the polar oval will be influenced more in the winter hemisphere by magnetospheric tail and plasma-sheet variations. Thus one can expect asymmetries between both hemispheres for magnetospheric phenomena observed at geomagnetic conjugate points.

3. A maximum seasonal Λ_D variation of 2°—3°, as reported by McDiarmid and Wilson (1968), could be realized in model calculations for the undisturbed magnetosphere and a seasonal change of the tilt angle $\Psi = \pm 25°$ (see Fig. 2). On the other hand, this result is in contrast to Aurora-1 data reported by Maehlum (1968). The author found average values $\Lambda_D = 79.7 \pm 2.7°$ (summer) and $\Lambda_D = 75.5 \pm 1.1°$ (winter). This has been verified by Burch (1972) for magnetically quiet conditions.

The resulting maximum seasonal variation of $\delta\Lambda_D \approx 4°$, as well as the difference of 7° between Λ_D and Λ_N for $\Psi = 0°$ (McDiarmid and Wilson, 1968), could only be simulated in a pre-substorm model configuration (compare with Tables 2a and 2b). For discussion of this discrepancy, see Conclusion.

Effects of Substorm Growth Phase Phenomena

The equatorward displacement of the polar cusp and the last closed field line boundary can be simulated in terms of a "standard substorm" growth phase. The polar cusp in the model is determined by the coordinates of the magnetopause neutral point ϑ_D and r_N, and the associated geomagnetic latitude Λ_D of the last closed field line on the dayside of the polar oval.

An inward motion of the dayside magnetopause in the early phase of a substorm (Aubry *et al.*, 1970) is responsible for an equatorward motion of ϑ_D and Λ_D. The equatorward extension of the nightside part of the last closed field line boundary is due to an earthward motion of the neutral sheet and an increase of it's magnetic field H_0. These growth phase characteristics, as summarized by Aubry (1972), have been computed by changing the corresponding parameters in the field model.

It should be repeated that the inward motion of the dayside magnetopause is not due to field line erosion associated with a reversal of the IMF direction (Aubry *et al.*, 1970), but it is realized in the model by a decrease of the stand-off distance which results in a compression of the dayside magnetospheric cavity.

The differences of ϑ_D, Λ_D, and Λ_N between a quiet and pre-substorm magnetosphere are caused by a change of the model parameters listed in Table 1 for $\Psi = 0°$. We want to restrict ourselves to the untilted earth's dipole in order to display the pre-substorm related variations of the high latitude quantities.

Fig. 4a shows the shape and position of the last closed field line boundary for the undisturbed (boundary I) and the pre-substorm magnetosphere (boundary II). Model calculations have verified that the equatorward extension of the dayside part of the boundary depends on the location of the subsolar point, whereas the nightside shift is controlled by the neutral sheets's position and magnetic field.

Table 3. Variations of the high latitude quantities in [°] due to substorm growth phase effects for the untilted dipole $\Psi=0°$. The differences, δ, between the undisturbed and pre-substorm magnetosphere result from a change of the model parameters listed in Table 1 for $\Psi=0°$. For tilt angles $\Psi\neq 0°$ see Figs. 2 and 3

[°]	magnetosphere-configuration undisturbed	pre-substorm	δ[°]
ϑ_D	30.2	39.2	9.0
Λ_D	81.5	78.0	3.5
Λ_N	72.0	71.0	1.0

The high latitude quantities belonging to Fig. 4a are listed in Table 3. The dayside latitude Λ_D moves equatorwards from 81.5° to 78.0°, the nightside latitude Λ_N from 72.0° to 71.0°. Hence it follows that the dayside extension of the boundary $\delta\Lambda_D=3.5°$ exceeds the nightside shift $\delta\Lambda_N=1.0°$ (Fig. 4a). One can conclude that this result is due to the predominant effect of the pre-substorm related inward motion of the subsolar point.

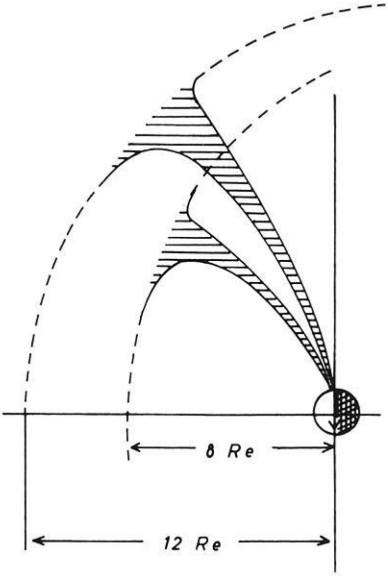

Fig. 5. Polar cusp topology for extreme cases of a quiet and compressed magnetosphere. For field line integration, the polar cusp was assumed to have a width of 1° in the ionosphere. The compression is due to a decrease of the standoff distance from 12 Re to 8 Re, an increase of the neutral sheet field from 10 γ to 30 γ, and an inward motion of the neutral sheet's inner edge from 11 Re to 9 Re. The polar cusp field line intersects the earth at $\Lambda=83\pm0.5°$ (quiet) and $\Lambda=78\pm0.5°$ (compressed). The neutral point moves equatorwards from $\vartheta_D=23.6°$ (quiet) to $\vartheta_D=39.2°$ (compressed). Compare these results with Fig. 6. The dashed lines show the geometry of the model magnetopause.

Generally, the stand-off distance was found to be the most sensitive parameter for dayside variations; it affects greatly the positions of the neutral points which tend equatorward by 9.0° from $\vartheta_D = 30.2°$ to $\vartheta_D = 39.2°$ during the early phase of a substorm (Table 3). Thus, magnetic disturbances related to the dayside magnetosphere will result in polar cusp displacements which occur more near the magnetopause than near the ionospheric edge.

This is demonstrated in Fig. 5 which shows the influence of a pre-substorm disturbance on the topology of the polar cusp and the position of the neutral point for extreme cases of a quiet and compressed magnetosphere. For field line integration, the polar cusp was assumed to have a

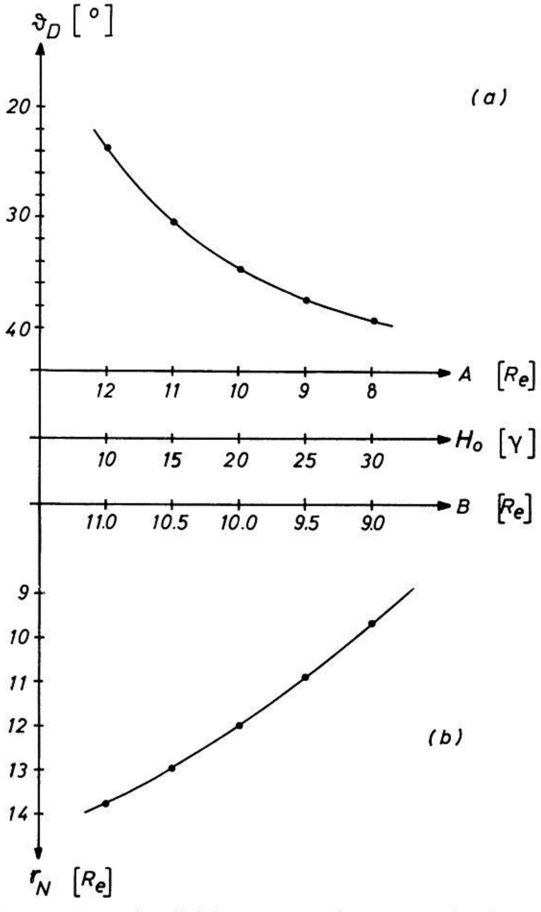

Fig. 6. Polar distance ϑ_D and radial distance r_N of the neutral point on the magnetopause in terms of a magnetospheric compression (untilted dipole $\Psi = 0°$). The compression is due to the variation of the model parameters as indicated on the abscissa. The compression related polar cusp topology is shown in Fig. 5

width of 1° in the ionosphere. The neutral point moves equatorwards from $\vartheta_D = 23.6°$ to $\vartheta_D = 39.2°$, whereas the polar cusp intersection point in the ionosphere moves from $\Lambda_D = 83°$ to $\Lambda_D = 78°$. Note that the experimental value of $\Lambda_D = 79 \pm 1°$ (Frank, 1971) corresponds with a pre-substorm model configuration (for discussion see Conclusion). The compression related changes of the model parameters are indicated on the abscissa of Fig. 6 which shows the continuous variation of the polar distance ϑ_D and the radial distance r_N of the neutral point in terms of a substorm growth phase.

Conclusion

1. Variations of the last closed field line boundary and the position of the magnetopause neutral points have been calculated in a "closed" magnetospheric field model with respect to a pre-substorm related compression of the magnetosphere and the dipole tilt angle. The variations result from a successive change of the model parameters. The model is limited by its static field configuration and is based on the Chapman-Ferraro problem. The interconnection with the interplanetary field and the magnetosheath has not been considered.

2. The boundaries of the polar oval and the cusp tend equatorward for model parameters describing a substorm growth phase. The dayside part of the last closed field line boundary depends on the position of the subsolar point, whereas the nightside part is determined by the neutral sheet's position and magnetic field. Generally, the stand-off distance was found to be the most sensitive parameter for magnetospheric variations. It affects mostly the position of the magnetopause neutral points.

3. Seasonal variations of the last closed field line boundary are due to the dipole tilt angle. Geomagnetic conjugate points are situated at different latitudes in both hemispheres in case of the tilted dipole. The dependence of the boundary on the tilt angle is different in winter and in summer. Thus, one can expect asymmetries of phenomena being related with magnetically conjugate points.

4. An agreement between experimental data of magnetic quiet conditions and model calculations could be found for pre-substorm magnetospheric model parameters. It remains a problem at present if this discrepancy can be reduced by

(a) leaving the concept of the "closed" model by superimposing the interplanetary magnetic field with arbitrary direction which results in an "open" magnetosphere, as proposed by Forbes and Speiser (1971);

(b) inserting an appropriate ring current model (Sckopke, 1972) which tends to shift the last closed field line boundary equatorward and the magnetopause neutral points poleward;

(c) calculating the high latitude boundaries by field line tracing along realistic magnetospheric field lines from the point of particle observation down to the ionosphere, instead of using the "invariant latitude" which is based on a dipolar field configuration.

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