SG

Gill

National Aeronautics and Space Administration
Goddard Space Flight Center
Contract No.NAS-5-12487

ST —PF —GM —10792

DIMENSIONS OF THE MAGNETOSPHERE TAIL'S CROSS SECTION AT VARIOUS INTENSITIES OF POLAR DISTURBANCES

by

A. D. Shevnin &
Ya. I. Fel'dshteyn

(USSR)

2 JANUARY 1969

ST -PF -GM -10792

DIMENSIONS OF THE MAGNETOSPHERE TAIL'S CROSS SECTION AT VARIOUS INTENSITIES OF POLAR DISTURBANCES

Kosmicheskiye Issledovaniya
Tom 6, vyp.6, 870-876
Izdatel'stvo "NAUKA", 1968

by A. D. Shevnin &
Ya. I. Fel'dshteyn

SUMMARY

The elliptically shaped magnetosphere tail's equatorial semiaxis is computed at the distances from 10 to 80 Earth's radii on the basis of magnetic field measurements on AES "IMP-1" and "EXPLORER-33". It is shown that, as polar disturbances increase, the process of tail contraction by solar wind prevails over the expansion due to the increase of magnetic flux in the tail, as the southern boundary of the oval shifts toward the equator.

*
* *

In the course of the last years the position of the magnetosphere boundary on the night side of the Earth was determined directly from magnetic measurements on the AES [1 - 3]. However, the number of boundary crossings by satellites is usually rather small and, besides, such crossings take place at quite different levels of geomagnetic activity.

The utilization of ground observations, alongside with measurements of magnetic field intensity carried out by satellites in the magnetosphere tail, allows us to compute the area of tail's cross-section at various intensities of polar magnetic disturbances DP and to determine, by the same token, the position of the magnetopause on the night side of the Earth for fixed values of DP.

Indeed, when determining the Q-index of magnetic activity at the high latitude observatories on the night side of the Earth, and the D_{st}- variations by the magnetograms of the low-latitude observatories, it is possible [4, 5] to establish the mean statistical position of the southern boundary of the aurora oval. Assuming that the geomagnetic tail is formed by field lines carried by the solar wind in the antisolar direction out of polar caps and bounded by the aurora oval, one may compute the magnetic flux in the magnetosphere tail. Assuming for tail's cross-section a circle [6], or, according to latest data, the shape of an ellipse with constant DT field magnitude over the entire area cross-section, and knowing this field from magnetic measurements on AES, it is not difficult to compute the equatorial semiaxis R_{equ} of the tail at various distances from the Earth for known Q-indices of magnetic activity.

The most complete measurements of the magnetic field in the magnetosphere tail were carried out on AES "IMP-1" and "Explorer-33", respectively in 1964 and 1966 [7, 3]. On IMP-1 the DT field was measured to 31.7 R_E and on the Explorer-33 up to 80 R_E.

IMP-1 observed the variations of the magnetic field over five orbits (33, 40, 43, 44 and 47) in a period of magnetic storms corresponding to 31 March 2 April, 27 - 29 April, 9 - 11, 13 - 15 and 23 - 25 May 1964. The scalar magnitude of field intensity and two angles characterizing the direction are represented in Figs 15, 20, 23, 25, 27 of the work [7]. Determined by them were the mean hourly values of field DT intensity only for intervals in which the field of the tail was close to solar or antisolar directions. About two-thirds of the material brought out in [7] have satisfied this condition.

The geocentric distances to the satellite were determined for each thus chosen hour and their projections R on the line Sun-Earth were computed.

The mean hourly Q-index of magnetic activity was taken down from high-latitude observatories on the night side of the Earth. The magnetograms of observatories at latitude ~65° were utilized for various UT intervals in the following sequence: Reykjavik (0 - 0600 h.UT), Minuk (0600-1000 h UT), College (1000 - - 1400 h.UT), Tiksi (1400 - 1900 h.UT) and Kiruna (1900- 2400 h.UT).

The values of D_{st}-variations are computed in [8] by magnetograms of the horizontal component of the field of six observatories, uniformly distributed in longitude along the 30° geomagnetic parallel and coincide within the limits of a few gammas with those brought out in [9].

Since during these disturbances it was impossible to determine the position of the southern boundary of the oval from direct observations of aurorae, its boundary was found by means of average statistical dependences of the oval's southern boundary position on the Q-index and on the ring current field [4, 5] on the night, as well as on the daytime side of the Earth.

Assuming then the southern boundary of aurora oval to be a circle, whose center was shifted by 3 - 4° relative to the geomagnetic pole toward the night side of the Earth, we computed the magnetic flux from the polar cap for every hour.

According to [3, 10], the correlation between the field intensity in the tail and the distance from the neutral sheet is practically absent, i.e., no notable field gradient are observed in the tail. This is why one may assume that in the transverse cross-section the field intensity is constant. It is altered by the neutral sheet only near and within the sheet, whose thickness is less than 1 R_E.

We shall assume the transverse cross-section of the magnetosphere tail in the shape of an ellipse with 3:2 polar to equatorial semiaxis ratio [3]. Then the magnetic flux F_2 from two polar caps may be equated to the product of the ellipse's are $\frac{3}{2}\pi R_{eq}{}^2$ by field's DT magnitude in the magnetosphere tail at the given geocentric distance R. The equatorial semiaxis of the tail's elliptical cross-section R_{eq} will in this case be

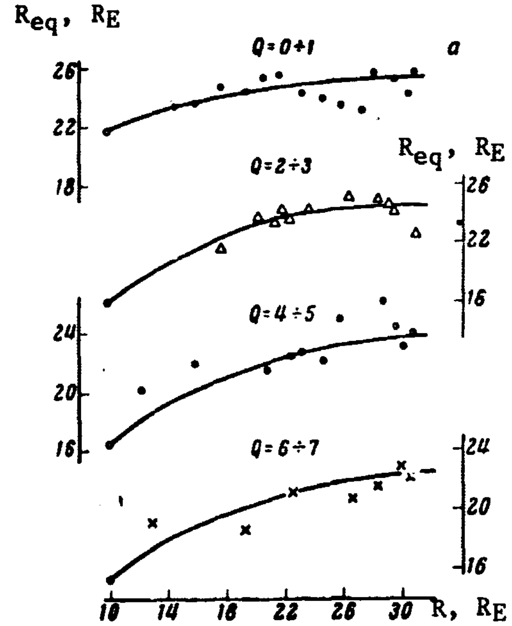
$$R_{eq} \sqrt{\frac{2F_2}{3\pi DT}} . \qquad (1)$$

R_{eq} was computed for various distances from the Earth (within the limits 10 - 31 R_E) for known Q-indices of magnetic activity using formula (1). Then, the results of calculations were grouped for 4 pairs of Q-indices (0—1, 2—3, 4—5, 6—7) and averaged for close values of R.

Shown in Fig.1,a is the variation of the equatorial semiaxis R_{eq} of magnetos!here tail's transverse cross-section with the increase of the geocentric distance R separately for each pair of Q-indices. It may be seen that the tail's dimensions, determined in [11] and corrected for cross-section ellipticity, are characteristic for geocentric distances < 12 R_E.

Starting from the fact that with a quiet magnetic field the southern boundary on the night side is on the latitude Φ = 70 – 71°, i.e. it drifts away along the field line by about 10 R_E, the dependence obtained in [11] of the magnetosphere tail's circular radius on DP intensity, should be related to the cross-section at the distance of 10 R_E. This cross-section is located at the very least no closer than 8 R_E, for the model, assumed in [9], and utilized in [11], presupposes that the neutral sheet has its origin on 8 R_E.

The values of R_{eq}, obtained in [11] are plotted in Fig.1,a by circles at the distance of 10 R_E. On the basis of these values smoothed out curves are drawn, reflecting the variation of the equatorial semiaxis of magnetosphere's transverse cross-section on the night side of the Earth for the corresponding intensity of polar DP disturbances.



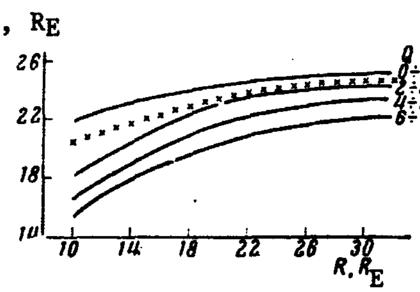


Fig.1. Dependence of the equatorial semiaxis R_{eq} of magnetosphere tail's cross-section on the geocentric distance R.

a) statistical values of R_{eq} for four pairs of Q-indices of magnetic activity
b) smoothed out curves for R_{eq} and magnetosphere boundary according to observations of "Explorer-33" (crosses)

The curves of Fig.1,a are brought out in Fig.1,b. Plotted by crosses here are the transverse dimensions of the tail obtained from observations of magnetopause position on the basis of measurements of the magnetic field on Explorer-33 [3]. The values of R_{eq}, computed by us to R = 31.7 R_E according to measurements on IMP-1 and the magnitude of the magnetic field in the magnetosphere tail, agree well with the measurements of magnetopause position on Explorer-33 for relatively quiet magnetic conditions. As may be seen from Fig.1,b, R_{eq} rises with the increase of R. As the latter increases from 10 to 31.7 R_E, the values of R_{eq}

increase by 3.4, 6.6, 7.2 and 7.1 R_E respectively for the pairs of Q-indices 0 – 1, 2 – 3, 4 – 5, 6 – 7, from the values of 21.8, 18.0, 16.6 and 15.4 R_E. For a fixed distance R, the tail's dimension decreases with the rise of the Q-index. The variation is greater at smaller geocentric distances and constitutes 6.4, 4.1 and 3.0 R_E. It was noted in [3] that, as solar wind intensity varies, the magnetopause shifts by ~ 10 R_E.

In essence, the first result is in agreement with experimental data of [3,10], which points the fact that, as R increases, the field in the tail decreases. Indeed, for a given Q-index, the magnetic flux on the Earth's surface is bounded by a certain polar region. If one considers that the vertical DT_z- component of the field in the tail is small [3, 10, 12], the area of the tail's transverse cross-section must increase at field magnitude decrease as the distance varies. Since the gradient of the DT field is by 10 to 25 R_E greater, then the equatorial cross-section semiaxis must also be the object of stronger variations over the same distances.

Let us consider now the second conclusion, following from calculations plotted in Fig.1,b. As the Q-index increases, the southern boundary of aurora oval shifts toward the equator, increasing by the same token the magnetic flux in the magnetosphere tail, which at preservation of solar wind's dynamic pressure would result in the increase of tail's cross-section. But, as the geomagnetic activity increases, so does the solar wind velocity [13, 14], i.e. the dynamic pressure on the magnetosphere increases and, consequently, solar wind begins to exert a stronger compression effect upon the tail. The latter results in field increase in the magnetosphere tail over the given geocentric distance [7, 9, 10]. The curves of Fig.1,b point to the fact that, as DP increase, the tail's compression effect by solar wind prevails over the expansion as a consequence of magnetic flux increase in the tail.

It should be noted that in Figs 1,a,b, R_{eq} values were obtained without taking into account the finiteness of the vertical DT_z-component of field intensity, which exists during the closing of magnetic field lines or their reconnection in the magnetosphere tail [12, 3, 10]. In this case, the magnetic flux in the tail decreases with the distance and, by way of consequence, so does also the dimension of tail's cross-section.

The estimate of the influence of line reconnection in tail by the value of R_{eq} will be conducted by us on the basis of experimental data obtained on Explorer-33 [3]. It is found that the equatorial semiaxis of tail's cross section constitutes ~ 20.5 R_E at the distance of 10 R_E. For R > 25 R_E, the value of R_{eq} varies little, reaching the magnitude ~ 25 R_E on R = 30 R_E and a constant value of 25.5 R_E at distances beyond 40 R_E.

Given in [3] is also the magnitude of the field in the magnetosphere tail at distances from 10 to 80 R_E for a planetary index $K_p \leq 2$, whereupon the experimental points satisfy better the values of the field comprised between the boundary curves described by relations $\sim|R|^{-0.1}$ and $\sim|R|^{-0.5}$.

Therefore, the field of the magnetosphere tail for quiet geomagnetic conditions and the cross section of the tail at 10 R_E are known from [3]. This allows us to compute the magnetic flux directly from satellite measurements on 10 R_E.

For the border (boundary) curves $\sim|R|^{-0.1}$ and $\sim|R|^{-0.5}$ the magnetic flux at the distance of 10 R_E is respectively obtained equal to $1.77 \cdot 10^{17}$ and $1.99 \cdot 10^{17}$ $gauss \cdot cm^2$. For one and the same equatorial cross section semiaxis R_{eq} = 20.5 R_E this distinction is due to various values of tail's field of two boundary curves respectively equal to 22.2 and 25.0 γ. The indicated values of magnetic flux in the magnetosphere tail are obtained from ground observations for Q, respectively equal to ~ 1.5 and ~ 3.0 and D_{st}-variation in —15 γ.

Leaving at the outset the above value of the magnetic flux invariable, we have computed the values of R_{eq} at field variation in the tail according to the relations $\sim|R|^{-0.1}$ and $\sim|R|^{-0.5}$. The results of such calculations are shown in Fig.2.

It may be seen from Fig.2 that, as R increases from 10 to 25 R_E, the experimental points coincide with those computed for a field proportional to $|R|^{-0.1}$. Then, from 25 to 80 R_E the computed radii of the cross section are more and more different from the corresponding experimental values. This discrepancy may be due to a decrease of the magnetic flux in the tail at the expense of the presence of field's DT_z vertical component, as well as to the fact that the tail's cross section can hardly remain constant at distances > 40 R_E, fact referred to in [3].

If we admit R_{eq} in accordance with [3], which is shown in Fig.2 by crosses and determine DT_z by flux variation (for any boundary curve), we find that the vertical component is equal to $6-4\gamma$ at the beginning of the tail, decreasing feebly with distance. In [3], its mean value on $10\ R_E \leq R \leq 80\ R_E$ is estimated at $\sim 2\ \gamma$, while it follows from direct observations $DT_z \sim 1\ \gamma$. This means that expansion takes place concomitantly with reconnection of field lines.

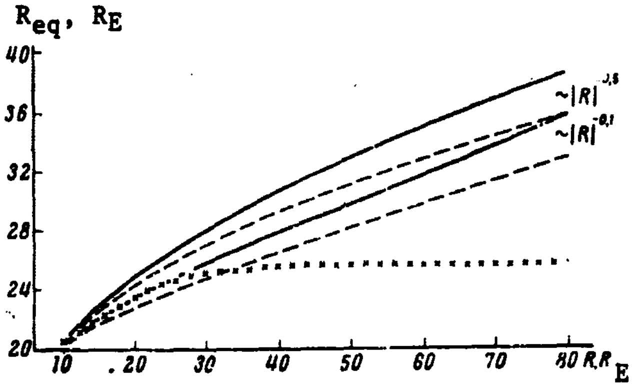


Fig.2. Dependence of R_{eq} on R for two boundary curves of the DT field in the tail without reconnection (solid lines) and taking into account the reconnection of magnetic lines of force (dashes), and also according to observations on Explorer-33 (crosses)

At close distances from Earth DT_z constitutes in the tail $\sim 4\gamma$ on the morning side and less than $1\ \gamma$ in the plane of the midday-midnight meridian [12]. For that reason we shall assume $DT_z = 3\ \gamma$ for the entire cross section on $10\ R_E$ and postulate the variation of the vertical component as being inversely proportional to the distance, i. e. $DT_z = \frac{30}{R}\ \gamma$. The decrease of the vertical component with the increase of R was indeed revealed in [10]. In case $DT_z = \frac{30}{R}\ \gamma$, the mean value of the vertical component from 10 to 80 R_E is obtained equal to $0.9\ \gamma$, and at the distance from 50 to 80 R_E it varies from 0.60 to $0.38\ \gamma$, which does not contradict the experimental data [3, 10].

The magnetic flux decrease ΔF_1 at the expense of the field's vertical component for the admitted assumptions relative to DT_z is computed by the formula

$$\Delta F_1 = 60\ R_{eq}\ \frac{\Delta R}{R}\ , \qquad (2)$$

and the new value of the equatorial semiaxis R'_{eq} of tail's elliptical cross section with the same semiaxis ratio 3:2, is determined from the relation

$$R'_{eq} = 2\sqrt{\frac{F_1 - \Delta F_1}{3\pi DT}}, \qquad (3)$$

where F_1 is the magnetic flux in the tail from one polar region.

The calculations were conducted for the $\Delta R = 2\ R_E$. First the variation of ΔF_1 was determined by formula (2) from 10 to 12 R_E and substituted into (3). The obtained value of R_{eq} was substituted into (2) for the determination of ΔF_1 at the distance of 12 − 14 R_E, which then was utilized in (3) for a new R_{eq} etc. The thus obtained values of R'_{eq} are plotted in Fig.2 by dashed lines for the very same extreme values of tail's field $\sim|R|^{-01}$ and $\sim|R|^{-05}$.

Although the dashed curves, taking into account the reconnection in the tail, get closer to magnetosphere boundary according to [3], they still are essentially different. The difference between the computed semiaxes of tail's cross section in the equatorial plane of the magnetosphere at 80 R_E and those brought out in [3], attains 9 R_E. Our calculations apparently point to the fact that in [3] the dimension of the magnetosphere tail is underrated over distances from 30 to 80 R_E. Since neither of the experiments has shown the existence of the vertical component $DT_z \sim 6\gamma$ in the tail's field on 30 $R_E \leq R \leq 80\ R_E$ and the constancy of DT with the increase of R, one at least may not assume that the tail's cross section remains constant from the distance of 40 R_E.

The accounting of field line reconnection in the tail results in a decrease of R_{eq} respectively by 8 and 3% at distance of 80 and 40 R_E. This is why in the results brought out in Fig.2, where R < 31.7 R_E, the reconnection of the lines of force in the magnetosphere tail was little manifest (< 3%).

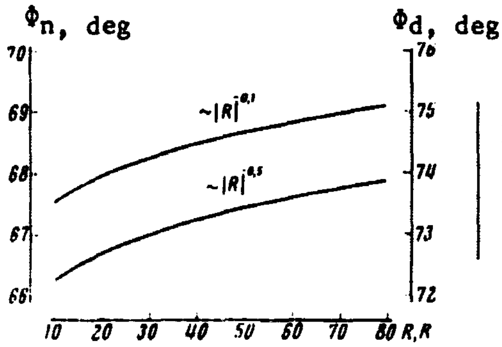


Fig.3. Geomagnetic latitude of the polar cap's boundary on the night (Φ_n) and daytime (Φ_d) sides of the Earth with open field lines

In conclusion we shall consider the position of the polar cap boundary with open geomagnetic lines of force over a given distance R. As in [11], we shall then assume that the magnetic flux, carried by the solar wind into the tail of the magnetosphere, is determined by the formula

$$F_2 = \frac{4\pi M}{R_E} \cos\theta_M \sin^2\theta, \tag{4}$$

where M is the Earth's mmagnetic moment, θ_M is the distance from the geomagnetic pole to the center of the cap in the form of a circle, θ is the cap's polar radius.

The same magnetic flux across the transverse area of the ellipse with semi-axis ratio 3:2 is

$$F_2 = \frac{3}{2}\pi R'^2_{eq} DT. \tag{5}$$

From (4) and (5) we determine the polar radius θ of the cap by the formula

$$\sin^2\theta = \frac{3R_E}{8M\cos\theta_M} R'^2_{eq} DT. \tag{6}$$

Then the geomagnetic latitude of the boundary of the polar cap, respecti on the night and daytime sides of the Earth is

$$\Phi_n = 90° - (\theta + \theta_M),$$
$$\Phi_d = 90° - (\theta - \theta_M). \tag{7}$$

Assuming $\theta_M = 3°$ and substituting into (6) the values of R'_{eq} for the bounda-curves $DT \sim |R|^{-0.1}$ and $DT \sim |R|^{-0.5}$, we obtain from (7) the latitude Φ_n and Φ_d of the region's boundary in the polar cap with open geomagnetic field lines at the preassigned distance. The computed values of Φ_n and Φ_d are plotted in Fig.3. Both curves practically yield an identical latitude increase, i. e., the polar radius θ of the cap decreases by 1.6° with the distance increase from 10 to 80 R_E.

Analogous calculations for the extrapolated curve of the field $DT = 75 \cdot |R|^{-0.5}$ show that between 80 and 200 R_E, θ decreases further by 1.0°.

*** T H E   E N D ***

Manuscript received on 24 May 1968