X-621-71-11
PREPRINT

TIME DEPENDENT PLASMAPAUSE MOTION

J. M. GREBOWSKY

JANUARY 1971

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-621-71-11
Preprint

TIME DEPENDENT PLASMAPAUSE MOTION

J. M. Grebowsky

Laboratory for Planetary Atmospheres

January 1971

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland

TIME DEPENDENT PLASMAPAUSE MOTION

J. M. Grebowsky

ABSTRACT

Assuming that the earth's magnetic field is dipolar and that the dayside magnetic field lines are electrically shorted to one another due to the high ionospheric conductivity, an analytic electric field model is developed which describes the flow of thermal plasma from the magnetosphere tail. Using this field model, the steady state plasmapause has a bulge centered at 2100 L.T. During periods of sudden magnetic quieting, the bulge tends to corotate with the earth. After a sudden onset of magnetic substorm activity, the model predicts that plasma will be peeled from within the original plasmasphere and will be transported out of the magnetosphere in the dusk-midnight sector. In agreement with previous studies, these temporal variations will cause considerable fine structure in the region of the bulge. However, this model is not valid during periods of intense magnetic activity since whistler measurements detect the bulge on dayside field lines under such conditions.

CONTENTS

PRECEDING PAGE BLANK NOT FILMED

TIME DEPENDENT PLASMAPAUSE MOTION

INTRODUCTION

It is well established that under steady state conditions the plasmapause is the boundary between plasma which convects always across closed field lines and plasma which in its motion is transported onto field lines which extend into the magnetospheric tail (Nishida, 1966; Brice, 1967; Axford, 1969). Detailed models describing the steady state configuration of this boundary have been developed beginning with the study of Nishida (1966) followed by the studies of Brice (1967), Kavanagh et al. (1968) and more recently by Wolf (1970). In all of these models, the pattern of the thermal plasma flow across the field lines in the equatorial plane is determined by superimposing an electric field which depicts the flow resulting from the solar wind-magnetosphere interaction onto an electric field which describes the corotation of the plasma with the earth — the relationship between the field and flow velocity is $\vec{E} = \vec{v} \times \vec{B}$. The models presented by Wolf (1970) differ from those in the earlier studies in that the effects of the ionospheric electrical conductivity have been explicitly included — the high ionospheric conductivity on the dayside on the earth tends to short out the magnetospheric electric fields.

From the results of whistler measurements (Carpenter, 1970) however, it is apparent that the plasmapause configuration is in a dynamic state indicating that the plasma flow induced by the interaction between the solar wind and the magnetosphere is "gusty" rather than steady. Hence the steady state model calculations yield plasmapause configurations which are valid approximations to the actual plasma state only during prolonged periods of steady magnetic activity.

Time dependent plasmapause model computations made by Chen and Wolf (1970) and Grebowsky (1970) indicate that the configuration of the plasmapause can become quite complex and much different from the steady state configuration when temporal variations in the thermal plasma flow across the magnetic field lines are considered. These model studies are inadequate, however, in that the electric field describing the solar wind induced flow from the magnetosphere tail was assumed to be spatially constant and directed from dawn to dusk in the equatorial plane (the corresponding velocity profile in the equatorial plane is shown in Figure 1). Under steady state conditions this flow results in a plasmapause configuration which has its maximum L position at 1800 LT and is symmetrical about the dawn-dusk line (see Figure 2) whereas whistler measurements (Carpenter, 1962, 1966, 1970) indicate that the maximum L position during periods of steady magnetic activity is more typically located in the dusk-midnight sector.

In order to determine the general behavior of the plasmapause motion during changes in the magnetic substorm activity an electric field model must be employed which takes into account the high ionospheric conductivity on the dayside of the earth — the corresponding convection electric field will vary spatially (e.g., Wolf, 1970). This paper will explore a simple time dependent model which considers the field lines on the dayside of the earth to be electrically shorted to one another. The computed changes in the plasmapause configuration during periods of increasing magnetic activity and during periods of magnetic quieting are to be compared with experimental observations of the plasmapause motion.

THE MODEL

In the magnetic equatorial plane the interaction between the solar wind and the magnetosphere results in a flow of thermal plasma within the inner magnetosphere that is directed from the magnetosphere toward the dayside magnetosphere. Since the ionospheric electrical conductivity is high on the dayside of the earth this flow may not penetrate very far into the dayside if field line reconnection at the magnetosphere boundary on the sunward side of the earth is not significant (Wolf, 1970). Although detailed model studies of the time dependent plasmapause motion should and will be eventually carried out by taking into account the exact relationship between the ionospheric electrical conductivity distribution and the electric field in the magnetosphere for a nondipolar magnetic field configuration, the qualitative features of the plasmapause motion can more easily be obtained by using simple analytical models to describe the plasma flow, treating the earth's magnetic field as dipolar, and ignoring the details of the plasma interaction at the magnetosphere boundary.

In the model to be developed it is assumed that the dayside magnetic field lines are shorted electrically to one another due to the high ionospheric electrical conductivity. Since reconnection of field lines on the dayside of the earth at the magnetopause implies the existence of a non vanishing electric field, this model will be a good approximation to the actual state only if dayside reconnection can be ignored. The model can be taken as characteristic of a convection pattern which is completed via viscous interactions at the magnetosphere boundary (see Axford, 1969).

The assumption of vanishing electric field on the dayside of the earth requires that the thermal plasma flow from the magnetosphere tail does not penetrate onto the dayside field lines. Thus the plasma will be directed outward along the dawn-dusk line in the equatorial plane. A conservative electric field which yields such a flow on the rightside is given by

$$\vec{E} = -K\,(y\hat{x} + x\hat{y})$$

where y is the distance along the dawn to dusk direction ($\hat{y}$) from the center of the earth and x is the distance from the earth along the noon to midnight direction ($\hat{x}$). This model field is particularly suited for simple time dependent studies since the tail wind field is a one parameter model. The flow from the tail is changed by modifying the magnitude of the model parameter K.

The convection velocity corresponding to this tail wind in a magnetic dipole field with magnitude B locally is

$$\vec{V} = -\frac{K}{B}\,(x\hat{x} - y\hat{y}).$$

The corresponding equatorial streamlines are hyperbolae

$$\text{i.e. } xy = \text{constant}$$

as depicted in Figure 3. If the velocity corresponding to pure corotation of the plasma with the earth is linearly superimposed on this velocity field depicting the tail wind, a plasmapause is obtained which has a maximum geocentric distance at 2100 LT (see Figure 4). The dayside plasmapause in the equatorial plane is circular since the tail wind does not penetrate onto the dayside field lines — the circular streamlines on the dayside correspond to corotation of the plasma with the earth.

The position of the steady state plasmapause computed for this model in the equatorial plane is depicted in Figure 5 as a function of the electric field governing the tail wind. For comparison Figure 6 shows the corresponding relation for a tail wind model in which the electric field is directed in the dawn to dusk direction with spatially invariant magnitude. It should be noted that in both models the steady state plasmapause location is the same at midnight as at noon whereas the minimum L position occurs at 0300 LT in the model with vanishing electric field on the dayside which contrasts with the situation in Figure 6 where the minimum L value occurs at 0600 LT. These two models represent extreme conditions: total penetration of the tail wind to the dayside of the earth; and non-penetration of the tail wind onto dayside field lines. More detailed measurements of the plasmapause than currently exist are required before it can be determined definitively whether either of these steady state models or a combination of them typify the actual configuration during prolonged periods when the magnetic activity is steady. The next section will explore the temporal variations expected in the plasmapause configuration when the magnetic substorm activity changes assuming the tail wind is excluded from the dayside field lines.

TIME DEPENDENCY

Since the geomagnetic activity fluctuates and the tail wind is related to the magnetic activity (see for example, Vasilyunas, 1968) the tail wind must be considered gusty rather than steady. The steady state plasmapause models can at best be good approximations only during prolonged periods of steady magnetic activity.

For example, assume that the tail wind is excluded from the dayside field lines and that the plasmapause is in one of the steady state configurations described previously. If the tail wind is suddenly enhanced, the streamline pattern will change to a configuration in which the stagnation streamline, depicting the steady state plasmapause in the equatorial plane, is located nearer to the earth than the initial plasmapause boundary. The original plasmasphere particles that are located outside of the new steady state boundary will be peeled away and transported to the magnetopause in the dawn-dusk sector (see Figure 7) where they will be lost from the magnetosphere. Hence significant filamentary structure in the plasmapause near the initial location of the bulge in the dusk-midnight sector would arise under these conditions. Also a slight bulge forms in the plasmapause radius near dawn which then corotates with the earth until it reaches the dusk-midnight sector where the plasma is transported out of the magnetosphere.

Under the opposite condition of sudden quieting (see Figure 8) the bulge in the plasmapause, initially centered at 2100 LT under steady state conditions, corotates with the earth as has been pointed out previously by Carpenter (1970), Chen and Wolf (1970) and Grebowsky (1970). After the sudden onset of quieting the plasmapause exhibits a continuum of configurations ranging from its original steady state form, to a roughly circular boundary, to a configuration which shows considerable structure in the form of a cusp (in Figure 8 this cusp is seen to form after 48 hours near 1800 LT). This motion of the plasmasphere boundary would be obscured after several days as plasma produced in the ionosphere fills up the depleted flux tubes within the final steady state configuration.

CONCLUSIONS

The extensive whistler measurements of Carpenter (1970) have established the general time dependent behavior of the plasmapause which results from changing magnetic activity. These measurements indicate that the bulge tends to corotate with the earth during periods of magnetic quieting. This is in agreement with both the convection model in which the tail wind penetrates onto dayside field lines and the model with a vanishing dayside convection field. However comparing these models, the nearly circular equatorial plasmasphere boundary observed on the dayside in the whistler studies implies, as Carpenter states, that the tail wind does not penetrate significantly into the dayside of the earth.

Carpenter (1970) sometimes detects a local reduction or trough in electron density in the region of the bulge. This could correspond to the formation of the cusp in the plasmapause location which arises from the temporal variation associated with magnetic quieting as described in the present study and in the previous study of Chen and Wolf (1970).

During periods of increasing magnetic activity, the bulge is observed to move westward. However, only during exceptionally high disturbance levels does it move significantly earlier than 1800 L.T. If the convection electric field is excluded from the dayside magnetic field lines, the model calculations show that the bulge will tend to move westward during a disturbance, but it will never move onto dayside field lines. This indicates that although the total shielding of field lines on the dayside of the earth may be a good approximation during quiet or moderately disturbed conditions, it is not a valid assumption during high disturbance levels. The tail wind must penetrate into the dayside during these active periods. Also it should be noted that the ionospheric electrical conductivity does not increase in a step like manner at dawn or dusk but is dependent upon solar zenith angle (see the model calculation of Wolf, 1970). Thus a slight penetration of the tail wind to the dayside will always occur.

Other plasmapause measurements made by satellites (Taylor et al., 1970; Chappel et al., 1970) show considerable structure in the plasma distribution near the bulge region. The model calculations indicate that this is to be expected since the midnight-dusk region is very sensitive to a changing tail wind. Under fluctuating conditions the plasmapause configuration in this region can become quite complex as was shown by Chen and Wolf (1970) and which is evident from the present study. Also since the earth's magnetic axis is tilted with respect to the geographic spin axis, the diurnal rotation of the earth will cause a variation in the location (in terms of L and magnetic local time) of sunrise and sunset. This will not cause large changes in the convection streamline pattern (Wolf, 1970), but even slight changes in this pattern near the bulge in a period of a day or so could obscure the pointed configuration predicted by the models. To study this a more accurate profile for the electrical conductivity than was used here is required. It is expected that the bulge region even under steady magnetic activity may be characterized by a non stationary configuration.

Thus the general features of the plasmapause configuration can be accounted for by a convection electric field which is shielded from the dayside magnetic field lines during quiet or moderate magnetic activity and which penetrates significantly into the dayside during severe magnetic disturbances. More extensive measurements of the plasmapause configuration than currently exist are required before the exact variations in the model parameters describing the tail wind and plasmapause can be determined.

ACKNOWLEDGEMENT

I would like to acknowledge that the analytical model studied was originally suggested by Dr. W. I. Axford.

BIBLIOGRAPHY

Axford, W. I., Magnetospheric Convection, Reviews of Geophysics, 7, 421-459, 1969.

Brice, N. M., Bulk motion of the magnetosphere, J. Geophys. Res., 72, 5193-5211, 1967.

Carpenter, D. L., The magnetosphere during magnetic storms; a whistler analysis, Stanford Electron. Lab. Tech. Rep. 12, SEL-62-09, 1962.

Carpenter, D. L., Whistler studies of the plasmapause in the magnetosphere, J. Geophys. Res., 71, 693-709, 1966.

Carpenter, D. L., Whistler evidence of the dynamic behavior of the duskside bulge in the plasmasphere, J. Geophys. Res., 75, 3837-3847, 1970.

Chappell, C. R., K. K. Harris, and G. W. Sharp, The morphology of the bulge region of the plasmasphere, J. Geophys Res., 75, 3848-3861, 1970.

Chen, A. J., and R. A. Wolf, On the dynamics of the plasmasphere, presented at A.G.U. meeting, spring, 1970, Abstract appears in Transactions, American Geophysical Union, 51, 1970.

Grebowsky, J. M., Model study of plasmapause motion, J. Geophys. Res., 75, 4329-4333, 1970.

Kavanagh, L. D., J. W. Freeman, and A. J. Chen, Plasma flow in the magnetosphere, J. Geophys. Res., 73, 5511-5519, 1968.

Nishida, A., Formation of the plasmapause or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail, J. Geophys. Res., 71, 5667-5679, 1966.

Taylor, H. A., H. C. Brinton, and A. R. Deshmukh, Observations of irregular structure in thermal ion distributions in the duskside magnetosphere, J. Geophys. Res., 75, 3848-3861, 1970.

Wolf, R. A., Effects of ionospheric conductivity on convective flow of plasma in the magnetosphere, 75, 4677-6698, 1970.

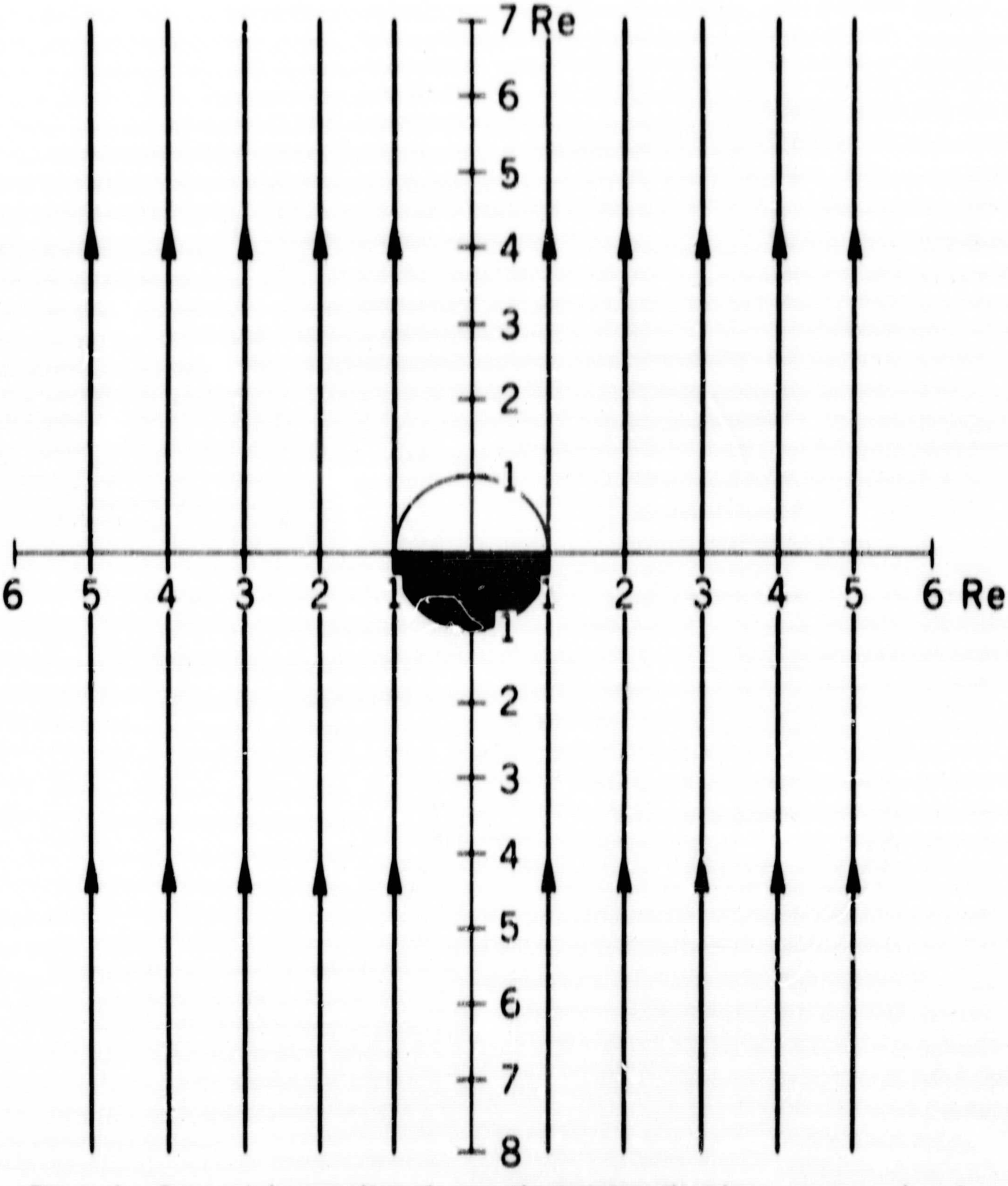


Figure 1. Equatorial streamlines for a tail wind described by a constant electric field directed from dawn to dusk are drawn for a magnetic dipole field configuration.

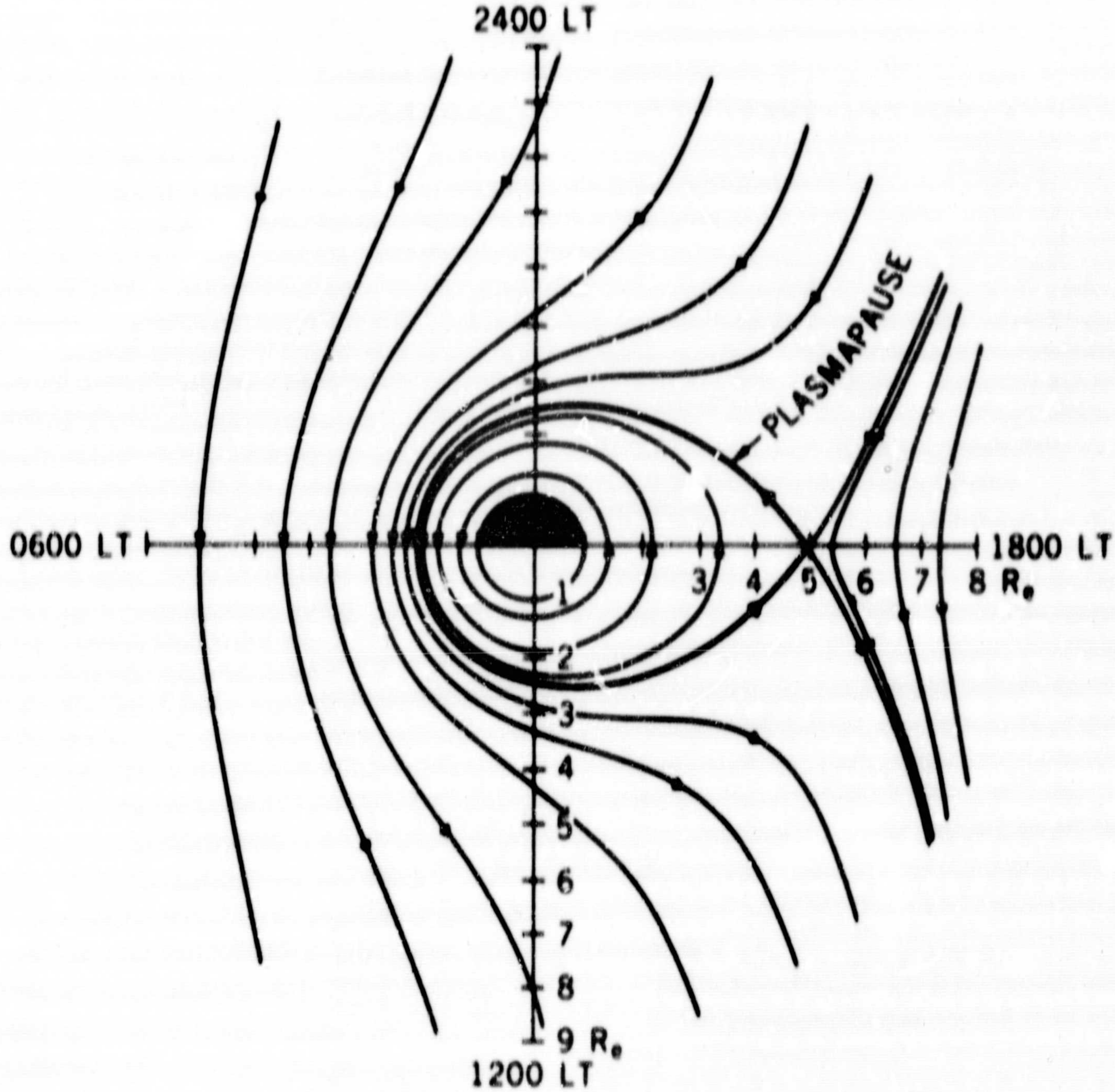


Figure 2. The equatorial convection streamline pattern shown corresponds to a superposition of the velocity field depicted by a constant dawn to dusk electric field of 0.58 mv/m on the velocity field arising from corotation. The plasmapause bulge is centered at 1800 LT.

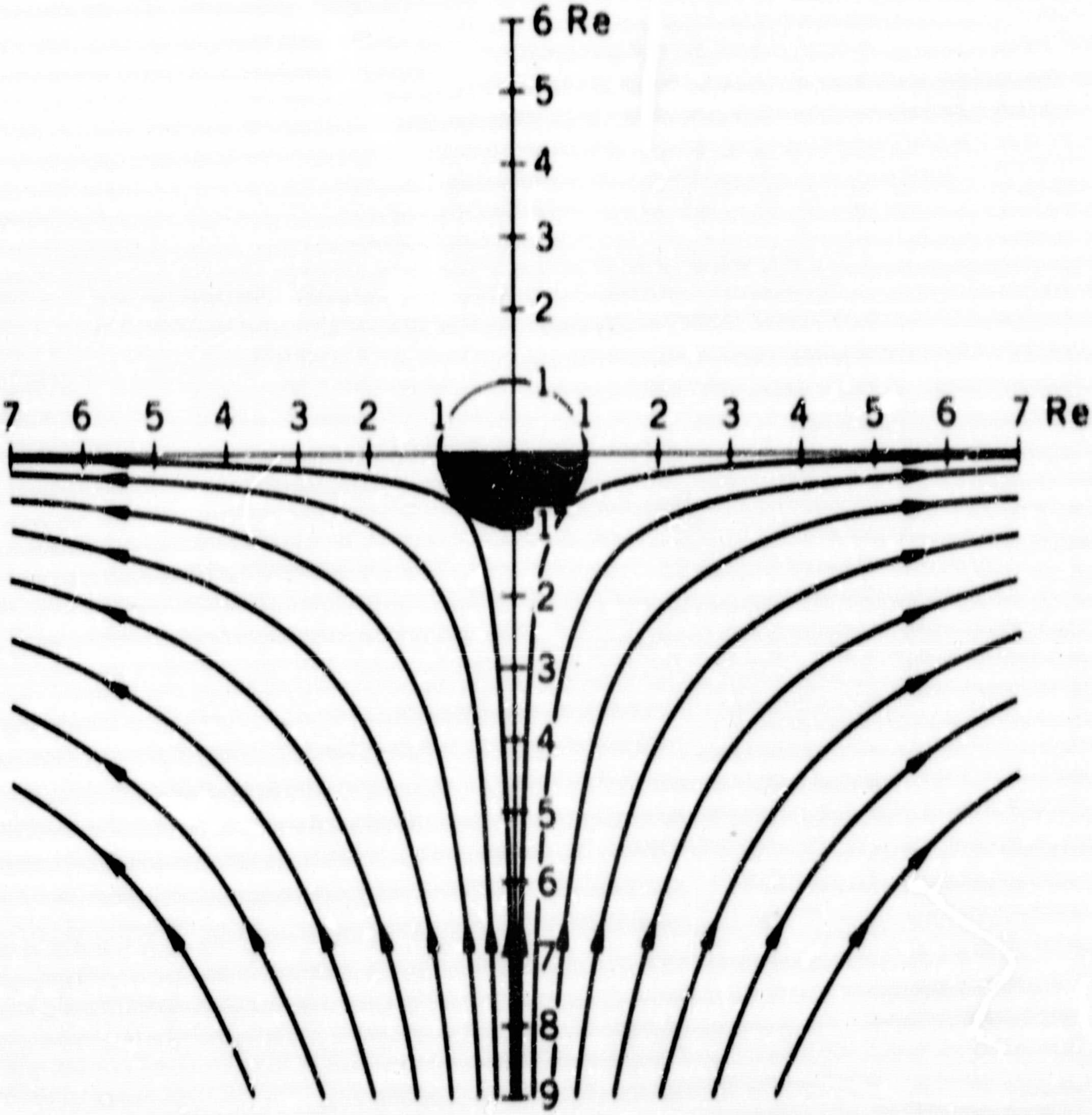


Figure 3. Equatorial streamlines for a tail wind which does not penetrate onto the dayside magnetic dipole field lines are plotted.

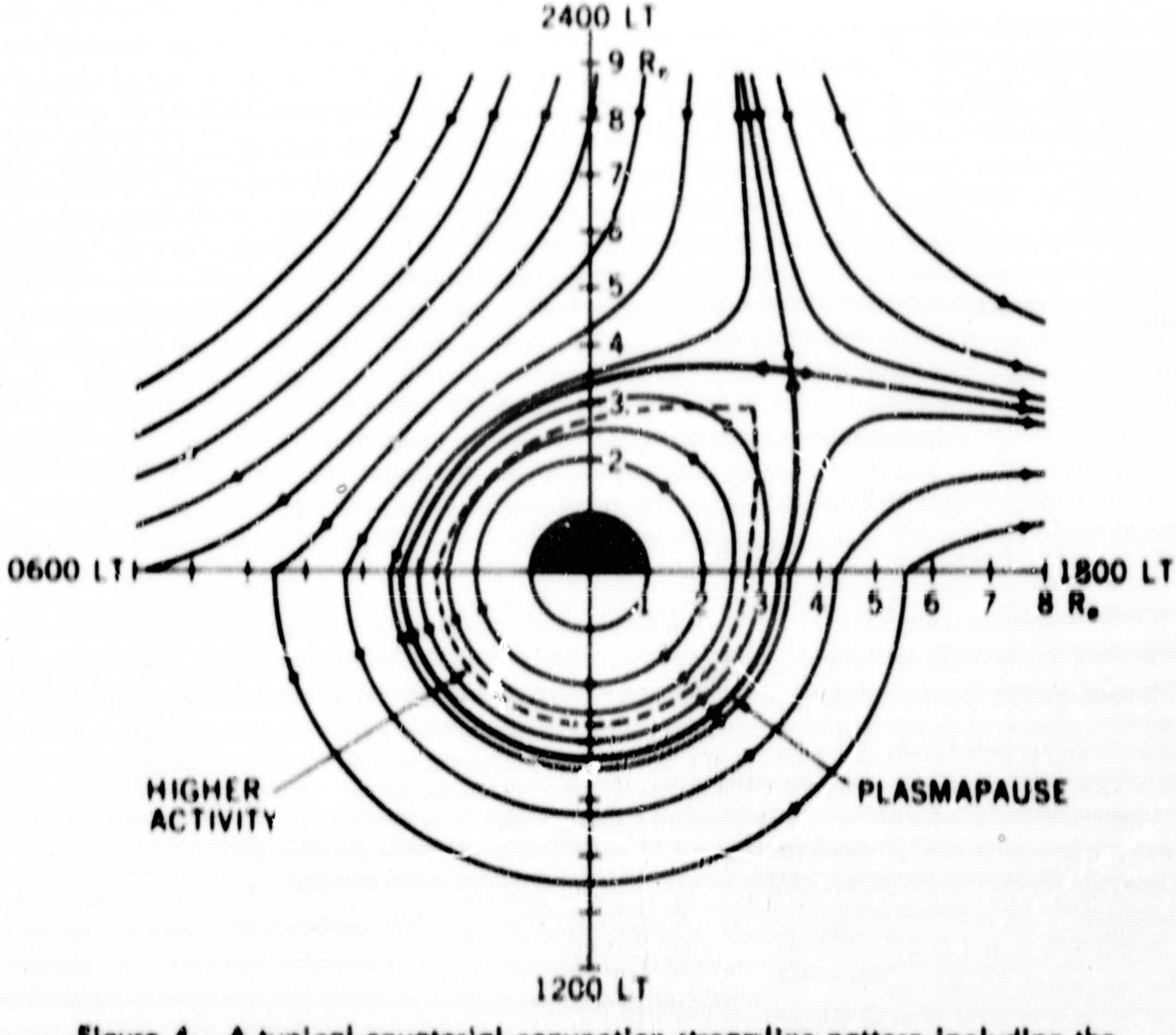


Figure 4. A typical equatorial convection streamline pattern including the corotation field and a tail wind which does not penetrate onto dayside field lines is shown. The plasmapause bulge is centered at 2100 LT.

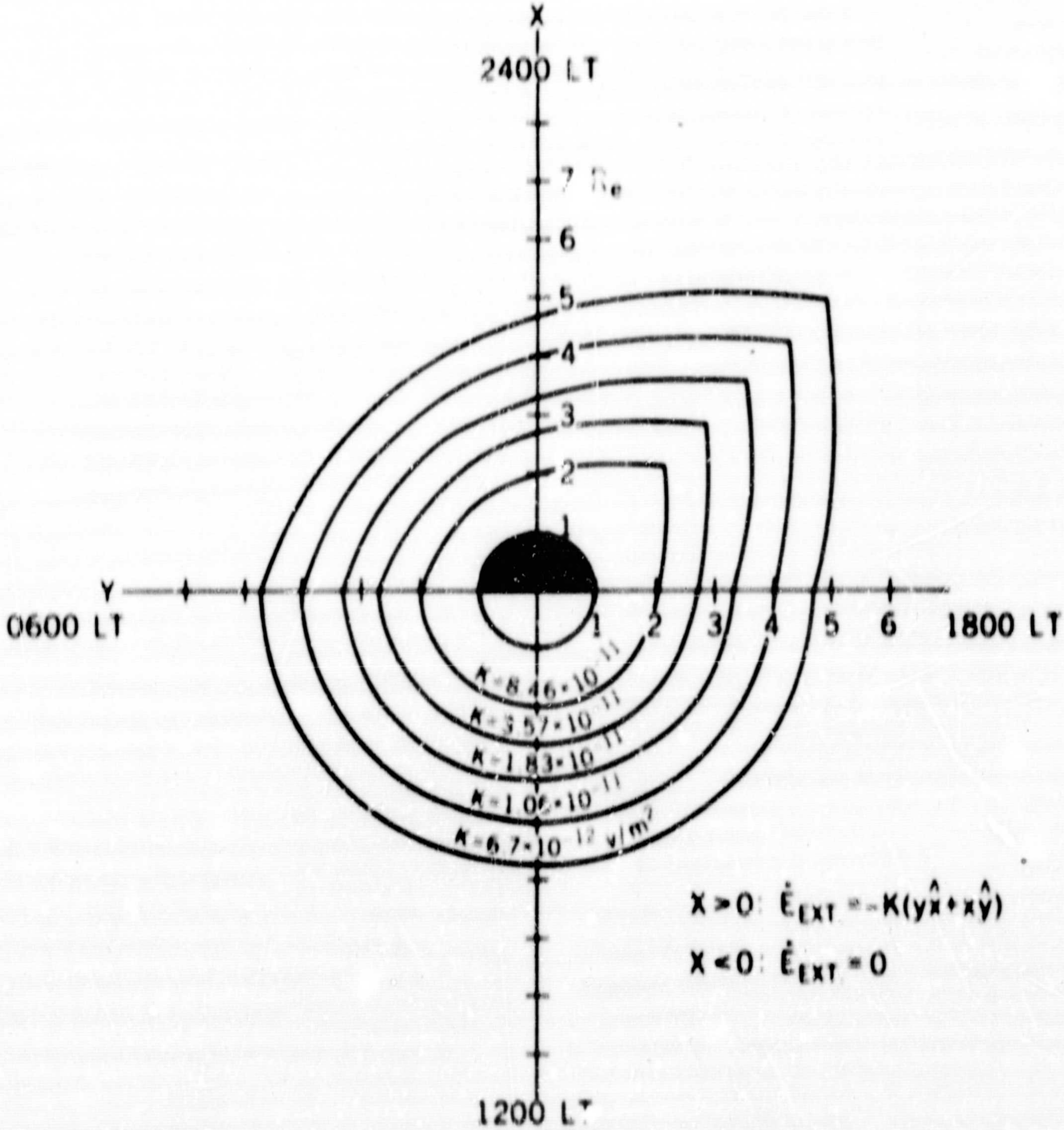


Figure 5. The steady state plasmapause configuration is depicted as a function of the model electric field when the tail wind is confined to right side magnetic field lines.

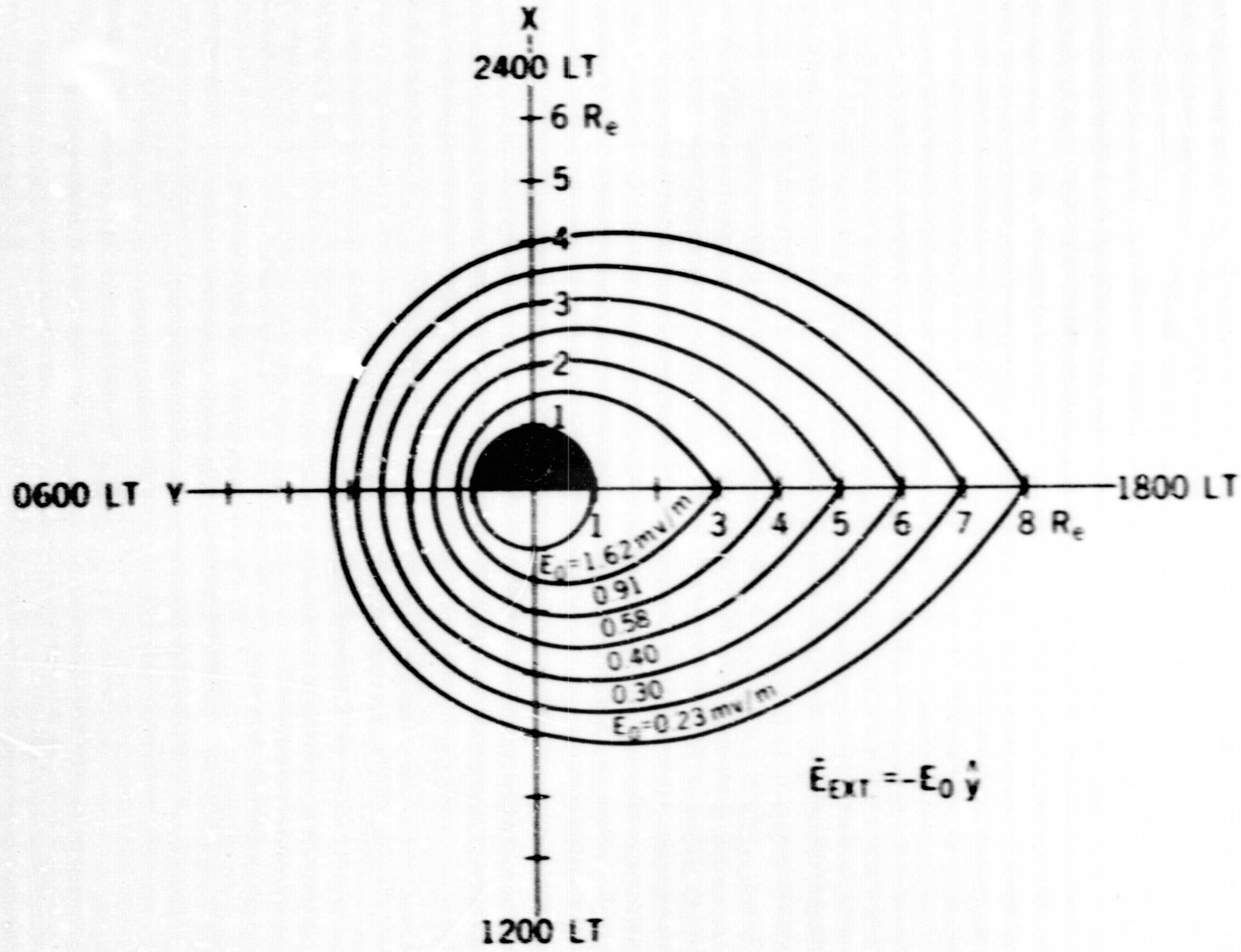
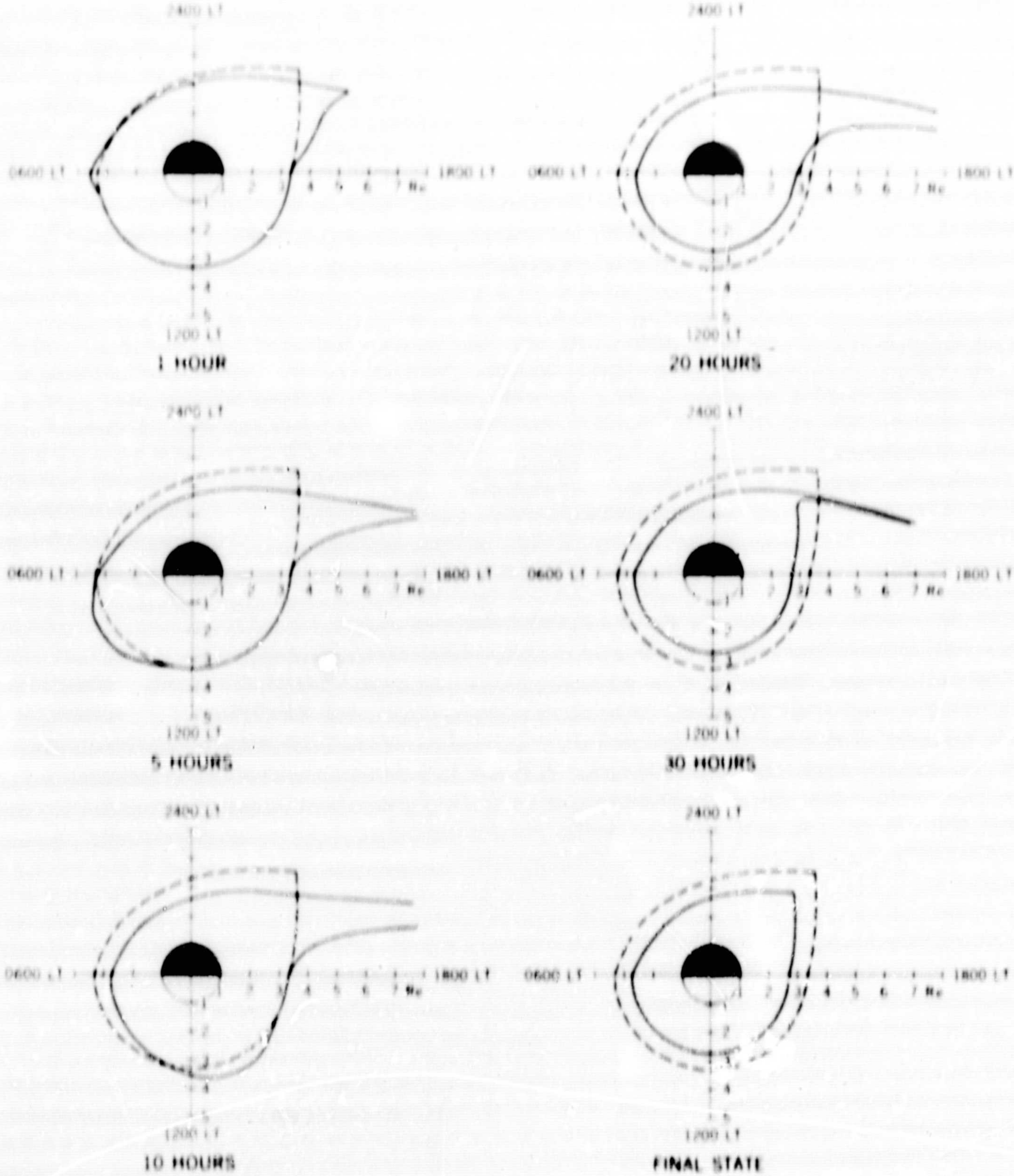
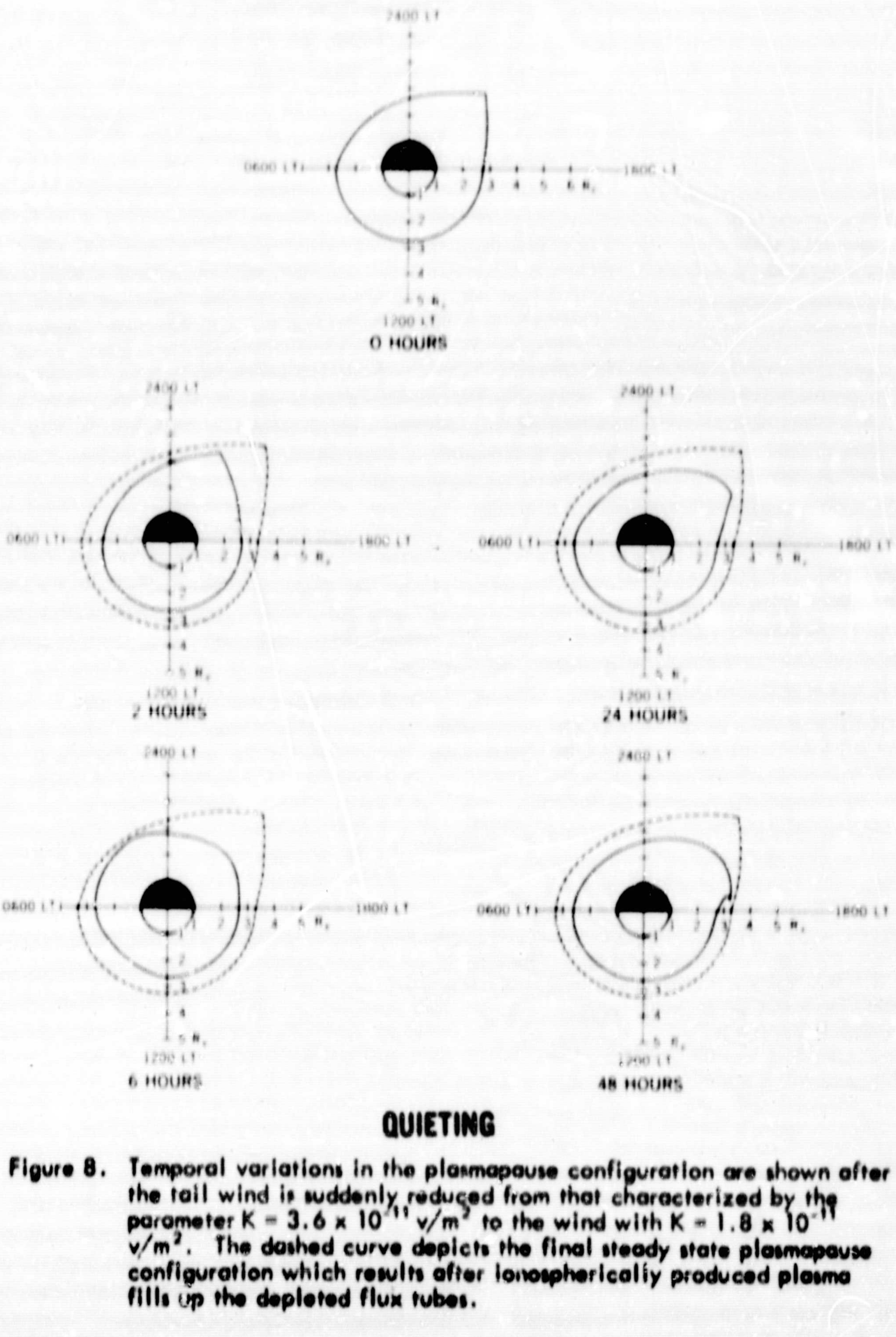


Figure 6. Steady state plasmapause configuration corresponding to a tail wind depicted by a constant dawn–dusk electric field is shown as a function of the electric field magnitude.



STORM

Figure 7. Temporal variations in the plasmapause resulting from a sudden enhancement of the tail wind are plotted. The initial plasmapause configuration was assumed to be the steady state configuration with the field parameter $K = 1.8 \times 10^{-11} v/m^2$. The enhanced wind corresponds to $K = 3.6 \times 10^{-11} v/m^2$. The bulge region will be characterized by complex structure due to this change.



QUIETING

Figure 8. Temporal variations in the plasmapause configuration are shown after the tail wind is suddenly reduced from that characterized by the parameter K = 3.6×10^{-11} v/m^2 to the wind with K = 1.8×10^{-11} v/m^2. The dashed curve depicts the final steady state plasmapause configuration which results after ionospherically produced plasma fills up the depleted flux tubes.