X-621-69-543
PREPRINT

NASA TM X- 63813

MODEL STUDY OF PLASMAPAUSE MOTION

J. M. GREBOWSKY

DECEMBER 1969

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FACILITY FORM 602

N70 - 18861 (ACCESSION NUMBER)	(THRU) 1
18 (PAGES)	(CODE)
NASA-TMX # 63813 (NASA CR OR TMX OR AD NUMBER)	25 (CATEGORY)

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J. M. Grebowsky

Laboratory for Atmospheric and Biological Sciences

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INTRODUCTION

A sharp drop in the ambient electron density with increasing altitude usually occurs at a geocentric distance of a few earth radii near the equatorial plane (Carpenter, 1963; Gringauz, 1963; Taylor et al., 1965). This region of abrupt change is commonly referred to as the knee or as the plasmapause while the high density region bounded by the plasmapause is called the plasmasphere.

The origin of the knee is best explained qualitatively by a model originally developed by Nishida (1966). In this model, under steady state conditions the knee is the boundary between plasma that drifts always across closed geomagnetic field lines and plasma which at some time in its motion drifts onto open field lines (i.e., field lines which extend deep into the magnetospheric tail). In the former plasma regime (the plasmasphere) plasma escape is always prevented by closed field lines. Outside of the plasmasphere, however, a depletion of the ambient plasma occurs due to escape along the open field lines into interplanetary space.

From whistler measurements (Figure 1) it is known that the knee position in the equatorial plane is a function of local time with its maximum geocentric distance usually occurring in the dusk sector. On the average, when the magnetic index K_p increases, the plasmapause moves to smaller L coordinates (Carpenter, 1966; Taylor et al., 1968; Binsack, 1967).

The time dependent motion of the plasmapause during magnetic substorms is best characterized by the behavior of the bulge as deduced from ground based whistler measurements (Carpenter, 1969). The bulge in the equatorial plasmapause is typically near 18LT when planetary magnetic activity is steady. As substorm activity decreases, the bulge moves in the direction of the earth's rotation; whereas, during periods of increasing substorm activity it moves counter to the earth's rotation into the afternoon sector. This paper is a development of a simple time dependent model for the plasmapause motion during periods of changing magnetic activity which accounts for the observed behavior of the bulge.

STEADY STATE MODEL

The plasmapause as observed near the equatorial plane corresponds to an abrupt decrease in the density of the ambient electron-proton plasma with increasing altitude. The characteristic thermal energy of this plasma may be of the order of 1 ev or less.

In the steady state, the drift velocity $\vec{v}$ of this low energy plasma across the magnetic field lines is given by the magnetohydrodynamic relation

$$\vec{v} = \frac{\vec{E} \times \vec{B}}{B^2} \tag{1}$$

where $\vec{E}$ is the gross electric field existing in the magnetosphere and $\vec{B}$ is the magnetic field. Plasma drift resulting from gradients in the magnetic field can be ignored in a zeroth order approximation since this latter drift velocity is proportional to the random plasma energy which is very small in the present investigation. (It should be noted that Equation (1) remains valid in the zeroth order even under time changes in the macroscopic E field if the characteristic time of the electric field variation is much larger than the average gyration period of the ambient plasma particles.)

Using Equation (1) the macroscopic plasma flow will be studied explicitly only in the equatorial plane. The flow at nonequatorial locations can readily be determined from the equatorial flow pattern by considering the field lines as frozen to the plasma (e.g., Axford and Hines, 1961).

For simplicity the geomagnetic field is assumed to arise from a magnetic dipole centered in the earth with no tilt between the dipole and rotation axes. The effects of currents external to the earth are ignored — this is a reasonable assumption since the geomagnetic field is dipolar to a good approximation at geocentric distances corresponding to the location of the plasmapause during prolonged periods of steady magnetic activity (Carpenter, 1966).

In the equatorial plane the gross electric field which drives the plasma flow consists of contributions from two sources. First the rotation of the conducting earth through the dipole magnetic field produces a polarization charge within the earth. This charge produces an electric field which is directed radially outwards from the earth and which decreases with geocentric distance as $1/R^2$ (Hones and Bergson, 1965). Acting alone this electric field would correspond to the corotation of the earth and its plasma envelope.

The second contribution to the gross electric field arises from the interaction between the solar wind and the magnetosphere either in the form of magnetic merging in the magnetosphere tail (Dungey, 1961) or in the form of a viscous interaction at the magnetopause (Axford, 1964). For either mechanism, in the equatorial plane this field component is of the order of 0.1-1.0 mv/m and is directed generally from dawn to dusk corresponding to a plasma flow towards the sun from the magnetosphere tail (Nishida, 1966; Brice, 1967; Kavanagh et al., 1968).

Combining the corotation and the externally imposed fields, the ambient plasma flow streamlines can be determined in the equatorial plane by using Equation (1). Figure 2 shows the streamline pattern when the externally imposed field is constant in magnitude (at 0.58 mv/m) and directed from dawn to dusk throughout the magnetosphere. Under steady state conditions the plasmapause corresponds to the stagnation streamline that separates streamlines which close upon themselves from streamlines which extend from the magnetosphere tail to the dayside magnetosphere (Nishida, 1966). In the model under consideration the processes leading to a plasmapause with a finite thickness — i.e., diffusion (Mayr, 1968) and energy dependent drifts (Block, 1966) — are not taken into account.

Under steady state conditions a reduction in the magnitude of the dawn-dusk electric field component causes an increase in the L coordinate of the plasmapause at all local times (for example see Figure 2). Since the plasmapause moves, on the average, to higher L coordinates with decreasing K_p it will be assumed that the flow velocity of the ambient plasma from the magnetospheric tail increases on the average with increasing magnetic activity. This increase in the flow velocity with increasing magnetic activity would arise either from increased rates of field line reconnection in the tail of the magnetosphere or from enhanced viscous coupling at the magnetopause.

Given the general model for the steady state position of the equatorial plasmapause, the problem now is to determine how the plasmapause changes in going from the initial steady state to the final steady state configuration. An approximate model for the plasmapause motion during periods of changing magnetic activity will now be explored.

TIME DEPENDENT MODEL

The general movement of the plasmapause to smaller L positions during increasing magnetic activity implies the existence of a general enhancement of the plasma flow from the magnetosphere tail. Nishida (1968a) has shown that the general plasma convective system generated in the magnetosphere is directly related to the DP 2 geomagnetic polar disturbance. Hence the characteristic time of changes in the electric field in the equatorial plane is given by the time delay between solar wind induced disturbances at the magnetopause and changes in the DP 2 currents. This time is of the order of a few minutes (Nishida, 1968b).

The characteristic time for changes in the dawn-dusk electric field is of the order of minutes, whereas the time it takes a convecting charged particle to traverse the plasmasphere is of the order of hours. Hence, in a first approximation it can be assumed that the convection electric field increases simultaneously throughout the magnetosphere. Thus in the simplified model under consideration a magnetic disturbance is assumed to begin with a step-like increase in the solar wind induced dawn-dusk electric field (which is spatially constant in the equatorial plane) and a period of quieting is assumed to begin with a step-like decrease in this component.

Assume initially a steady state configuration exists corresponding to a dawn-dusk electric field of magnitude 0.28 mv/m. If this electric field component everywhere is suddenly increased in magnitude to 0.58 mv/m, then the plasma in the region between the initial plasmapause (dashed curve in Figure 2) and the final steady state plasmapause (thick streamline in Figure 2) will travel along the streamlines corresponding to the enhanced field until it is lost from the magnetosphere at the magnetopause.

Following the motion of the plasmapause plasma along the streamlines, the time dependent variation in the plasmapause position can be determined for this disturbance. Figure 3 and Figure 4 depict this evolution. It is seen in Figure 3 that the bulge in the plasmapause, originally located at 1800LT, moves towards the dayside magnetopause. Following such a disturbance a wide region of enhanced plasma density will exist for a few hours in the noon-dusk quadrant. In Figure 4 it can readily be seen that the most rapid changes in plasmapause position occur near dusk and that the final plasmapause configuration in the noon-dusk quadrant may not be attained until 15 or 20 hours after the electric field increase.

In order to determine what occurs during the process of quieting, it is assumed that the initial steady state configuration corresponds to a dawn-dusk field of 0.58 mv/m. If the quieting is represented by a sudden decrease in this field to 0.28 mv/m, the plasmapause motion can be traced along the streamlines corresponding to this reduced field. This time evolution is plotted in Figure 5, where the dashed curve labeled 0 hours is the initial steady state plasmasphere boundary. These computations indicate that the bulge will tend to rotate with the earth during periods of decreasing substorm activity.

In the quieting process, the ionosphere supplies plasma to the region between the initial and final plasmasphere boundaries. Since this region is characterized by closed equatorial convection streamlines, no loss of plasma occurs via transport out of the magnetosphere. Thus the motion of the bulge depicted in Figure 5 will become obscured after a few hours by the increasing plasma density arising from transport of ionospherically produced plasma along the magnetic field lines.

In the simplified model described above it has been assumed that the electric field change occurs instantaneously throughout the magnetosphere. Thus no significant delay occurs between the onset of the plasmapause motion at night and the onset of the dayside motion. Such a delay would occur only if a component of the solar wind induced electric field propagated through the magnetosphere with a velocity comparable to the general convection velocities. For example, Figure 6 depicts the plasmapause motion which would occur if an enhanced equatorial dawn-dusk electric field propagated slowly across the magnetosphere from the night side of the earth. The solar wind induced equatorial dawn-dusk field was assumed to be:

$$E(X) = \begin{cases} 0.58 \text{ mv/m} & \text{if } X > vt - X_0 \\ 0.28 \text{ mv/m} & \text{if } X \leq vt - X_0 \end{cases}$$

where X (positive on the right side) is the perpendicular distance from the dawn-dusk line, v is the speed of the disturbance propagating from the nightside (its value was set at 1 km/sec — a velocity typical of the general convective flow) and X_0 (set at 4 Re) is the position of the spatial discontinuity of the electric field at time $t = 0$. This disturbance propagates very slowly compared to the characteristic speeds expected from the DP 2 investigations by Nishida.

However this example gives an indication of the complex plasmasphere behavior which may arise if the gross electric field existing in the magnetosphere is characterized by both spatial and temporal variations.

CONCLUSIONS

Carpenter's observations of the motion of the plasmasphere bulge are in agreement with the model developed in this paper. The motion of the bulge towards the dayside arises from an increase in the magnetosphere tail wind flow velocity during increasing substorm activity. On the other hand the apparent corotation of the bulge with the earth arises if the speed of this flow rapidly decreases. Thus the plasmapause is probably in a very dynamic state since the flow velocity from the magnetospheric tail depends upon fluctuating conditions in the solar-wind magnetosphere interaction. Spatial inhomogeneities in the tail wind would further complicate this motion.

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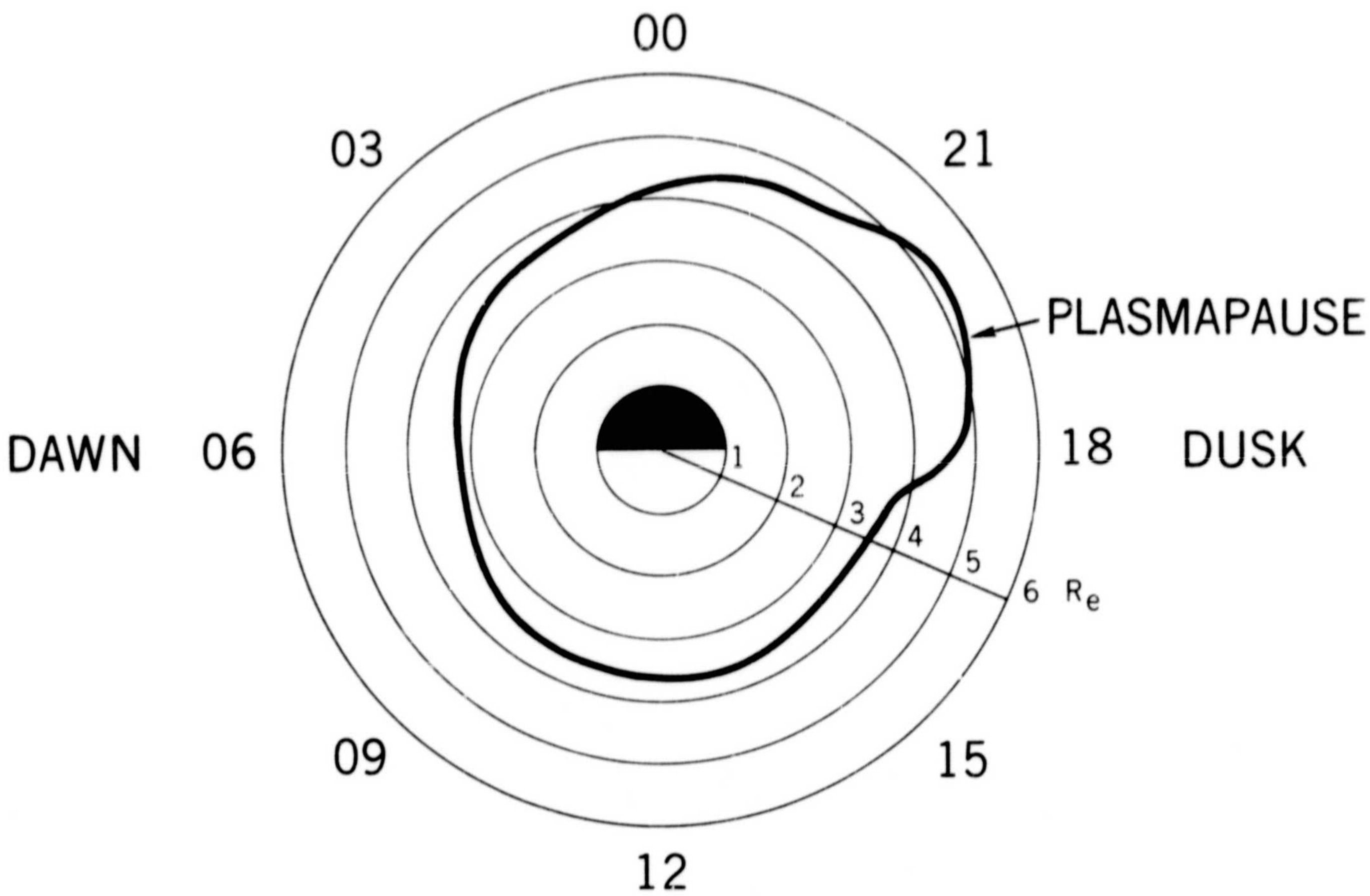

Figure 1. Average equatorial radius of the plasmapause as a function of local time for moderate geomagnetic activity (after Carpenter, 1966).

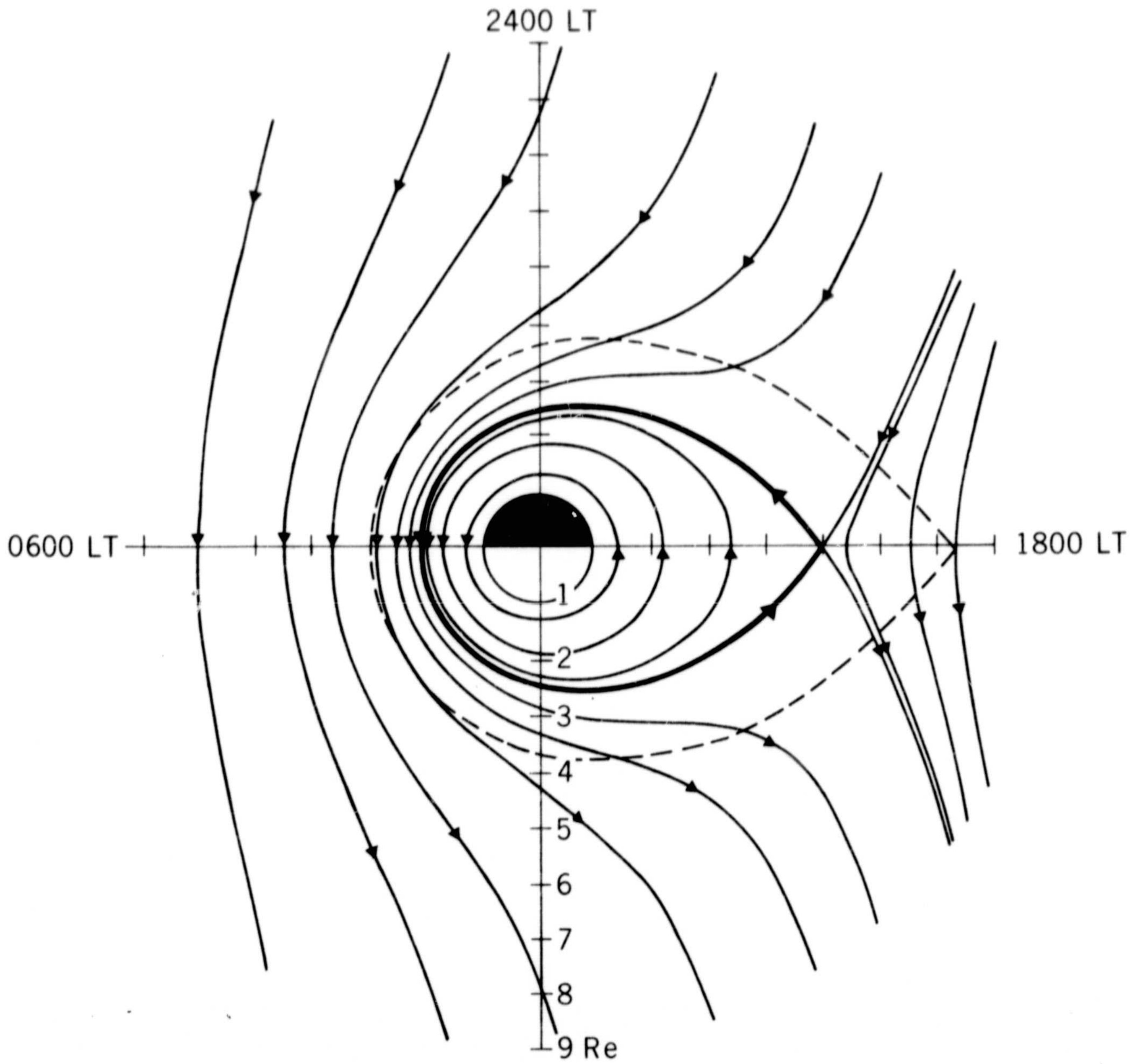

Figure 2. The solid lines depict streamlines of plasma flow in equatorial plane when a constant electric field of magnitude 0.58 mv/m directed from dawn to dusk is superimposed on the corotation field of the dipole. The thick solid line depicts the plasmapause for this electric field whereas the dashed curve depicts the plasmapause when the dawn-dusk field is 0.28 mv/m.

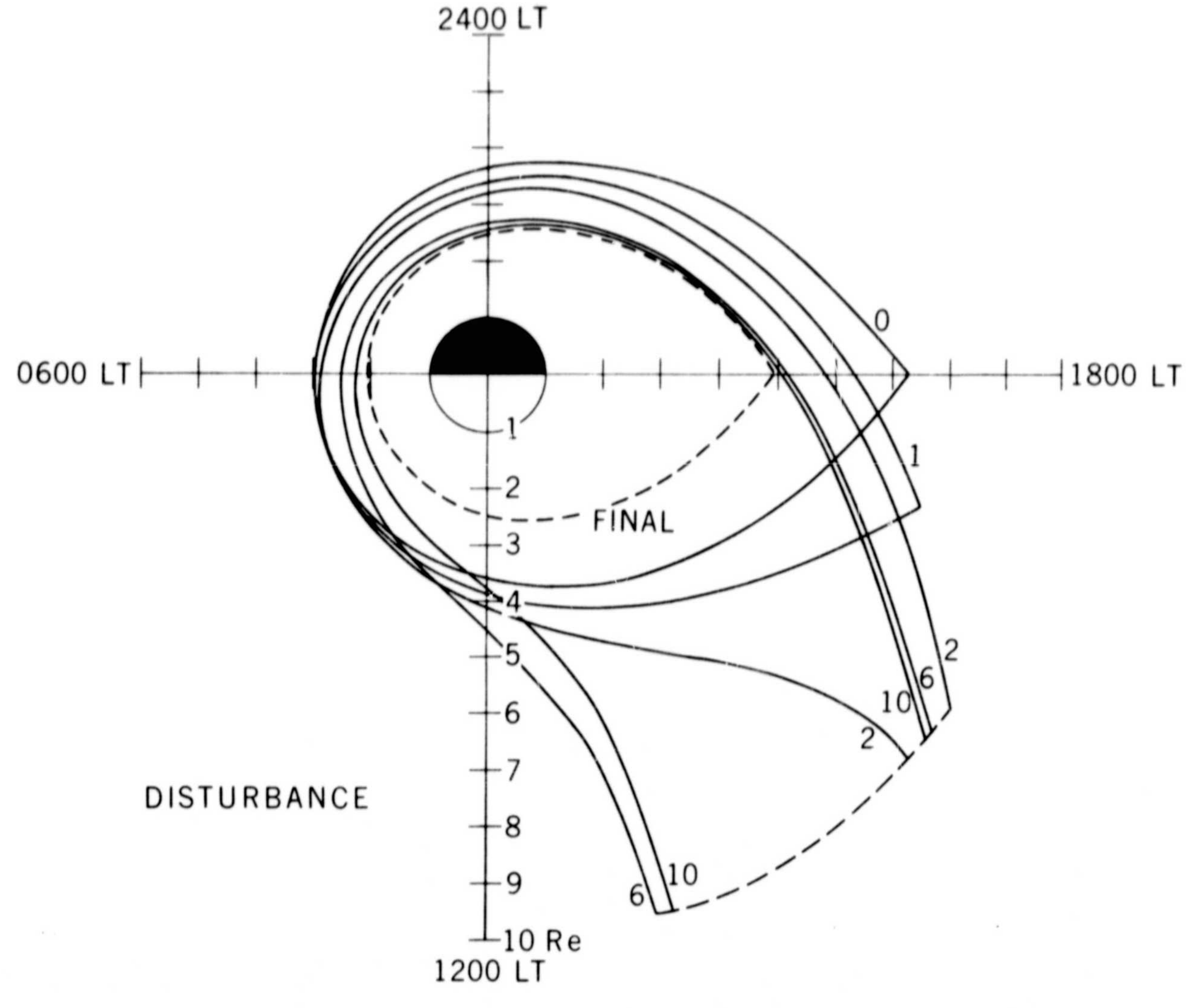

Figure 3. Plasmapause location is plotted for selected times (in hours) after the dawn-dusk electric field component is increased suddenly to 0.58 mv/m from its initial steady state value of 0.28 mv/m.

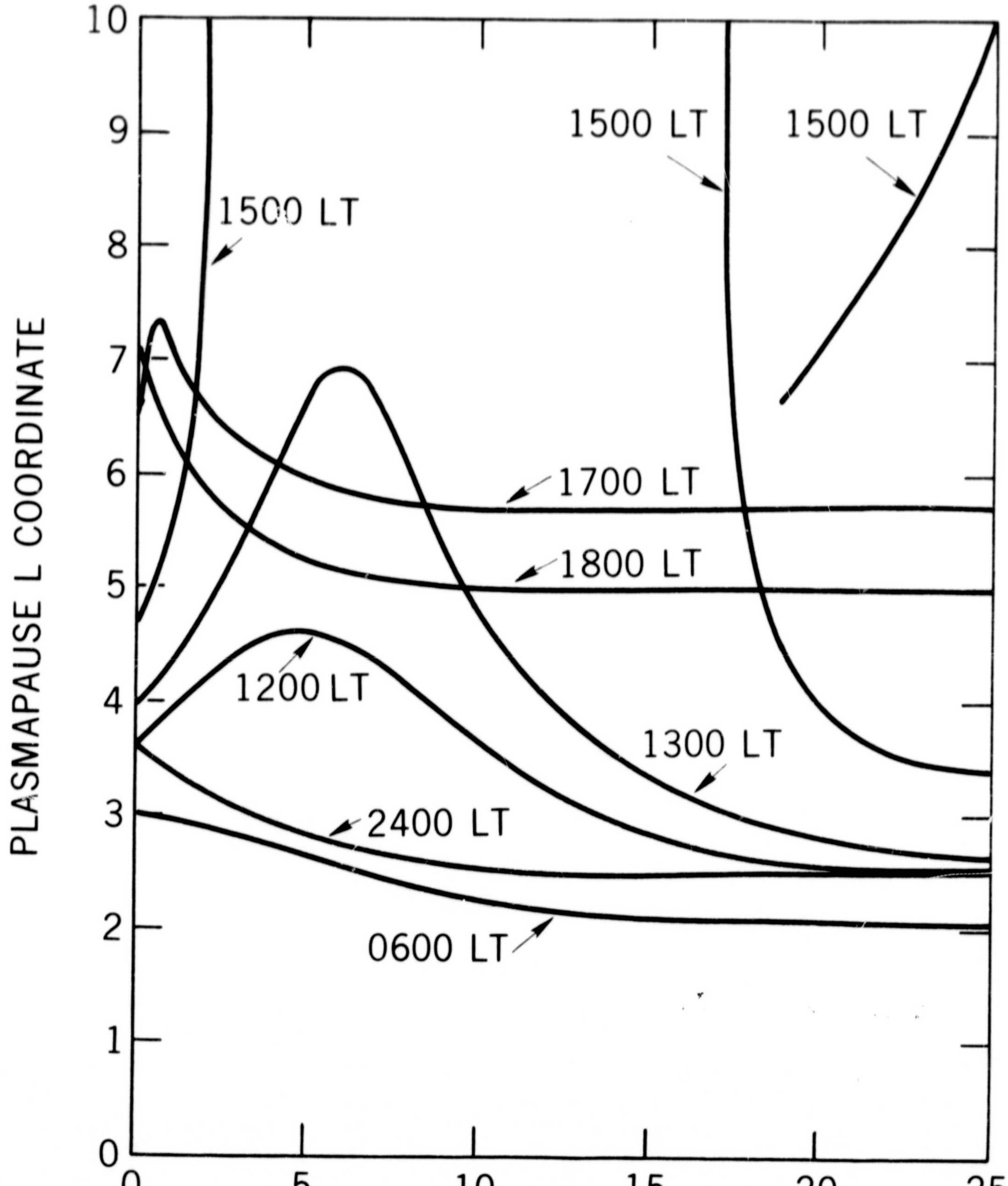

Figure 4. Plasmapause L coordinate at selected local times is plotted as a function of time after the sudden increase of the dawn-dusk electric field from 0.28 mv/m to 0.58 mv/m.

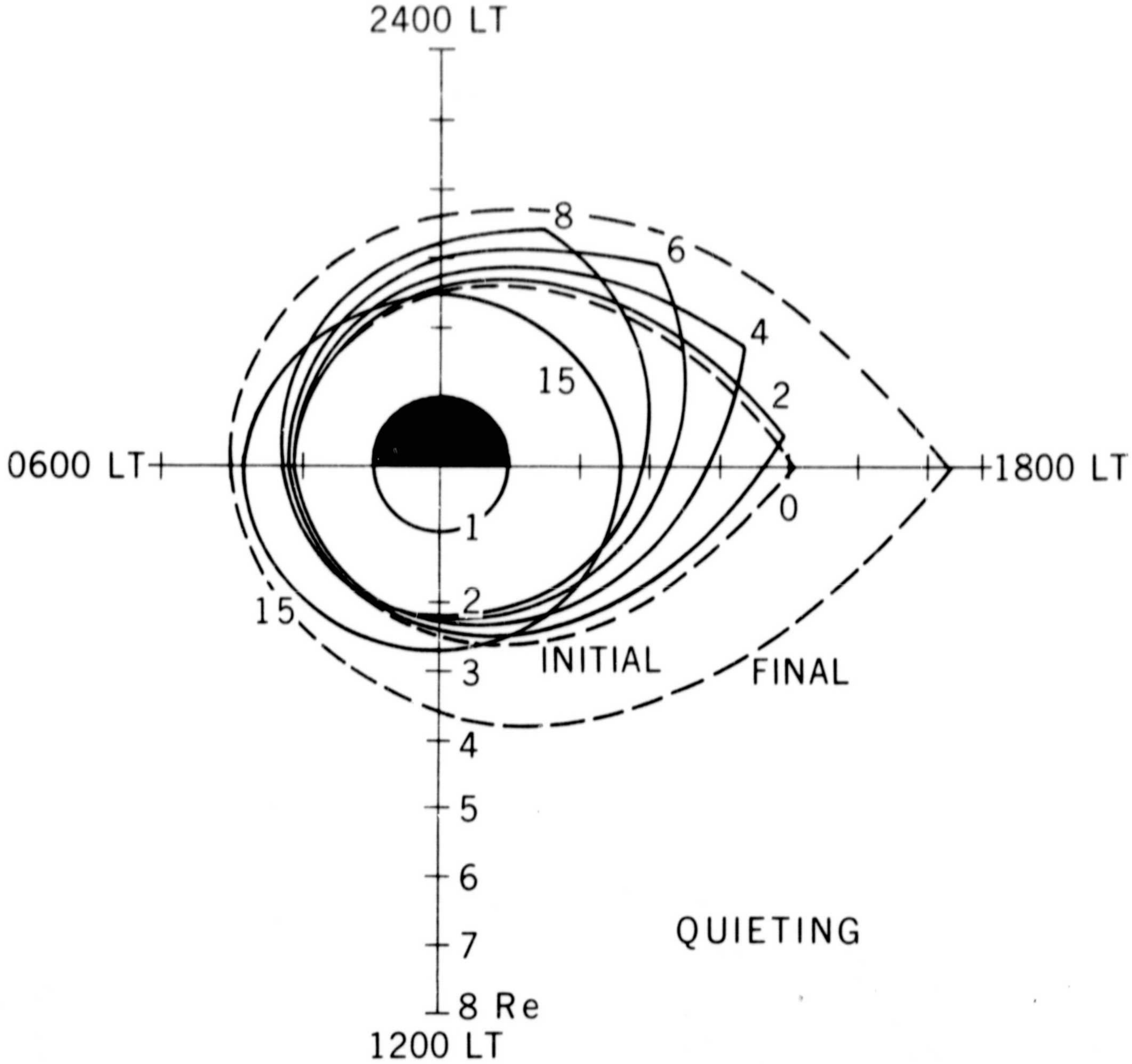

Figure 5. If the initial steady state dawn-dusk field of 0.58 mv/m is suddenly decreased to 0.28 mv/m, the plasmapause bulge tends to corotate with the earth. The region between the time development of the initial plasmapause (labeled by hours) and the final plasmapause is being continually supplied with ionospherically produced plasma. Thus the bulge motion depicted may be obscured after a few hours.

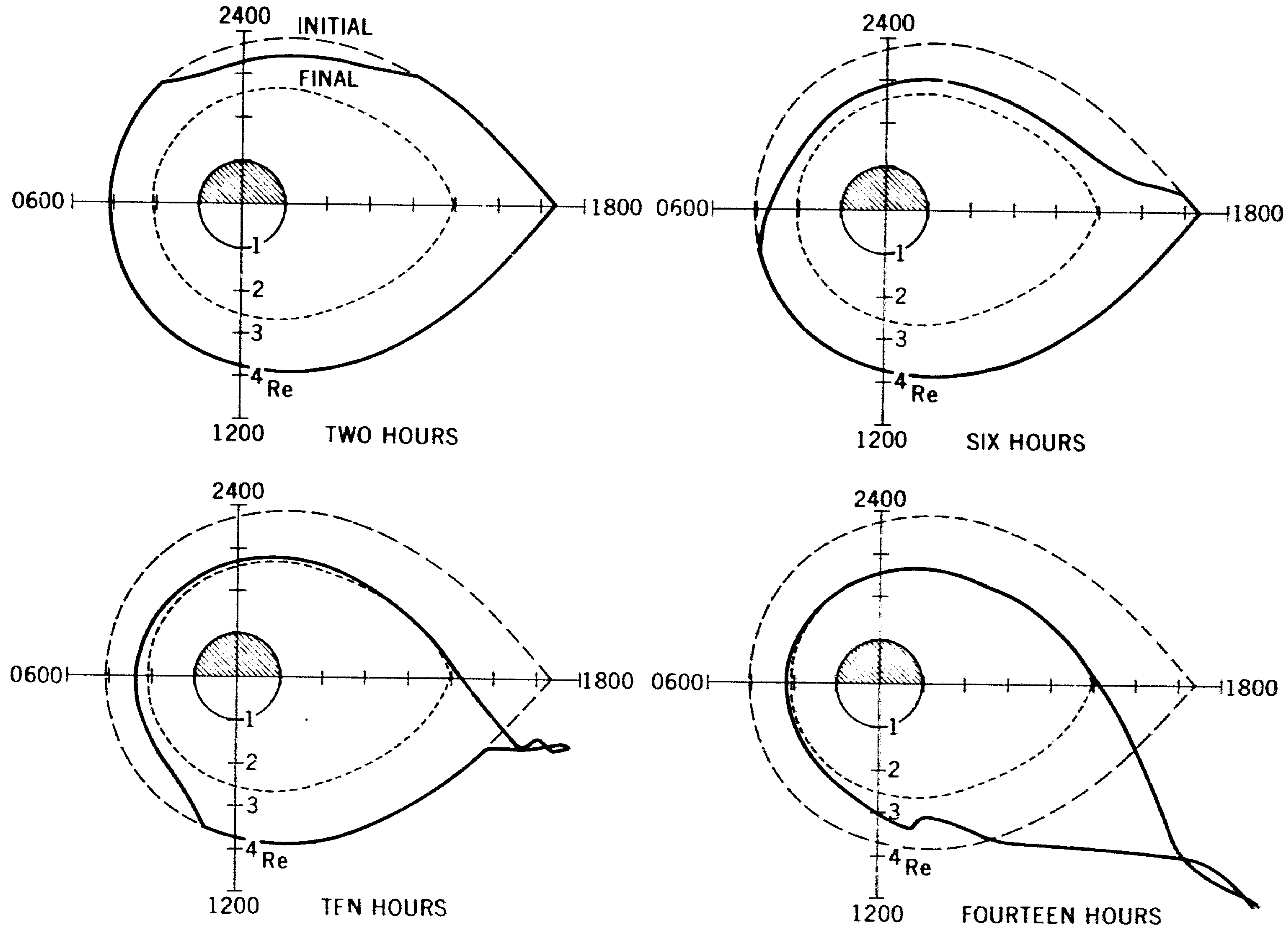

Figure 6. Steady state plasmapause corresponding to a solar wind induced dawn-dusk electric field of 0.28 mv/m is disturbed by an enhanced dawn-dusk field of 0.58 mv/m propagating from the night side with a velocity of 1 km/sec. The initial field discontinuity was located 4 Rd from the dawn-dusk line on the night side.