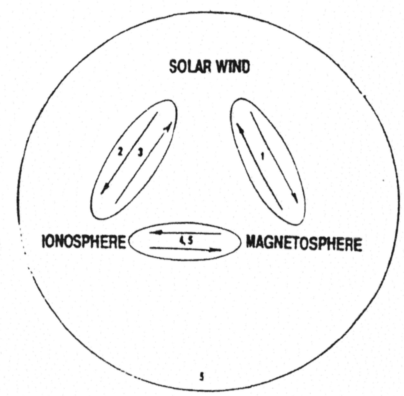
SOLAR WIND - MAGNETOSPHERE - IONOSPHERE COUPLING

LECTURE 1

THE MAGNETOPAUSE



The standard linked chained paradigm of Solar-Terrestrial Research (STR) is:

Sun → Corona → Solar Wind → Magnetosphere → Ionosphere → Thermosphere

By the end of this series, it will be replaced by the bilaterally interactive paradigm of STR:

Sun ⇄ Corona ⇄ Solar Wind ⇄ Magnetosphere ⇄ Ionosphere ⇄ Magnetosphere

But we will start with the standard paradigm and pick it up where the solar wind contacts the magnetosphere -- the magnetopause.
We will conclude by noting that the unsolved problem of how the solar wind couples to the magnetosphere prevents our predicting by a numerical code the magnetospheric condition corresponding to a given solar wind condition.

MAGNETOPAUSE =

A NON-INTERACTIVE, STRUCTURELESS, TANGENTIAL DISCONTINUITY

Historically there have been two phases to magnetopause modeling:

1. a non-interactive phase, and
2. an interactive phase.

1. Non-Interactive Phase: Magnetopause = Structureless Tangential Discontinuity

   This phase has two parts

   A. Vacuum magnetosphere, and

   B. Magnetosphere with current sheet.

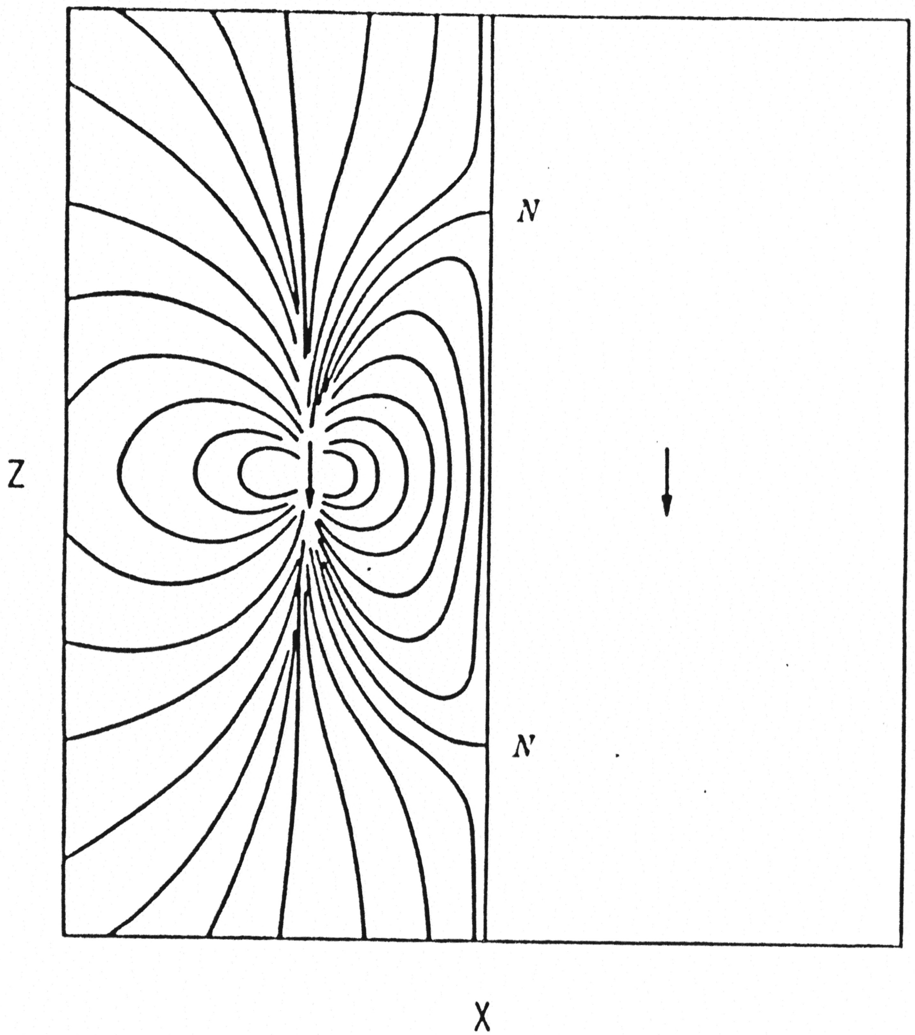
A. Magnetopause is like an inert membrane separating solar wind plasma on the outside from a vacuum, geomagnetic field on the inside.

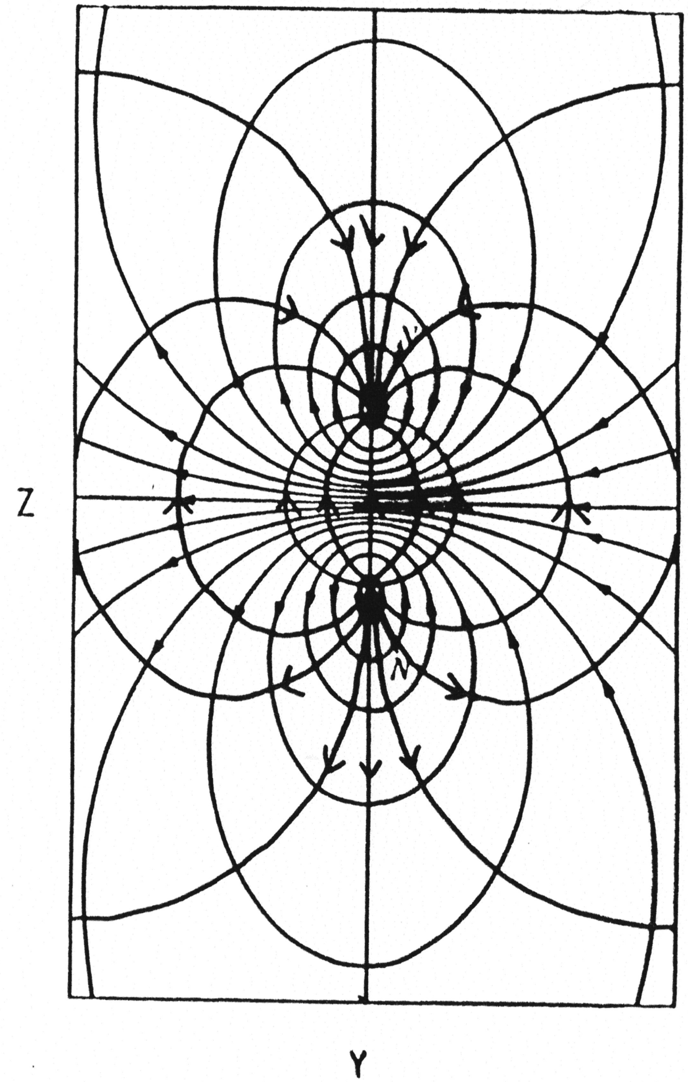
Two problems: i. Topology of field lines

ii. Shape of magnetopause.

i. Solved by Chapman and Ferraro (1931)

(In general, topology problems are solved by superposition of fields.)





Chapman and Ferraro [1931]

1.A.ii. The Shape of the Chapman-Ferraro Magnetopause

formed by a hypersonic solar wind hitting the geomagnetic dipole field.

Two conditions:

1. momentum balance:

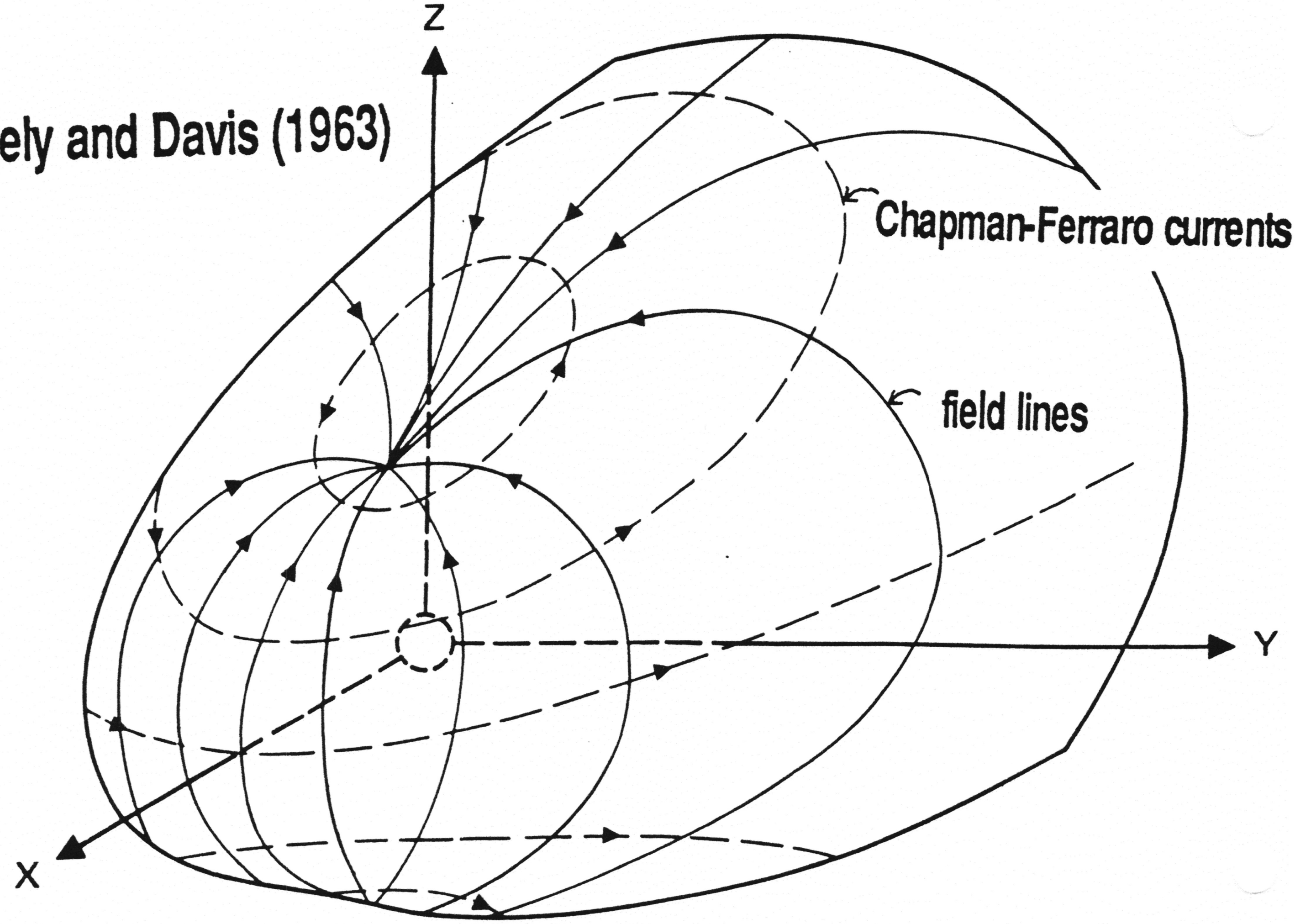
$$p_{st}\cos^2\psi = \frac{B^2}{2\mu_0} \quad \text{at magnetopause}$$

outside pressure = inside pressure

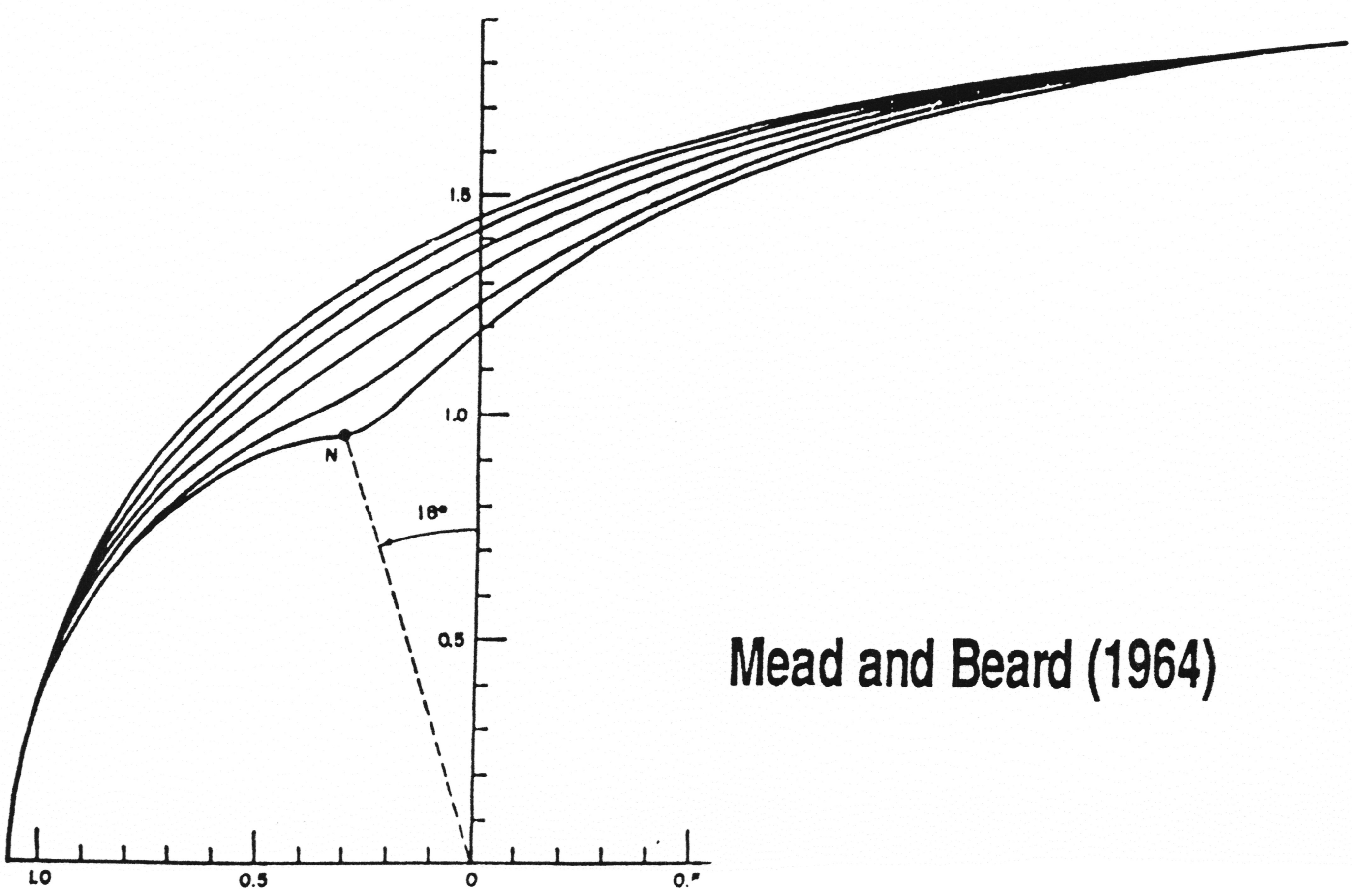
2. Tangential Discontinuity: $B_n = 0$

The problem is well posed, can be formulated analytically, and solved numerically to arbitrary accuracy, for arbitrary tilt of the dipole relative to the solar wind (Olson, 1969).

Midgely and Davis (1963)



Mead and Beard (1964)



1.B. The T. D. Magnetopause with Magnetic Tail.

Again there are two problems:

i. topology, and

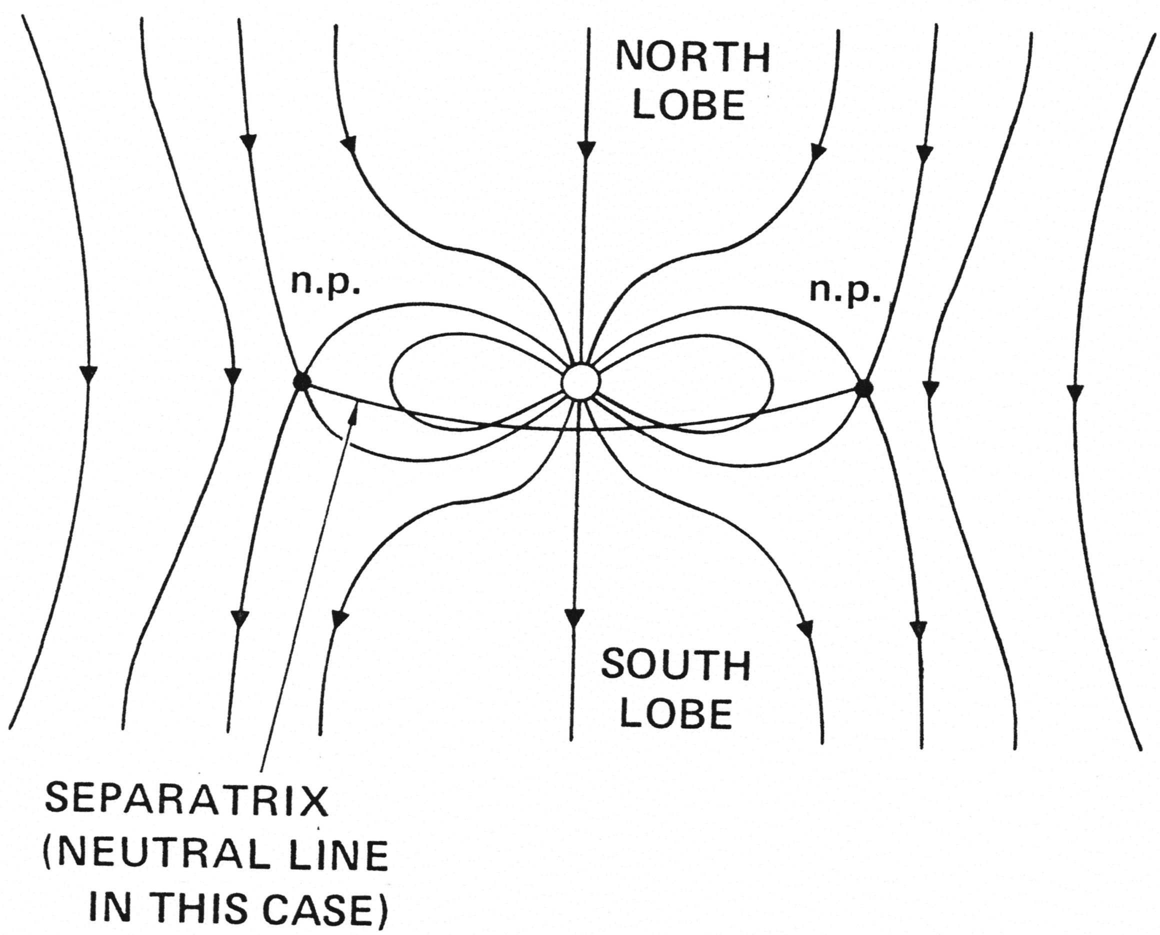
ii. shape.

1.B.i. Topology.

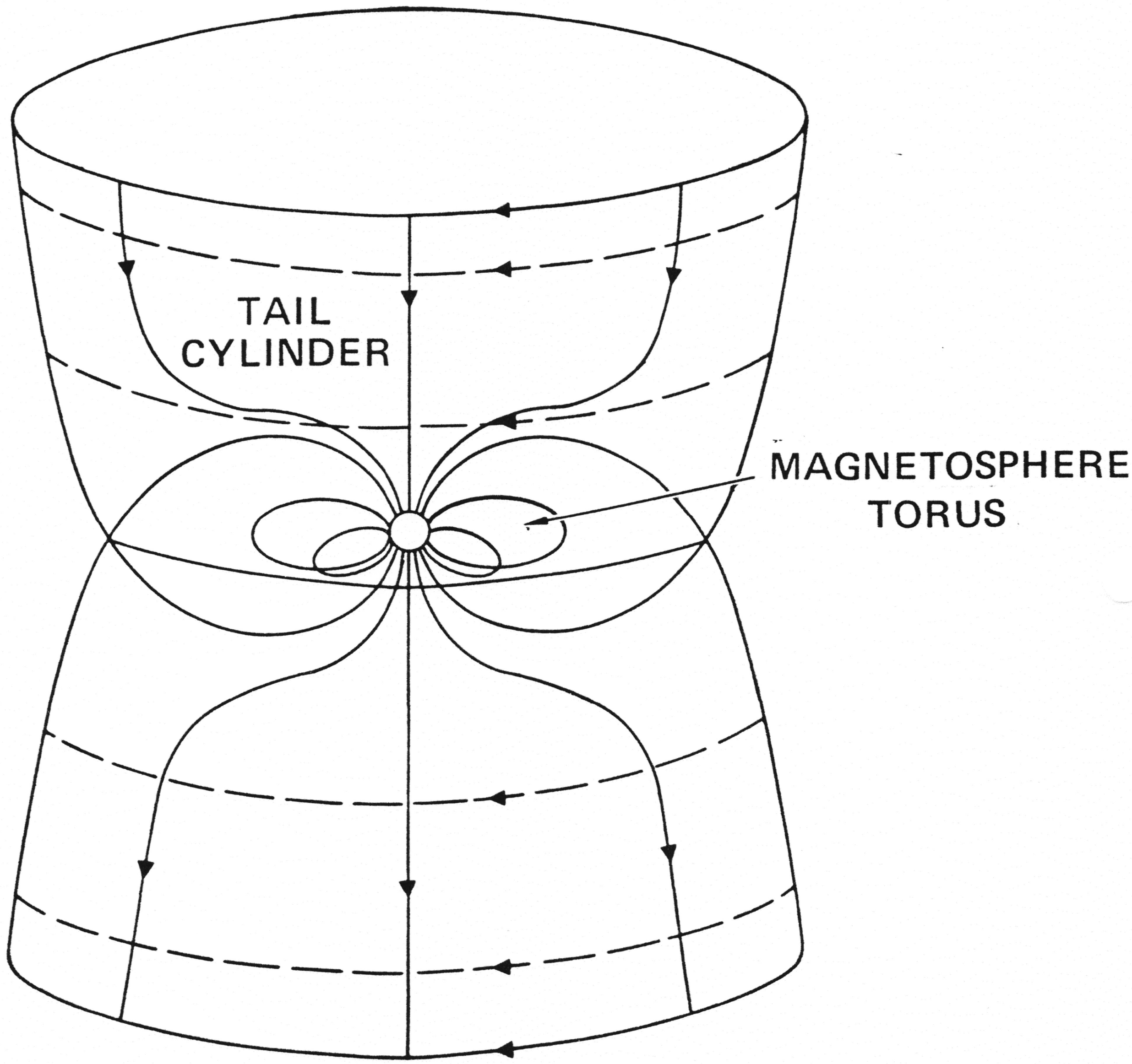
Taking the approach of superposition of fields, there are in this case three fields:

1. the earth's dipole,
2. a uniform field representing the tail, and
3. an image dipole + uniform field representing the magnetopause currents.

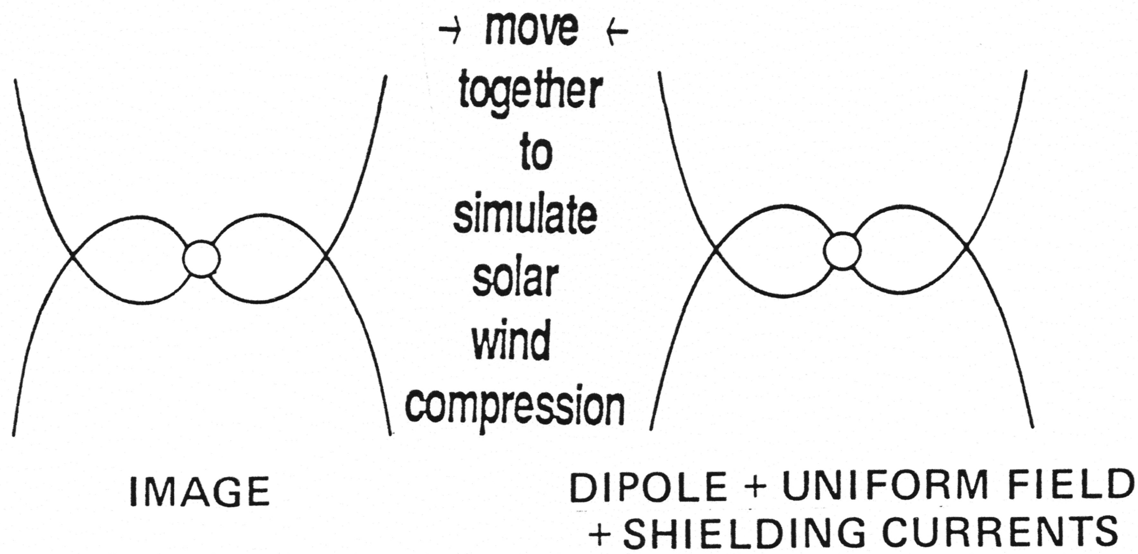
The dayside push of the solar wind bares the closed-field-line magnetospheric torus to the magnetosheath. The nightside pull of the solar wind forces the lobes together and traps the tail current between them, forming an interior current sheet. The magnetosphere is no longer current free, and must contain plasma to carry the current. The trapped tail current sheet is a continuation of the tail boundary current sheet and, in effect, brings the influence of the boundary directly into the interior of the dual-lobe tail.

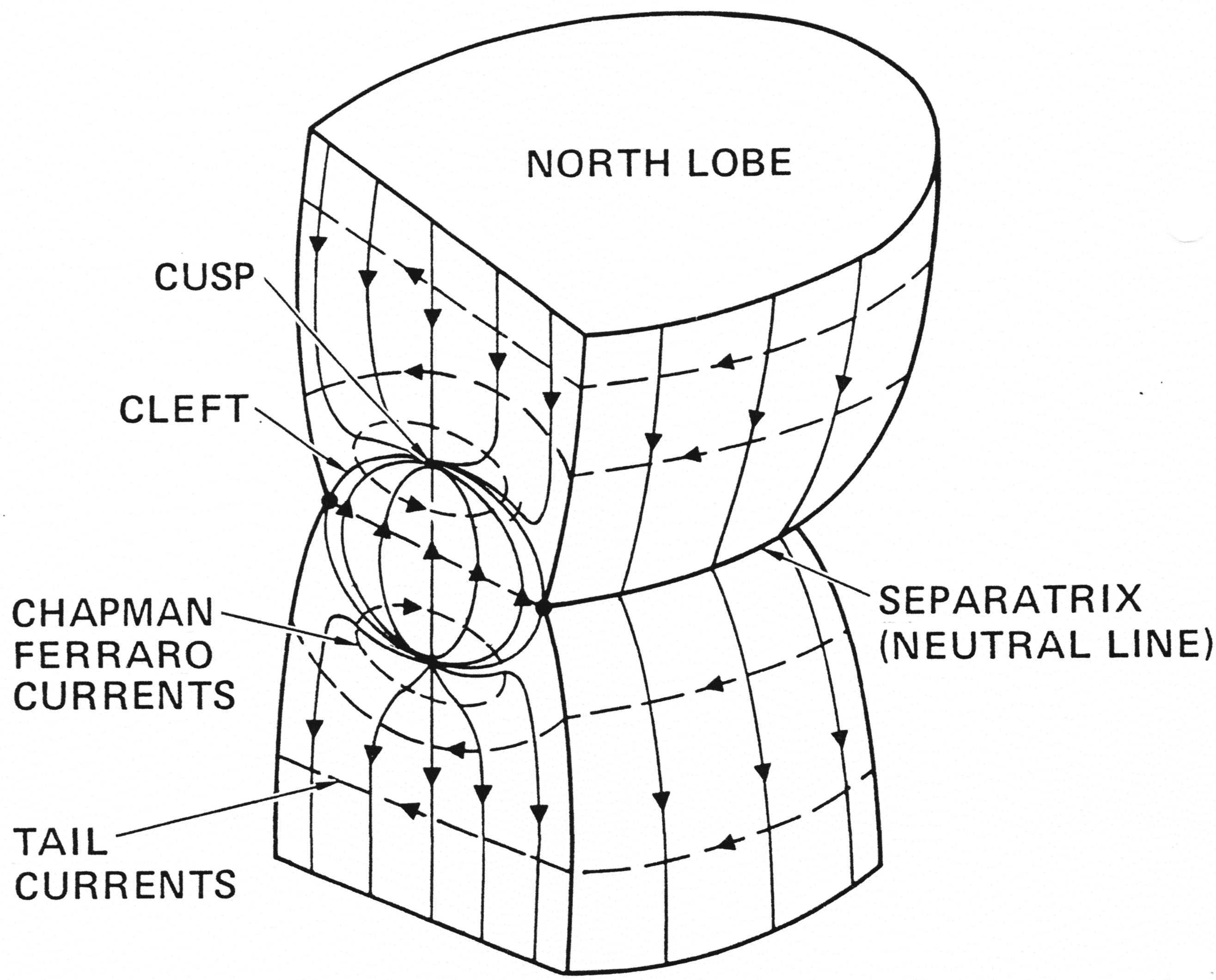


DIPOLE + UNIFORM FIELD



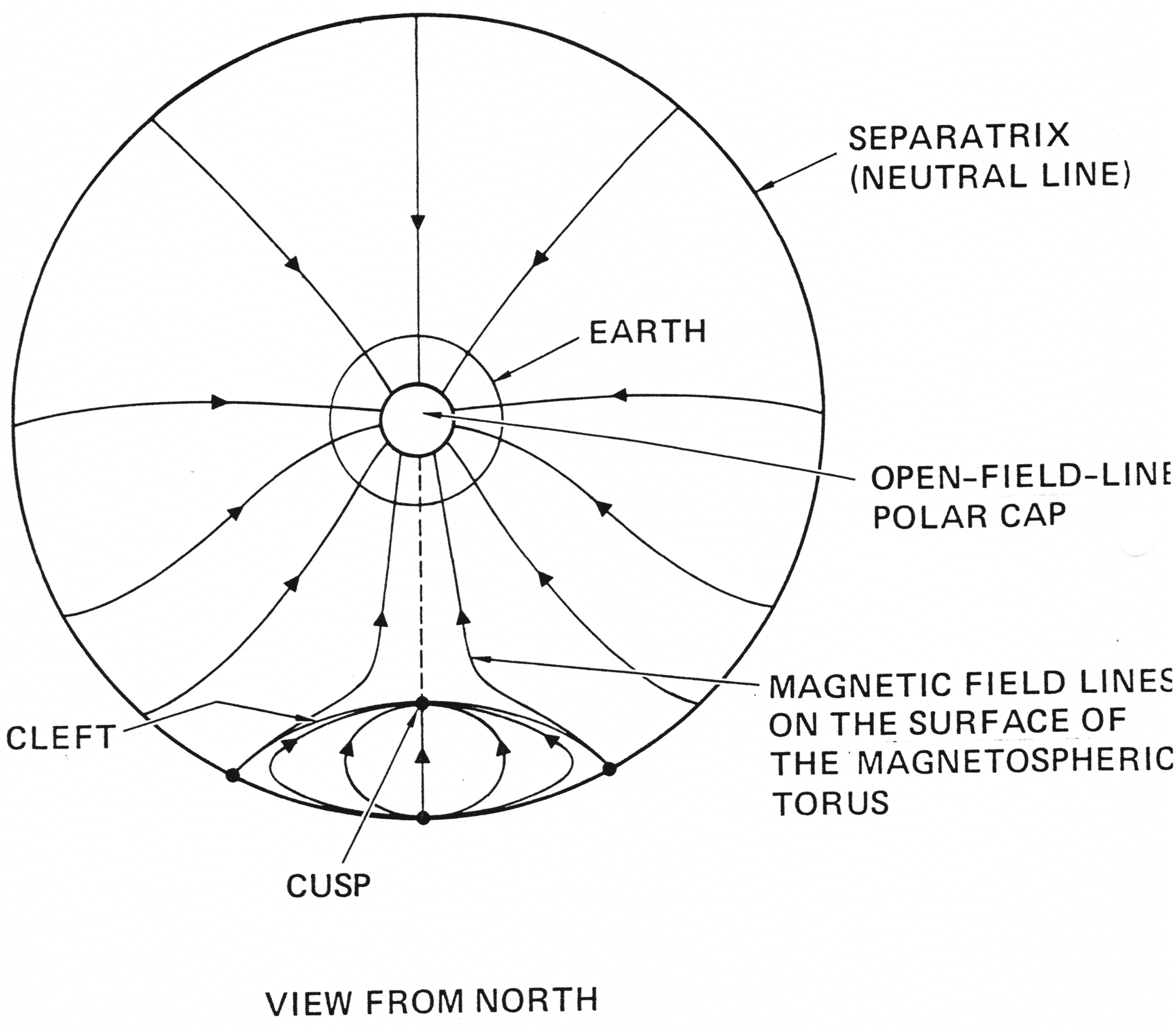
DIPOLE + UNIFORM FIELD + SHIELDING CURRENTS



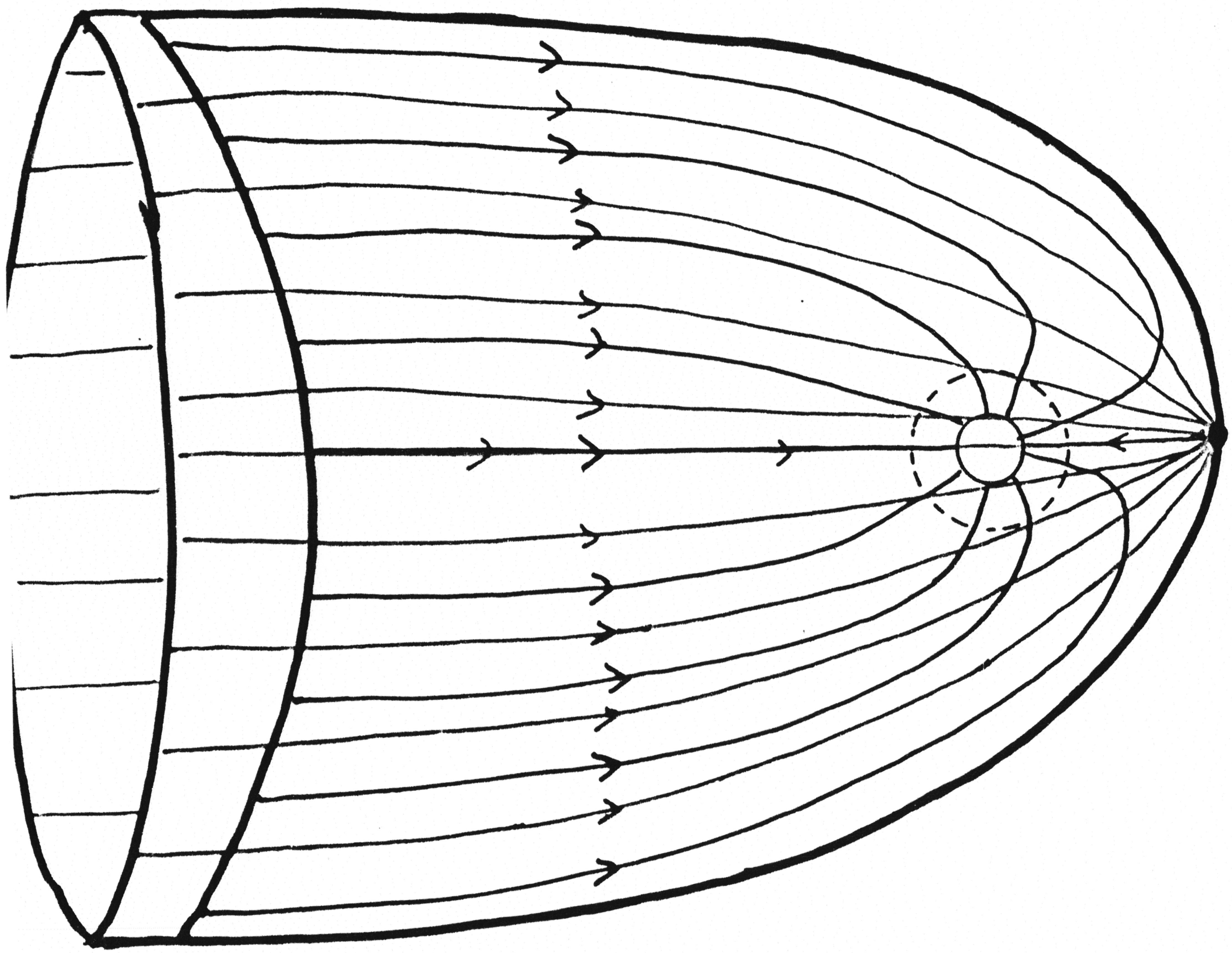


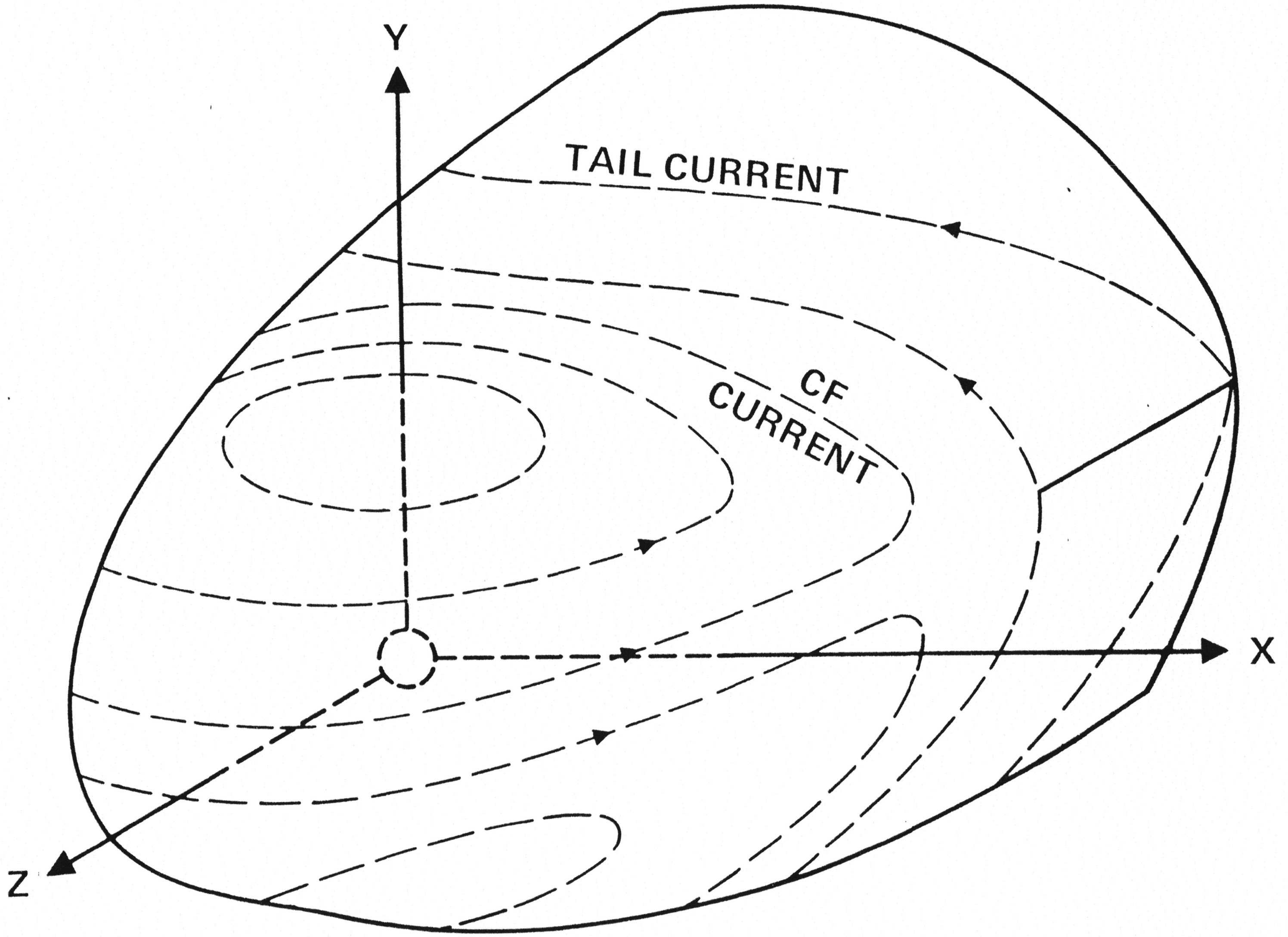
The boundary currents that enforce compression split the separatix (Foreseen by Stern, demonstrated explicitly by Crooker)

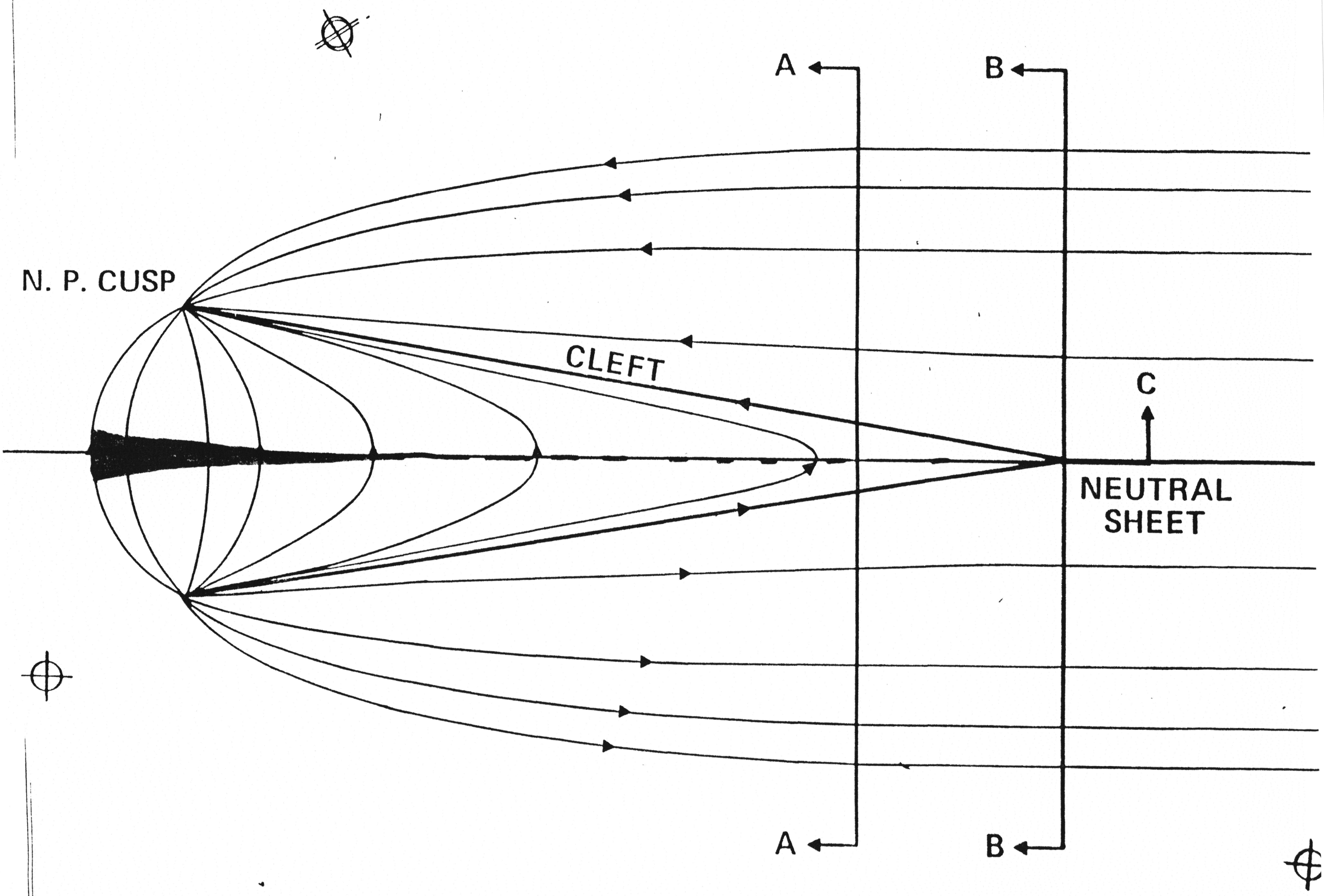
Mapping to Earth

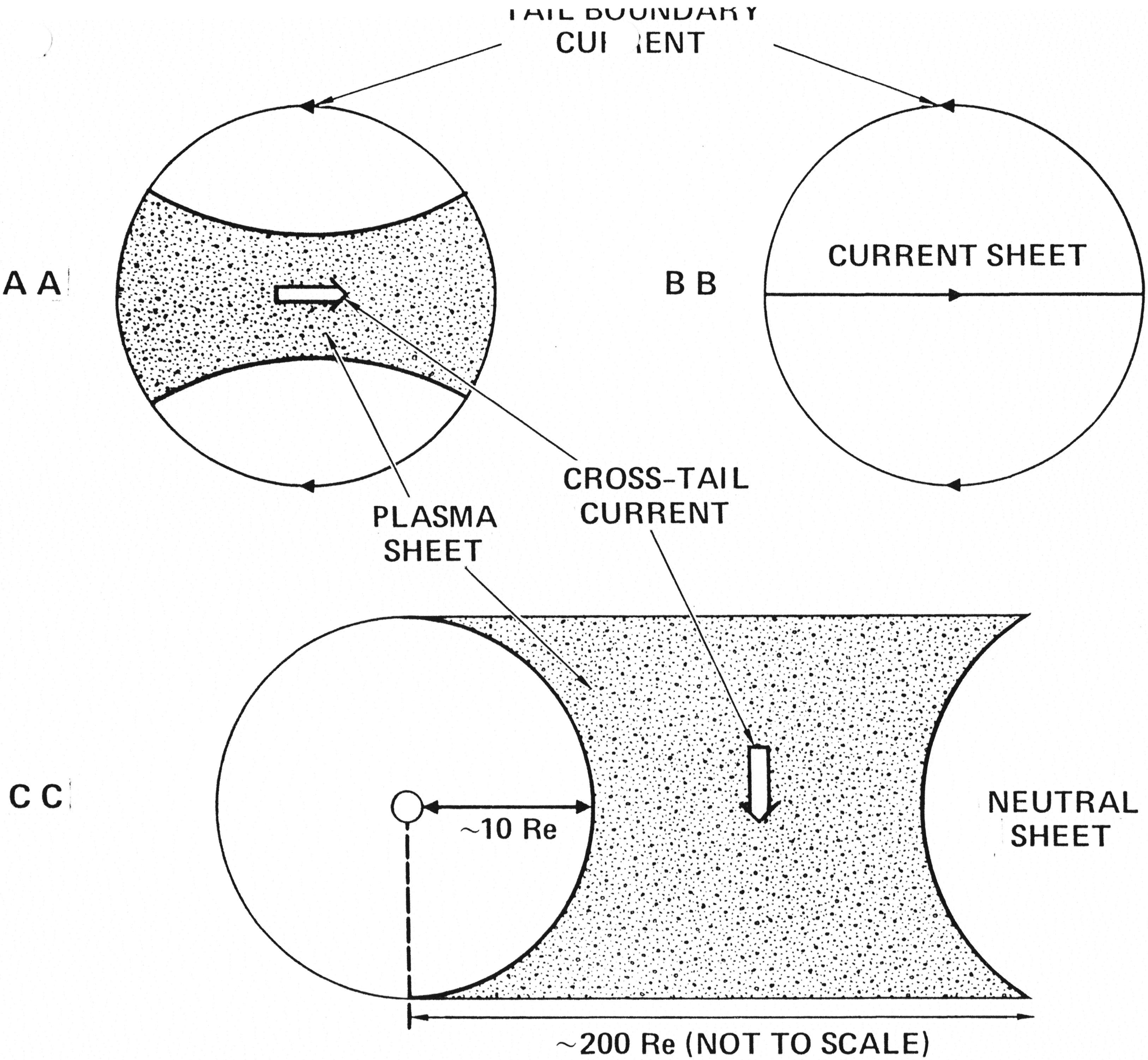


Separatrix forms entire polar cap boundary.
The border of the closed-field-line magnetopause maps to a single point in the ionosphere.




Y
TAIL CURRENT
CF
CURRENT
X
Z


A
B
N. P. CUSP
CLEFT
C
NEUTRAL SHEET
A
B

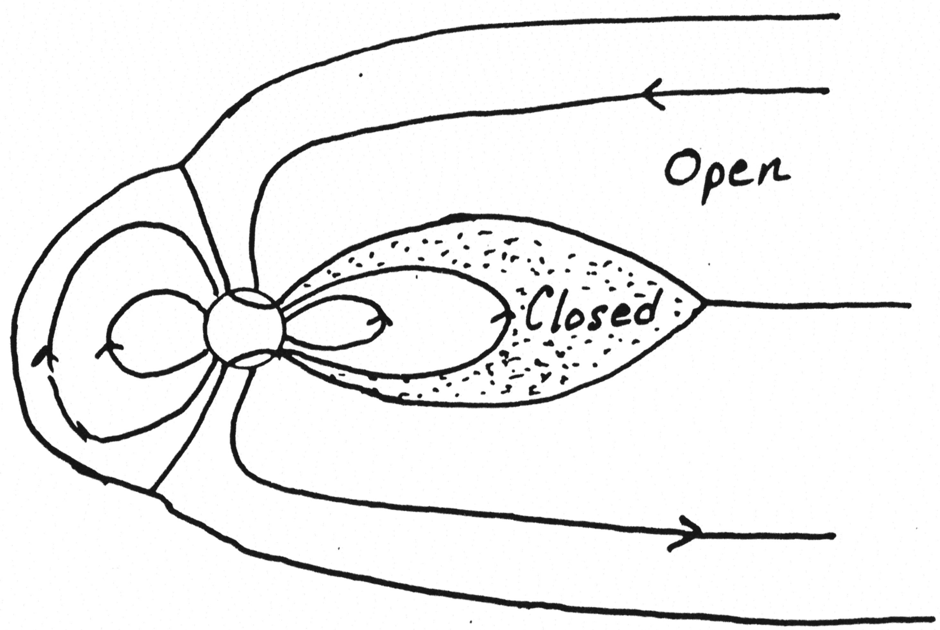


A A
B B
CURRENT SHEET
PLASMA SHEET
CROSS-TAIL CURRENT
C C
~10 Re
NEUTRAL SHEET
~200 Re (NOT TO SCALE)

1.B.ii. The Problem of shape:

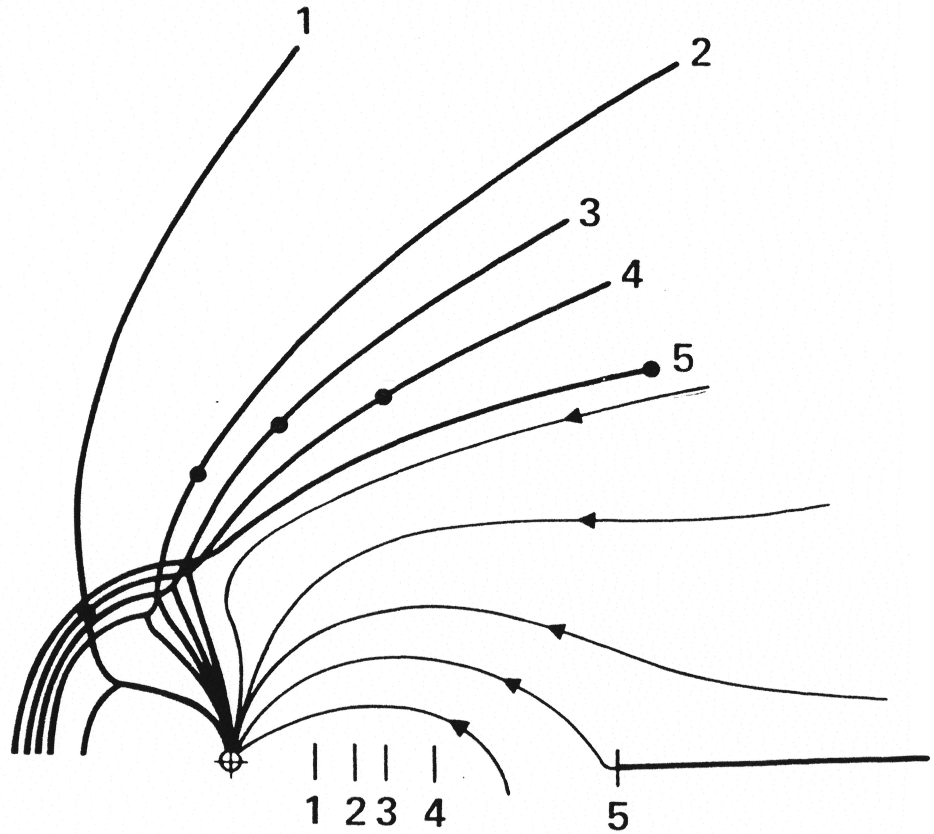
Extra Factors:

1. Internal plasma must be self-consistently represented.
2. Open and closed field lines require separate physics to specify B_n at midplane and the down-tail boundary condition.
3. Need static pressure in solar wind to confine open field lines.



No complete (3D), self consistent (plasma + field), solution to the global (CF + Tail) problem with closed magnetopause exists.

A 2-D, non-self consistent (only open field lines-no plasma), complete (CF + Tail) solution exists



Unti and Atkinson (1968)

Features: Shows qualitative relation between open flux in the tail, the distance to the sunward edge of the tail current, the flaring of the tail, and the erosion of the dayside. As the amount of open flux increases (as a model parameter), the current sheet moves sunward and the boundary flares out behind and moves in in front.

Model incorporates the qualitative aspects of the global instability model of the magnetospheric substorm.

1 . B . ii. continued.

The 2-D problem with plasma could also be done for the case of static for

balance and isotropic pressure. Then if

$\vec{A} = A(x, z)\,\hat{y}$ is the vector potential, $p = p(A)$, and the momentu
equation becomes

$$\frac{dp}{dA} = -\nabla^2 A$$

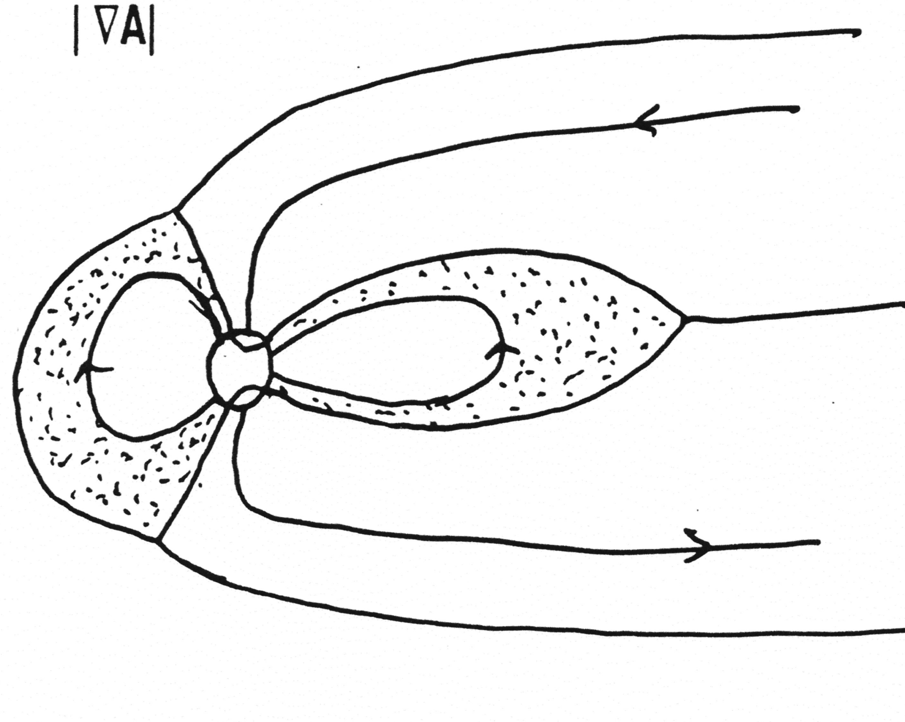
with boundary condition

$$p_{st} \cos^2\psi + p_o = \frac{(\nabla A)^2}{2\mu_o}$$

on the line $A = 0$

where $\cos\psi = \dfrac{|\hat{x} \cdot \nabla A|}{|\nabla A|}$

Specify $p(A)$, p_{st}, and p_o to generate a family of models.



This is a missing study in the hierarchy of magnetospheric models.

The only 3-D model of this type was presented by Coroniti and Kennel in 1972. As in the Unti-Atkinson 2-D model, for a given flux in the tail, it gives the flare and shape of the tail boundary and the distance to the inner edge of the current sheet: the flare and shape from local force balance at the boundary, and the distance to the inner edge of the current sheet from the global force balance between the solar wind's push on the tail and the earth's pull on the tail. Also as in the 2-D model, no flux crosses the current sheet. Thus the plasma is not included. The model is quasi-global in that it is not self-consistently matched to the C-F currents. The physics is approximate and does not lend itself to computer encoding with accuracy determined by computer limitations.

This model is extensively used to relate polar cap flux measurements to tail parameters.

Many more quantitative empirical and theoretical models of the tail field, some including the plasma self-consistently, have been developed subsequently. But they do not have realistic solar wind boundary conditions, and do not self-consistently attach to the magnetosphere, nor to the dayside magnetopause. Nonetheless, one important result of global consequence comes out of these 3-D tail models: they predict dayside erosions too small by more than a factor of 2.

2. Interactive Phase: M gnetopause = transport boundary layers, rotational discontinuities, and expansion fans.

- Three general classes of observations led researchers to abandon the non-interactive, structureless, tangential discontinuity model of the magnetopause:
  1. circulation of magnetic flux from the dayside to the tail and back,
  2. energy dissipation within the magnetosphere and ionosphere, and
  3. variable amount of open flux.

- Within a T. D. magnetopause model, 1. and 2. require boundary layers on closed field lines to transport momentum and energy from the solar wind into the magnetosphere and from there to the ionosphere. The 3rd class of observation requires variable merging with the IMF, thus $B_n \neq 0$ at the magnetopause. MHD structures that satisfy $B_n \neq 0$ and perform the functions of observations 1 and 2 are rotational discontinuities and slow mode expansion fans.

- To answer these observational imperatives, there arose two qualitatively different classes of models: A. low-latitude, closed-field-line boundary-layer models, and
  B. high-latitude, open-field-line R. D. and S. M. E. F. models.

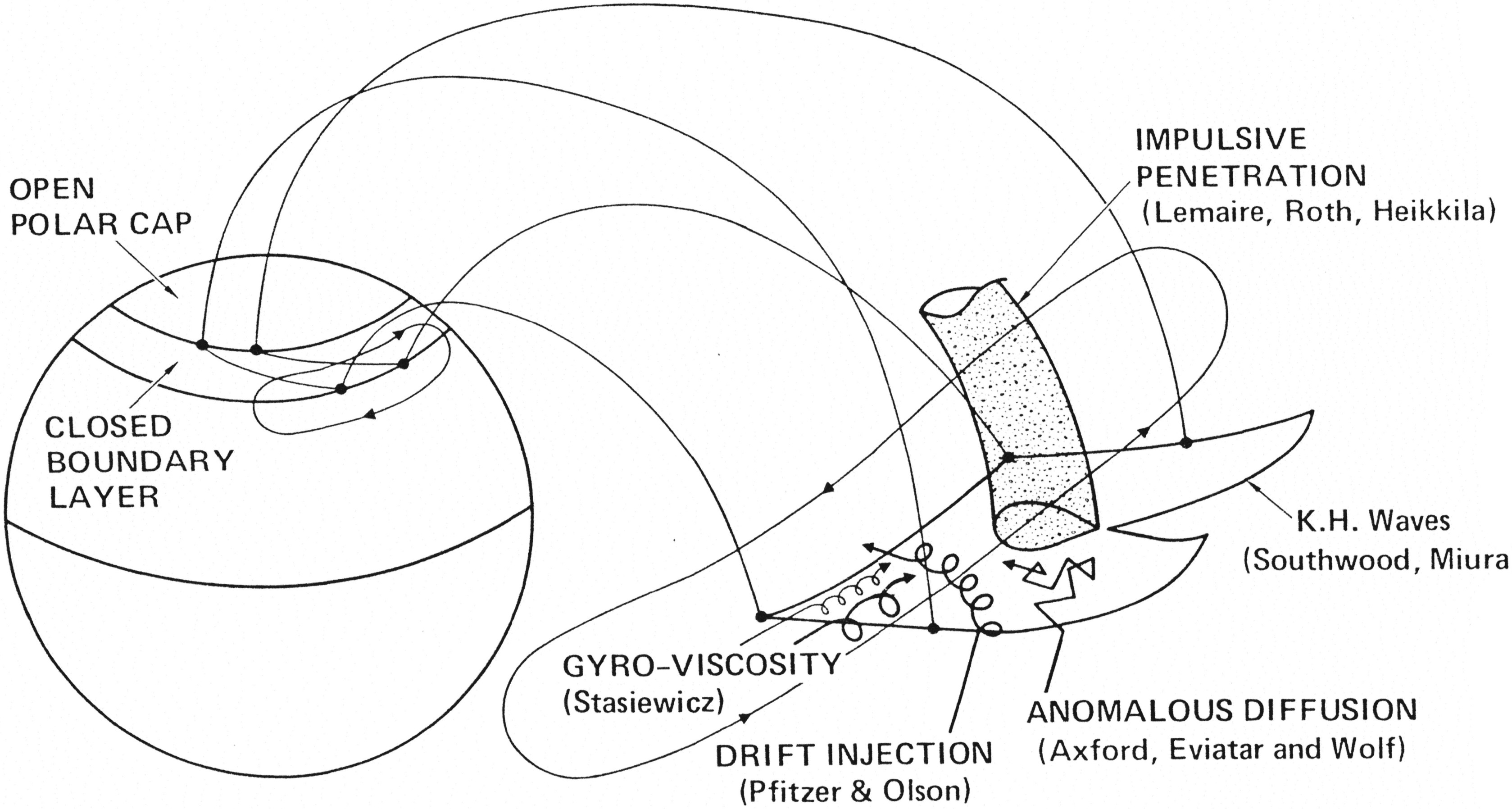
- In addition to these, a third type of magnetopause plasma feature, called the entry layer, was discovered observationally. It is associated with the high latitude, noon cusps, which are apparently vulnerable to direct entry of magnetosheath plasma.

2. A Types of low latitude boundary layers transport phenomena

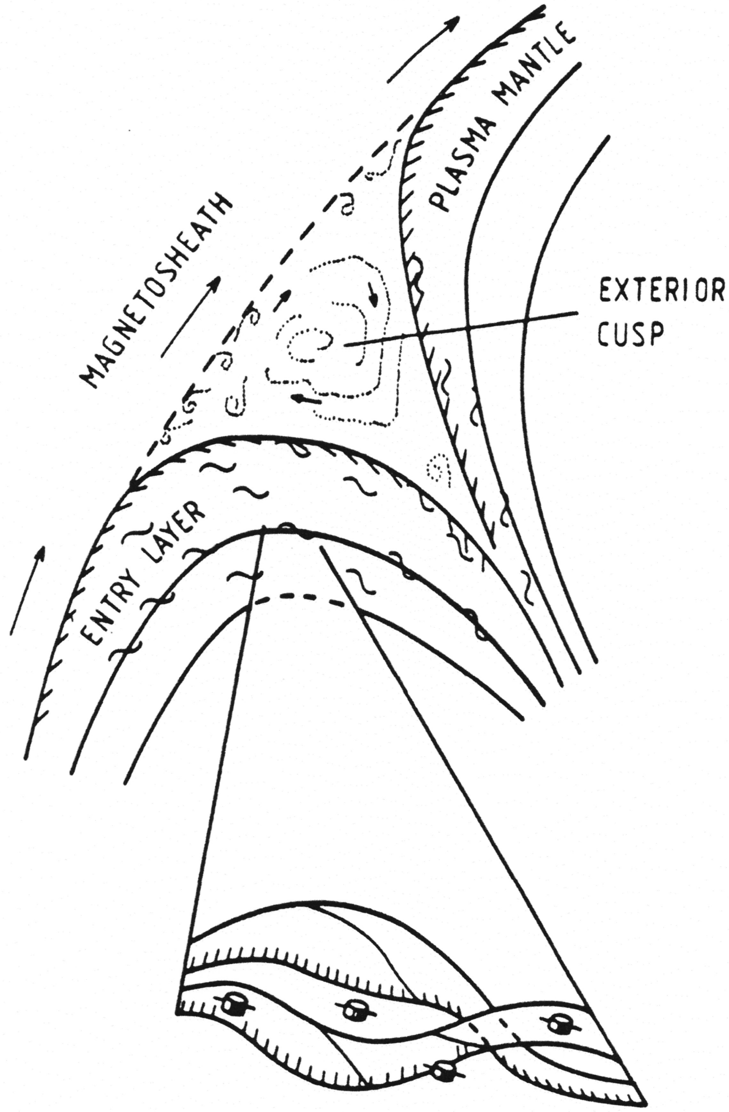
1. Anomalous Diffusion
2. Drift injection
3. Kelvin-Helmholtz waves
4. Impulsive penetration.

Observations:

1. Closed field line boundary layer exists in presence of open field line "window" at higher latitudes.
2. It maps to the dayside portion of an annulus bordering the open field line polar cap. Tangential momentum transfer adds new force to be considered in determining shape. The problem has not been solved.
3. All but gyro-viscosity insensitive to sign of IMF B_Z.
4. Magnetospheric circulation and energy dissipation strongly sensitive to sign of IMF B_Z.
5. Closed-field-line magnetic flux transported tailward in the boundary layer does not induce tailward motion of open field lines at higher latitudes.
6. The tailward transport of open field magnetic flux exceeds that in the boundary layer typically by more than a factor of five. (This ratio is probably highly variable.)
7. Direct measurements of rate of tailward transport of magnetic flux in the low latitude boundary layer gives an upper limit of about 20% of total rate of flux transport.


OPEN
POLAR CAP
CLOSED
BOUNDARY
LAYER
IMPULSIVE
PENETRATION
(Lemaire, Roth, Heikkila)
K.H. Waves
(Southwood, Miura)
GYRO-VISCOSITY
(Stasiewicz)
DRIFT INJECTION
(Pfitzer & Olson)
ANOMALOUS DIFFUSION
(Axford, Eviatar and Wolf)

2. A' The entry layer



(From Haerendel)

Properties: Seen in the vicintiy of the high latitude, noon cusps. Density and temperature of the plasma similar to that in the magnetosheath, but flow speed and direction are irregular - unlike those in the magnetosheath.

2.B. Non-T.D. Magnetopause.

Two problems:

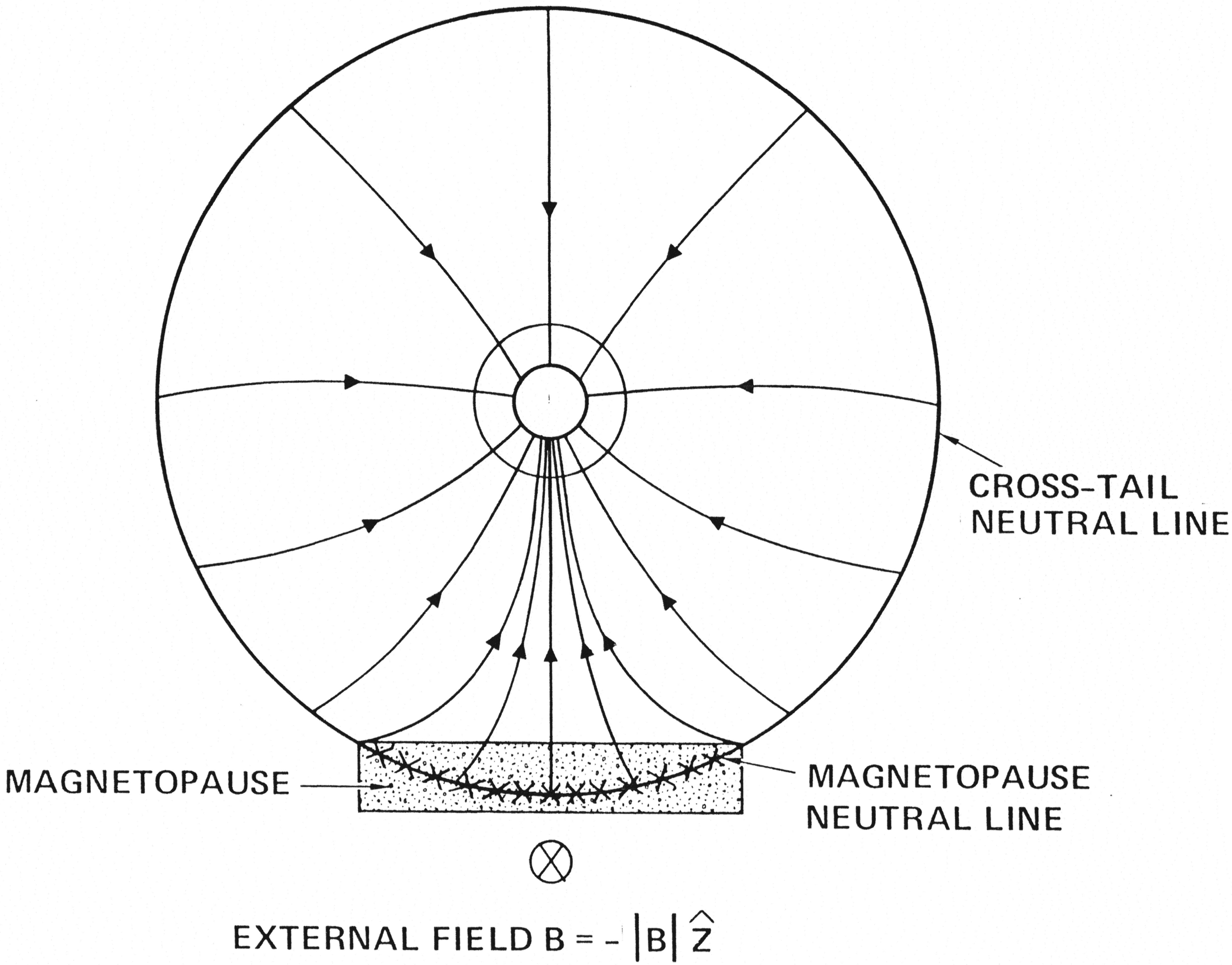
i. topology, and

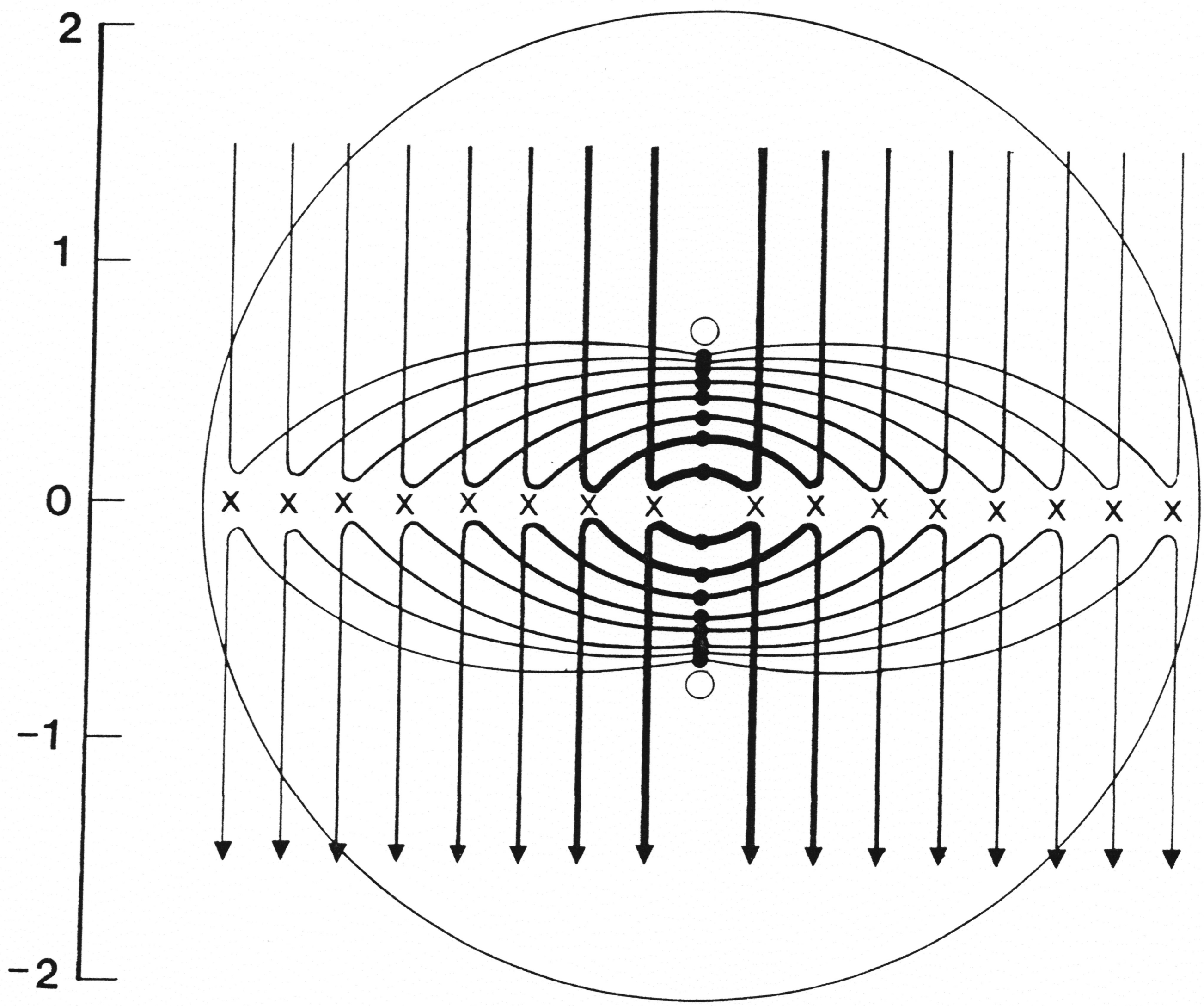
ii. structure.

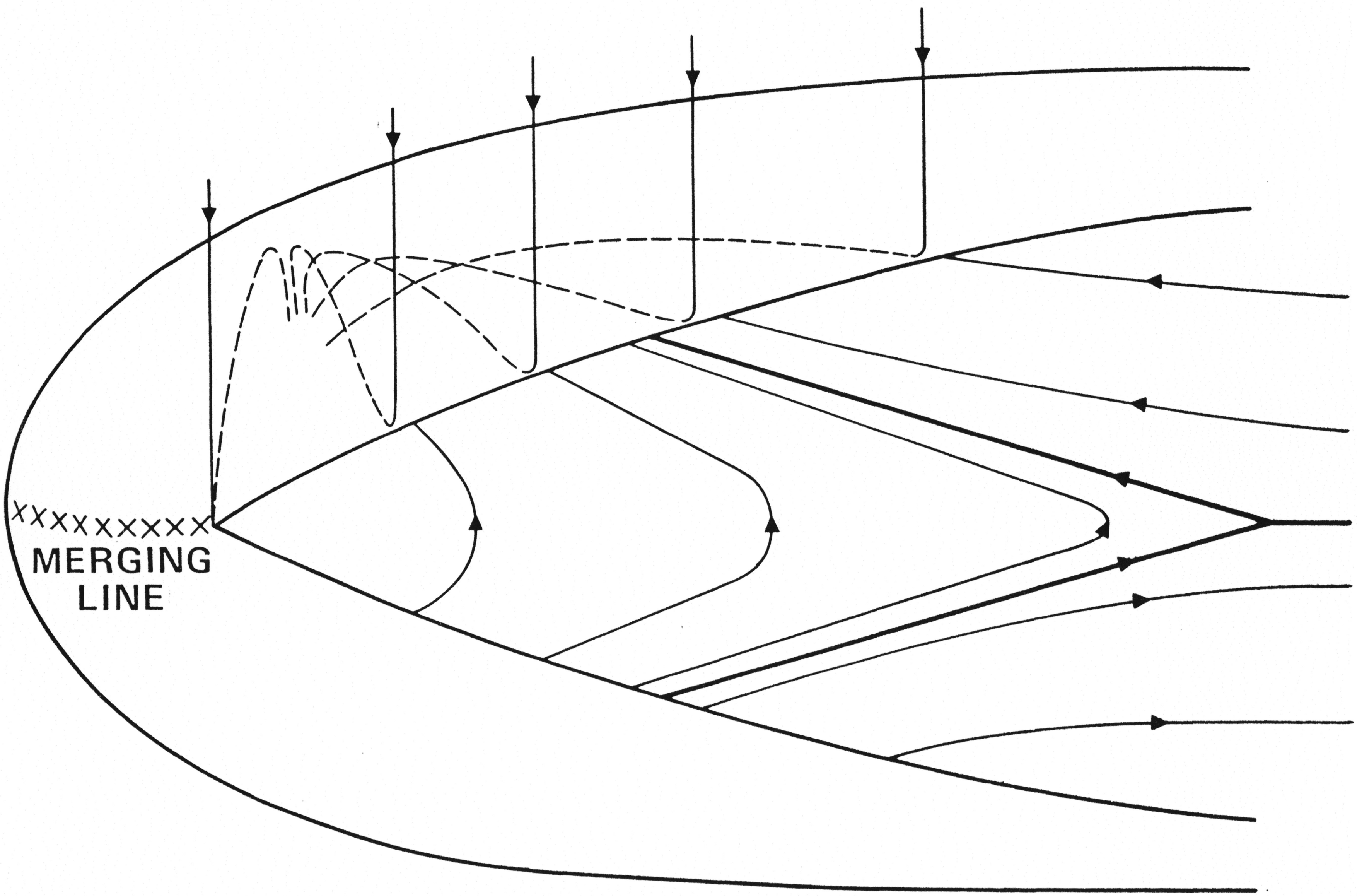
2.B.i. Topology.

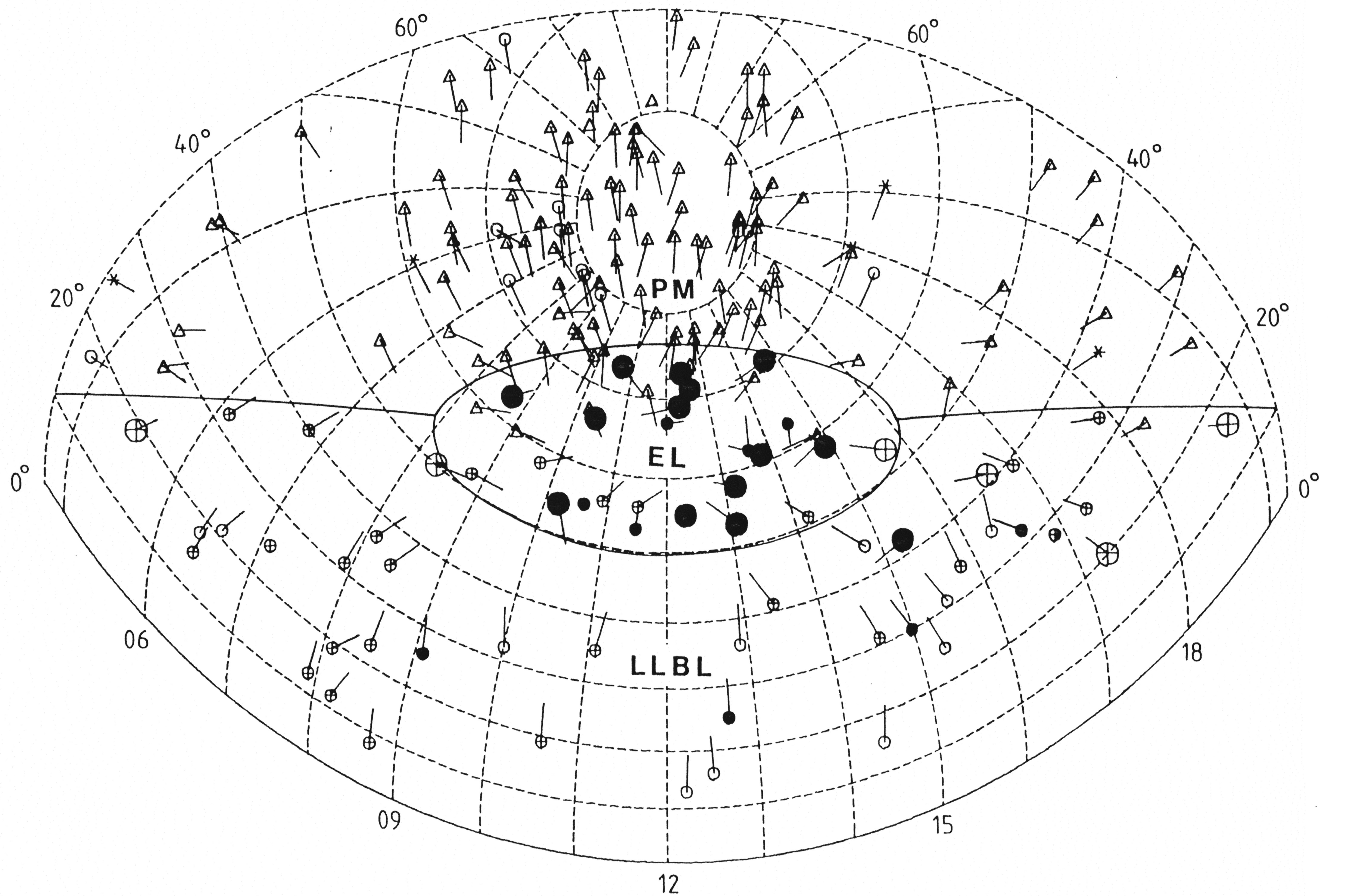
If $B_n = 0$, the magnetosheath wind will continually carry the penetrating flux tailward, thus producing a time dependent return to a $B_n = 0$ situation, or requiring continual conversion of closed to open field lines to constantly feed to the magnetosheath wind. Topologically that conversion must take place at a neutral point or a neutral line at the magnetopause. A second (though non-topological) requirement is that MHD must be violated by some dissipative process in a volume that contains the neutral point or neutral line, where the actual conversion of closed to open field lines takes place. We saw that in the case of the T.D. magnetopause with tail, the neutral line starts on the boundary of each flank at points too far tailward of the earth to be useful for merging at the dayside magnetopause.

Finite thickness magnetopause and southward external field produce continuous neutral line. Cusp opens to a true cleft, and maps to a finite dayside merging line in the ionosphere. The length of this line doubtless depends on the strength of the external field, but it has not been calculated.


CROSS-TAIL
NEUTRAL LINE
MAGNETOPAUSE
MAGNETOPAUSE
NEUTRAL LINE
EXTERNAL FIELD B = - |B| $\hat{z}$


2
1
0
−1
−2


XXXXXXXXX
MERGING
LINE



60°
60°
40°
40°
20°
20°
0°
0°
PM
EL
LLBL
06
09
12
15
18

2.B. Structure of high-la..tude, open-field-line magnetopause.

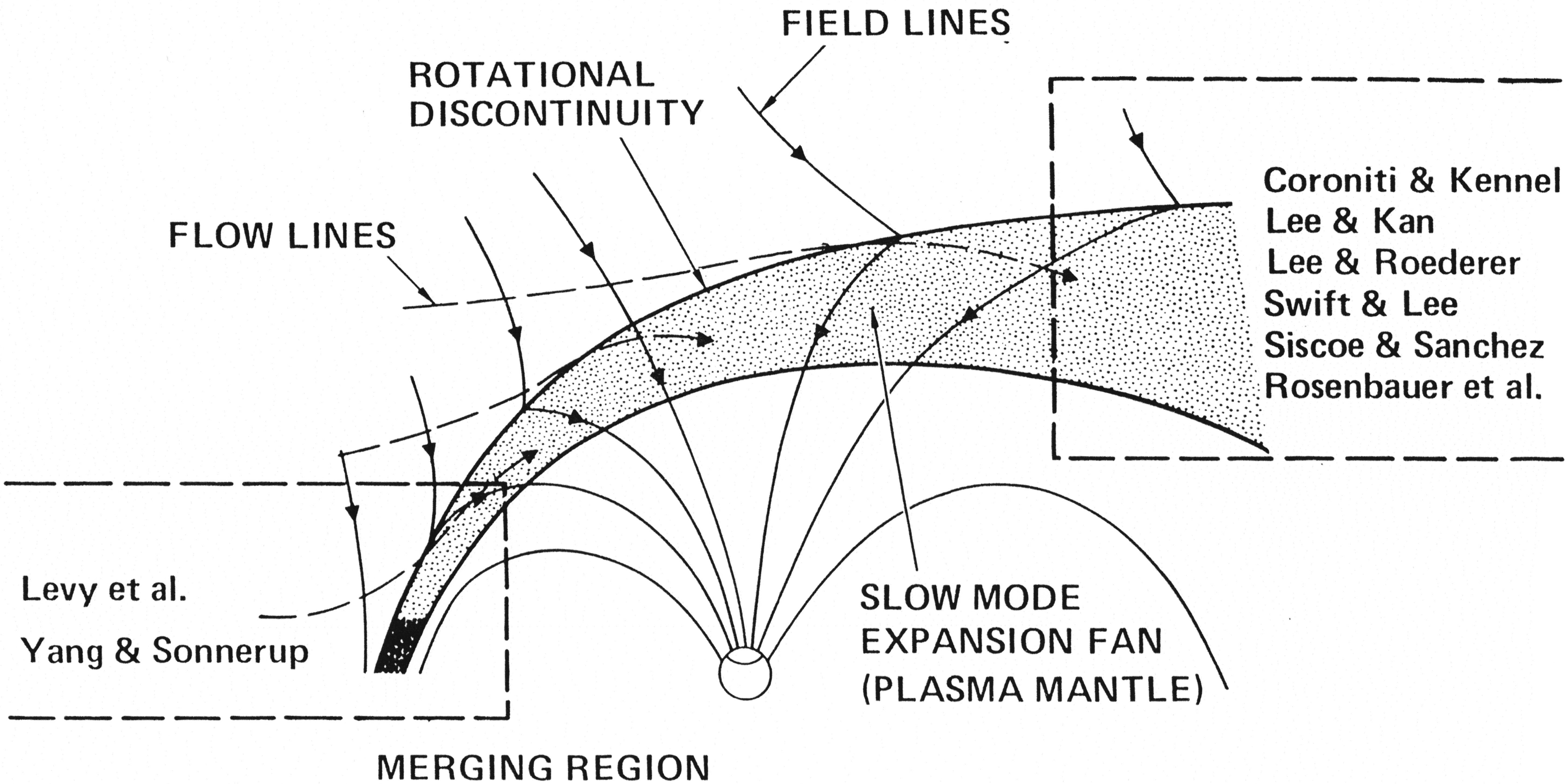
Features:

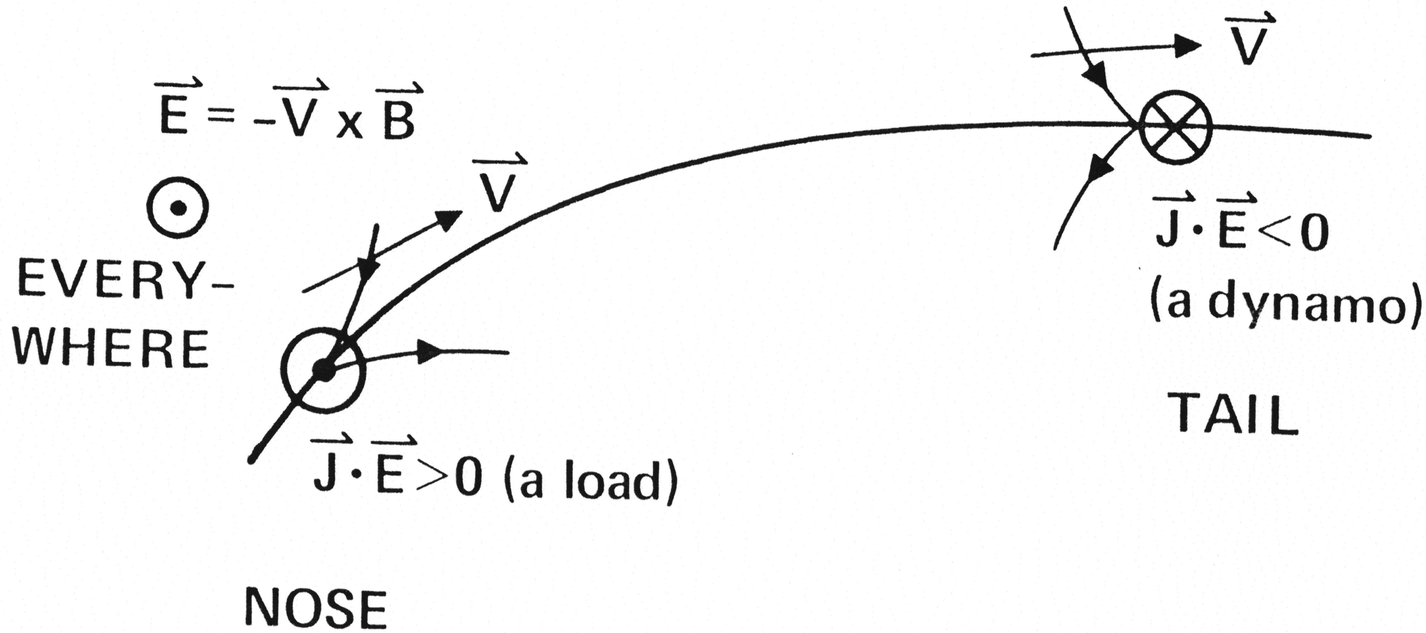
1. Merging region where local dissipation processes violate MHD and allow the IMF (shown here to be purely southward) to link onto geomagnetic filed lines.
2. Outside of the non-MHD, merging region, a R.D. pivots the IMF to give it the right orientation to link onto the geomagnetic field.
3. A S.M.E.F. continuously transforms the high-particle-density, low-field-strength conditions that characterize the magnetosheath plasma into the low-particle-density high-field-strength conditions that characterize the magnetosphere and tail.
4. Magnetic energy is converted into thermal and flow energy in the nose part of the magnetopause. (This is a "load" in the language of circuit theory.) Flow energy is converted into magnetic energy and Poynting flux at the tail magnetopause (a "dynamo") (MHD electromechanical energy conversion theorem

$$-\vec{J} \cdot \vec{E} = \frac{\partial}{\partial t} \frac{B^2}{2\mu_0} + \nabla \cdot \vec{S}$$

The total energy consumed by the boundary load is less than generated by the boundary dynamo.

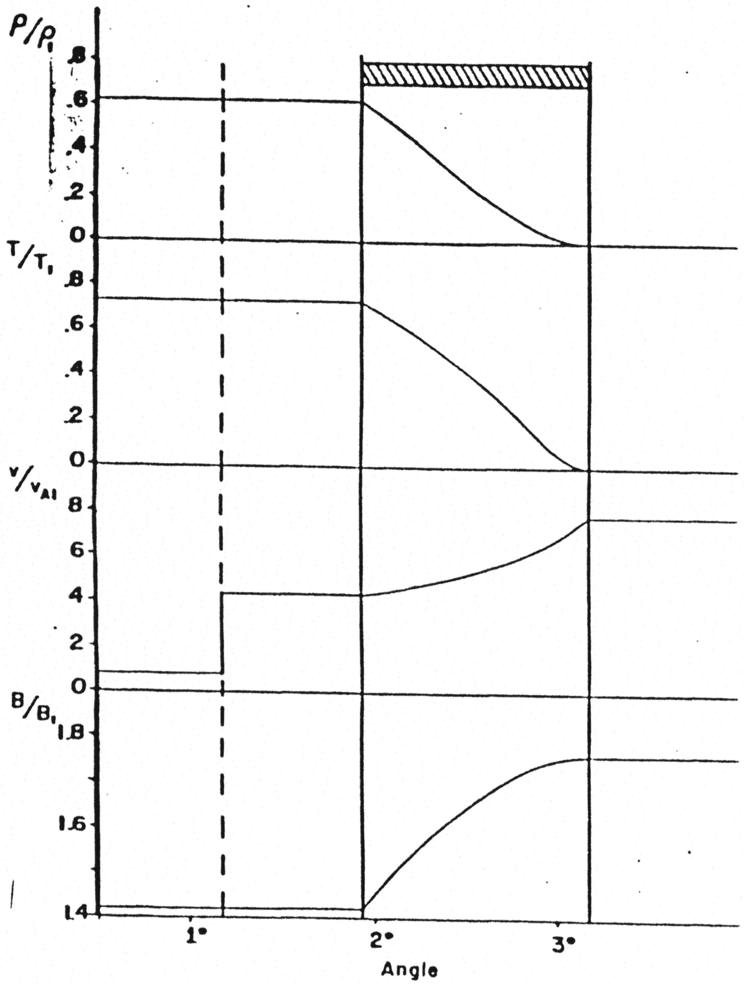
5. The problem of shape not solved.


FIELD LINES
ROTATIONAL DISCONTINUITY
FLOW LINES
Coroniti & Kennel
Lee & Kan
Lee & Roederer
Swift & Lee
Siscoe & Sanchez
Rosenbauer et al.
Levy et al.
Yang & Sonnerup
SLOW MODE
EXPANSION FAN
(PLASMA MANTLE)
MERGING REGION



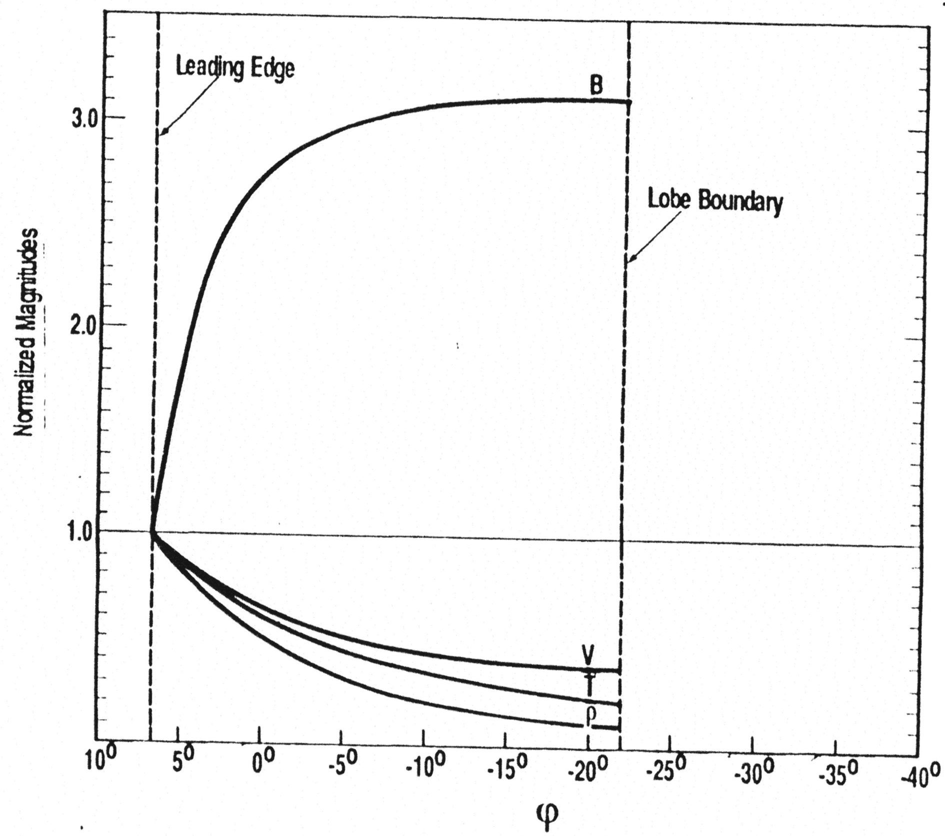
$\vec{E} = -\vec{V} \times \vec{B}$
$\odot$
EVERY-
WHERE
$\vec{V}$
$\vec{J} \cdot \vec{E} > 0$ (a load)
NOSE
$\vec{V}$
$\vec{J} \cdot \vec{E} < 0$
(a dynamo)
TAIL

NOSE



YANG & SONNERUP 1977

TAIL



SISCOE & SANCHEZ 1987

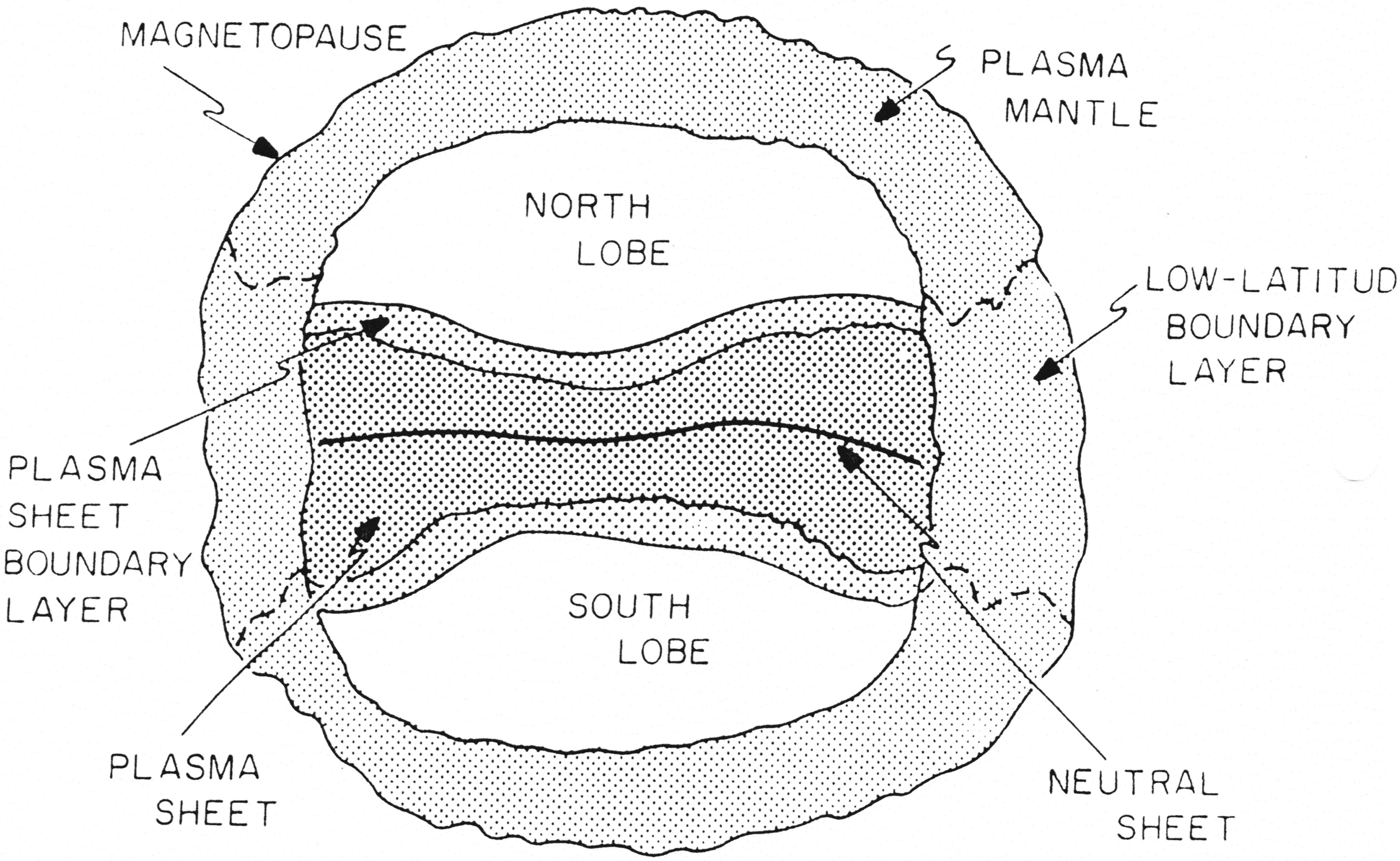
2.A&B. Synthesis of High and Low Latitude Boundary Models.

The consensus view is that the tail boundary comprises a T.D. bounding closed field lines at low latitudes and a S.M.E.F. propagating into open field lines at high latitudes. Together they carry the tail boundary current from the dusk side to the dawn side. But one is thin and the other is thick. How do they join to make a composite tail? The answer to this question is a first step toward a quantitative model of the complete tail boundary.

The figure shows one proposal that solves the problem. The thickness of the S.M.E.F. is a strong function of the initial inclination of the entering magnetic field. The draping of the IMF around the tail boundary, as pivoted by the R.D. into the S.M.E.F.'s plane, automatically changes the inclination to make the fan thin at the juncture.

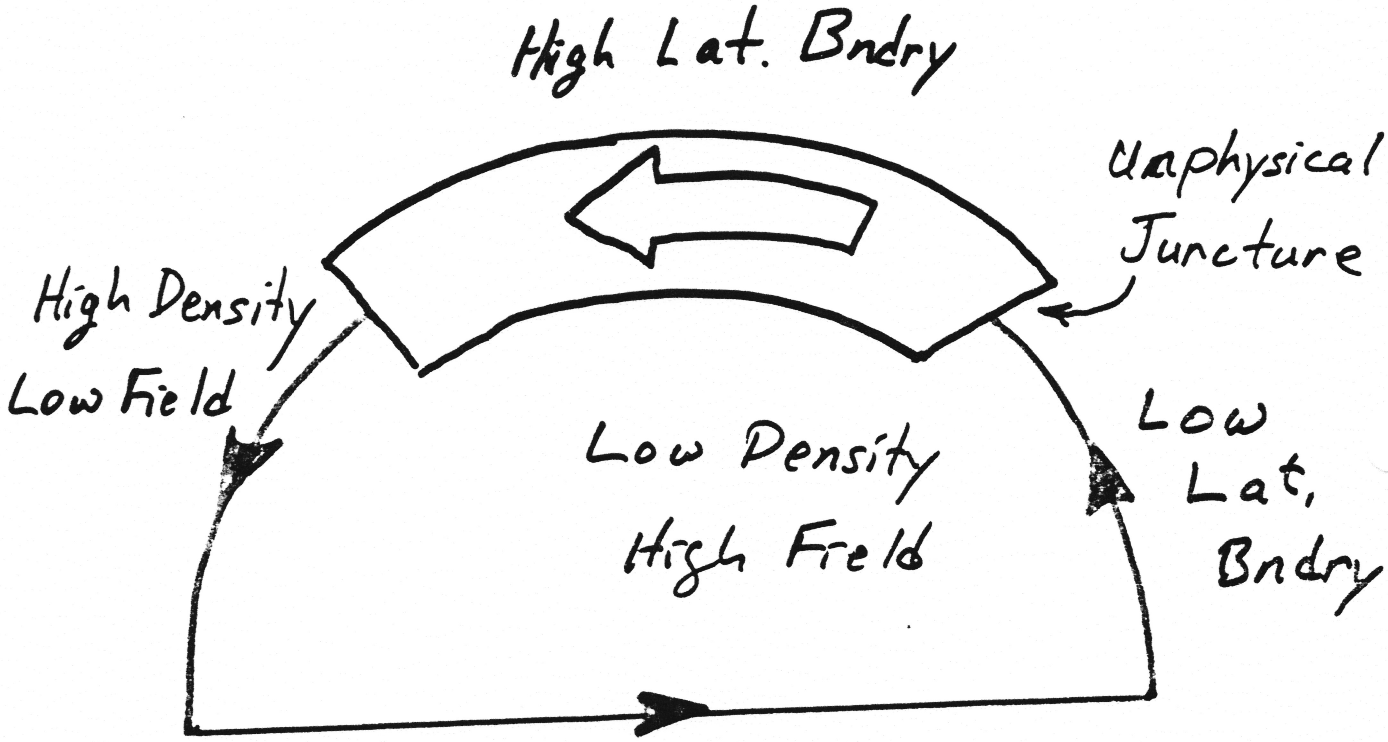
This boundary model is dynamic. The juncture propagates poleward at the Alfven speed. Thus the width of the open field line window decreases down the tail (Stem) and the tail cross section elongates in the direction of the IMF (Sibeck et al.).

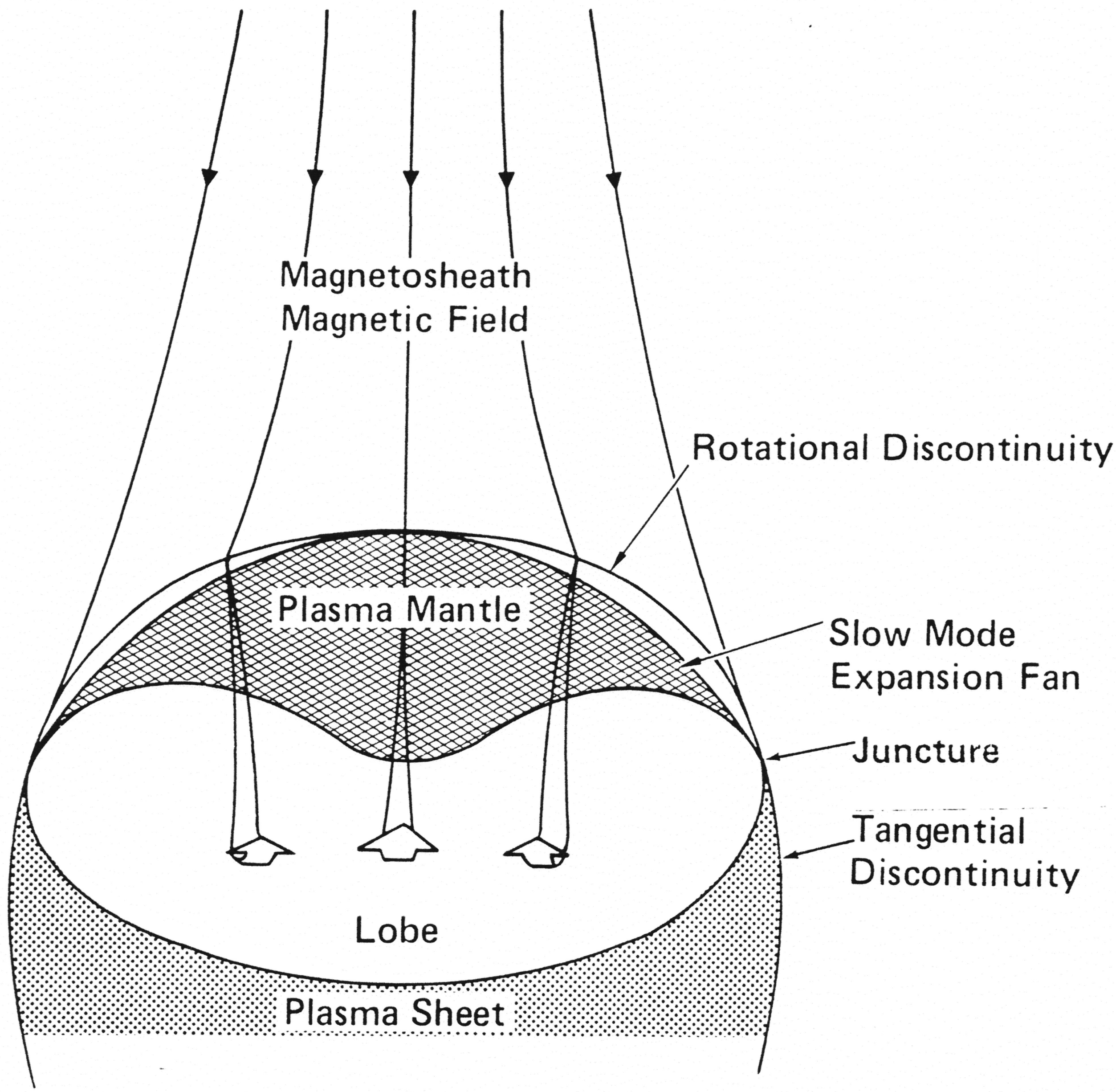
Note inconsistency with T.D. model: cleft goes equatorward.
Note mapping to ionospheric p.c. boundary.



MAGNETOTAIL CROSS-SECTION AT $\sim 40\ R_E$

THE PROBLEM


High Lat. Bndry
Unphysical Juncture
High Density
Low Field
Low Density
High Field
Low Lat. Bndry



MHD Structure