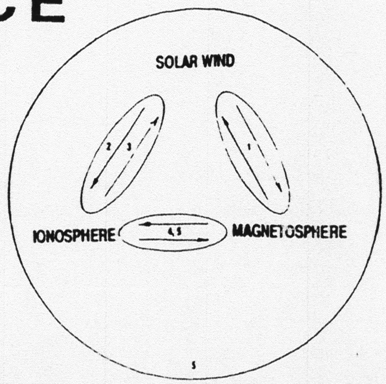
# SOLAR WIND - MAGNETOSPHERE - IONOSPHERE COUPLING

## LECTURE 3

## THE IONOSPHERE'S RESPONSE TO THE SOLAR WIND'S INFLUENCE



# THE IONOSPHERE AS A RECORDER OF SOLAR WIND - MAGNETOPAUSE PROCESSES

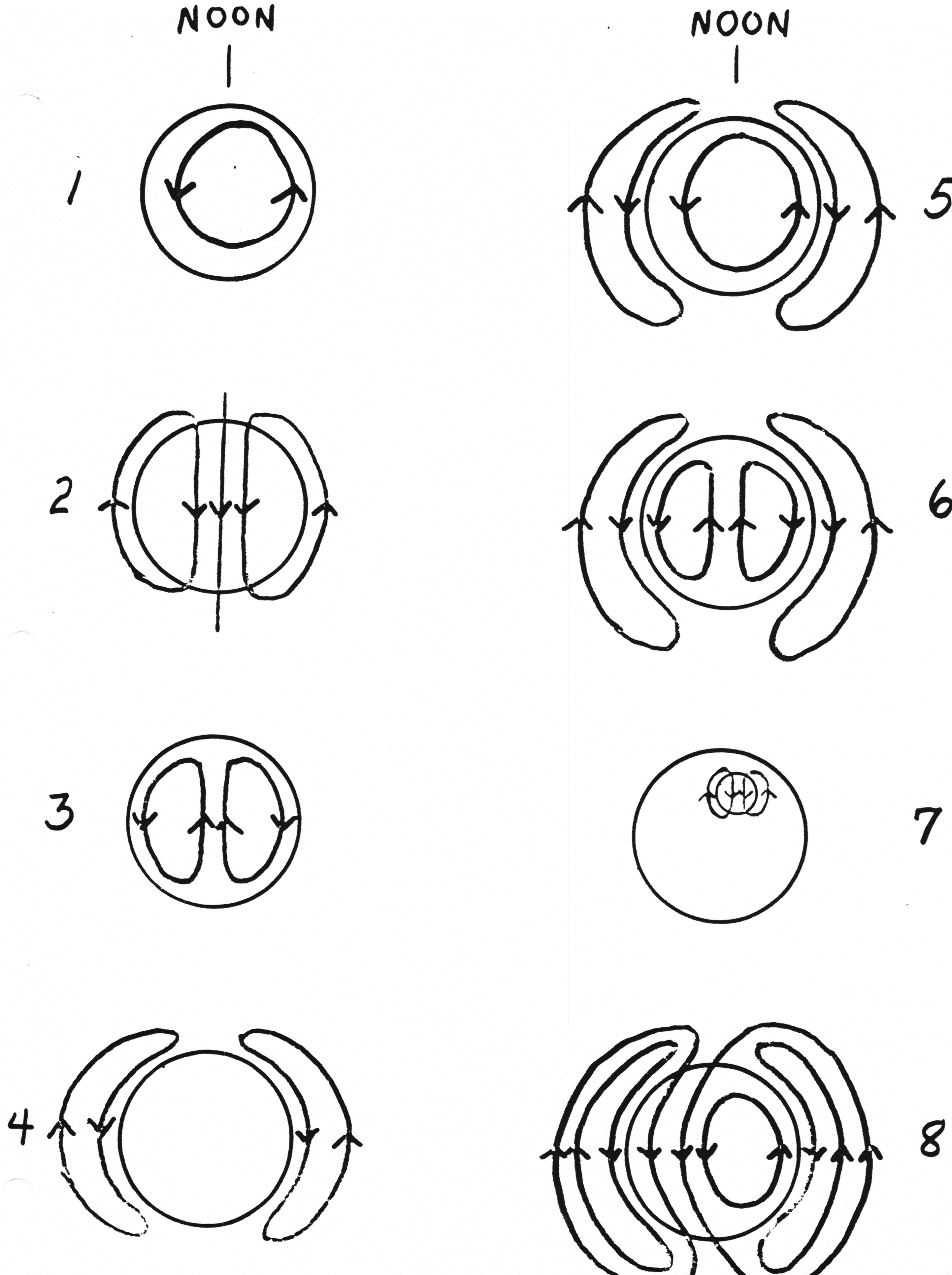
The last lecture left us with a program for eventually determining how the solar wind imparts its influence on the magnetosphere-ionosphere system. It will take time to work it all out. In the meantime the autoanalog computer – the magnetosphere-ionosphere system itself – has solved the problem. Our problem in using nature's computer is reading the output. Though it may not be hopeless, the global configuration is difficult to infer from satellite soundings of the magnetopause. Coordinated multispacecraft campaigns offer the best hope. But there is another approach. After merging has occurred, solar wind field lines and electric field map directly to the ionosphere. The ionosphere records the imprint of the field, and thereby inscribes a history of the event itself and its consequences. The ionosphere is more accessible than the magnetopause, and there are already a wealth of data containing parts of the master imprint. From these parts, "climatological" high-latitude flow patterns have been constructed statistically or inferred by informed extrapolations, and these tell us much about how the solar wind couples to the magnetosphere-ionosphere system.

## Dayside - Nightside
## Magnetopause - Tail
## Different processes, Different timescales, Different time profiles

The solar wind exerts its influences on the magnetosphere-ionosphere at the magnetopause, which maps to the sunward portion of the polar cap and its boundary. We treat the solar wind-dayside processes in this lecture and the tail-nightside processes in the next. This means we set the rate of open-to-closed field merging (which occurs in the tail and governed by processes there) equal to zero. We know by the fact that the amount of open field line flux in the polar cap varies that the rates of closed-to-open and open-to-closed are not always (and possibly rarely) equal. Thus, our isolation of the two regions and the processes they control is reasonable both pedagogically and observationally.

# CATALOG OF HIGH-LATITUDE CONVECTION PATTERNS POSSIBLE FROM MAGNETOPAUSE PROCESSES

1. 1 cell – open-to-open; merging at tail-lobe boundary, open field lines only (Lobe cell)
2. 2 cell-direct – closed-to-open merging, $B_Z < 0$
3. 2 cell-reversed – open-to-open merging, $B_Z > 0$
4. 2 cell-direct – viscous; closed field lines only
5. 3 cells – combination of 1 and 4
6. 4 cells – combination of 3 and 4
7. Moving patches – FTE's
8. General combinations of the above



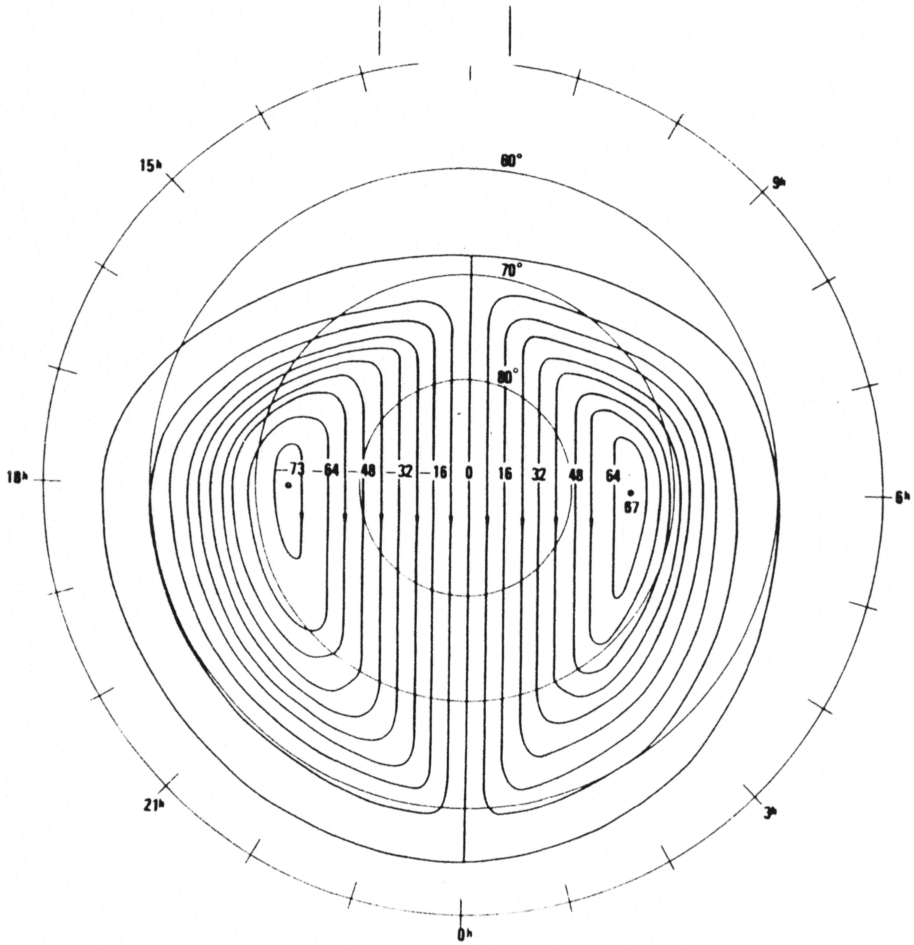
NOON
NOON
1
2
3
4
5
6
7
8

# DYNAMICS AND KINEMATICS OF SOLAR WIND INDUCED, HIGH-LATITUDE FLOWS

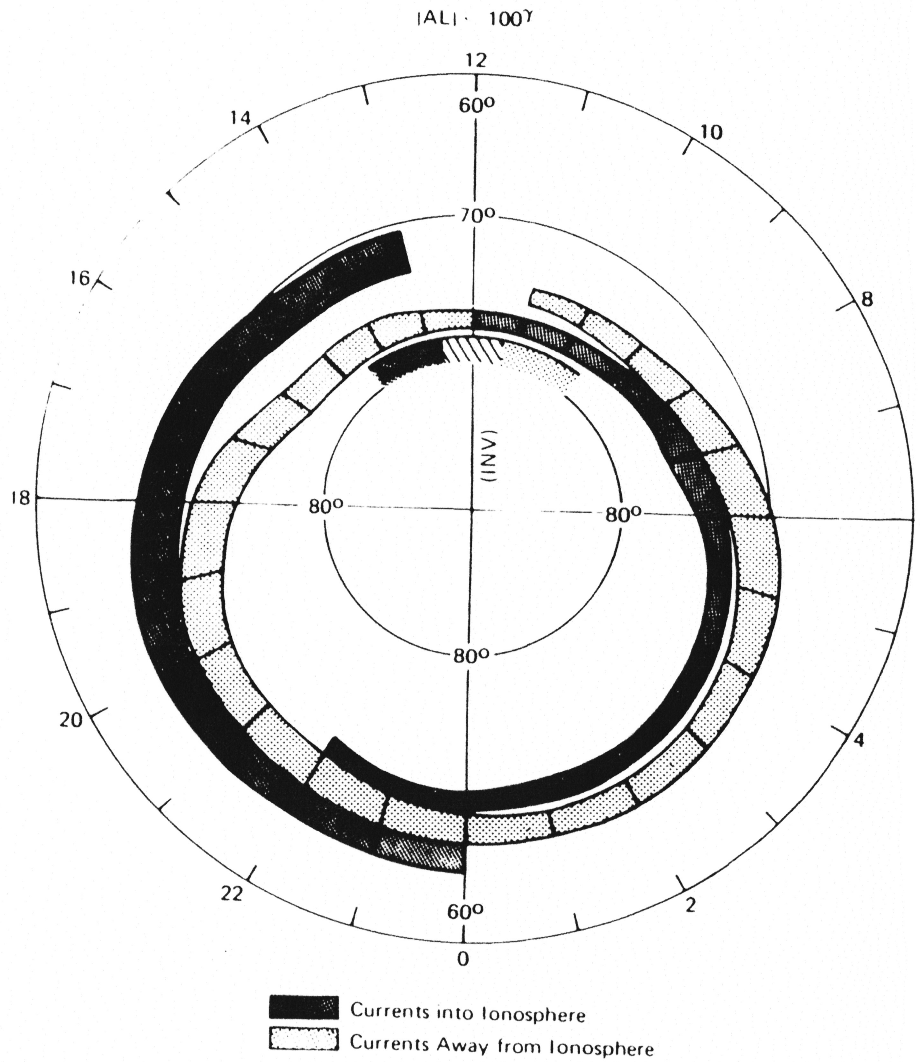
## Mathematical Modeling

Simplifications:
1. The ionosphere is a plane and all quantities are 2-D.
2. The magnetic field is vertical and constant.
3. Conductivities are uniform. (except possibly at discontinuities)

- 2. $\Rightarrow$ $\nabla \times \vec{E} = 0$ and hence $\vec{E} = -\nabla\phi$
- Define flow velocity by $\vec{V} = \dfrac{\vec{E} \times \vec{B}}{B^2} = \dfrac{1}{B}\,\hat{Z} \times \vec{E}$
- Streamlines of $\vec{V}$ are equipotentials
- $\nabla \cdot \vec{V} = 0$ incompressible 2-D flow
- $\vec{J} = \Sigma_p \vec{E} + \Sigma_H \vec{E} \times \hat{Z}$ ionospheric Ohm's law
- $\nabla \cdot \vec{J} = J_{\parallel}$ current continuity eq. (N. H.)
- $$\left\{ \begin{aligned} \nabla \times \vec{V} &= \frac{J_{\parallel}}{\Sigma_p B}\,\hat{Z} \\ \nabla^2 \phi &= -\frac{J_{\parallel}}{\Sigma_p} \end{aligned} \right\}$$ $J_{\parallel}$ is the proximal source of $\vec{V}$ and $\phi$



MODEL "AD": SUN ALIGNED



## TYPES OF MODELS

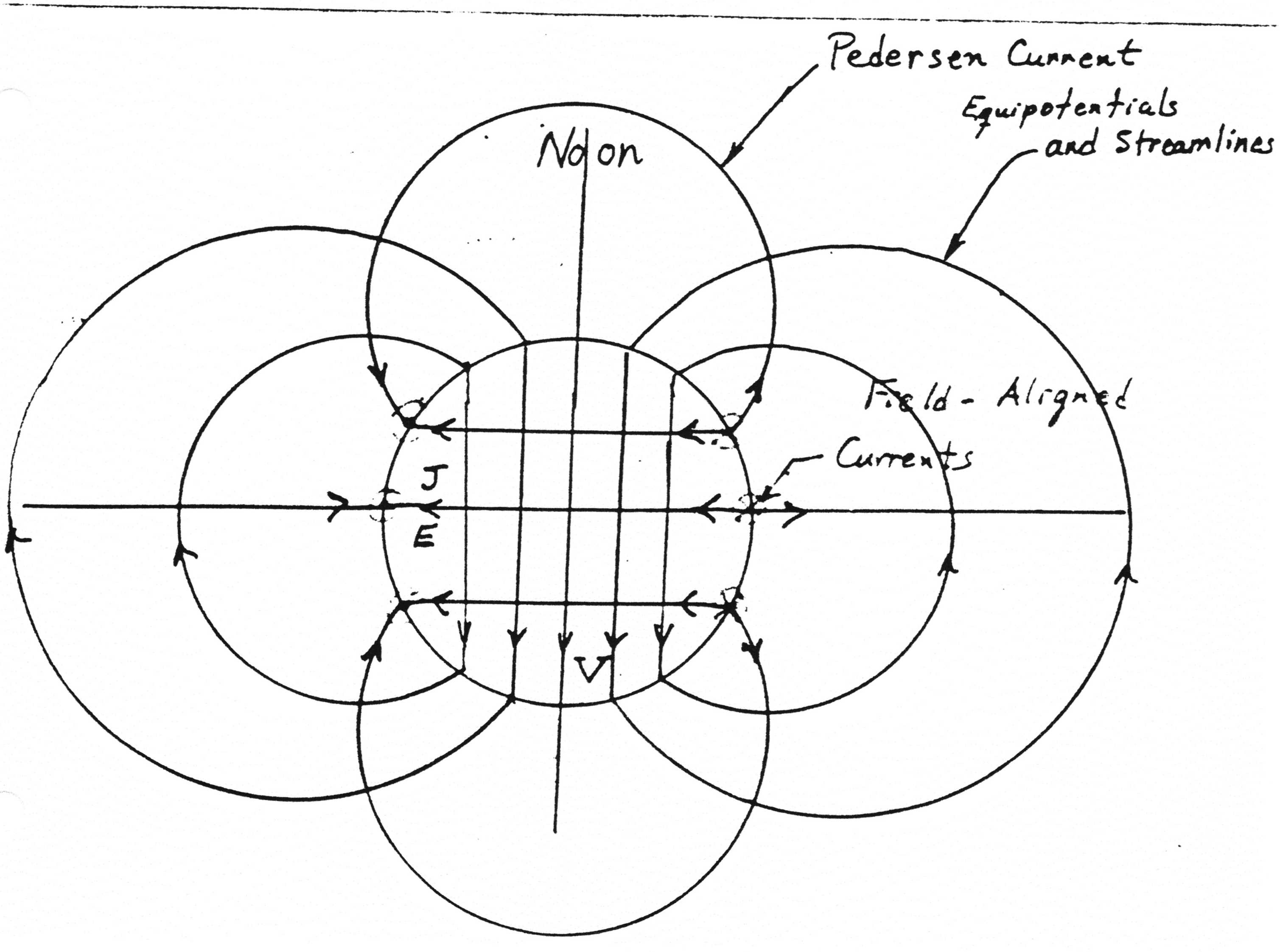
1. $J_{\parallel} = 0$ except on discontinuities
   - A. Specify $J_{\parallel}$ on discontinuities (like equation says).
   - B. Specify $\phi$ on discontinuities (the solar wind is a voltage dynamo)

   Idealization good for developing and illustrating concepts.
2. $J_{\parallel}$ spatially distributed as inferred from observations. Realistic conductivity models. Good for generating "weather maps" of ionospheric flows.
3. $J_{\parallel}$ tied to magnetospheric processes. Good for developing magnetosphere-ionosphere coupling models.


1. Yasuhara and Akasofu (1977), Barbosa (1979, 1984), Volland (1979), Siscoe and Huang (1985), Moses et al. (1987)
2. Nisbet et al. (1978), Nopper and Carovillano (1978), Bleuler et al. (1982), Rich and Kamide (1983)
3. Vasyliunas (1970, 1972), Harel (1979)

# THE SOLAR WIND ELECTRIC FIELD
# AS THE SOURCE FOR IONOSPHERIC CONVECTION

1. The solar wind imprints its velocity and electric field on the polar cap ionosphere ($B_z < 0$)
2. That field at the polar cap boundary gives the boundary condition to the solution of the $\nabla^2\phi = 0$ equation at lower latitudes
3. Pedersen currents flow in response to the E field
4. The divergence of the Pedersen current at the polar cap boundary sets up field-aligned currents
5. Since $\vec{E}$ maps directly from the solar wind, but $J_{\parallel} = \Sigma_p \nabla \cdot \vec{E}$ depends on ionospheric conductivity, $\vec{E}$ must be primary and $J_{\parallel}$ secondary



# VOLTAGE SOURCE VS CURRENT SOURCE

Are the two viewpoints different? Or are they equivalent ways to calculate the same thing? Answer - if ionospheric conductivity is not uniform (and it isn't), a current source and a voltage source with the same spatial distribution give different potential patterns. The observed patterns favor a current source. To see this, we must know about three factors that distort the symmetric two cell pattern that occurs for a pure southward IMF, uniform conductivity case:

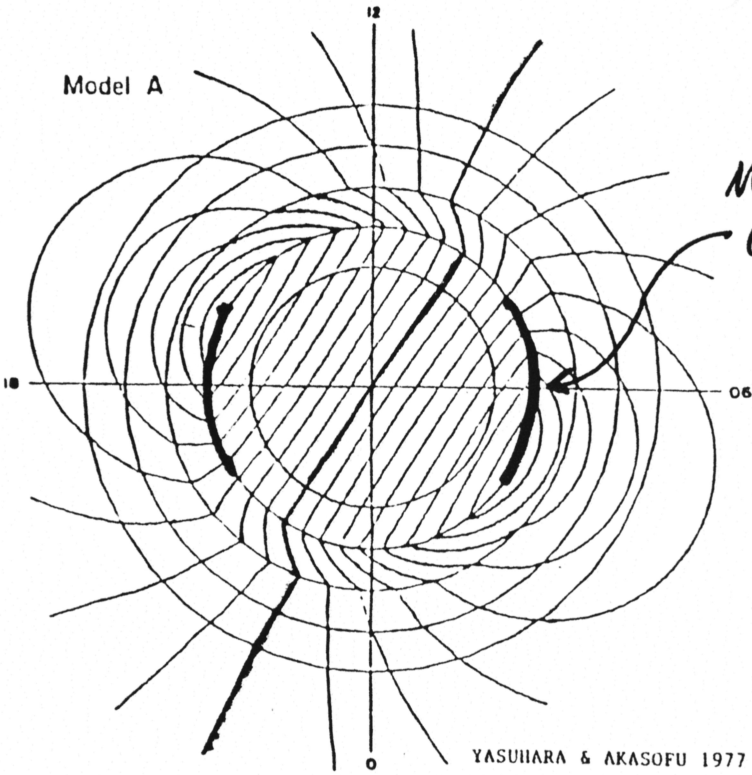
1. the latitudinal gradient in conductivity (it is largest in the auroral zone),
2. the day - night gradient (largest in the sunlit side), and
3. the IMF $B_y$ component, which stirs the flow clockwise or counterclockwise in the polar cap depending on whether $B_y > 0$ or $< 0$, respectively (for N.H.).

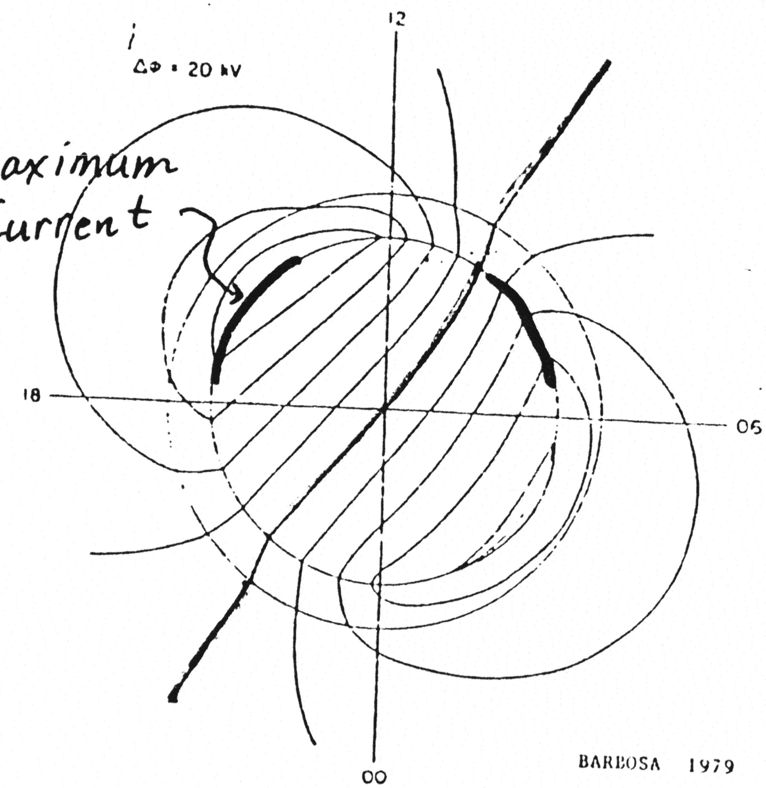
1. In the presence of a high conductance auroral annulus, a current source rotates the potential pattern clockwise. A clockwise shift of the dayside "throat" is consistently seen, while the cusp signature remains centered on noon.

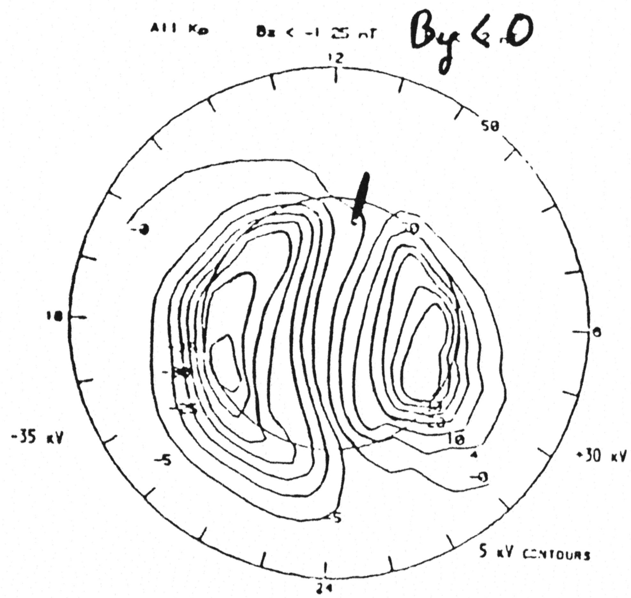
2. Day - night conductivity contrast directs the tailward polar cap flow duskward. This is true for current and voltage sources. For a current source more flux circulates around the dusk cell than the dawn cell. Not so for voltage source. More flux is observed to flow around the dusk cell.

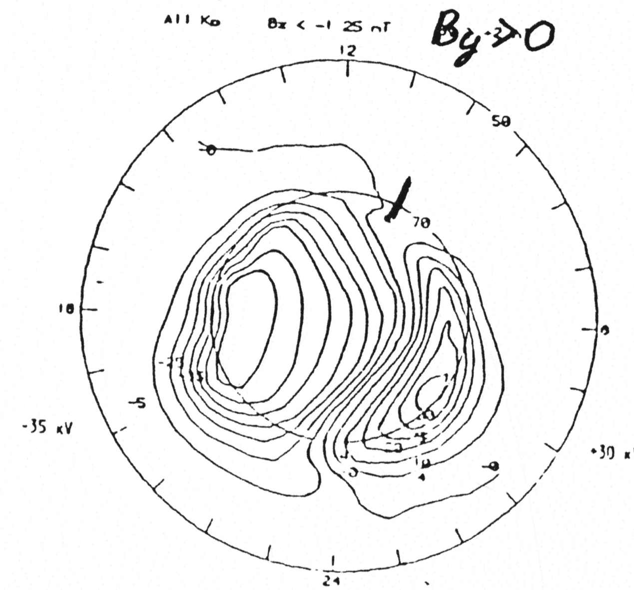
3. The $B_y$ effect has no obvious use in distinguishing between a current and a voltage source.

Final note: Using the fact that current sources distribute current around resistances so as to miminize Joule dissipation, Barbosa (1989) showed that ionospheric currents seem to be so distributed.



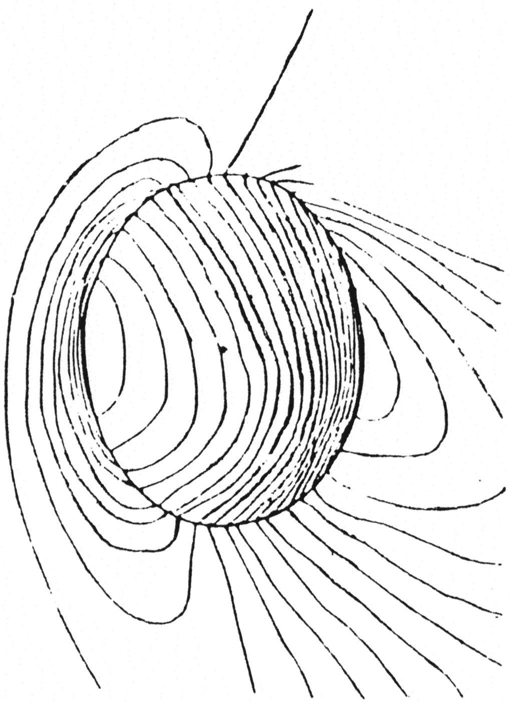



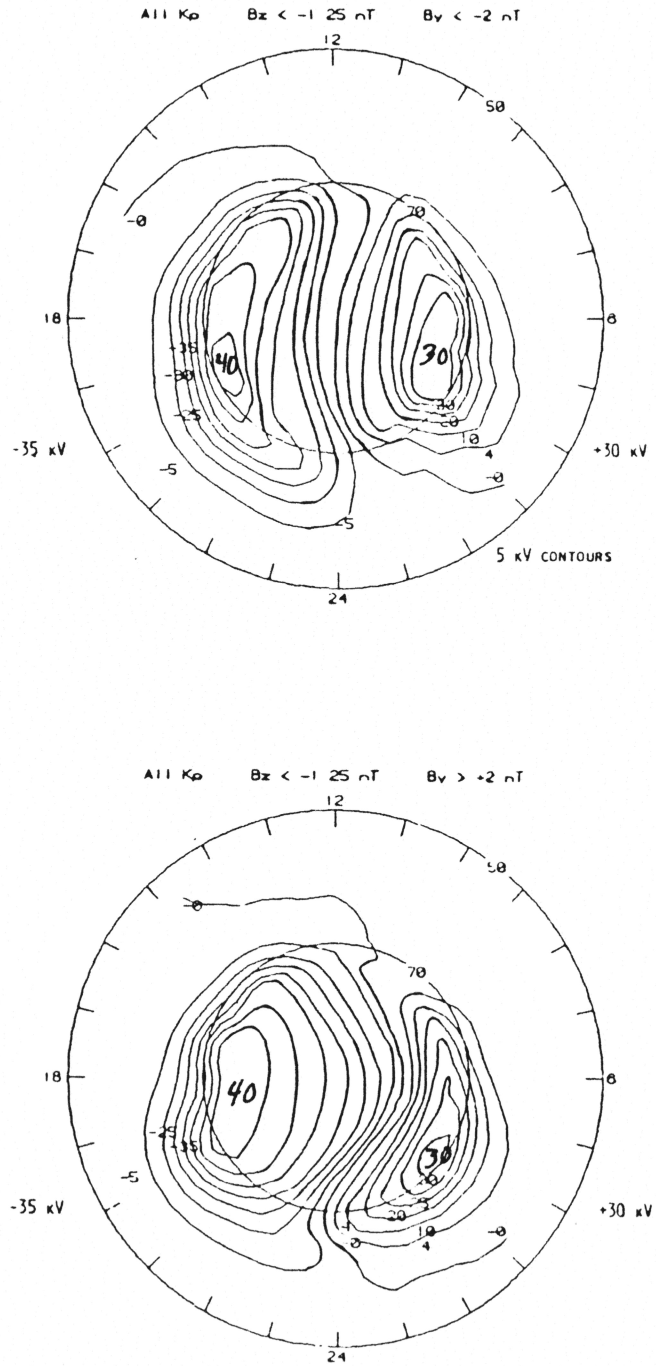




(b)

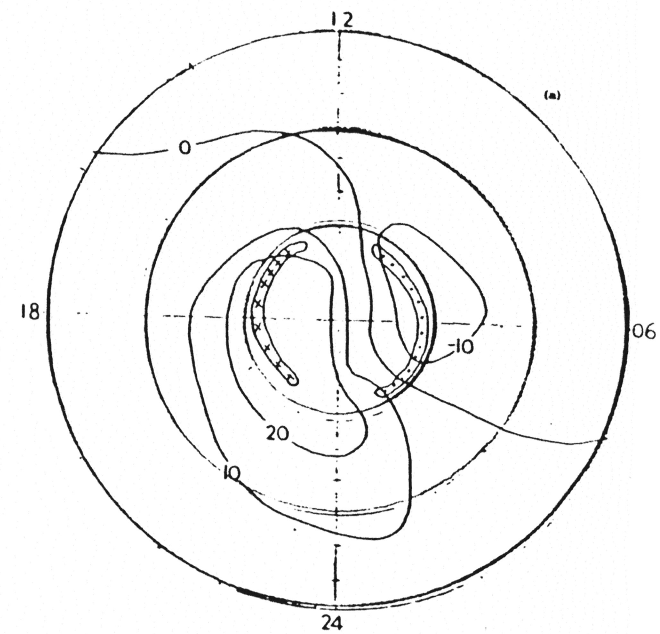
FOSTER ET AL



ATKINSON 1978




(b)




NOPPER 1978

If the solar wind acts like a current source to the ionosphere, then a change in ionospheric conductance changes the transpolar potential

$$\phi = \frac{I}{\Sigma}$$

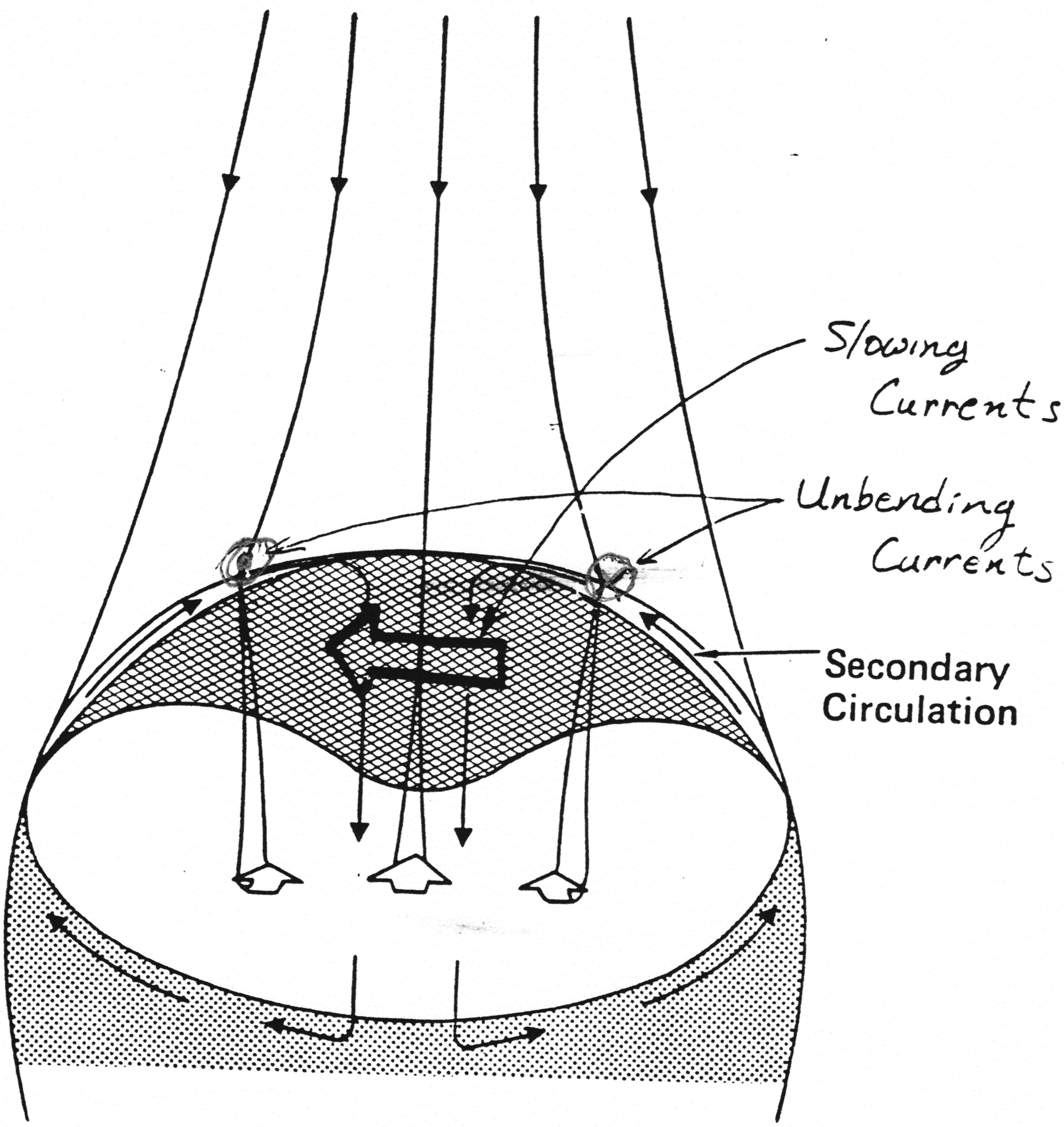
But $\phi$ is determined by the dayside merging rate. Does this mean that the ionosphere is regulating dayside merging? Maybe it regulates merging, but probably also and more importantly the ionosphere is in series (in the language of circuit theory) with a large inductor (the tail) with a variable inductance. The circuit equation then has the form

$$\text{Solar Wind EMF} = \frac{I}{\Sigma} + I\frac{dL}{dt} = \left(\frac{1}{\Sigma} + \frac{dL}{dt}\right)I$$

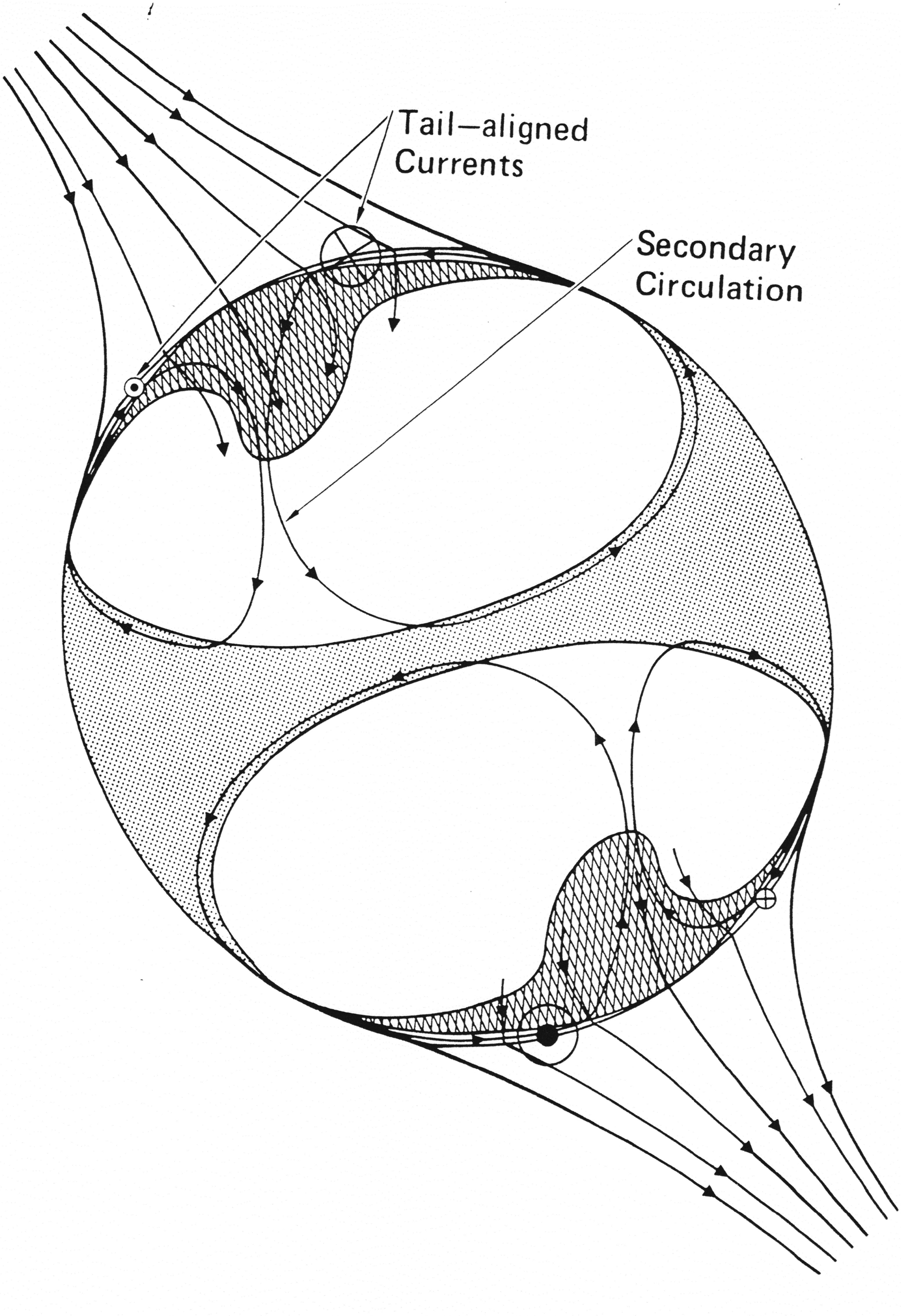
Evidently $\frac{dL}{dt} >> \frac{1}{\Sigma}$, thus I stays roughly constant under changes in $\Sigma$, and the ionosphere sees a current source.

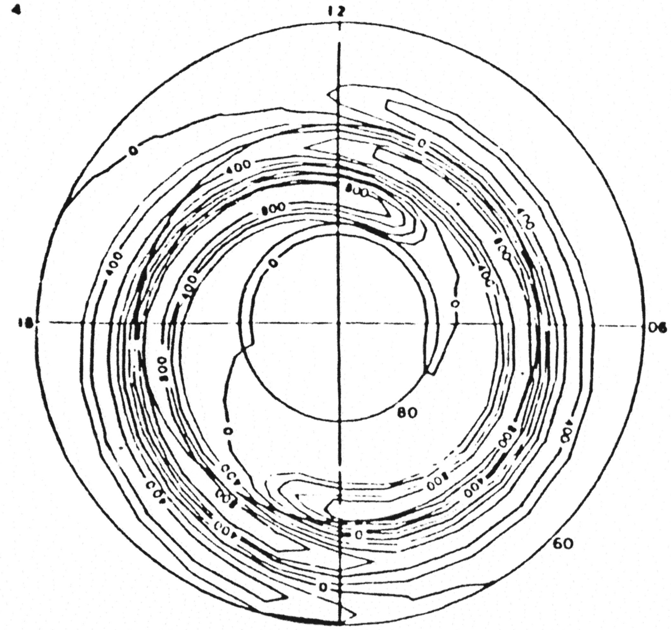
# $B_Y$ EFFECTS AND CUSP CURRENTS

As noted earlier, in the mechanical magnetic-field-lines-are-like-rubber-bands analog, one expects the dawn-dusk skewness of the magnetic field line geometry to deflect the tailward cross-polar-cap flow dawnward (N. H.) for $B_y > 0$ and duskward for $B_y < 0$. This happens. For the mechanical picture to work physically, electrical field-aligned currents must connect the tugger (the solar wind) and the tuggee (the ionosphere) to convey the force from the one to the other. These are not just the region 1 currents rotated to give the flow a kick in the right direction, as dictated by the magnetic geometry. The region 1 currents arise to communicate the ionosphere's resistance to the solar wind's flow, and thereby to slow it. The deflecting current conveys the ionosphere's resistance to the solar wind's attempt to straighten out its field lines that were distorted by coupling to the earth's field. The breaking currents and the unbending currents take different paths on the magnetopause. The former map to where the region 1 currents are found. The latter map to the polar cusp, and have also been found.



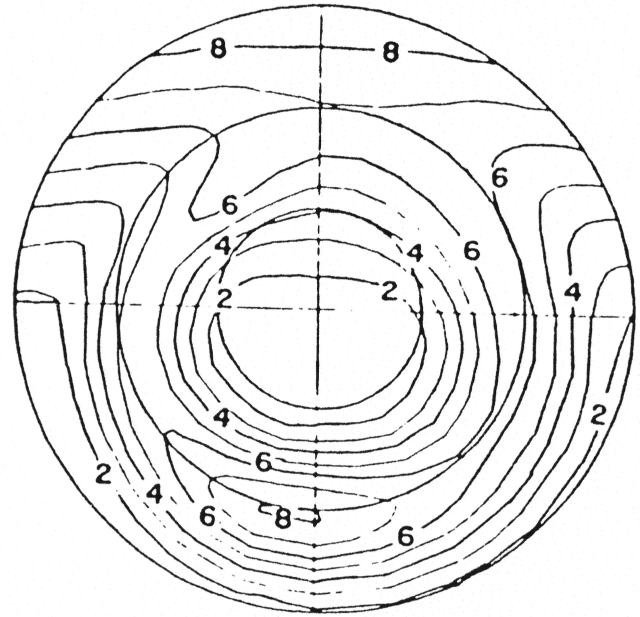

View from Earth


Tail—aligned
Currents
Secondary
Circulation

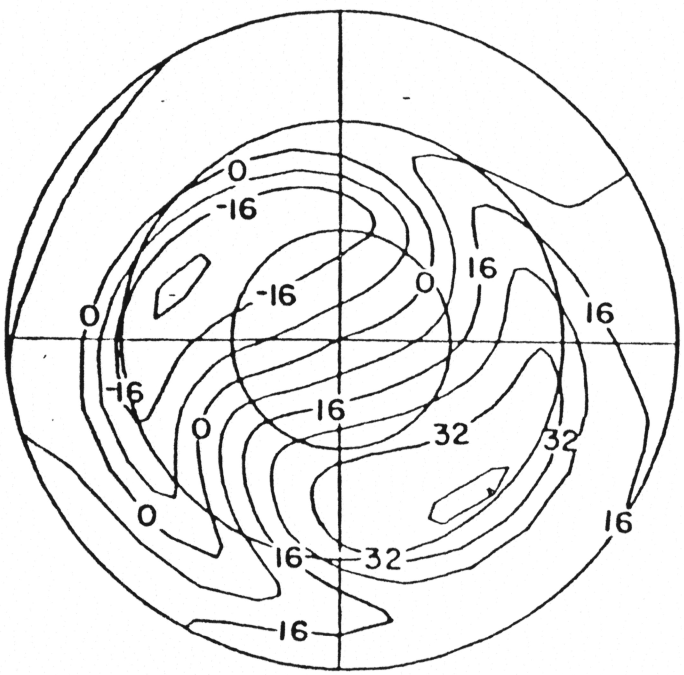



FIELD-ALIGNED CURRENTS
RICH & KAMIDE 1983

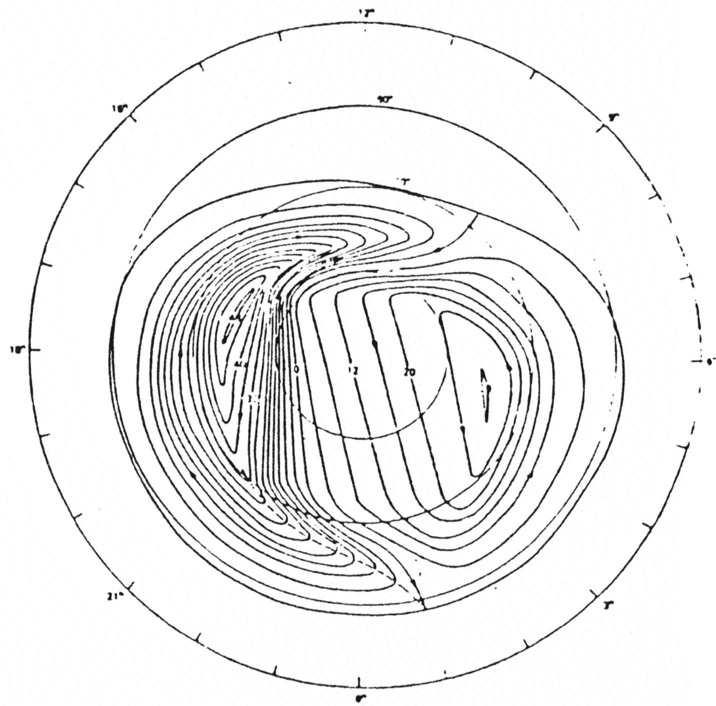
$B_y < 0$




CONDUCTIVITY
RICH & KAMIDE 1983




EQUIPOTENTIALS



## SUBJECTS UNDER THIS HEADING

- Ambiguity in interpreting the observations to determine exactly where the ionosphere impression of the cusp currents lies, what they look like, and how they relate to the region 1 currents.

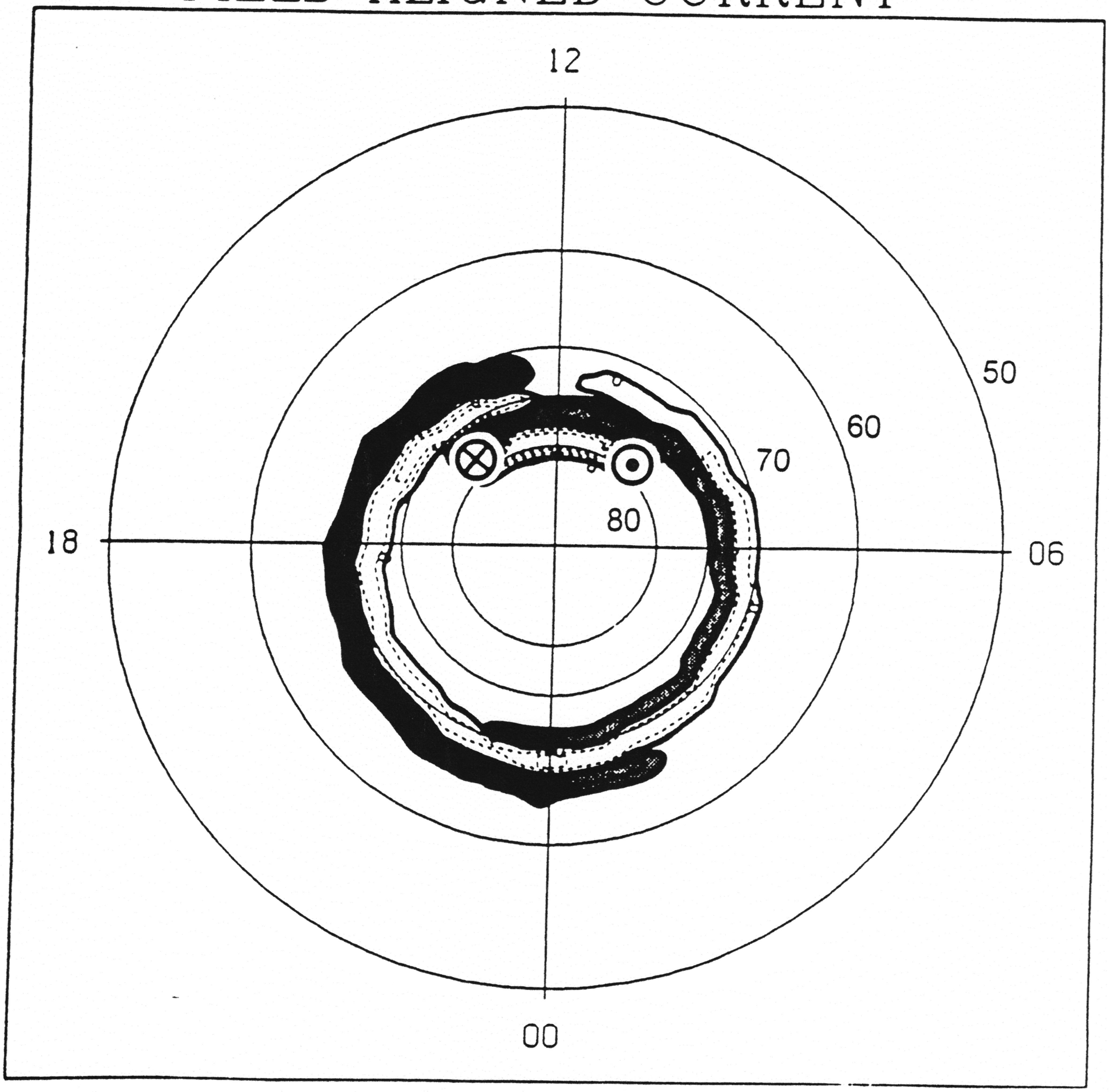
- Possibly two kinds of cusp currents: DPY and DPZ

- No consensus about where they map in the magnetosphere

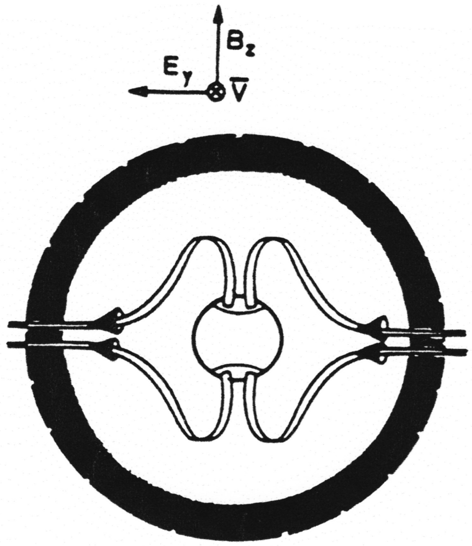
- No consensus about the role played by DPZ currents

- Relation of DPY currents and the " Svalgaard-Mansurov Effect "

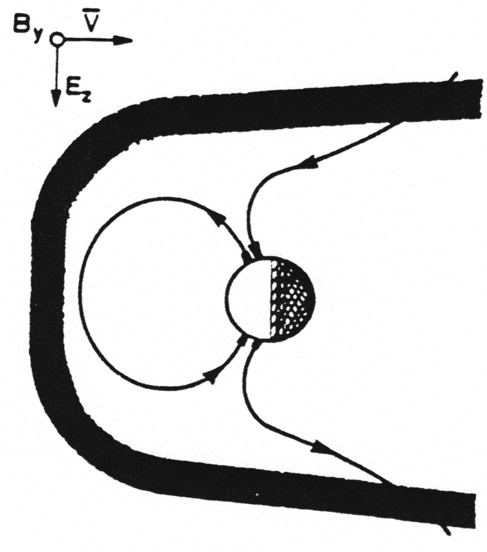
# FIELD ALIGNED CURRENT




CLAUER & BANKS 1986




A




B

BANKS ET AL., 1984

# POLAR CAP KINEMATICS

Definition: The polar cap contains all of the open field lines and none of the closed field lines.

Necessary Consequence: The polar cap boundary separates open and closed field lines. In the language of topology, it is the intersection of the ionosphere and the separatrix surface.

Observation: The separatrix line can comprise neutral line segments (merging segments) and finite B segments (non-merging segments). The merging segments can contain active and inactive parts.

Terminology:

1. The mapping of an active part of a merging line onto the polar cap boundary we call a <u>merging gap</u>. Magnetic flux crosses a merging gap as it converts from closed to open (ingress) or from open to closed (egress). A non-zero voltage exists across a merging gap in the frame of reference in which the merging gap is at rest.

2. Any portion of the polar cap boundary that is not a merging gap is an adiaroic line (no - flow - across line). No magnetic flux crosses an adiaroic line. An <u>adiaroic line</u> is an equipotential in the frame of reference in which it is at rest. Adiaroic lines will move with the polar cap boundary as it expands and contracts, when the amount of open flux increases or decreases. But during an expansion or contraction of the polar cap, as an adiaroic line passes a fixed point in the ionosphere, the field at that point changes from closed to open or open to closed, and in the ionosphere's frame of reference, there is a potential change along the adiaroic line - but not in the frame of reference moving with the line.

## EXAMPLES TO ILLUSTRATE POINTS

1. Time stationary, 2-cell convection.

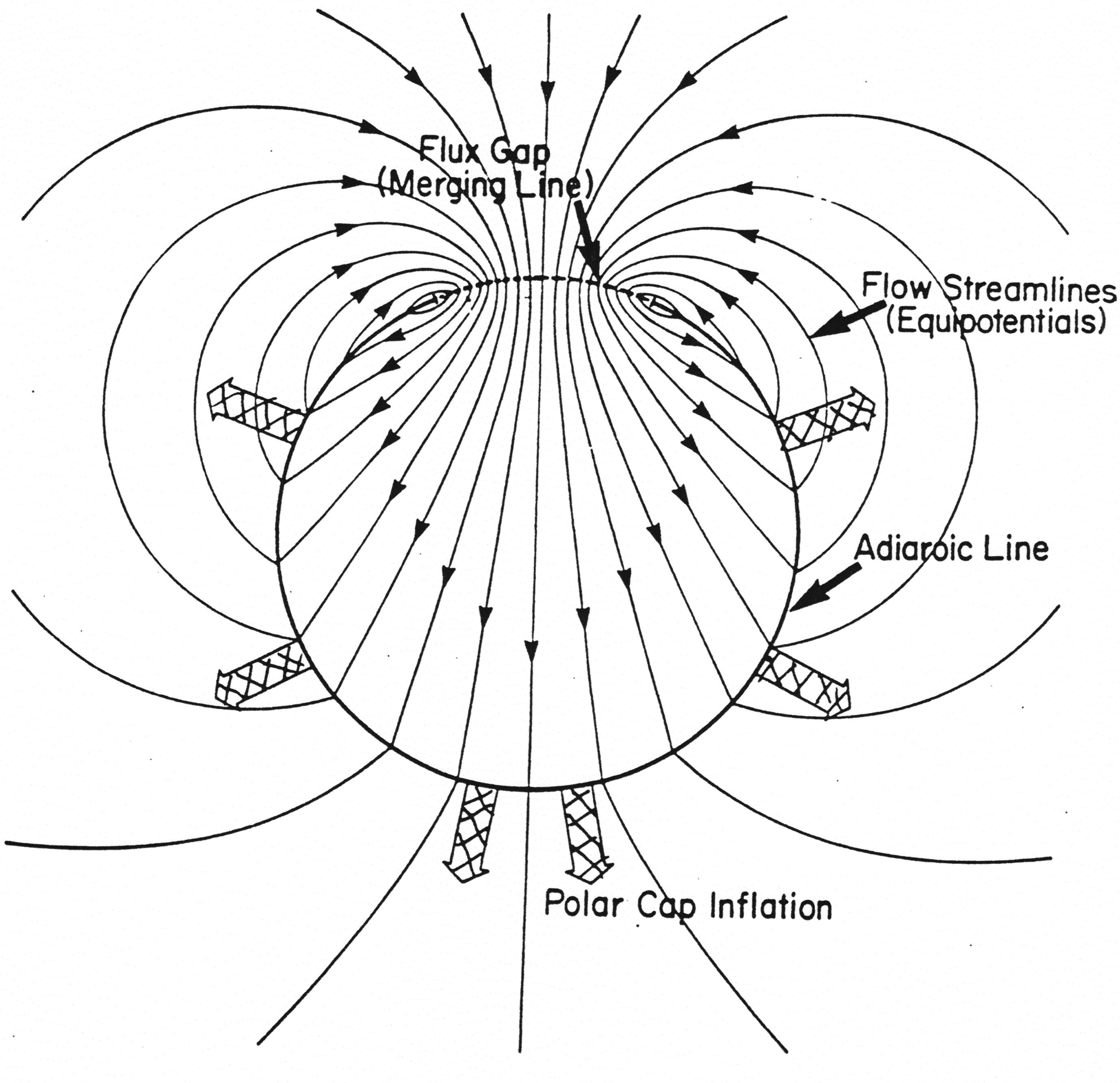
a. Balanced ingress and egress with and without adiaroic lines spaced between dayside and nightside merging gaps.

b. Complete adiaroic line - moving polar cap. 2-D incompressible, inviscid flow analogy - closed cylinder moving through water.

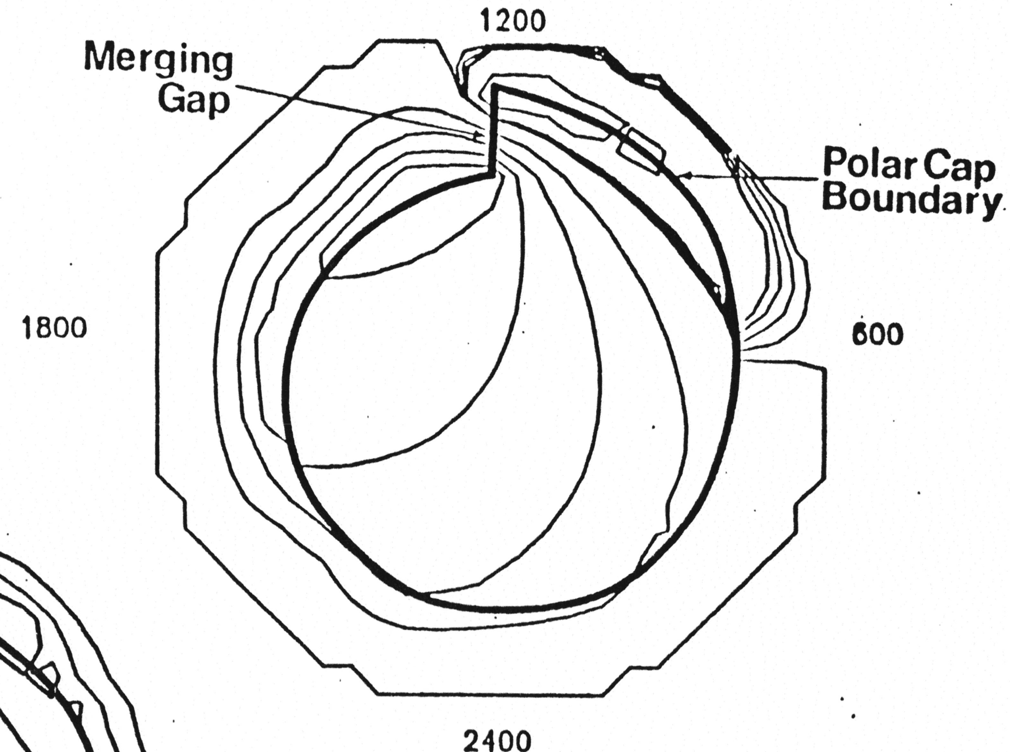
2. Time dependent geometry.

a. Unbalanced ingress and egress - polar cap expansion and contraction. Water flowing through a gap in an expanding or contracting cylinder. Generates two cell convection with a single merging gap. Observed two cell convection does not require balanced merging, or even two merging gaps. Example of the difference between weather in climatology in the ionosphere.

b. Moving merging gap - an expanding or contracting polar cap can occur with no transpolar potential. This is a transient phenomenon. Because of the large inductance of the current loops connecting the solar wind and the ionosphere, it takes about 30 minutes to set up the transpolar potential after merging has started. Thus for about 30 minutes, open or closed field lines are being created - but not moving. The merging line must move instead. In its frame of reference the full merging potential appears.

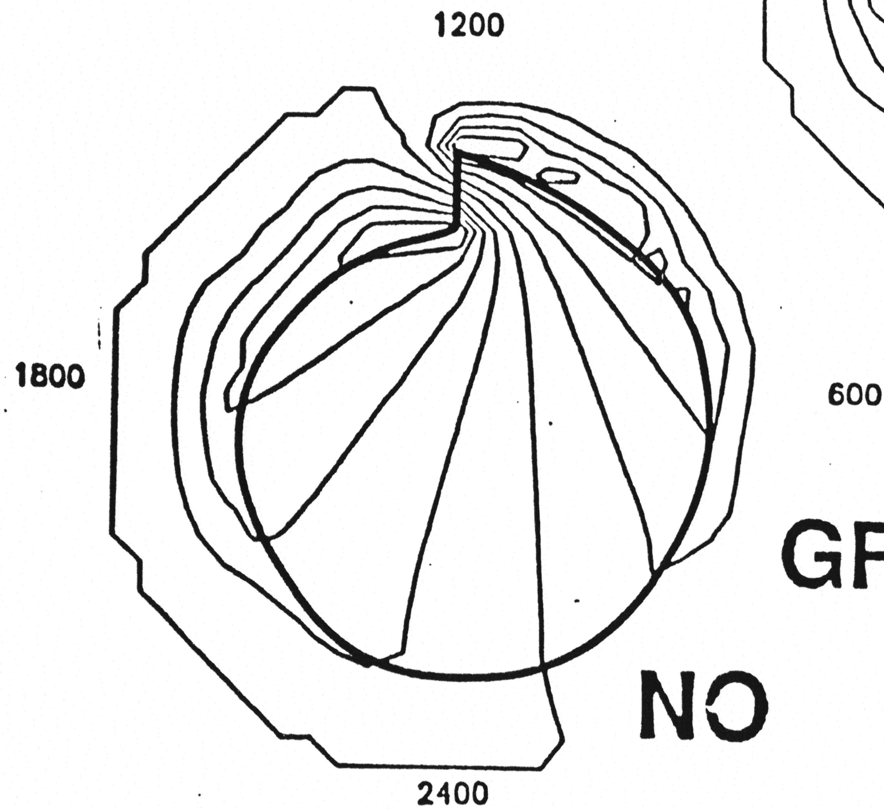

Flux Gap
(Merging Line)
Flow Streamlines
(Equipotentials)
Adiaroic Line
Polar Cap Inflation

$B_y > 0$

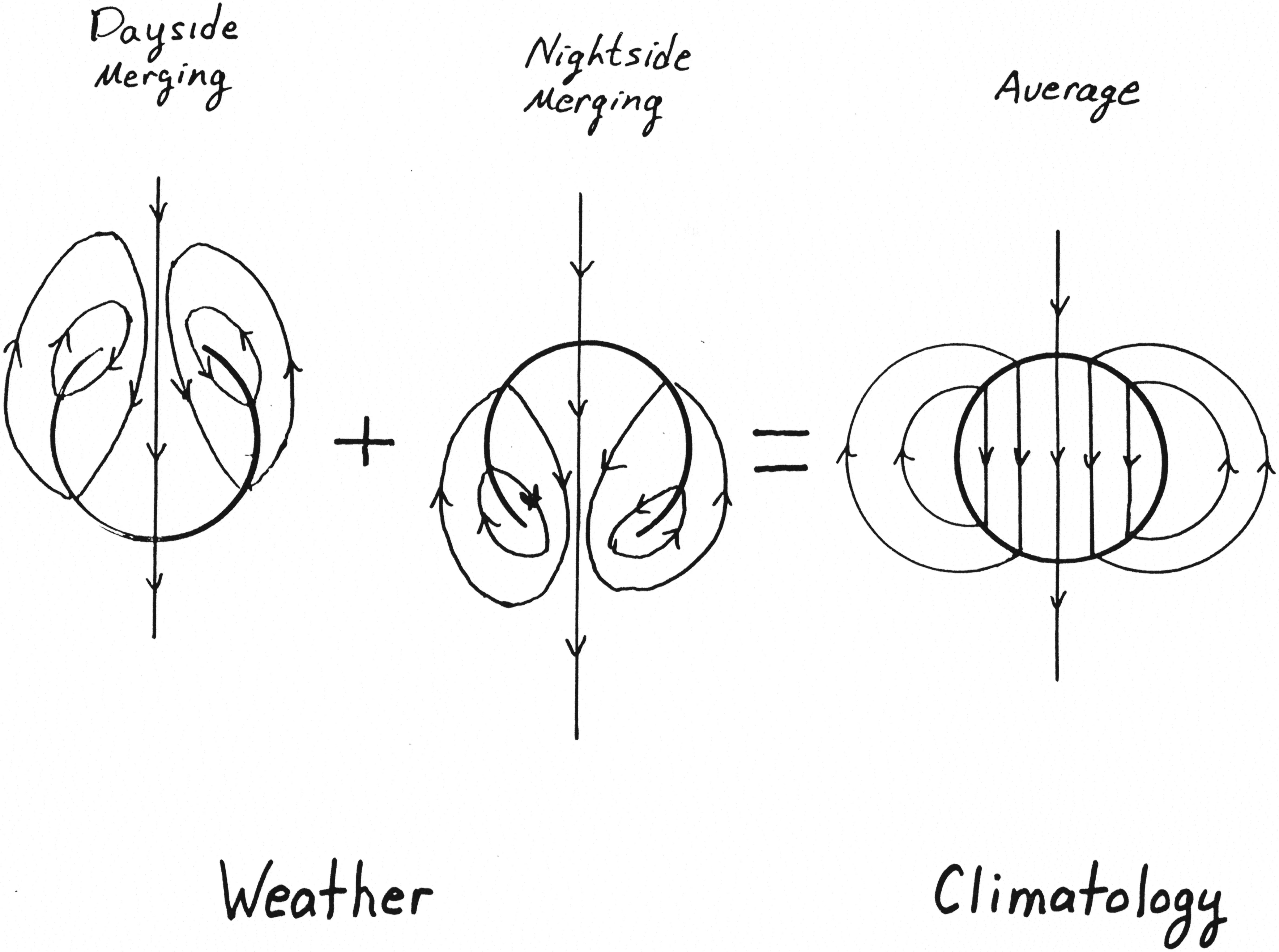



YES

GRADIENT?

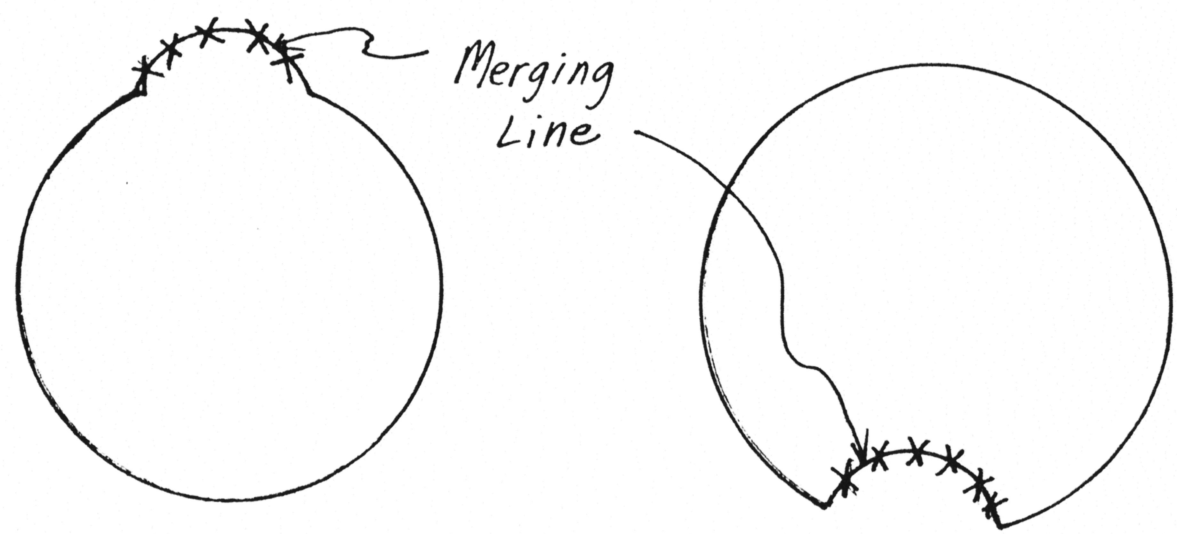



NO

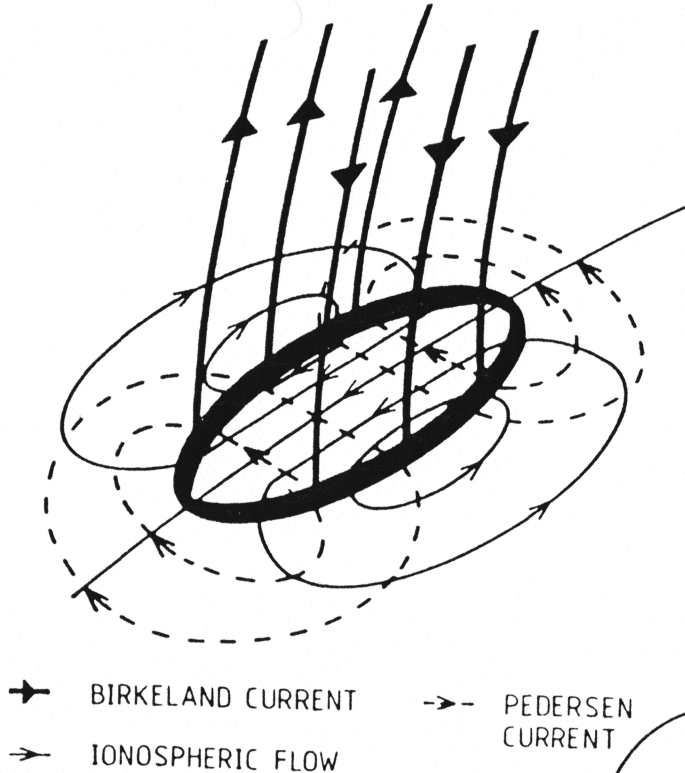

Dayside Merging
Nightside Merging
Average
+
=
Weather
Climatology

# DISTORTIONS OF THE POLAR CAP BOUNDARY AND FTE's

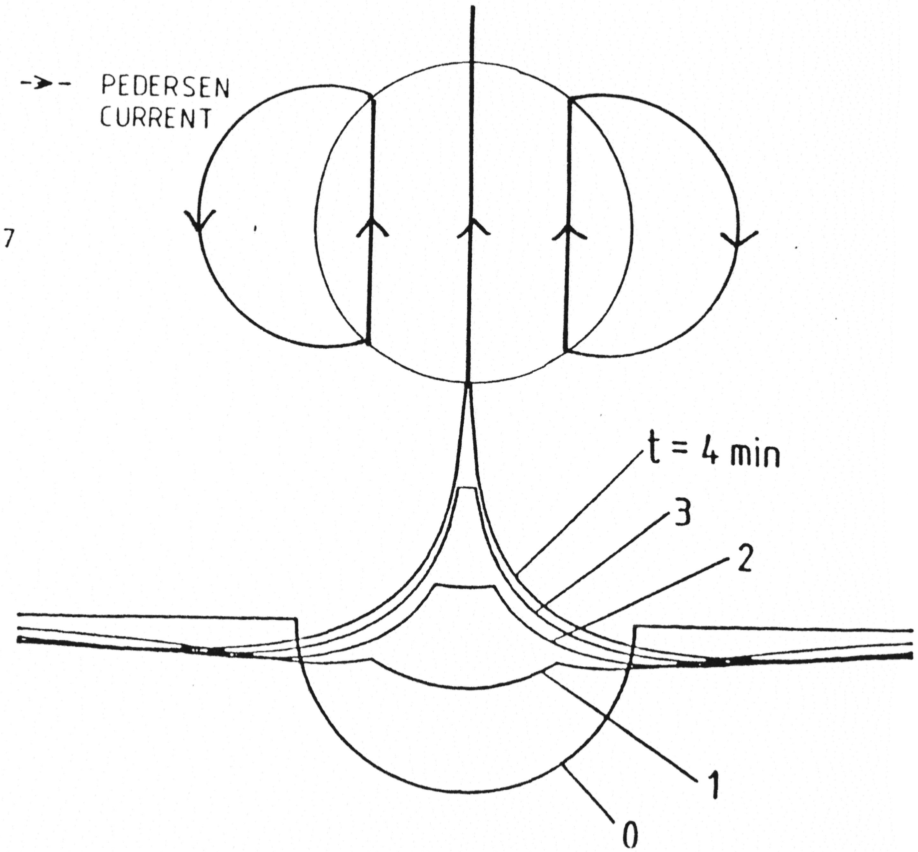
1. A moving merging gap in the absence of a transpolar potential distorts the polar cap boundary because the adiaroic segments are not moving.

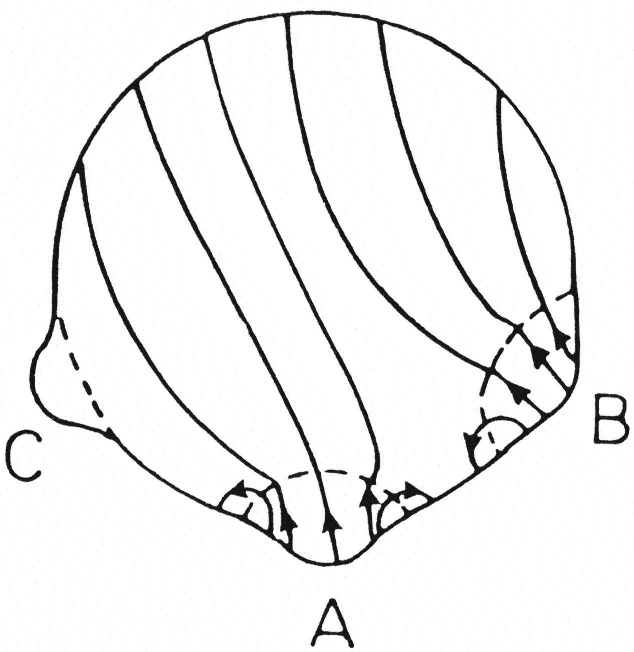



2. FTE's. FTE's can be modeled as closed cylinders moving through water (Southwood, 1987). One gets a moving 2-D dipole flow pattern that distorts the boundary out of which the FTE emerges.

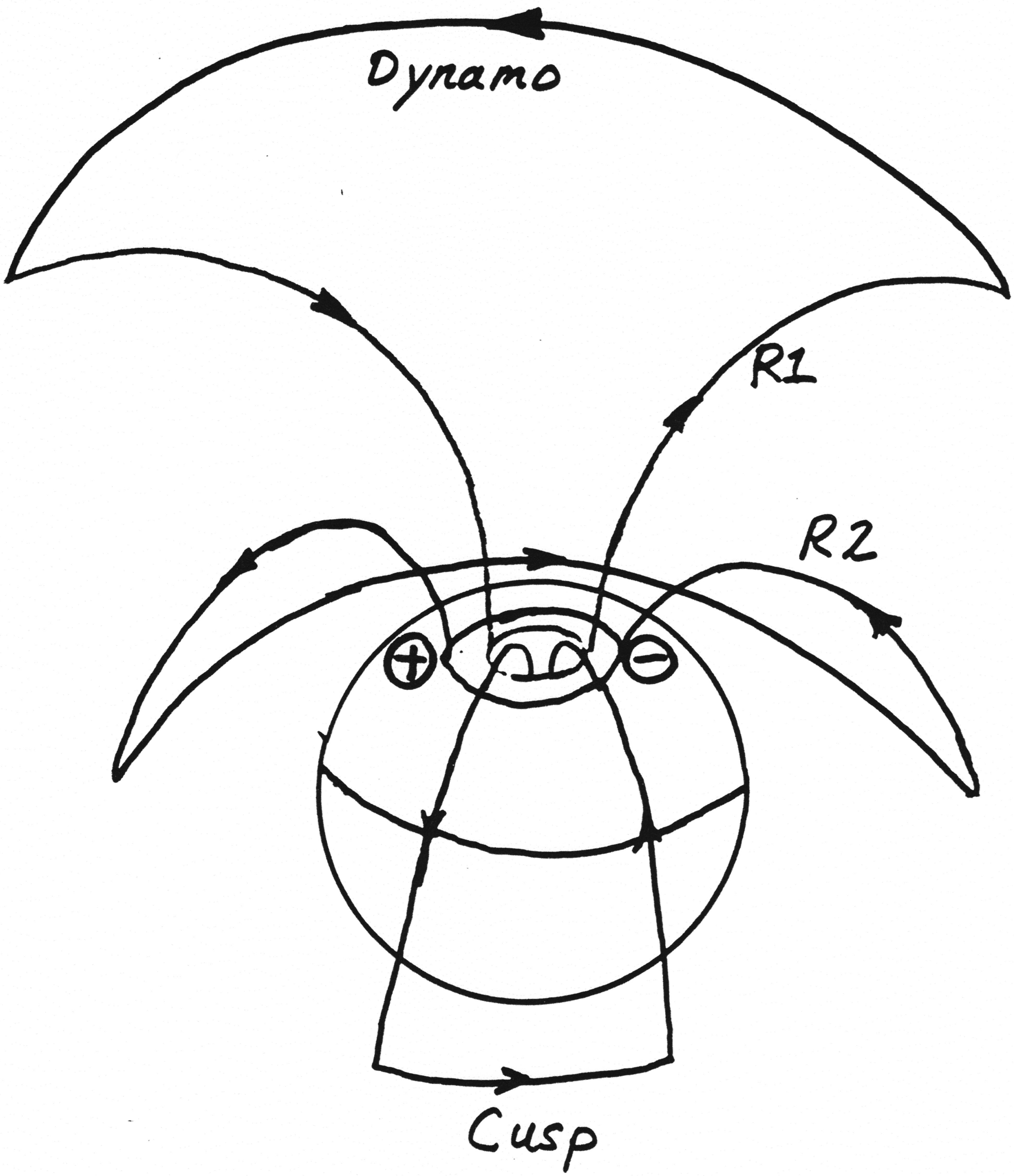


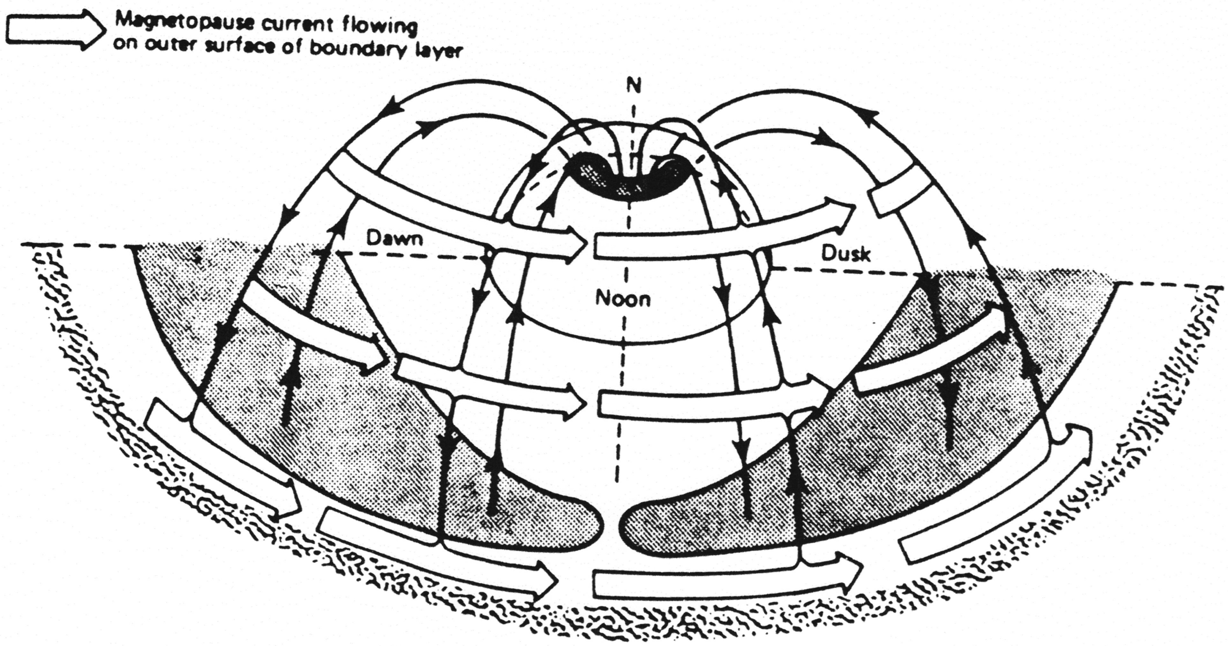

SOUTHWOOD 1987



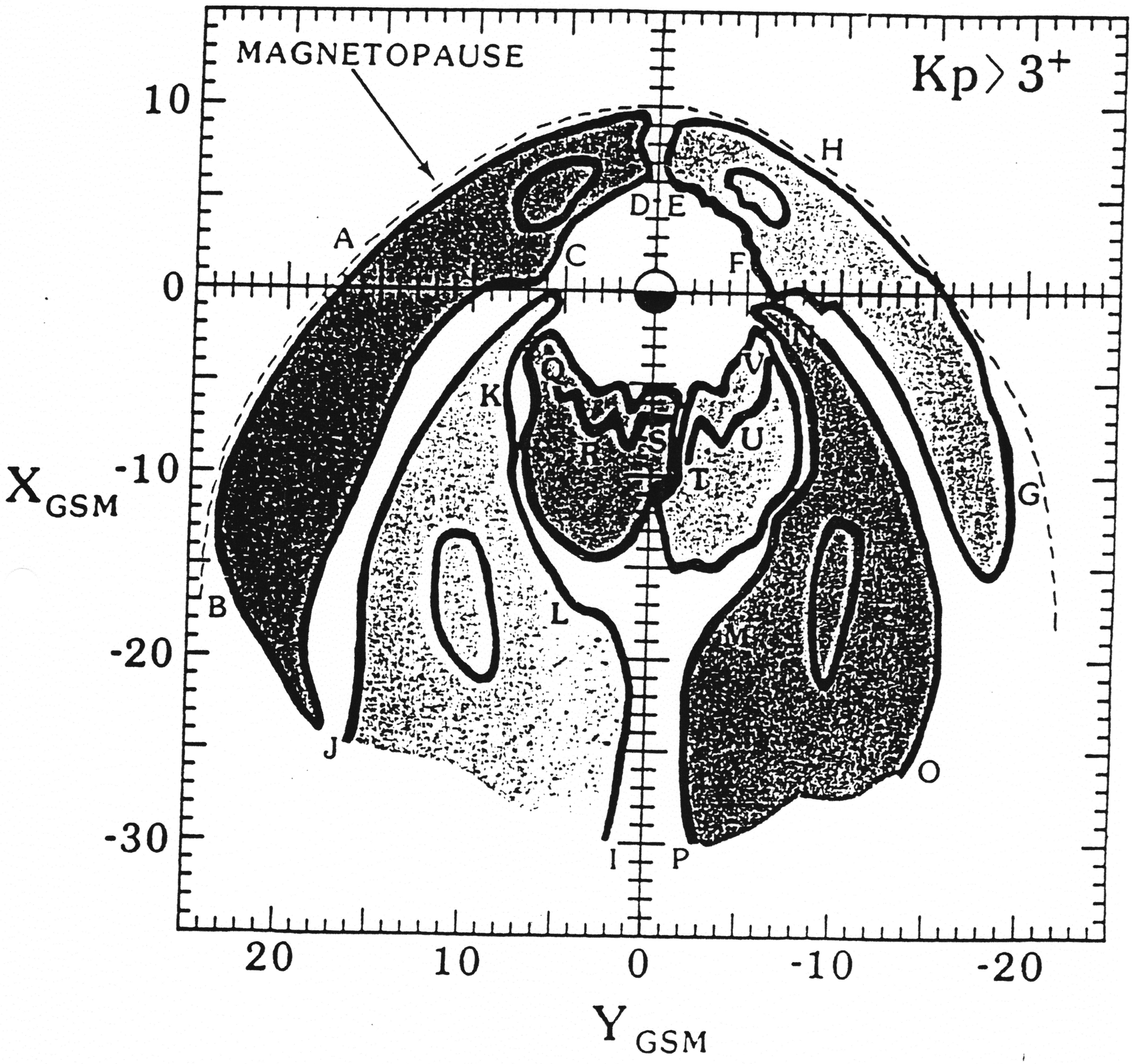




SOUTHWOOD 1987


Dynamo
R1
R2
+
−
Cusp




POTEMRA ET AL., 1979




SPENCE ET AL., 1987

# CONCLUDING WORDS

- We need quantitative maps of how the solar wind electric field is distributed over the polar cap for all IMF orientations

- In general we need synoptic scale, continuous maps of the high latitude convection pattern (weather maps) for all IMF orientations

- We need simultaneous $J_{||}$ maps

- Particular question:
  What is the relation between lobe cells, polar cusp currents and $B_y$ ?