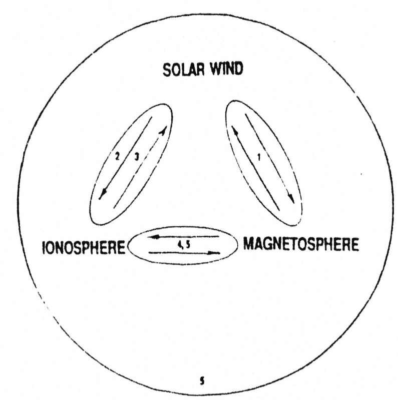
SOLAR WIND - MAGNETOSPHERE - IONOSPHERE COUPLING

LECTURE 2

MERGING - MAPPING - CONVECTION



THE GENERAL CIRCULATION OF THE MAGNETOSPHERE

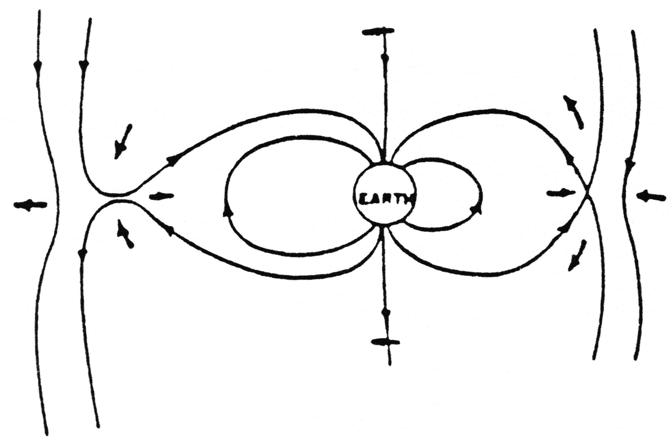
A meteorological analog: From the observed existence of the trade winds and the mid-latitude westerly winds, Hadley in 1735 conceived of the general circulation of the atmosphere, in which high altitude winds carried heat from the equator to the poles and low altitude winds returned carrying "cold" from the poles to the equator. From the observation that auroras and current carrying, ionospheric electrons move away from the sun at high latitudes and toward the sun at slightly lower latitudes, Dungey and, independently, Axford and Hines in 1961 conceived of the general circulation of the magnetosphere (magnetospheric convection).

MHD serves as the working framework for the discussion of the magnetospheric circulation.

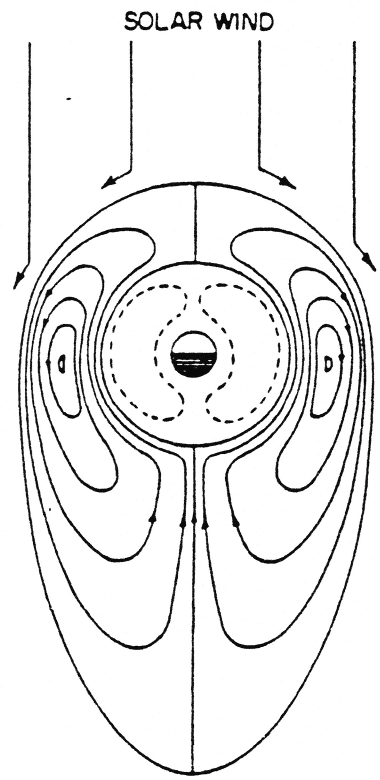
$$\vec{E} = -\vec{V} \times \vec{B} \Rightarrow \vec{V}_{\perp} = \frac{\vec{E} \times \vec{B}}{B^2}$$

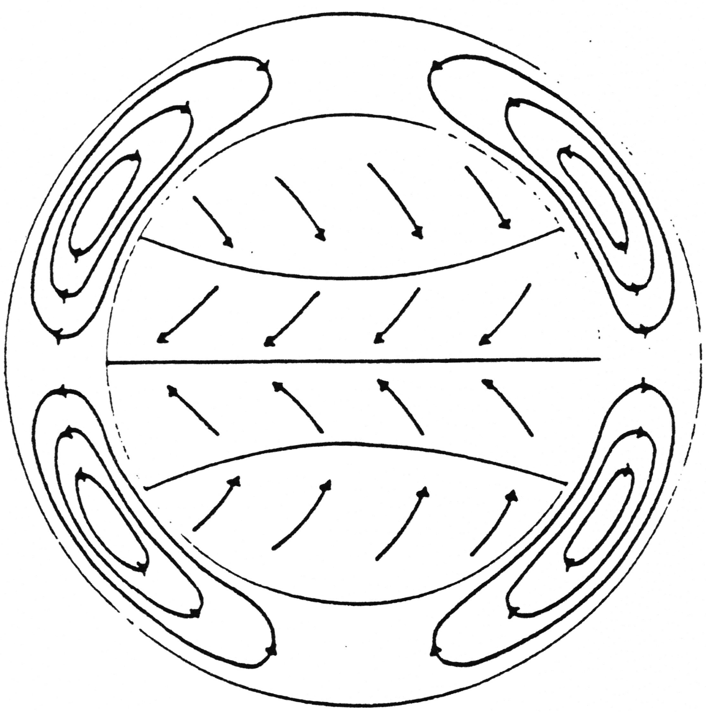
and

$$\vec{E} \cdot \vec{B} \cong 0$$



Dungey, 1961



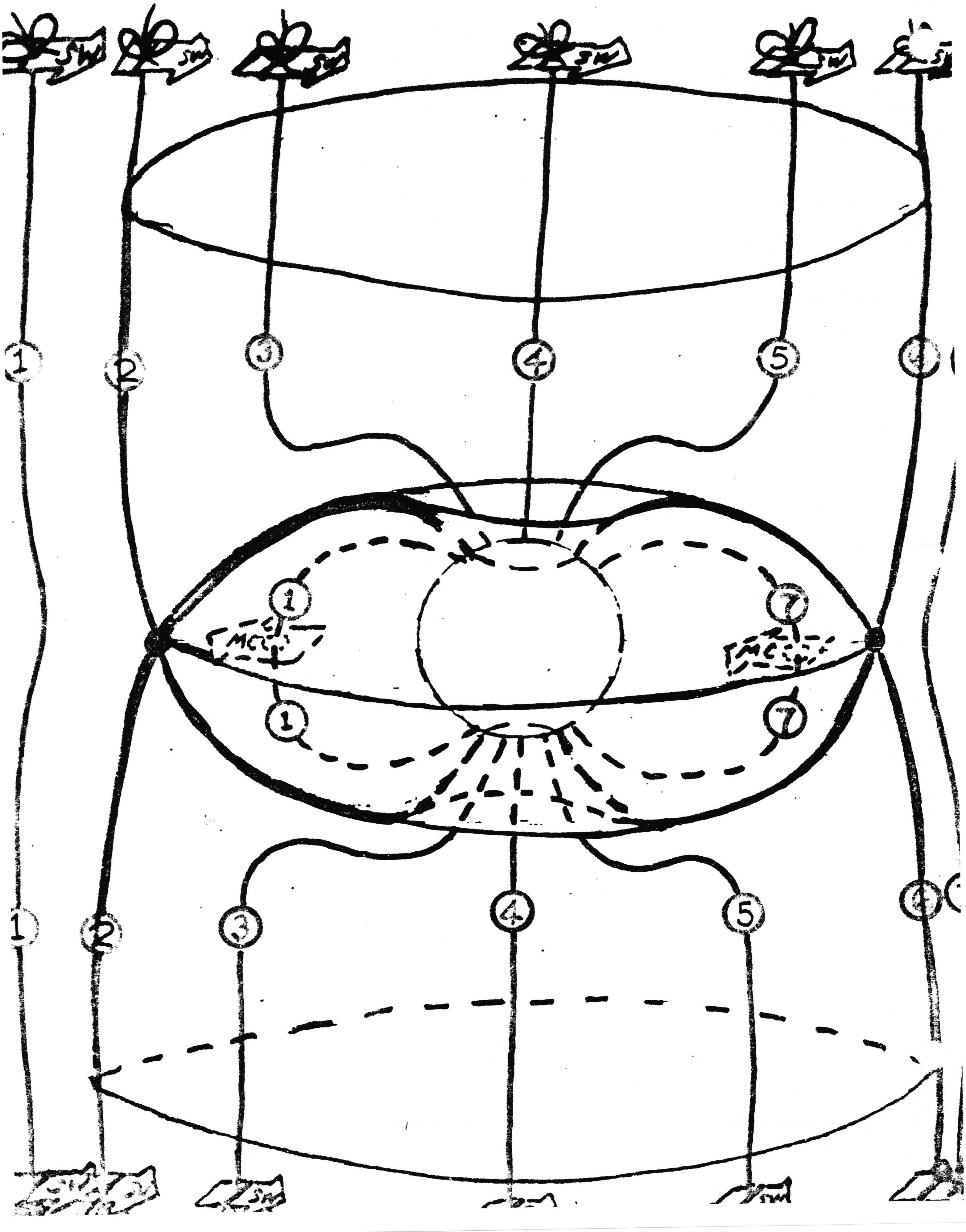


Hadley, 1735

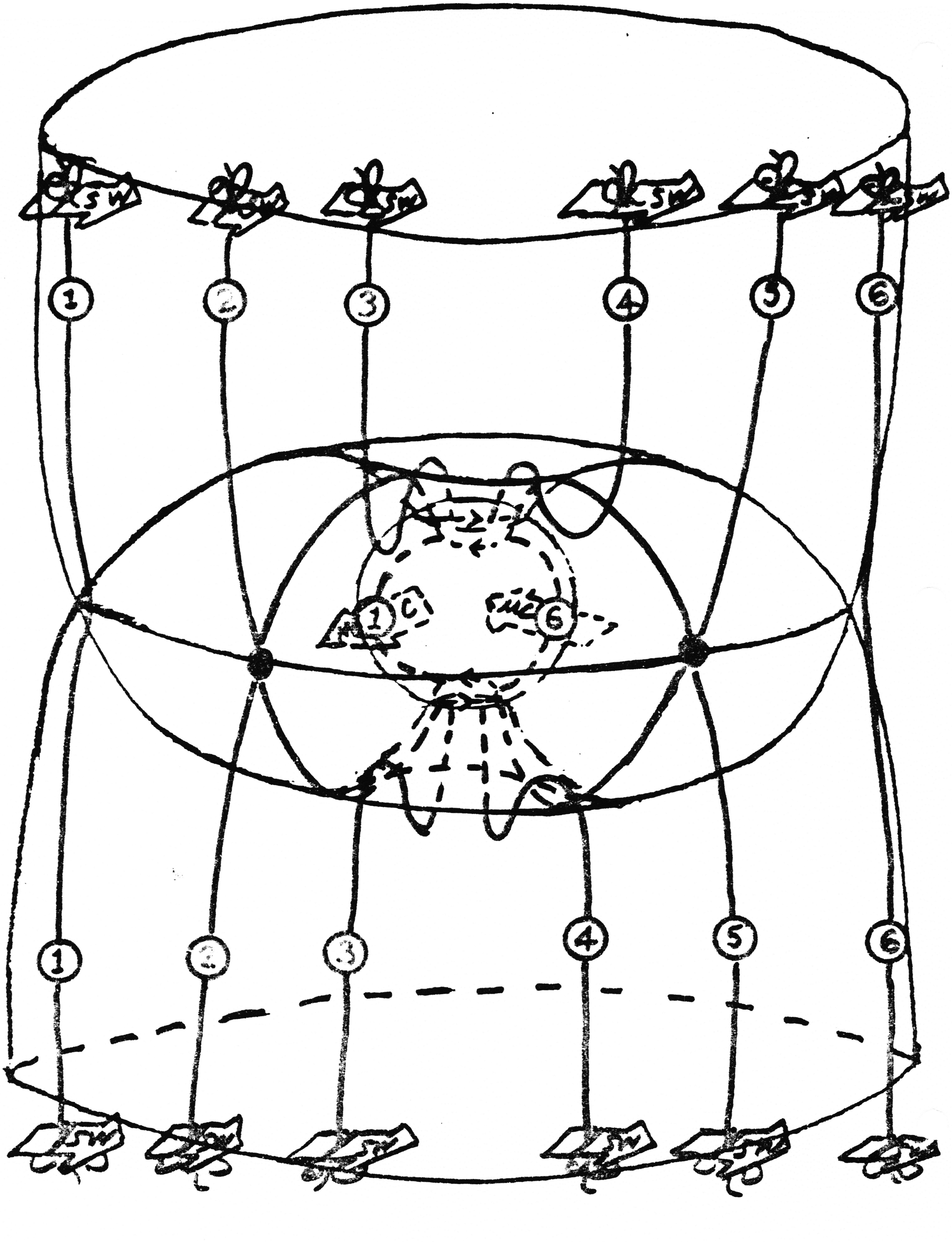
Axford and Hines, 1961

In the late '60's and '70's, it was established that the solar wind motional electric field $\vec{E}_{SW} = -\vec{V}_{SW} \times \vec{B}_{SW}$ acting through the magnetic connection between the solar wind magnetic field and the geomagnetic field was the main source of the electric field associated with magnetospheric circulation (Dungey's mechanism).

Since the key is field-line connection and solar wind motion, the basic picture is seen by super-posing a uniform, purely southward solar wind field (maximum connection direction) onto the geomagnetic dipole in the absense of boundary and tail currents ("vacuum merging") and imposing a uniform flow perpendicular to the solar wind field, giving a uniform electric field in the solar wind.



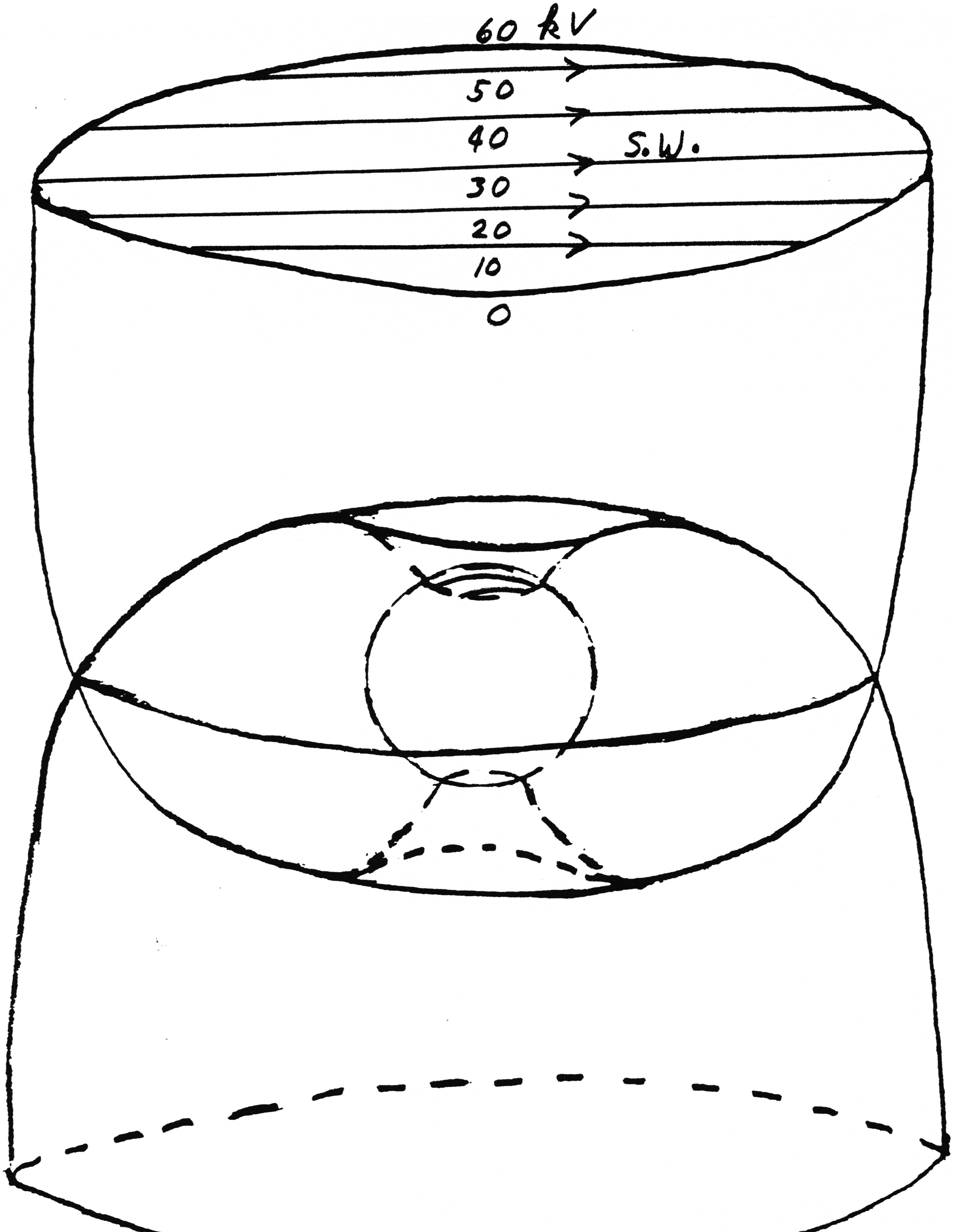
1
2
4
5
1
7
MC
1
7
1
2
3
4
5

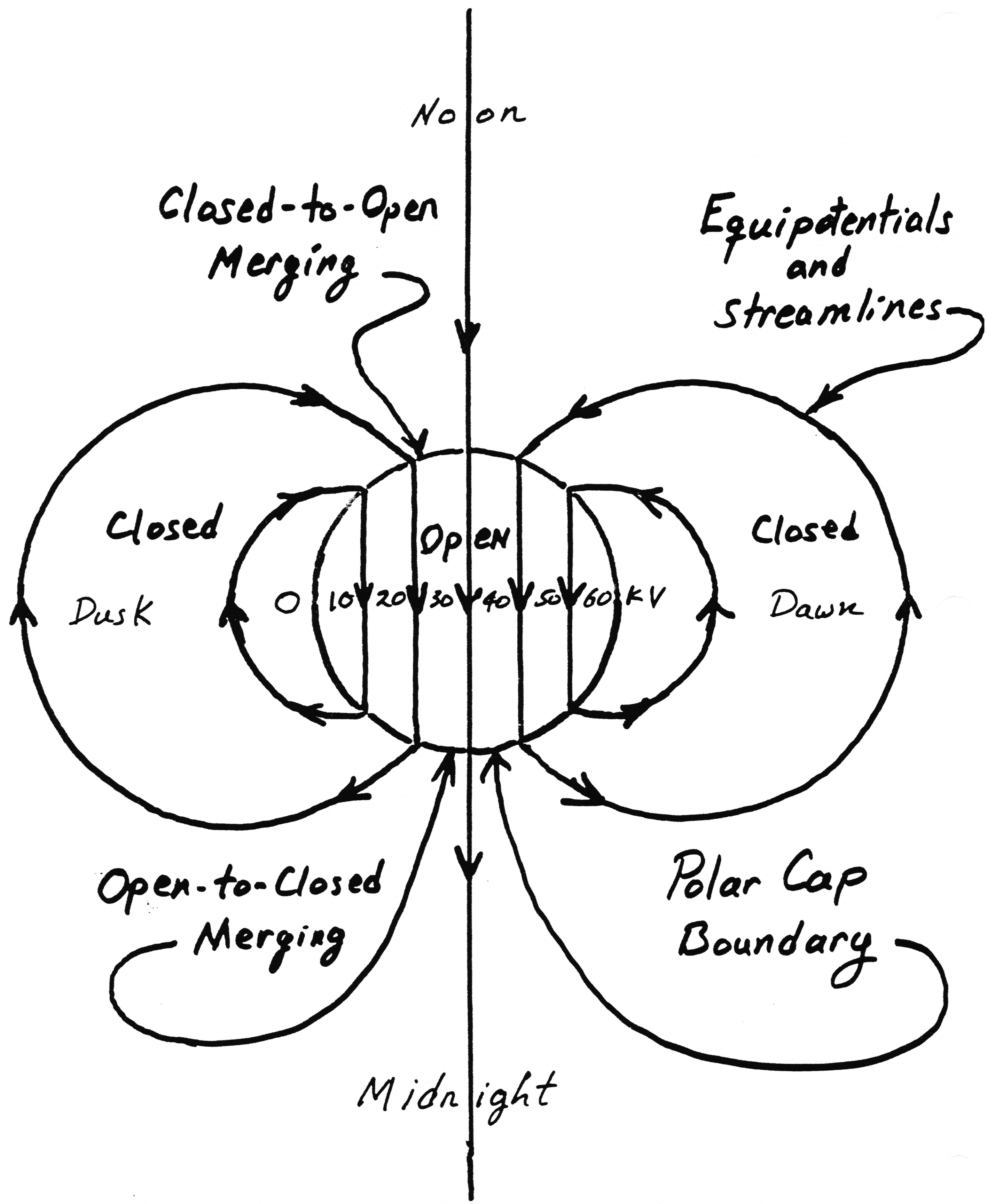

1
2
3
4
5
6
SW

The uniform solar wind electric field maps along the open field lines to impose a uniform electric field across the circular polar cap. The field spreads from the polar cap to the lower latitude ionosphere, underlying the closed-field-line magnetospheric torus, by means of ohmic currents. For a uniformly conducting ionosphere, these produce an electric potential throughout the ionosphere that satisfies the Laplace equation $\nabla^2\phi = 0$. The uniform field in the polar cap (which trivially satisfies this equation) sets the boundary condition for the lower latitude solution – a 2-D dipole. Now, the equipotentials (ϕ = const. lines) are streamlines drawn on the ionosphere by the magnetic field as it undergoes the magnetospheric circulation.

$$\vec{V}\cdot\nabla\phi = \vec{V}\cdot(-\vec{E}) = \vec{V}\cdot(\vec{V}\times\vec{B}) = 0$$

$$\Rightarrow \phi = \text{const. on streamlines of } \vec{V}$$

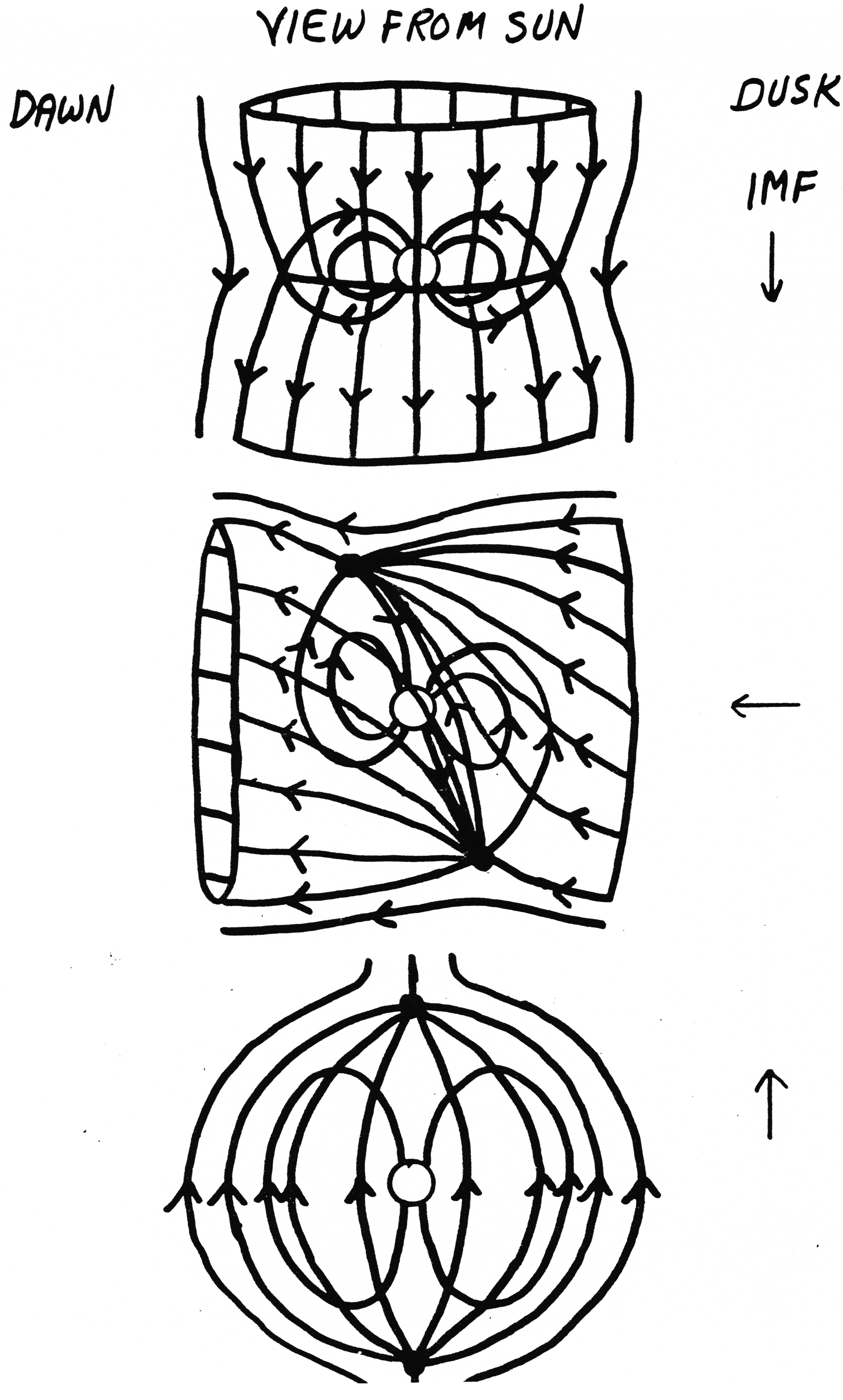

60 kV
50
40
S.W.
30
20
10
0



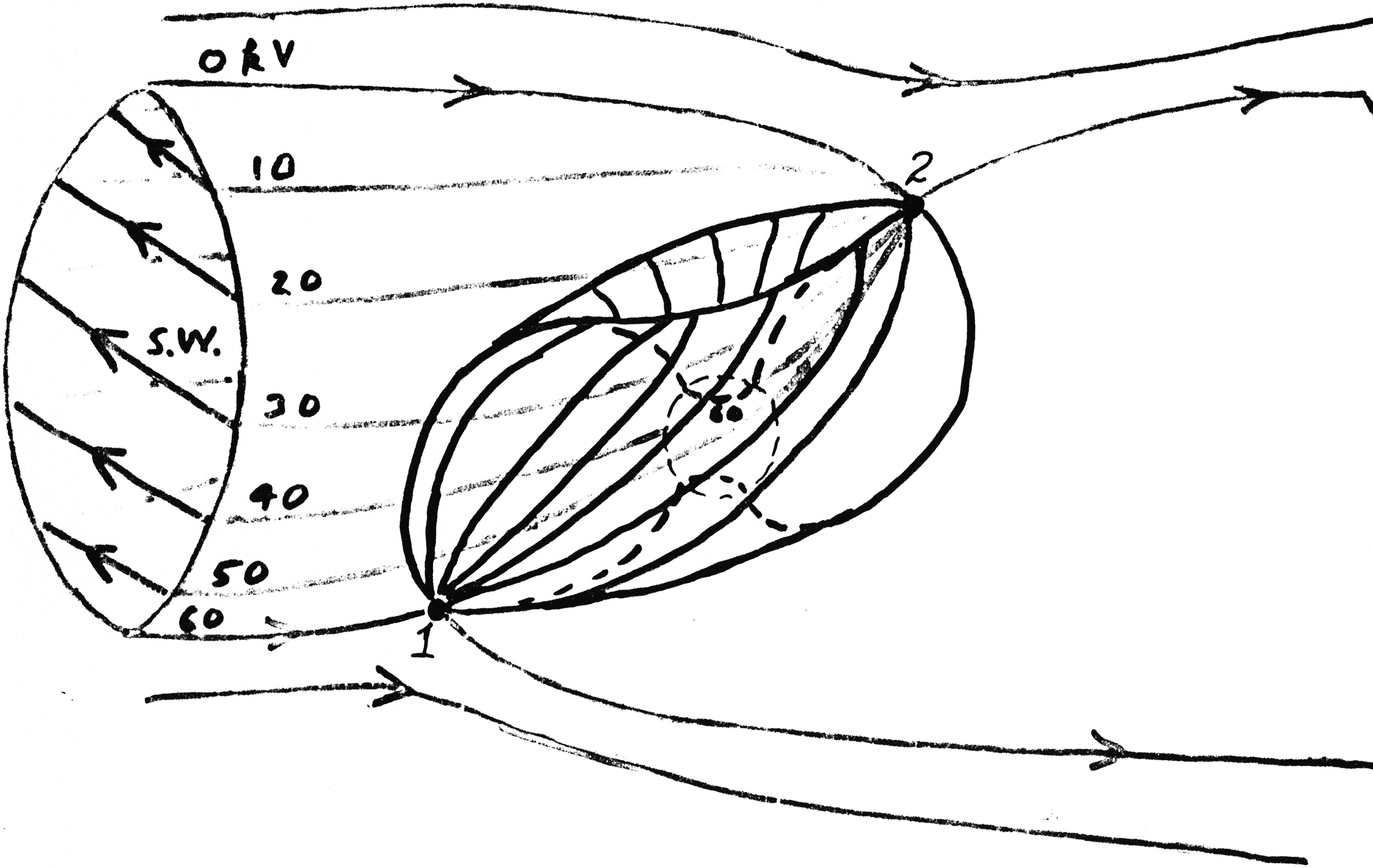
"Double Cell Convection"

The global topological problem. For any but a purely southward IMF, the neutral line vanishes and is replaced by two neutral points connected by a "separatrix" – a line (in this case a circle) that like the neutral line in the purely southward case divides volumes containing closed, open, and unconnected field lines, but unlike that case is not neutral.

The problem is that, for vacuum merging, no one has found a way to merge a finite amount of closed-to-open or open-to-closed magnetic flux. The only quantitative attempt (Lyons) merges disconnected-to-open and open-to-disconnected field lines at the neutral points. Cowly and Stern have given geometrical pictures showing how to engage closed field lines in the process, but because of the singularity in the geometry, there is no prescription for determining ϕ there. Both the quantitative and geometrical pictures of merging entail infinite electric fields at the neutral points and its mapped point in the ionosphere.

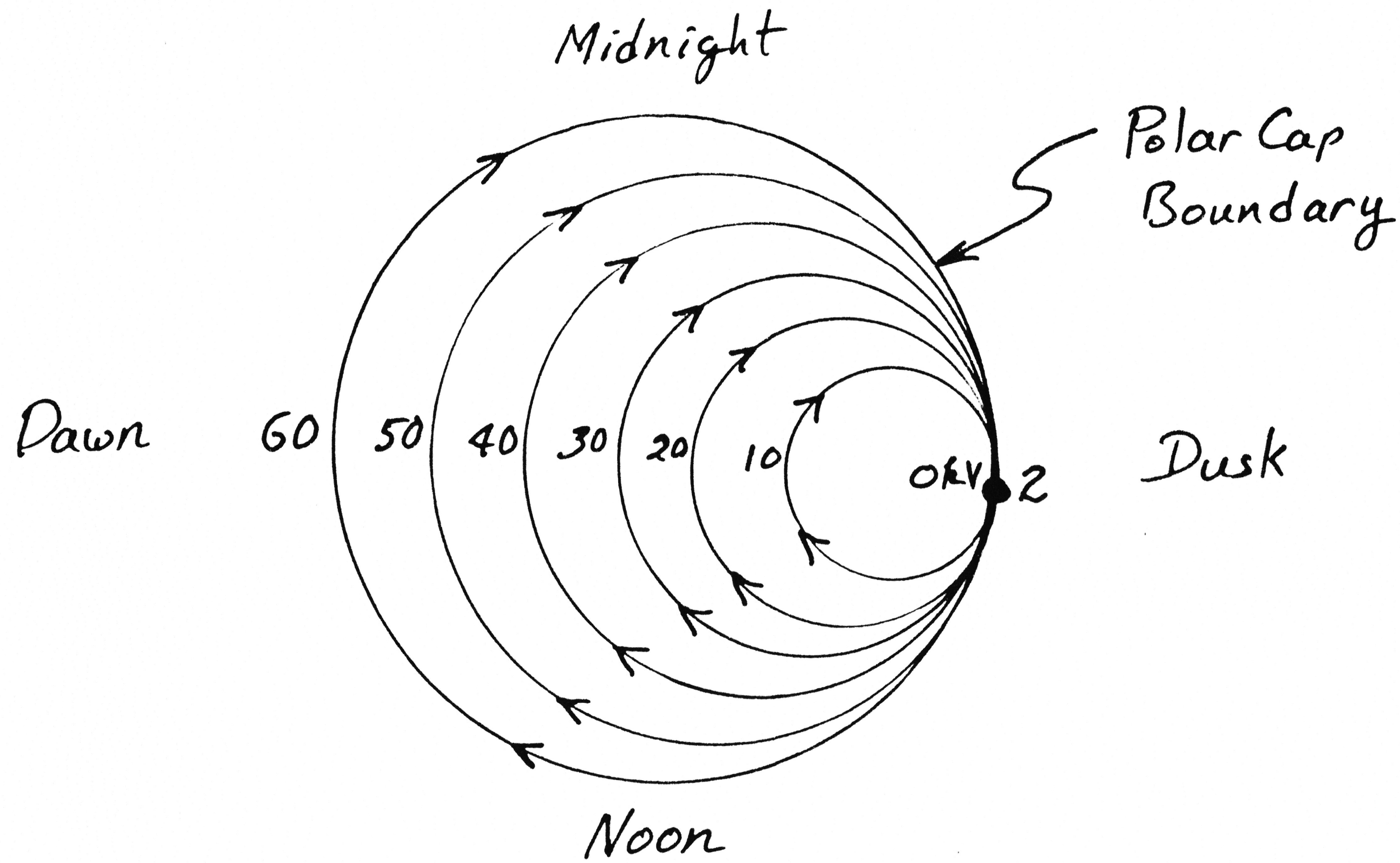

VIEW FROM SUN
DAWN
DUSK
IMF

+IMF By



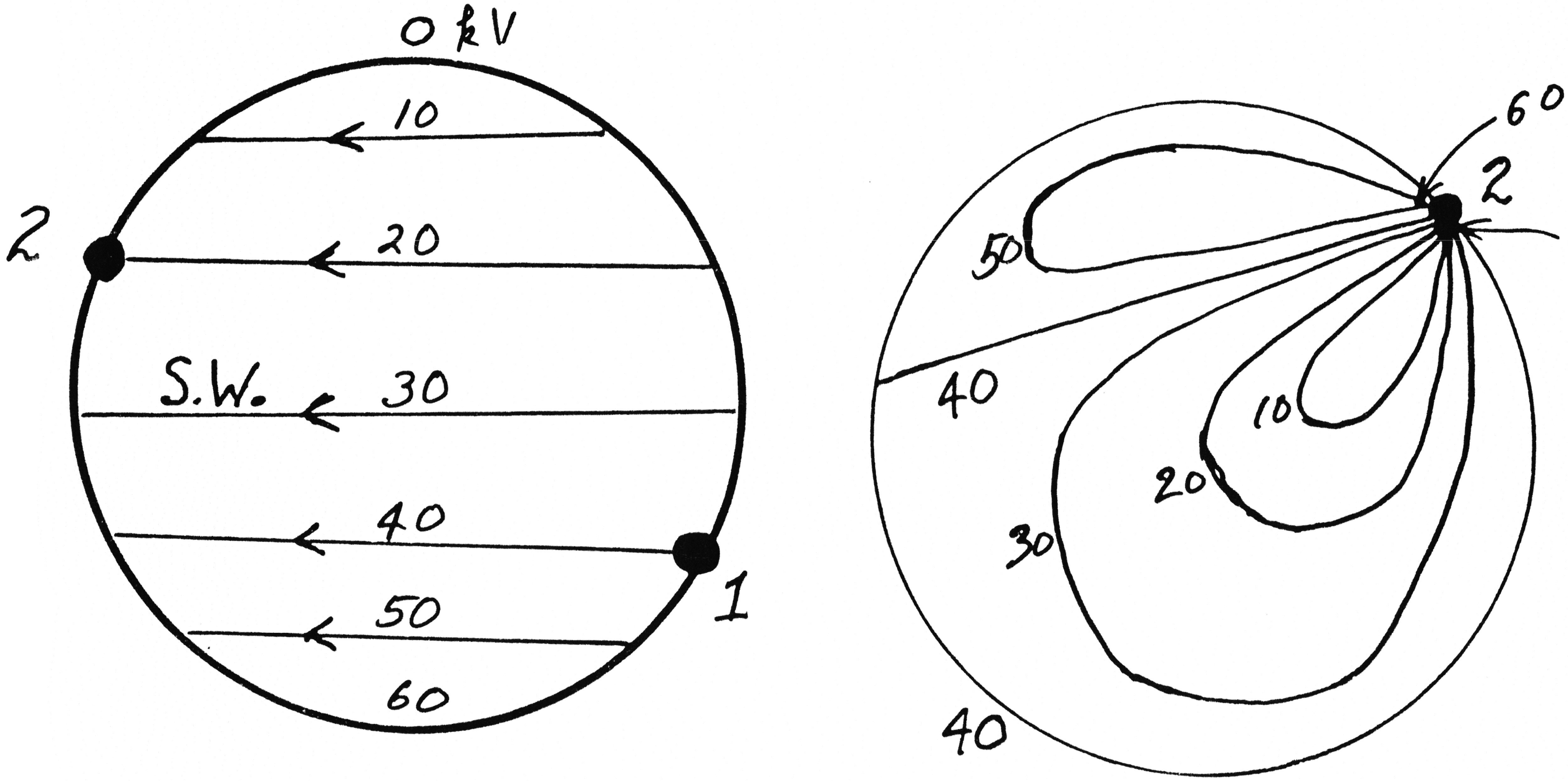
View From Sun

Northern Hemisphere Polar Cap Circulation



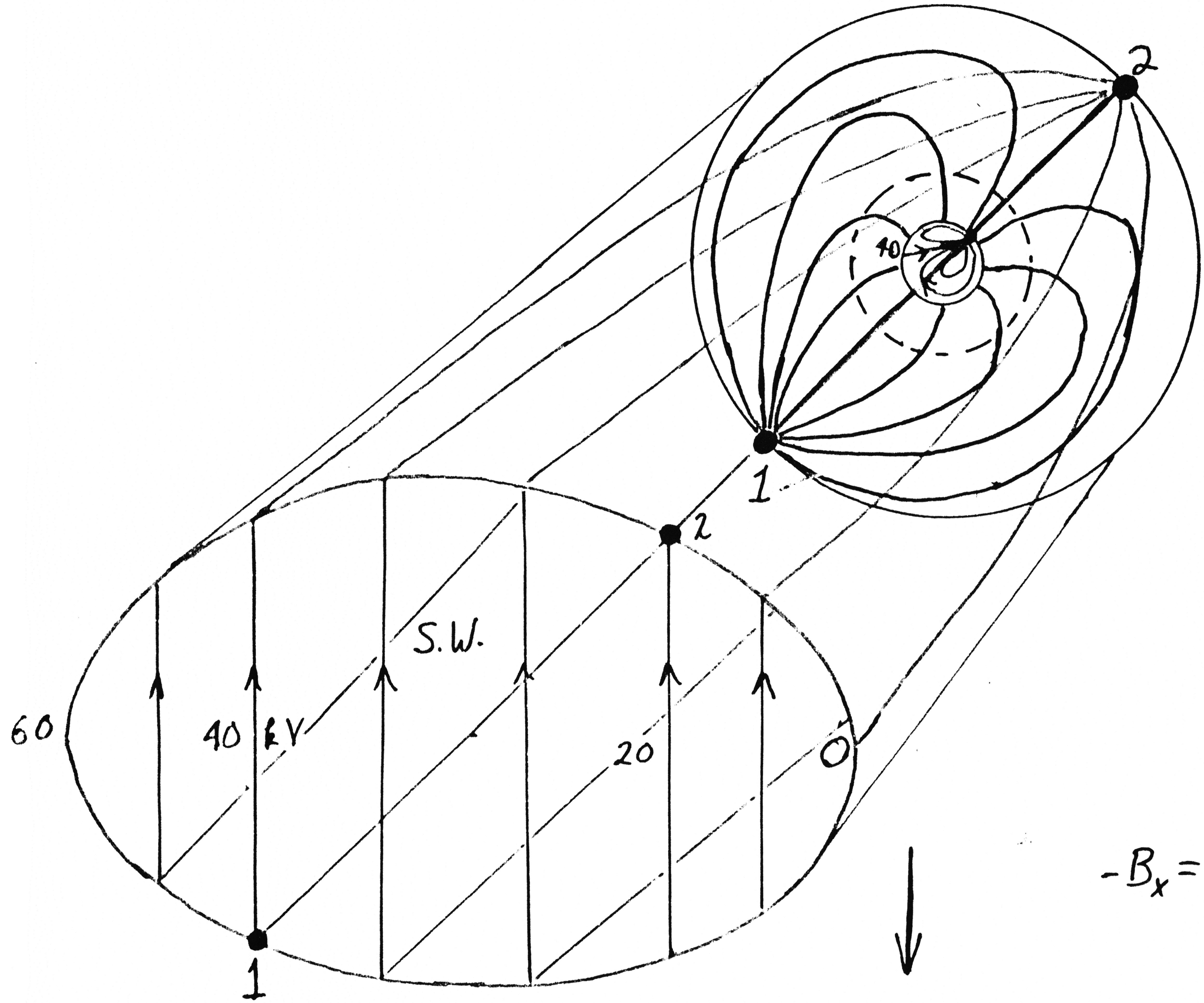
"Single Cell Convection"

Requirement for Double-Cell Convection

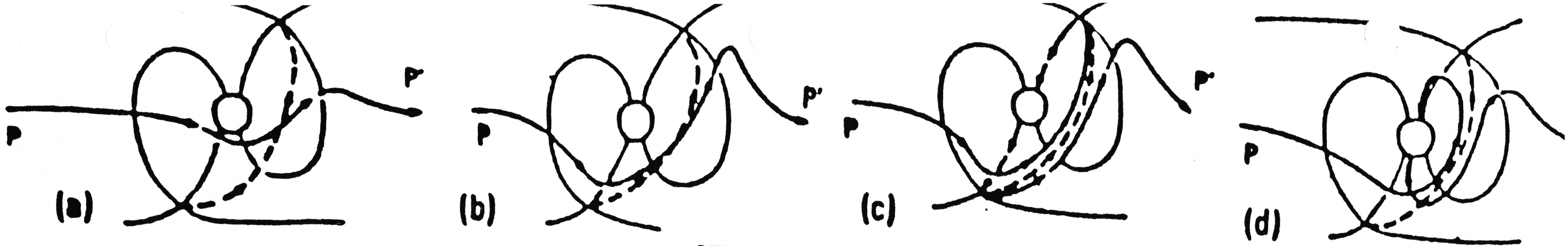


Open-Field-Line Cylinder

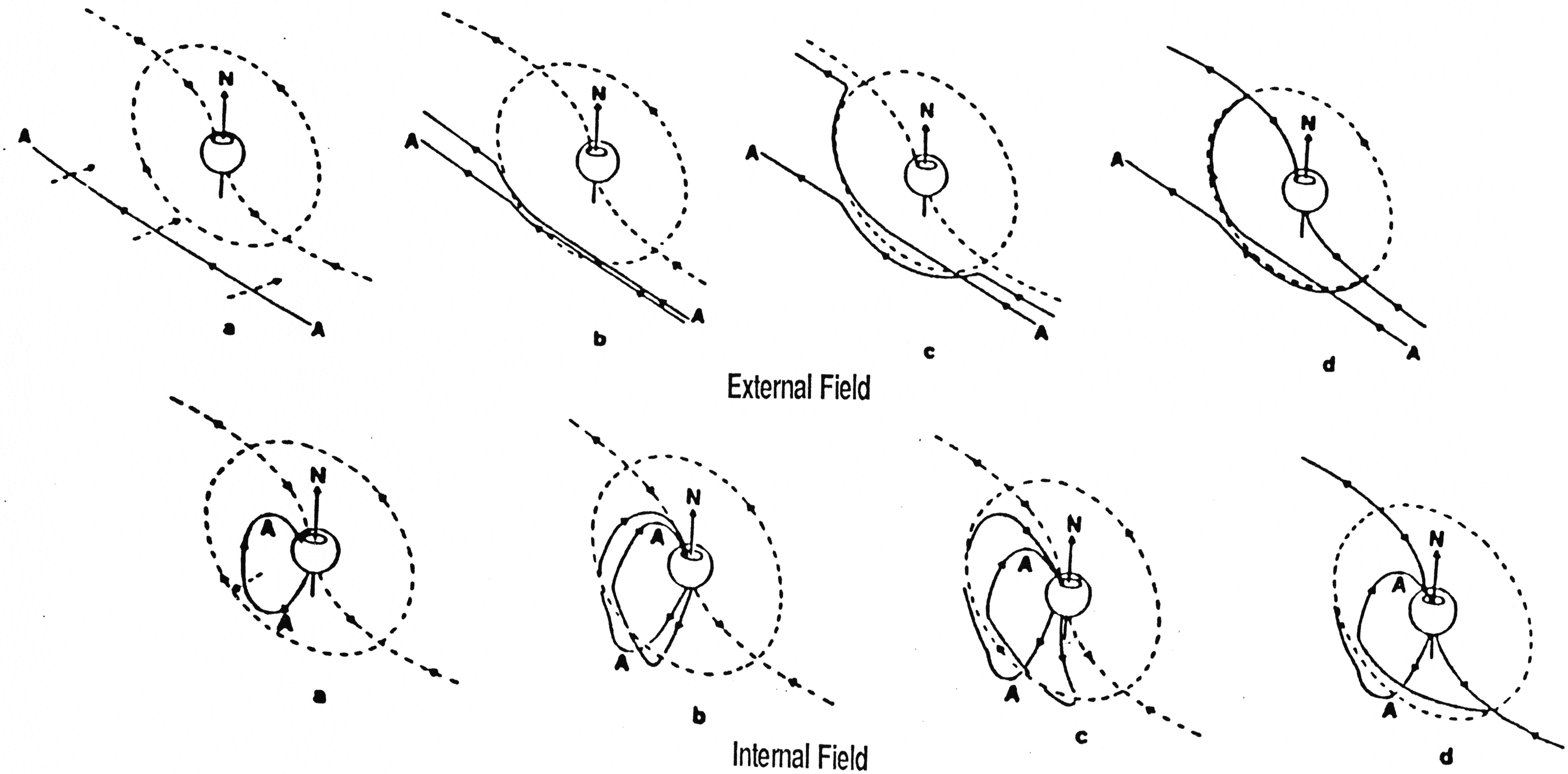
View from North



$-B_x = B_y = -B_z$



STERN, 1973



COWLEY, 1973

There are internal inconsistencies inherent in the attempts to infer magnetospheric circulation patterns by mapping the $-\vec{V} \times \vec{B}$ electric field from the solar wind to the ionosphere along vacuum field lines:

1. The electric field mapping $\vec{E} \cdot \vec{B} = 0$ requires plasma to convey the field and the currents from the solar wind to the ionosphere. The currents supply the momentum and energy consumed by the ionosphere under the direction of the imposed electric field. Thus a vacuum is not possible for the mapping to work.

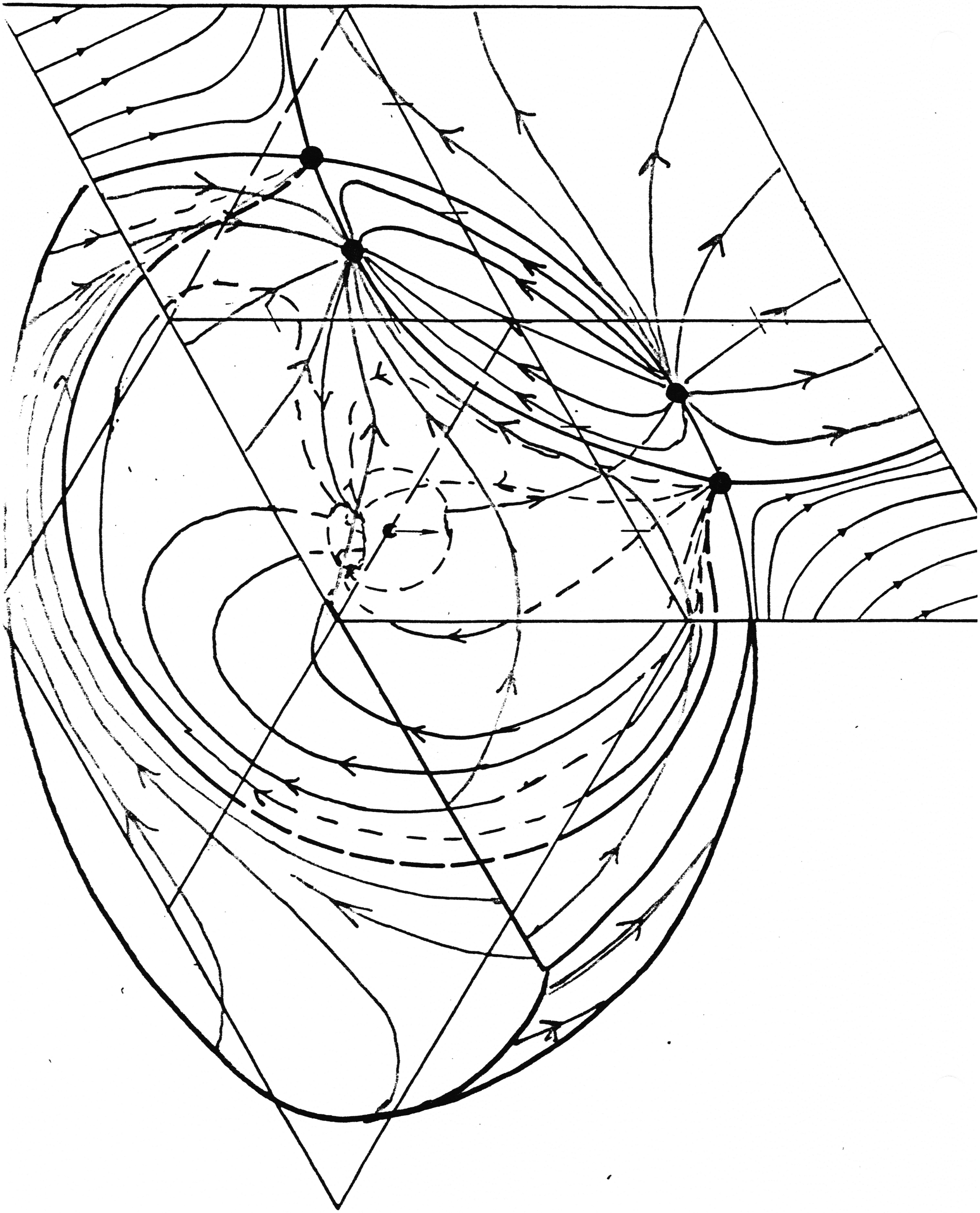
2. There is no $\vec{J}_\perp$ in the vacuum geometry and thus no way to supply the $J_\parallel$ required by the ionosphere.

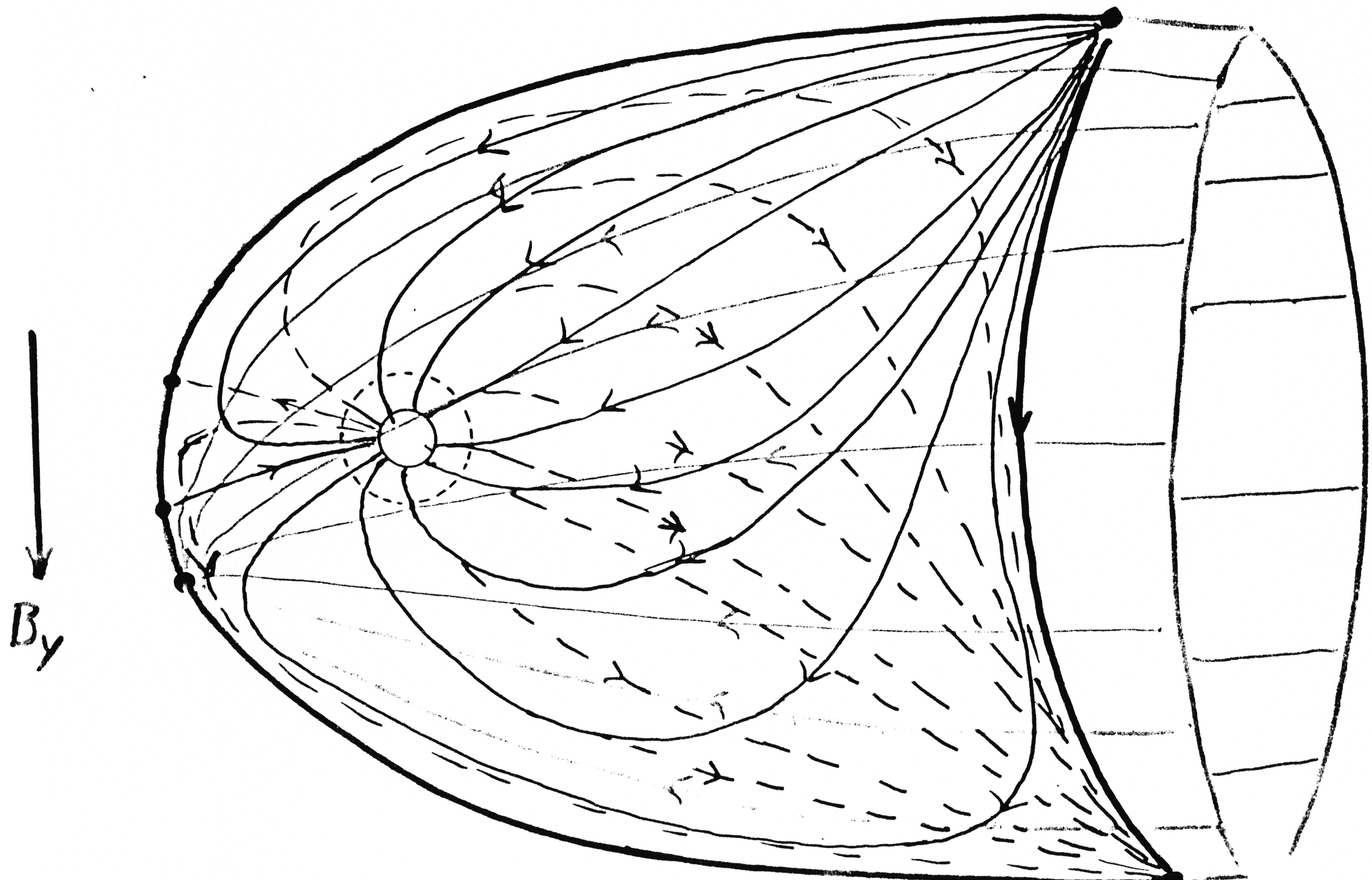
3. The conditons $\vec{E} \cdot \vec{B} = 0$ and $\vec{E} = -\vec{V} \times \vec{B}$ in the presence of a plasma are precisely the conditions for which all of the theorems fo MHD hold - particularly the frozen flux theorem. Thus there will be shielding currents separating fluxes of different origins, and compression currents if they are forced together. Neutral point plasma physics must be considered explicitly to diffuse the flux through.

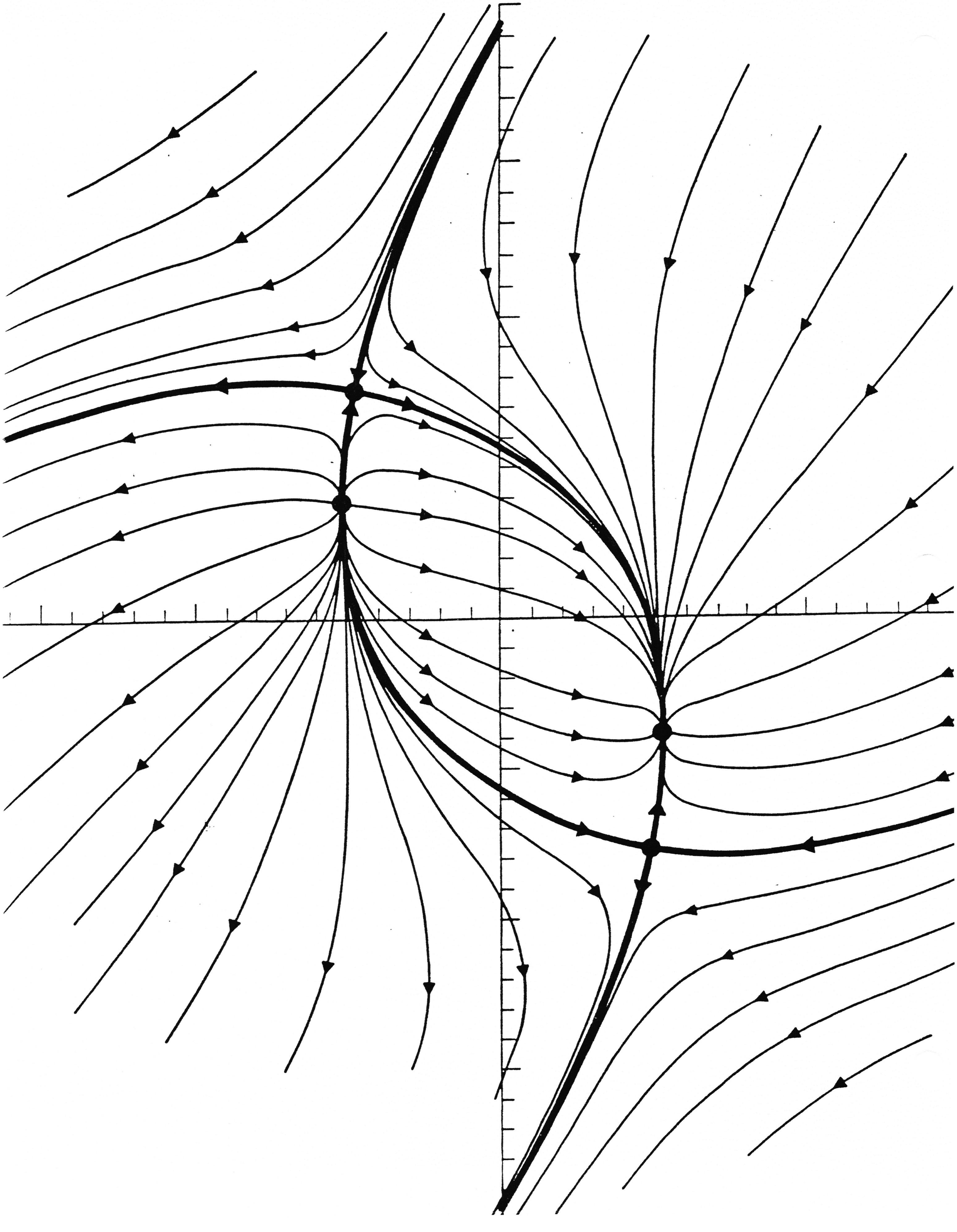
4. The distortions or splitting of the field lines necessary to get them to approach the n.p.'s and merge require additional currents. These features are not present in the superimposed vacuum fields.

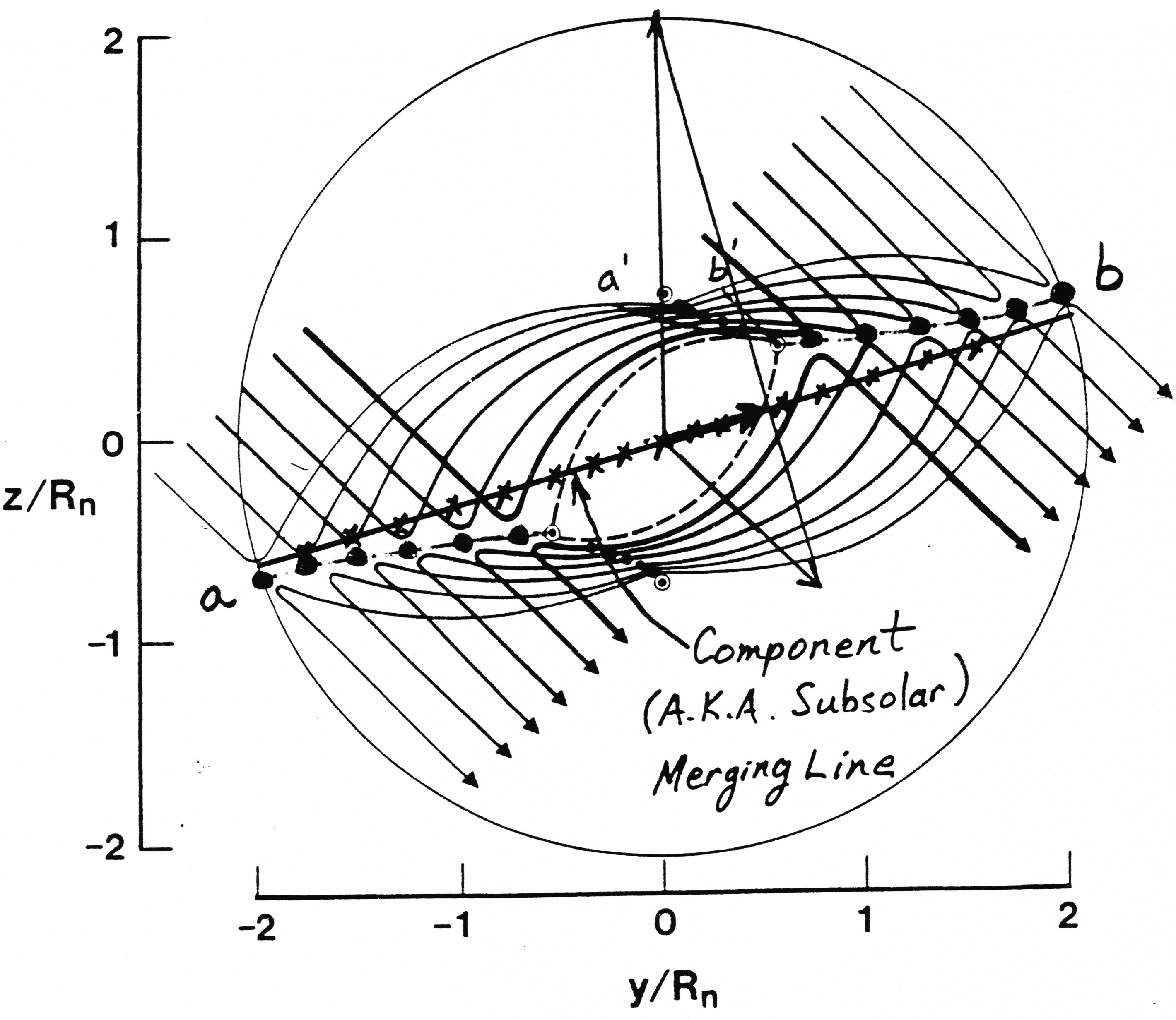
In addition to the internal inconsistencies, there are problems of basic physics (infinite electric field), incompleteness (no compression or shielding currents), and conflict with observations (the ionospheric impress of solar wind merging is more localized to the noon sector.)

Additional comment: The only way to solve the topology problem with a finite E field tangential to the separatrix surface and $\vec{E} \cdot \vec{B} = 0$ is to change the neutral point into a neutral line, as in the purely southward IMF case. (The ostensible alternative is to let $E_{\parallel} \neq 0$ such that $E = 0$ at the neutral point. But this entails $\nabla \times \vec{E}$, and thus $\frac{\partial \vec{B}}{\partial t}$, $\neq 0$. The resulting change in $\vec{B}$ moves the separatrix with the flow, and no flow crosses.) The compressional-shielding boundary currents go far toward solving many of these problems. Stern (1973) recognized that the separatrix line would bifurcate in the presence of surface currents. Haerendel (1978) observed that the field in the Chapman-Ferraro plane goes through all orientation possible around the cusp neutral point, and thus merging-type neutral points will necessarily appear in the plane for all IMF orientations. Crooker (1985) synthesized these ideas.




B_y



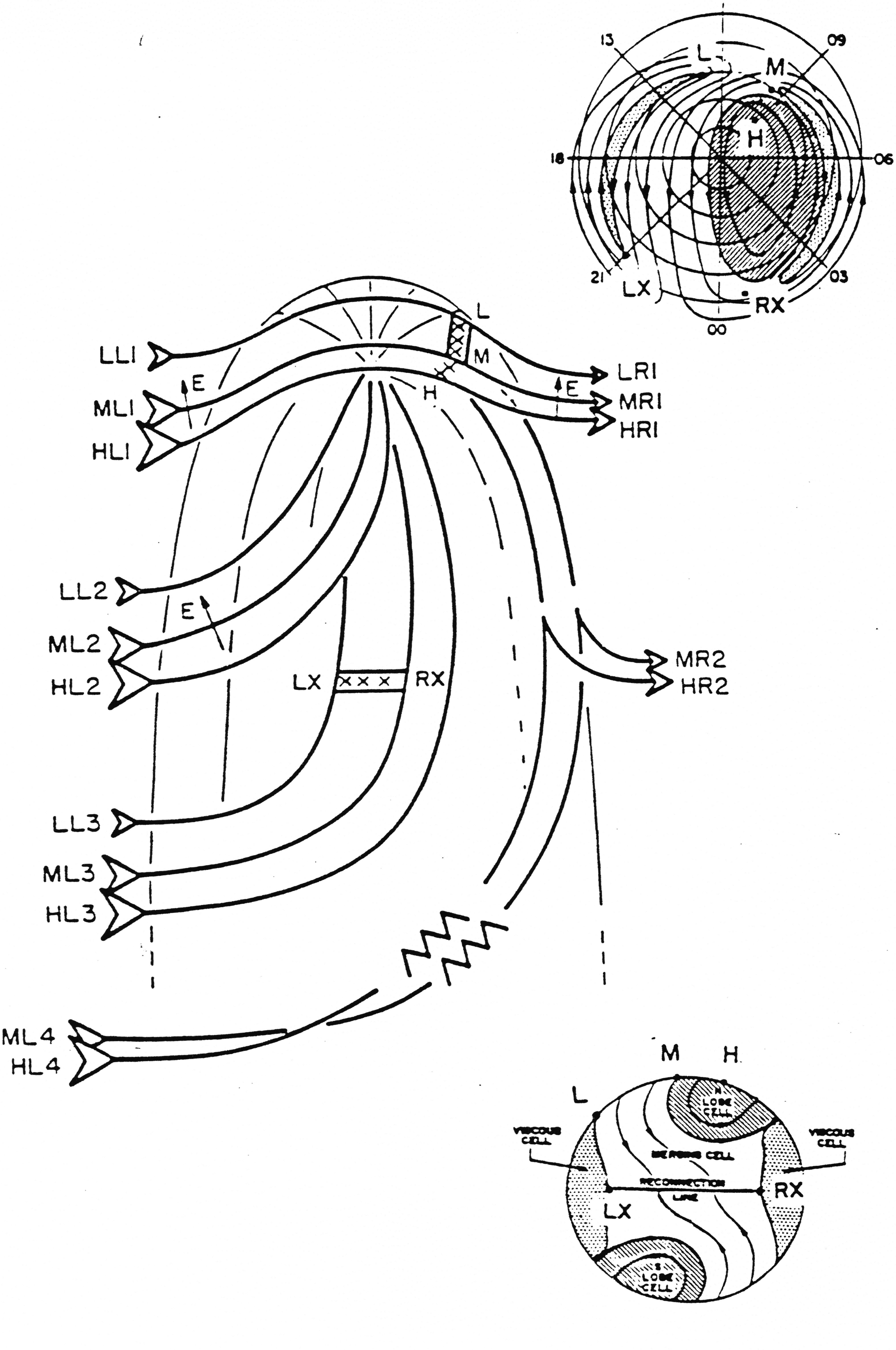

2
1
0
z/Rn
−1
−2
a
a'
b'
b
Component
(A.K.A. Subsolar)
Merging Line
−2
−1
0
1
2
y/Rn

Magnetopause currents do the following:

1. They move the neutral points to the boundary;
2. They introduce cusp neutral points which locate the ionospheric mapping near noon;
3. The finite thickness boundary converts the neutral points into neutral lines to permit conversion of a finite flux of one category of field line to another; and
4. Qualitative mapping of merged field lines to ionosphere gives convection patterns that simulate those observed (in one case, predicted a pattern subsequently and independently reported.)

Three major problems remain before this approach can be used to make quantitative predictions without adjustable parameters:

1. Redo the superposition using the solution to the 3-D MHD magnetosheath flow problem to give the proper field on the magnetosheath side of the boundary;
2. Quantitatively map the superposed fields to the ionosphere; and
3. Solve the merging problem for neutral points off the flow stagnation point.



Reiff & Burch 1985

COMPONENT - SUBSOLAR MERGING – AN OSTENSIBLE ALTERNATIVE TO NEUTRAL LINE MERGING.

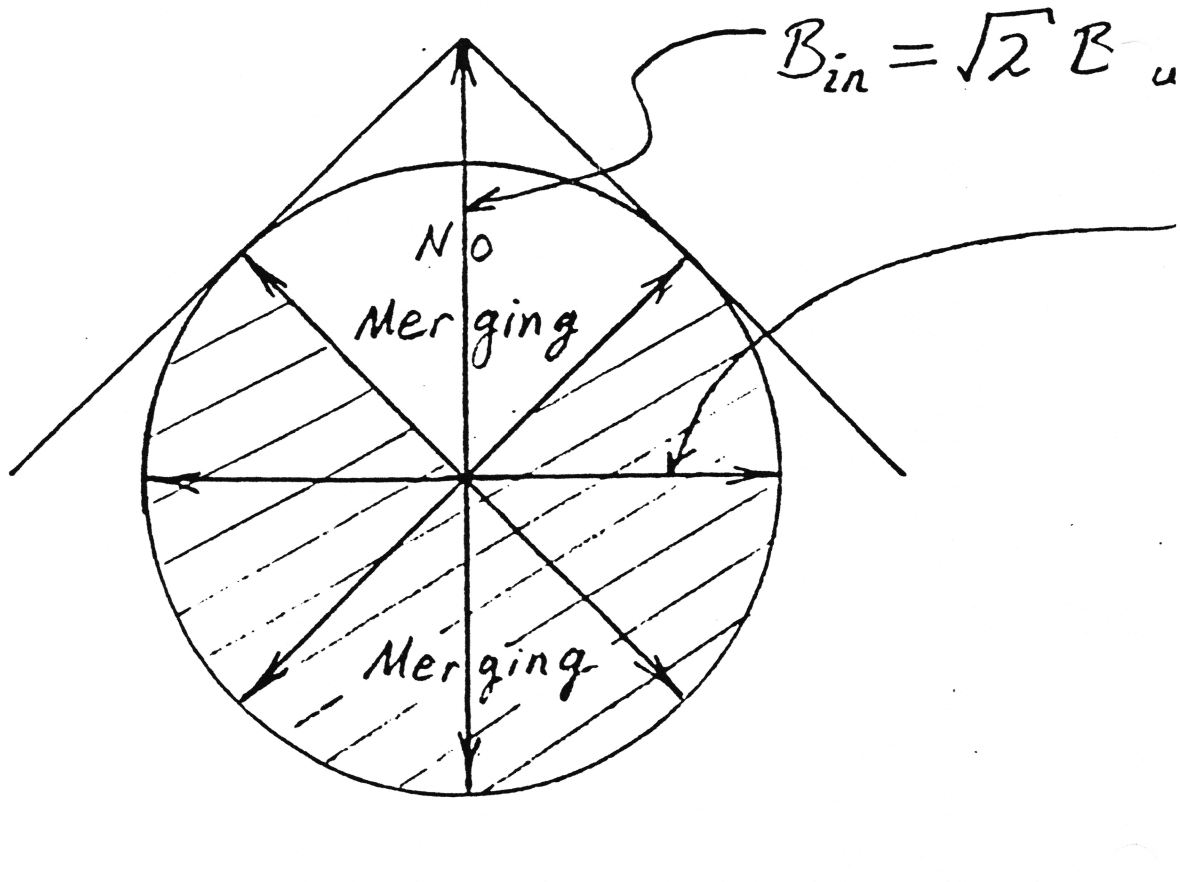
It exploits the fact that the solutions of the dynamical equations of merging flows are not affected by a uniform component of the magnetic field parallel to the merging line. Virtues:

1. It locates merging at the stagnation point where present merging theory applies;

2. If merging occurs at the stanation point, it won't be blown away (this solves an ill-formulated requiremnt that merging time < flow time);

3. It specifies merging line orientation for given IMF orientation;

4. Since the merging line is a streamline, merging can occur while its being blown away (nearly true for neutral line merging).



Merging can occur for all IMF orientations in the shaded region.

Problems:

1. Locating merging at the stagnation point is arbitrary as far as the dictates of component merging are concerned – it could be any place on the magnetopause. Stagnation point merging is one way to solve the $T_M < T_F$ problem. Another way to solve it is to merge quickly. Theory (Quest and Coroniti, 1981) predicts that merging of antiparallel fields is several orders of magnitude greater than for other orientations. Antiparallel fields occur along the neutral line. Thus the main reason for locating merging at the stagnation point applies as well to the neutral line.

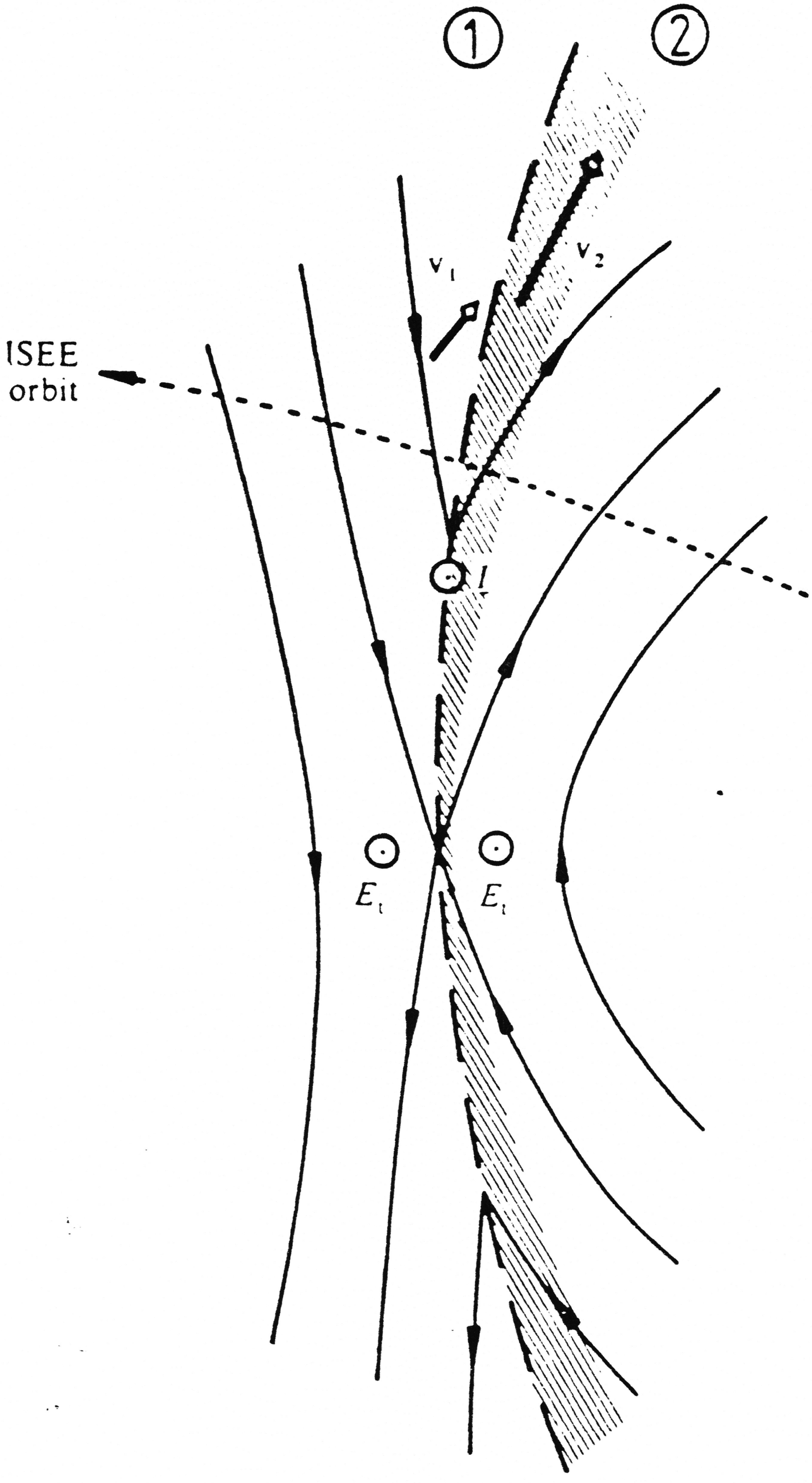
2. Field lines at the stagnation point do not pass through a neutral point for any but strictly southward IMF field lines. This is a fundamental topological problem.

3. Even if the field lines did pass through a neutral point, the merging region would have to extend to it to get finite flux to change types, all of the problems that apply to neutral line merging apply to component merging.

4. The problem of mapping to the ionosphere has not been addressed since this entails locating the neutral points. Component merging's ability to create, let alone simulate, ionospheric convection is unproven.

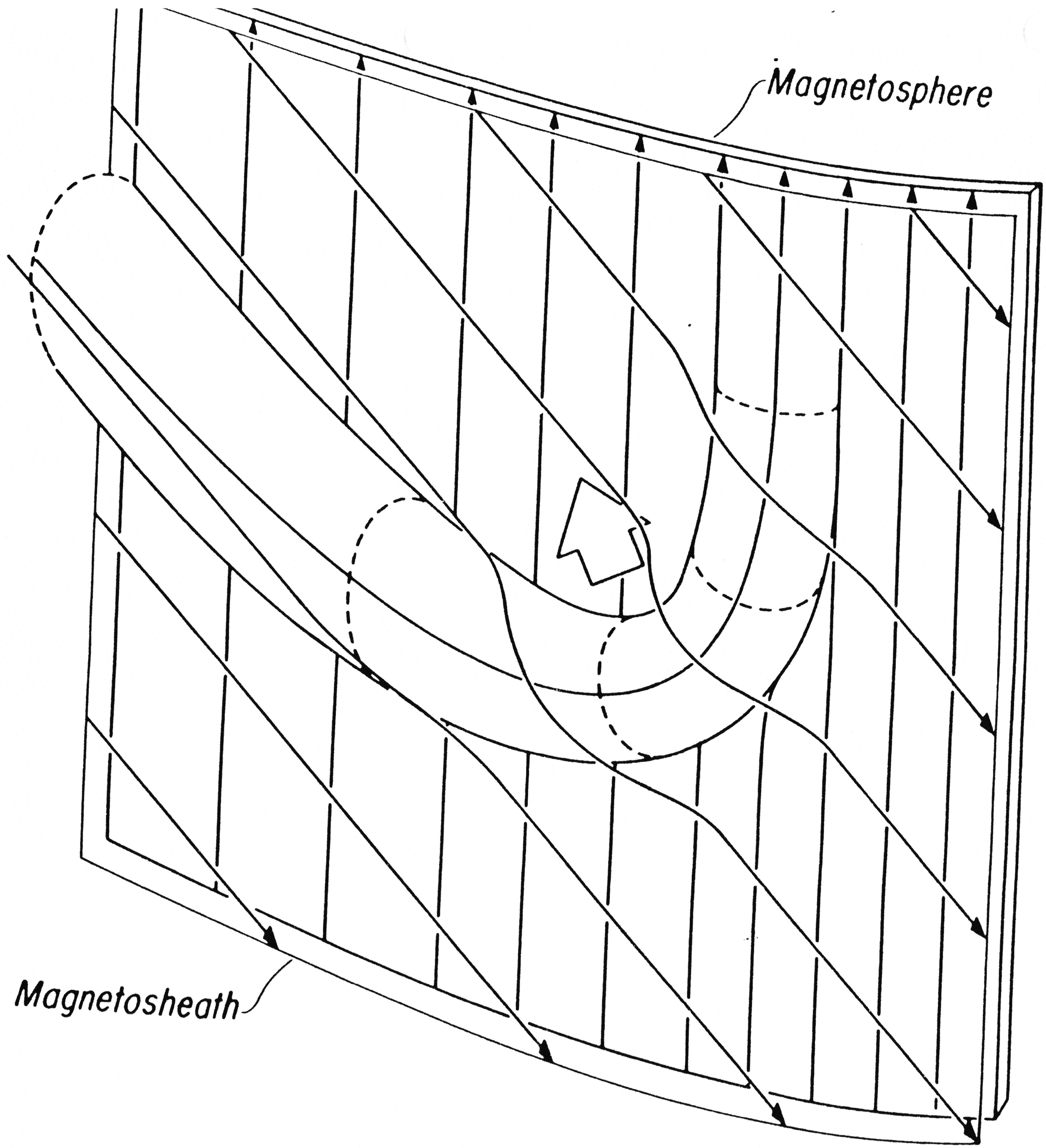
STEADY REGIONAL MERGING (ACCELERATED BOUNDARY LAYER FLOWS) and SPORADIC, LOCALIZED MERGING (FTE's)

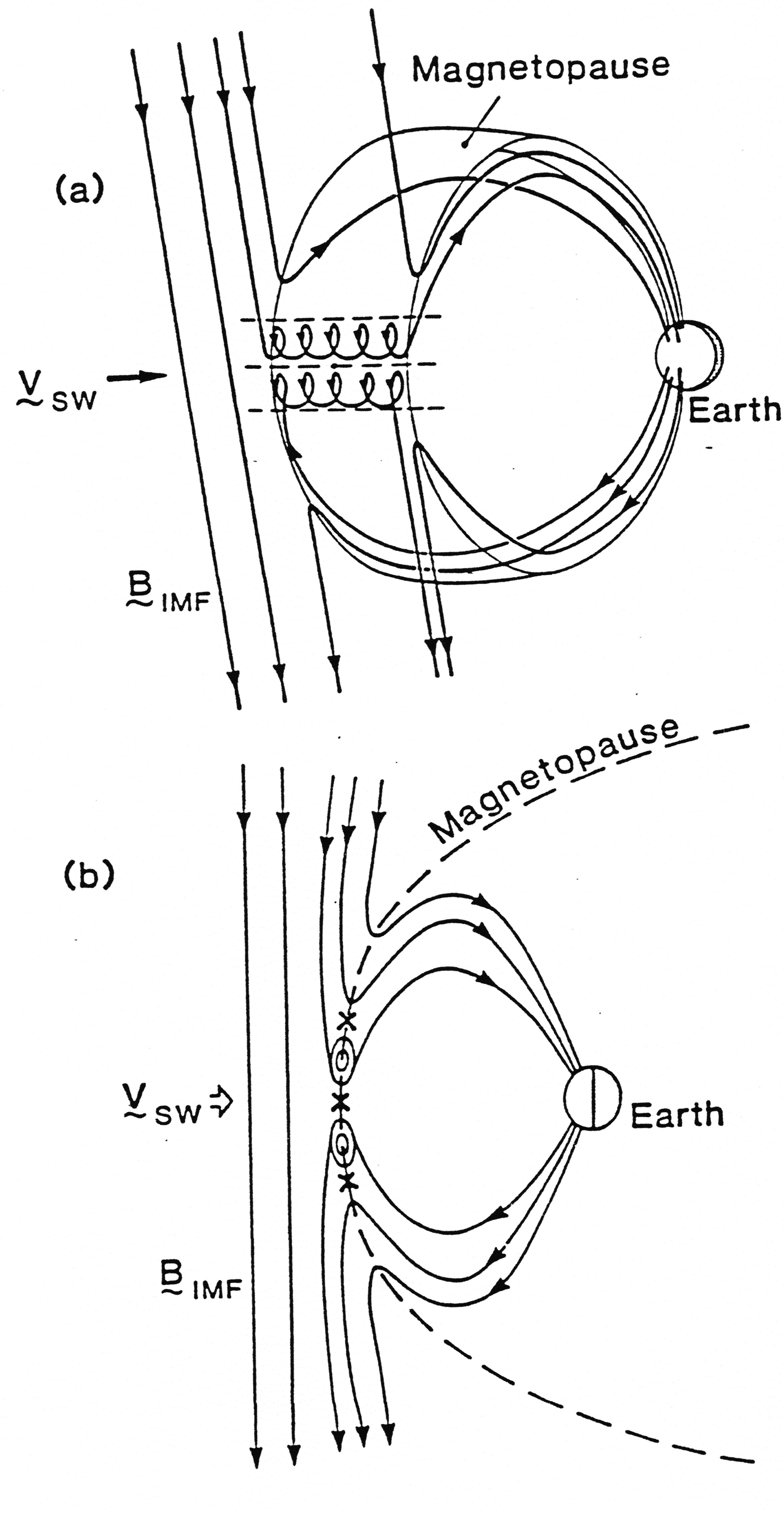
Judging from observations of fields and flows near the magnetopause, merging comes in two kinds – as the title declares. Conventional merging theory seems able to account for so-called "accelerated boundary layer flows". FTE's are another matter. I show two attempts to simulate FTE's with numerical codes (Lee and Sato). How FTE's relate to the field line topology in the boundary layer, and where they map in the Ionosphere are open questions.



Paschmann et al., 1979

- INTERFACE = AN ALFVEN WAVE


Magnetosphere
Magnetosheath



Magnetopause
(a)
V SW
Earth
B IMF
Magnetopause
(b)
V SW
Earth
B IMF

L. C. Lee

CONCLUDING WORDS

Extending merging theory, which is well developed for stagnation point merging, to treat regions away from the stagnation point, this means matching the merging solution to the external flow field, and combining it with topological maps of the neutral line in the boundary layer determined from properly draped magnetosheath field and the MHD calculated magnetosheath flow is a program for developing the solar wind-magnetosphere link in a predictive global coupling code. This is difficult. The existence of FTE's suggests the solution may be inherently unstable. Observations have given us signatures of boundary merging processes and should, in principle, provide answers or at least clues to the global merging picture. But now all contestants find observations to support their models, and refute competitors. (CLUSTER may help.) Numerical simulations hold much promise to aid our understanding of boundary merging processes. (They could right away resolve the neutral line - component merging controversy.) Once these steps are taken, the solar wind electric field can be mapped quantitatively and predictively to the ionosphere.