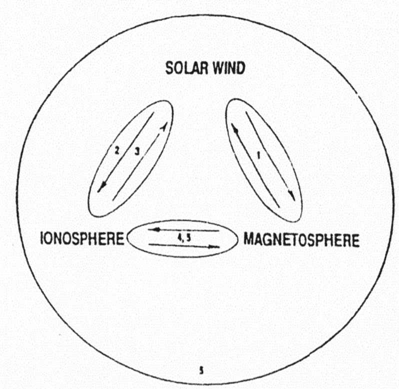
SOLAR WIND - MAGNETOSPHERE - IONOSPHERE COUPLING

LECTURE 4

MAGNETOSPHERE - IONOSPHERE COUPLING



Of magnetosphere - ionosphere coupling, it has been said:

' Curiouser and curioser ! ' cried Alice
Lewis Carroll - Alice in Wonderland

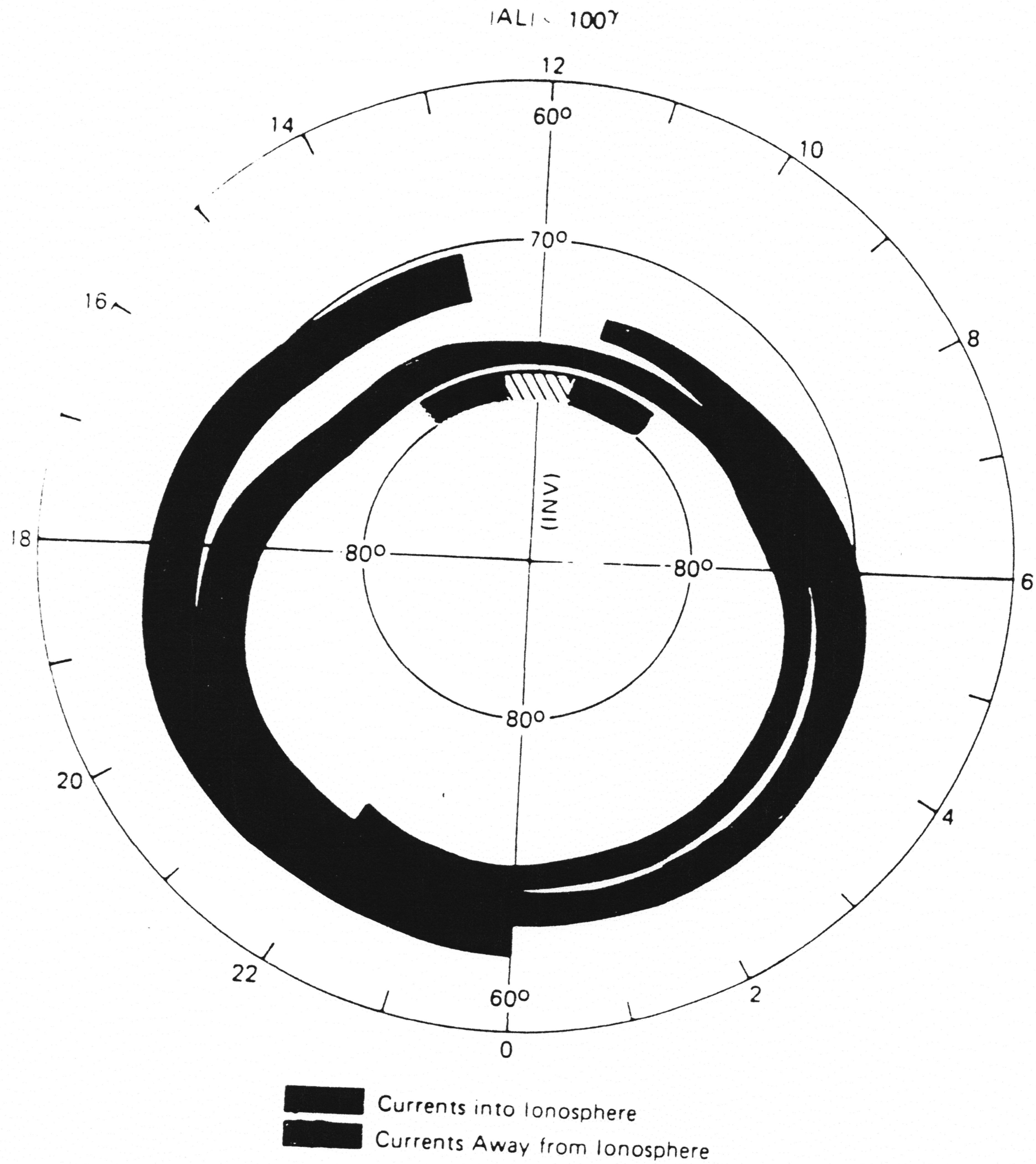
Oh day and night, but this is wondrous strange !
Shakespeare - Hamlet

THE NATURE OF THE PROBLEM

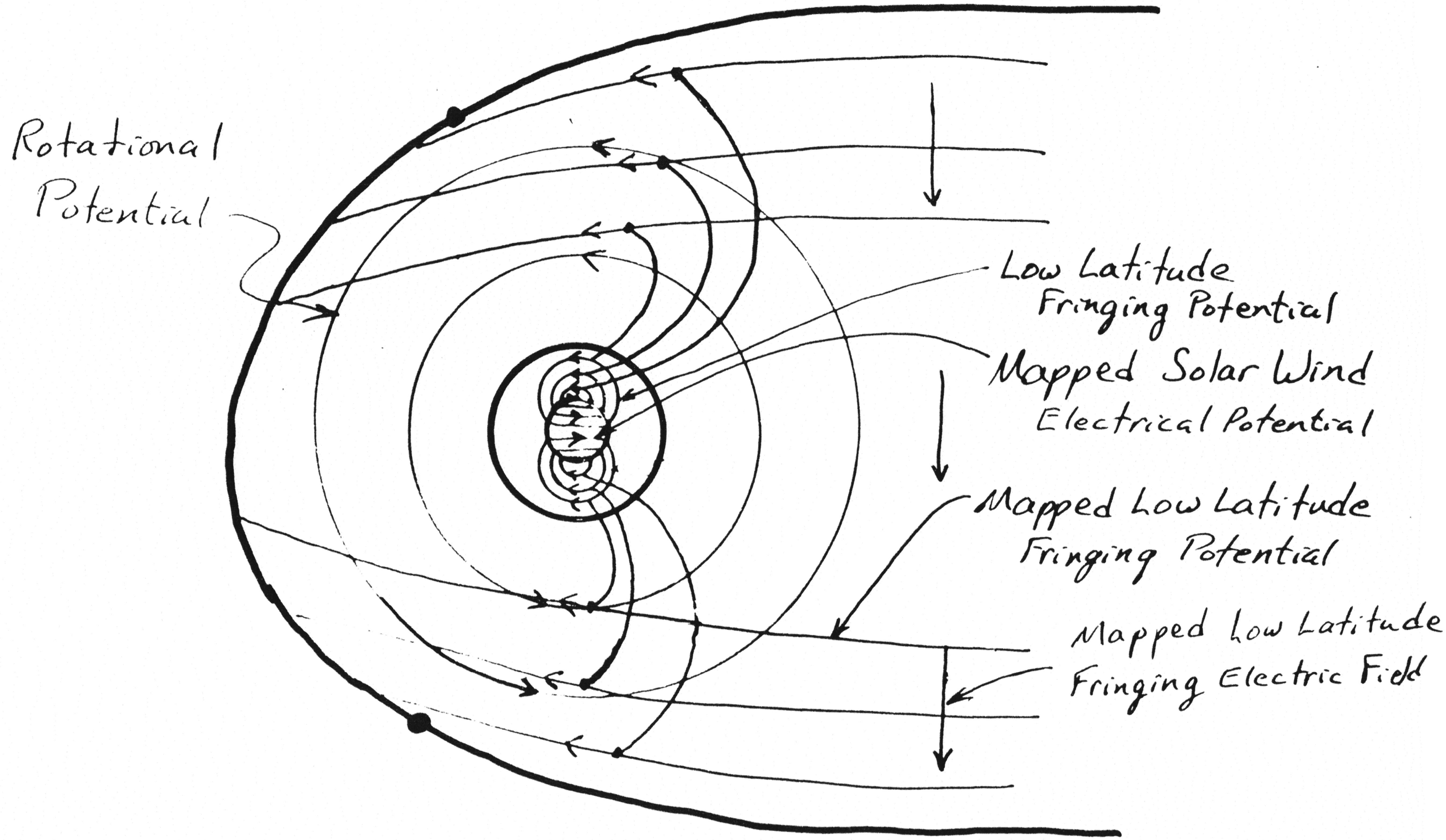
After exposing that self-regulating, IMF-articulated oriface it uses to feed on the solar wind, flashing glimpses of the tortuous magnetic net it casts through that opening to snag the wind's energy, and partially revealing the mysterious inner circulations that distribute and consume that energy, what more can the magnetosphere offer to surprise and entertain ?

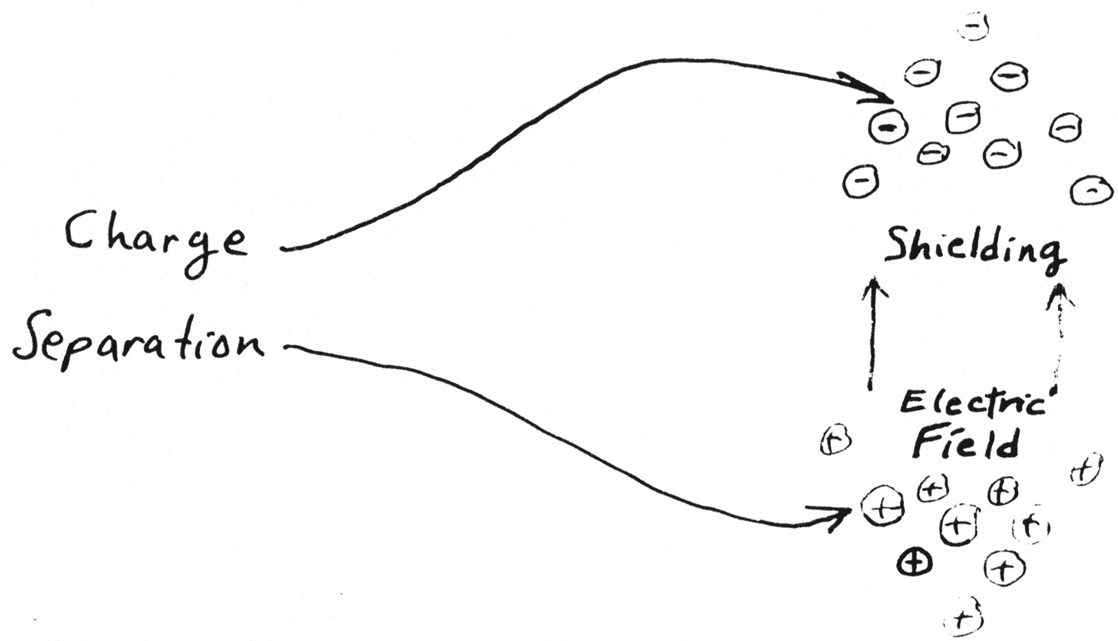
ANSWER: MAGNETOSPHERE - IONOSPHERE COUPLING

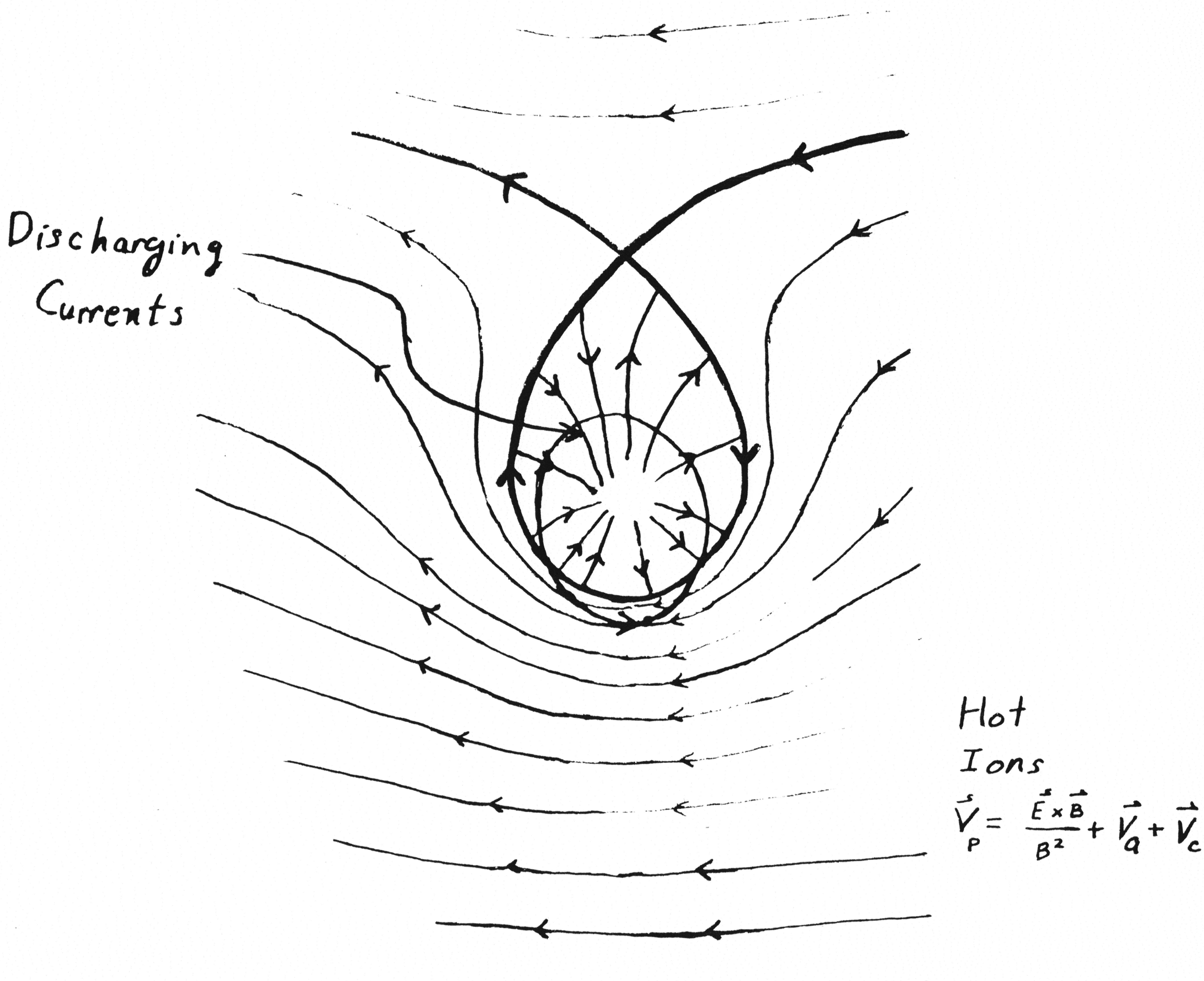
Here we encounter a new kind of complexity. The magnetosphere and the ionosphere are two partners in a game of electrical 'currency' exchange, and the stakes run into the millions of amperes. The interesting thing is that, like characters in Alice's wonderland, each plays by a different set of rules. The problem is to arrange things so that the partners can exchange their electrical currency and not be aware that the other is playing a different game. The region 2 currents are that exchange in progress.



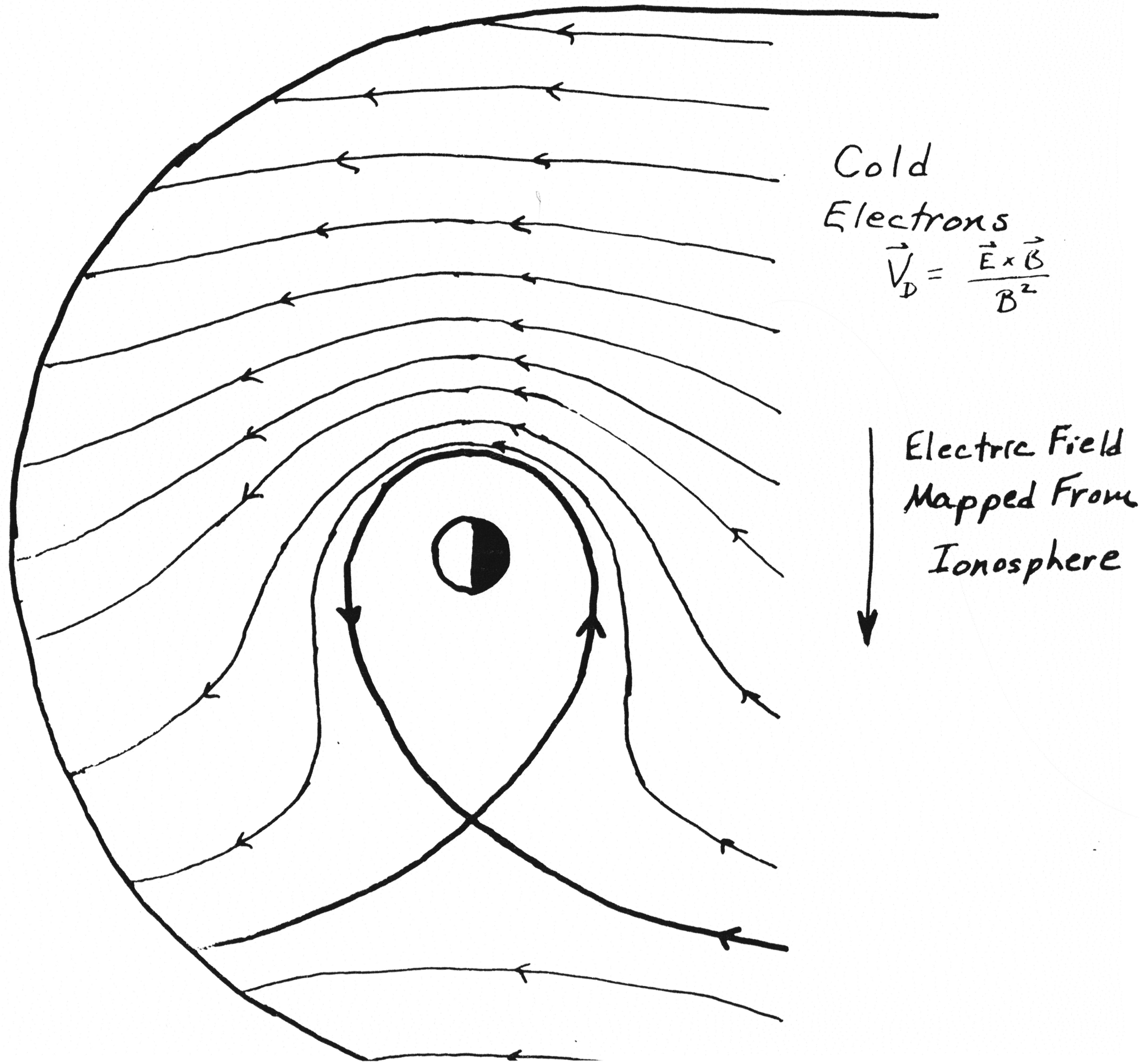
12
60°
14
10
16
70°
8
(INV)
18
80°
80°
6
80°
20
4
22
60°
2
0
Currents into Ionosphere
Currents Away from Ionosphere


Rotational Potential
Low Latitude Fringing Potential
Mapped Solar Wind Electrical Potential
Mapped Low Latitude Fringing Potential
Mapped Low Latitude Fringing Electric Field


Charge
Separation
Shielding
Electric
Field



Discharging Currents
Hot Ions
$\vec{V}_p = \frac{\vec{E} \times \vec{B}}{B^2} + \vec{V}_g + \vec{V}_c$



Cold
Electrons
$\vec{V}_D = \frac{\vec{E} \times \vec{B}}{B^2}$
Electric Field
Mapped From
Ionosphere

VASYLIUNAS MAGNETOSPHERE - IONOSPHERE COUPLING EQUATION

Magnetospheric Current

$$\vec{I}_m = eN(\vec{V}_B + \vec{V}_D) - eN\vec{V}_B + \vec{I}_M$$

$$\vec{V}_B = \vec{E} \times \vec{B}_I / B_I^2$$

Current into Ionosphere from Magnetosphere

$$J_{\parallel} \sin\chi = -\nabla \cdot \vec{I}_m$$

Continuity Equation for Protons

$$\frac{\partial N}{\partial t} + \nabla \cdot N(\vec{V}_B + \vec{V}_D) = 0$$

Combining above gives

$$J_{\parallel} \sin\chi = \nabla \cdot eN\vec{V}_B + e\frac{\partial N}{\partial t}$$

Which can be written as

$$J_{\parallel} \sin\chi = -\nabla \cdot \Sigma_H^* \frac{\vec{B}_I}{B_I} \times \vec{E} + e\frac{\partial N}{\partial t}$$

$$\Sigma_H^* = \frac{eN}{B_I}$$

Ionospheric current continuity equation

$$\nabla \cdot (\overleftrightarrow{\Sigma} \cdot \vec{E}) = J_{\parallel} \sin\chi$$

Combining above gives

$$\nabla \cdot (\overleftrightarrow{\Sigma} + \overleftrightarrow{\Sigma}_H^*) \cdot \vec{E} = e\frac{\partial N}{\partial t}$$

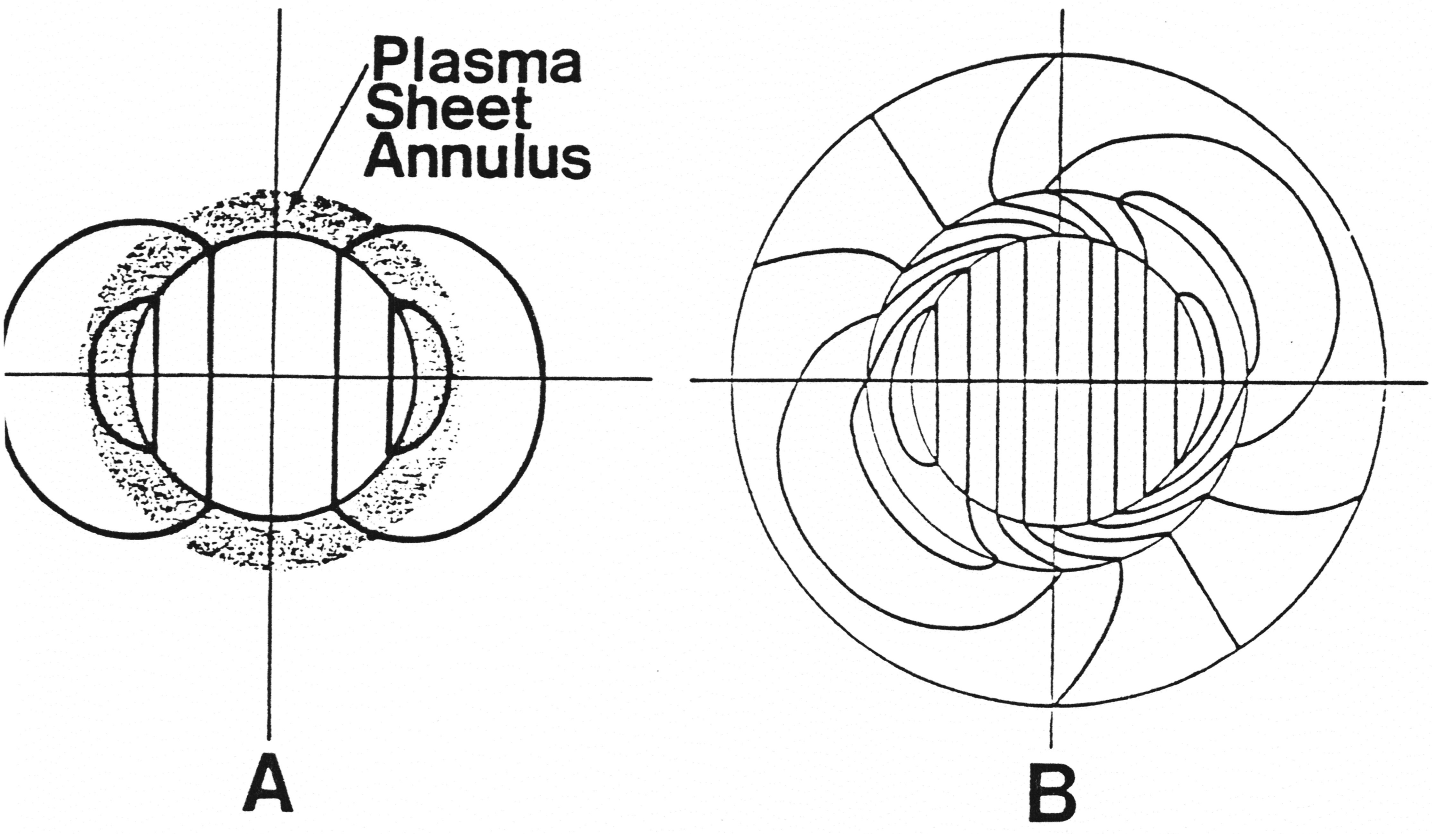
Vasyliunas (1972)

VASYLIUNAS' SELF-CONSISTENCY EQUATION

$$\nabla \cdot (\overleftrightarrow{\Sigma} + \overleftrightarrow{\Sigma}^{*}_{H}) \cdot \vec{E} = e \frac{\partial N}{\partial t}$$

$$\Sigma^{*}_{H} = \frac{eN}{B_i}$$

VASYLIUNAS' STEADY-STATE, 2-D, ZONAL MIC MODEL



1. THE IMPOSED 2-CELL, 2-D DIPOLE CONVECTION PATTERN DISTORTED BY ANTI-CLOCKWISE TWIST IN PLASMAL SHEET ANNULUS

2. FIELD STRENGTH EQUATORWARD OF ANNULUS REDUCED BY THE ORDER OF Σ_p/Σ_H^*. (THE SHIELDING EFFECT)

THE TWO GAMES OF CURRENT EXCHANGE

Both derive their exchange current, $J_{\parallel}$, by taking it from or adding it to $\vec{J}_{\perp}$ (where $\vec{J} = \vec{J}_{\perp} + J_{\parallel}\vec{B}/B$) according to

$$\nabla \cdot \vec{J} = 0 \Rightarrow \nabla \cdot \vec{J}_{\perp} = -\nabla \cdot J_{\parallel}\frac{\vec{B}}{B} = -B\frac{\partial}{\partial s}\frac{J_{\parallel}}{B}$$

For the ionosphere, as noted earlier, this is

Ionospheric game $\quad \nabla \cdot (\overleftrightarrow{\Sigma} \cdot \vec{E}) = J_{\parallel} \sin\chi$

For the magnetosphere, the operative equation for $\vec{J}_{\perp}$ is the force balance condition, which for isotropic pressure is:

$$\nabla p = \vec{J}_{\perp} \times \vec{B}$$

Solved for $\vec{J}_{\perp}$, this is

$$\vec{J}_{\perp} = \frac{\vec{B} \times \nabla_p}{B^2}$$

Giving for the magnetospheric exchange current the expression

$$B\frac{\partial}{\partial s}\frac{J_{\parallel}}{B} = -\nabla \cdot \frac{\vec{B} \times \nabla_p}{B^2}$$

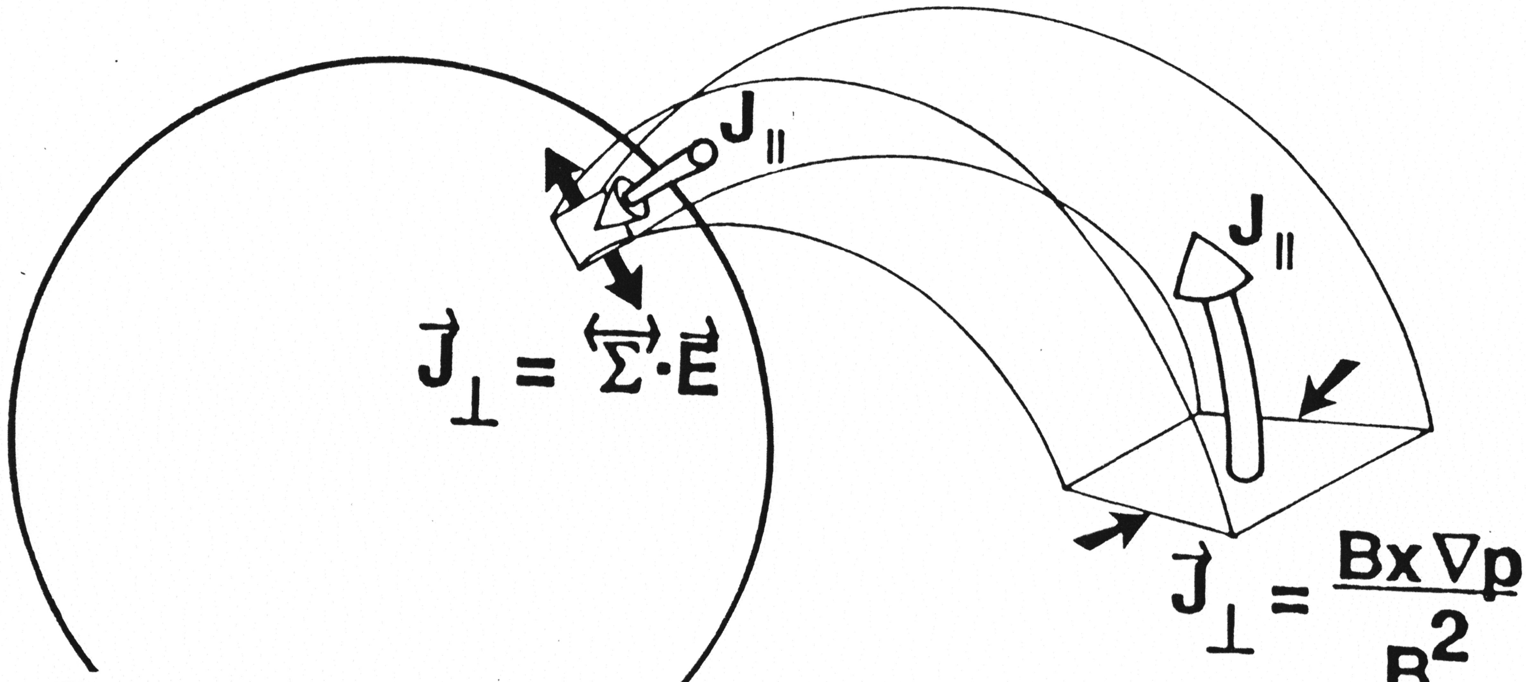
which can be integrated to yield (Wolf, 1983)

Magnetospheric game $\quad J_{\parallel} = -\frac{B_i}{2B_e}\,\hat{z} \cdot (\nabla_e p \times \nabla_e V)$

where e and i denote quantities evaluated at the equatorial and ionospheric ends of a flux tube, and

$$V \equiv \int \frac{ds}{B}$$

is the volume of a unit flux flux tube

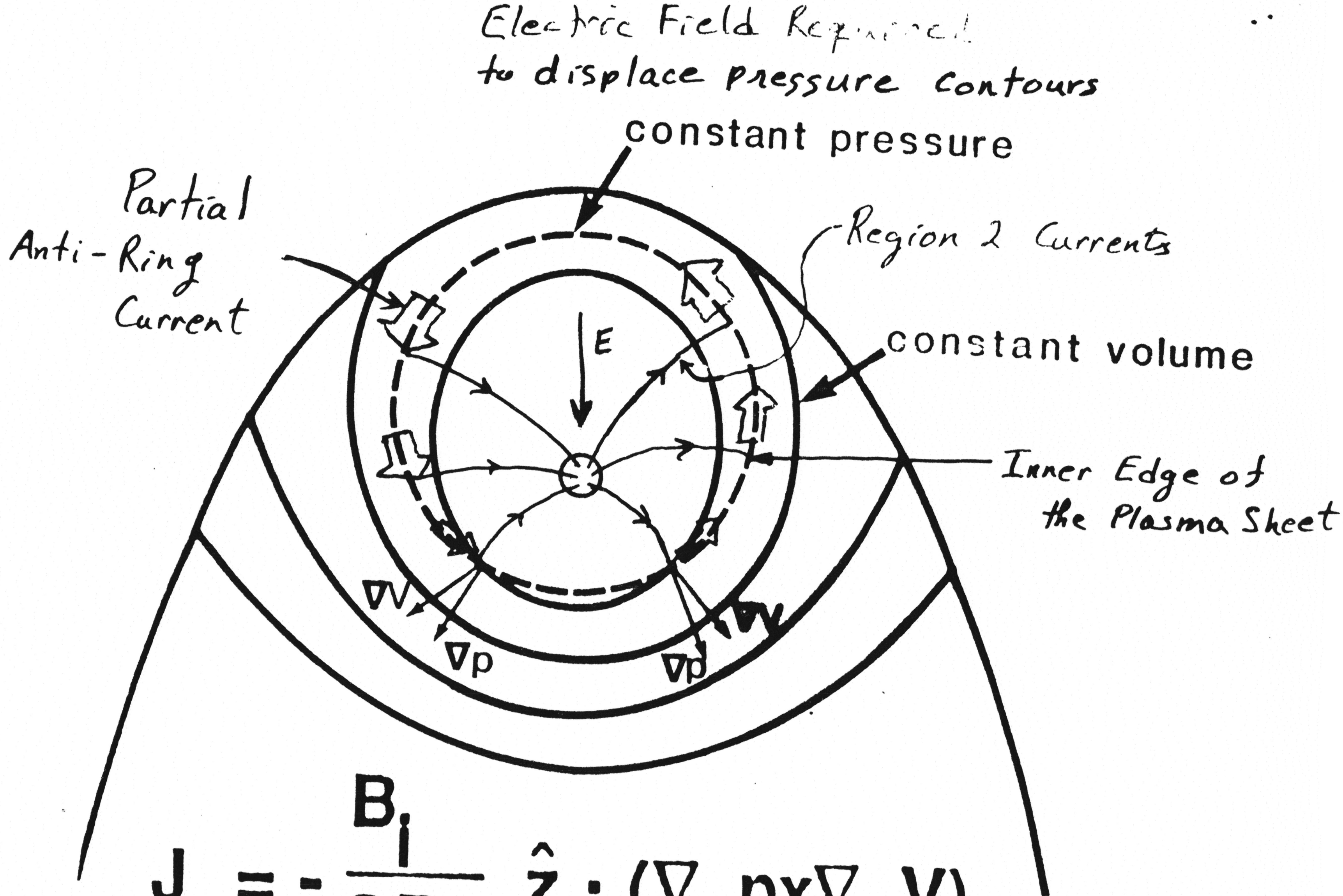


SELF-CONSISTENCY REQUIREMENT

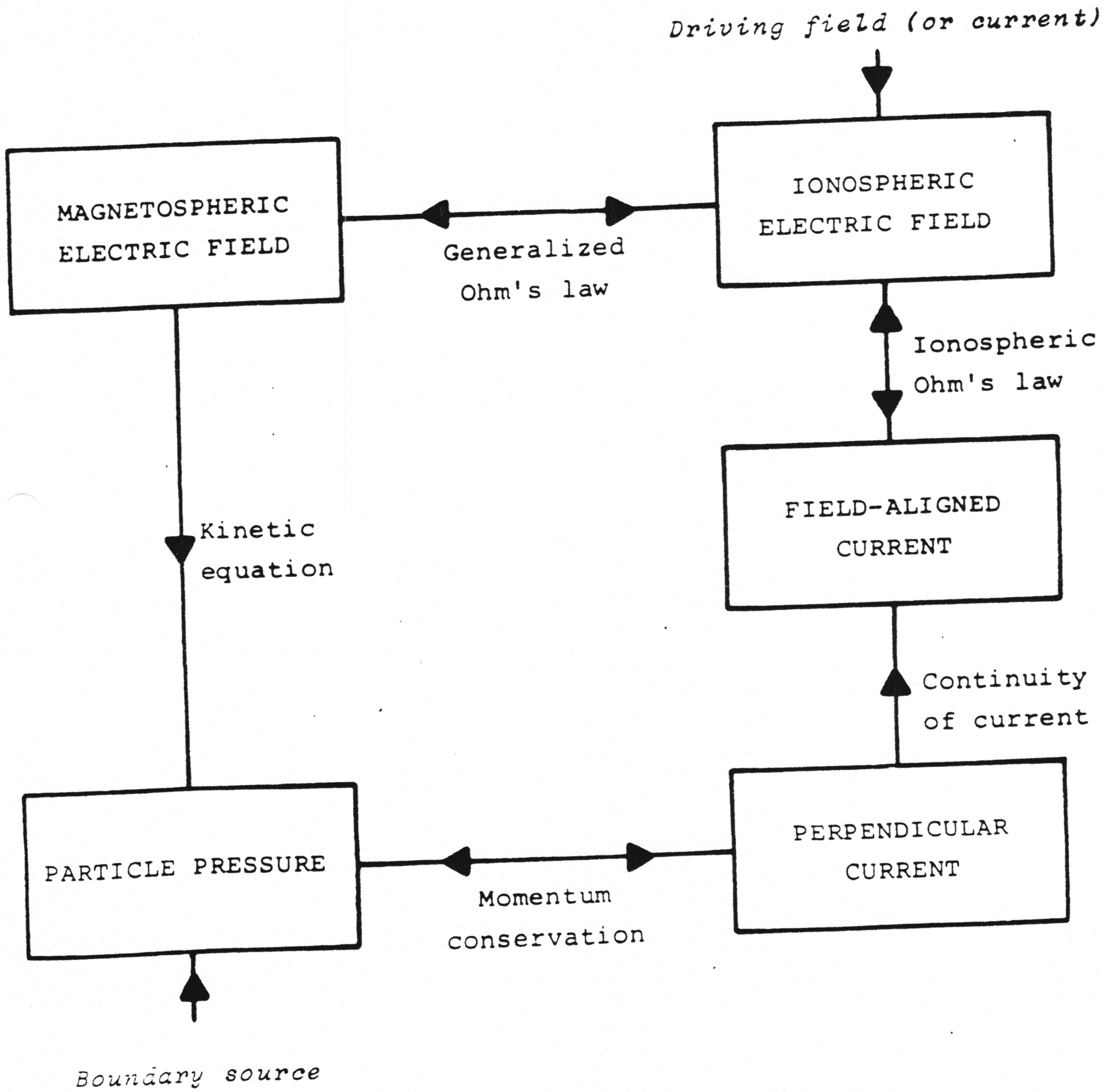
$$\nabla \cdot \vec{J}_{\parallel} = - \nabla \cdot \vec{J}_{\perp}$$

$(J_{\parallel})$ IONOSPHERE

$= (J_{\parallel})$ MAGNETOSPHERE

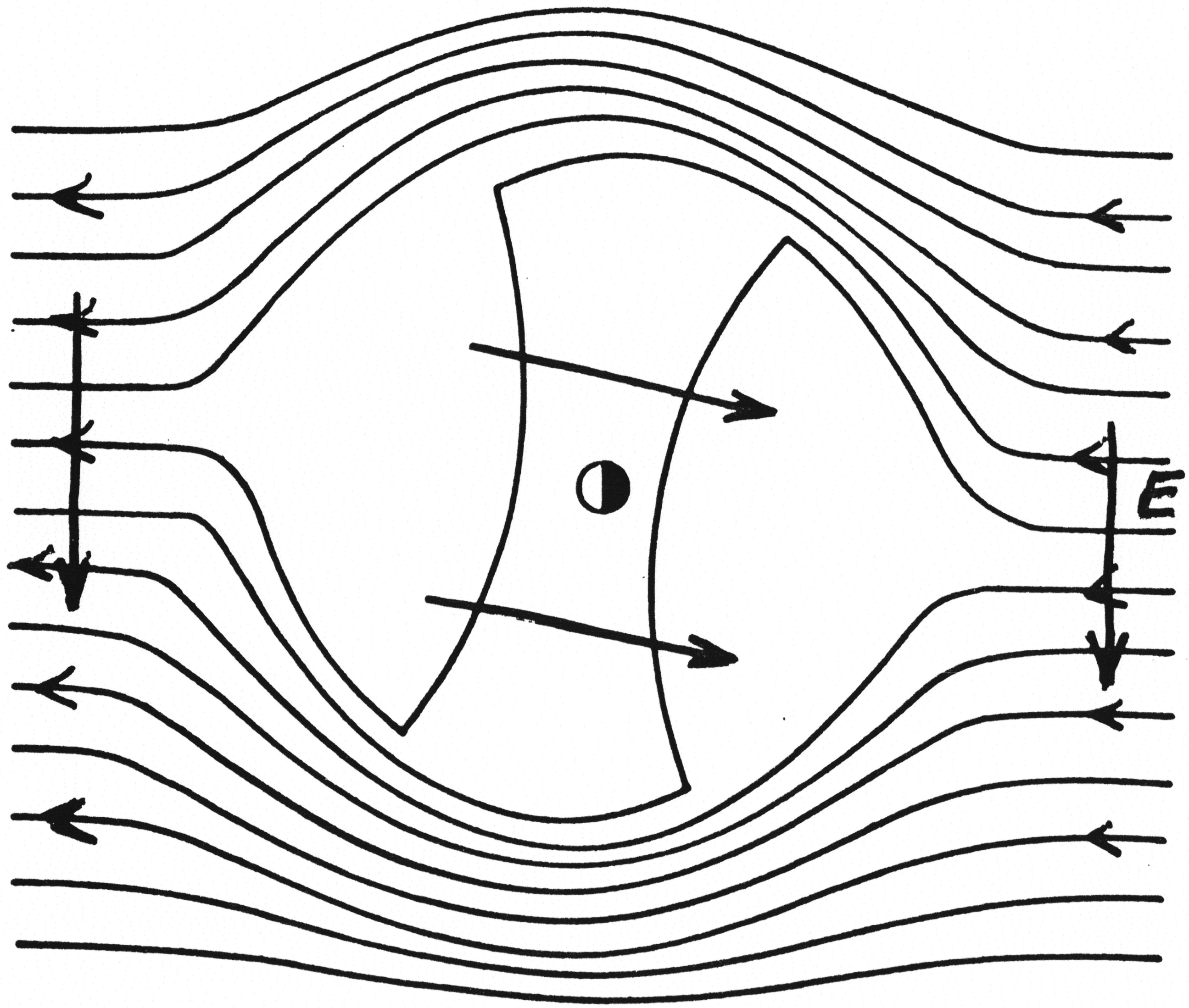


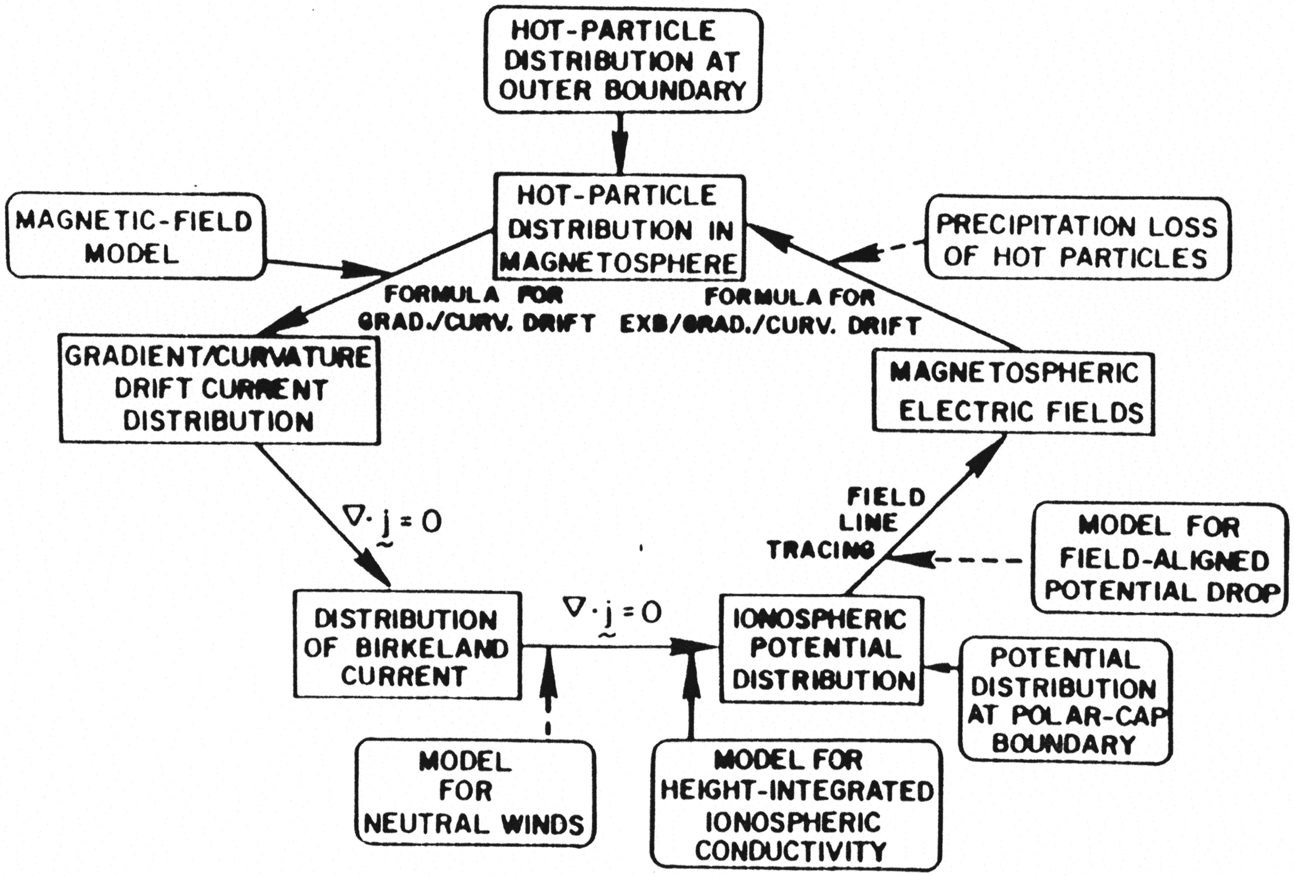
$$J_{\parallel} = - \frac{B_i}{2B_e} \hat{z} \cdot (\nabla_e p \times \nabla_e V)$$

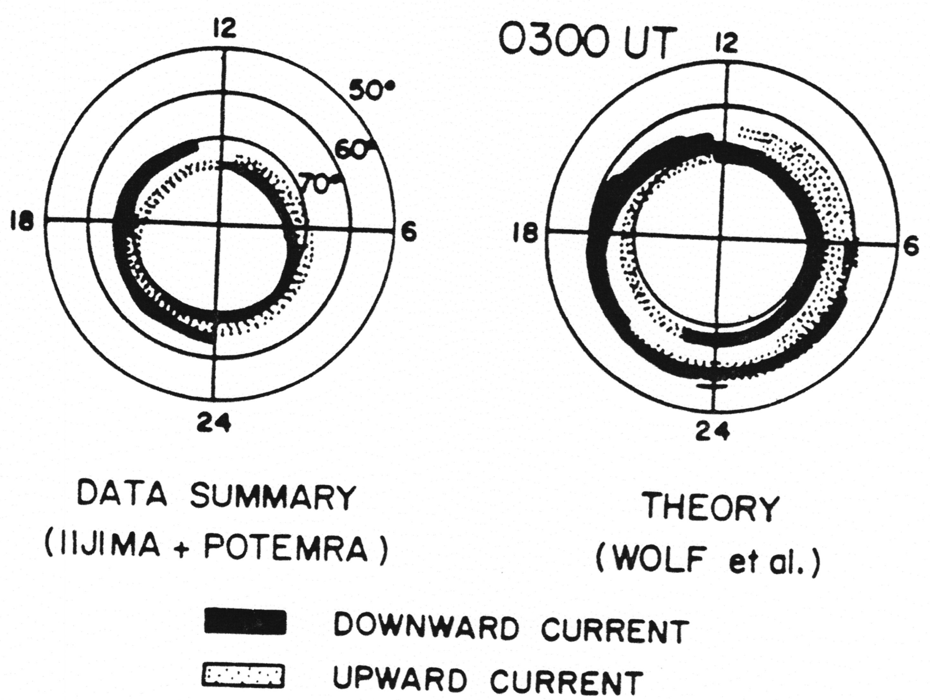


Driving field (or current)
MAGNETOSPHERIC ELECTRIC FIELD
Generalized Ohm's law
IONOSPHERIC ELECTRIC FIELD
Ionospheric Ohm's law
FIELD-ALIGNED CURRENT
Kinetic equation
Continuity of current
PARTICLE PRESSURE
Momentum conservation
PERPENDICULAR CURRENT
Boundary source

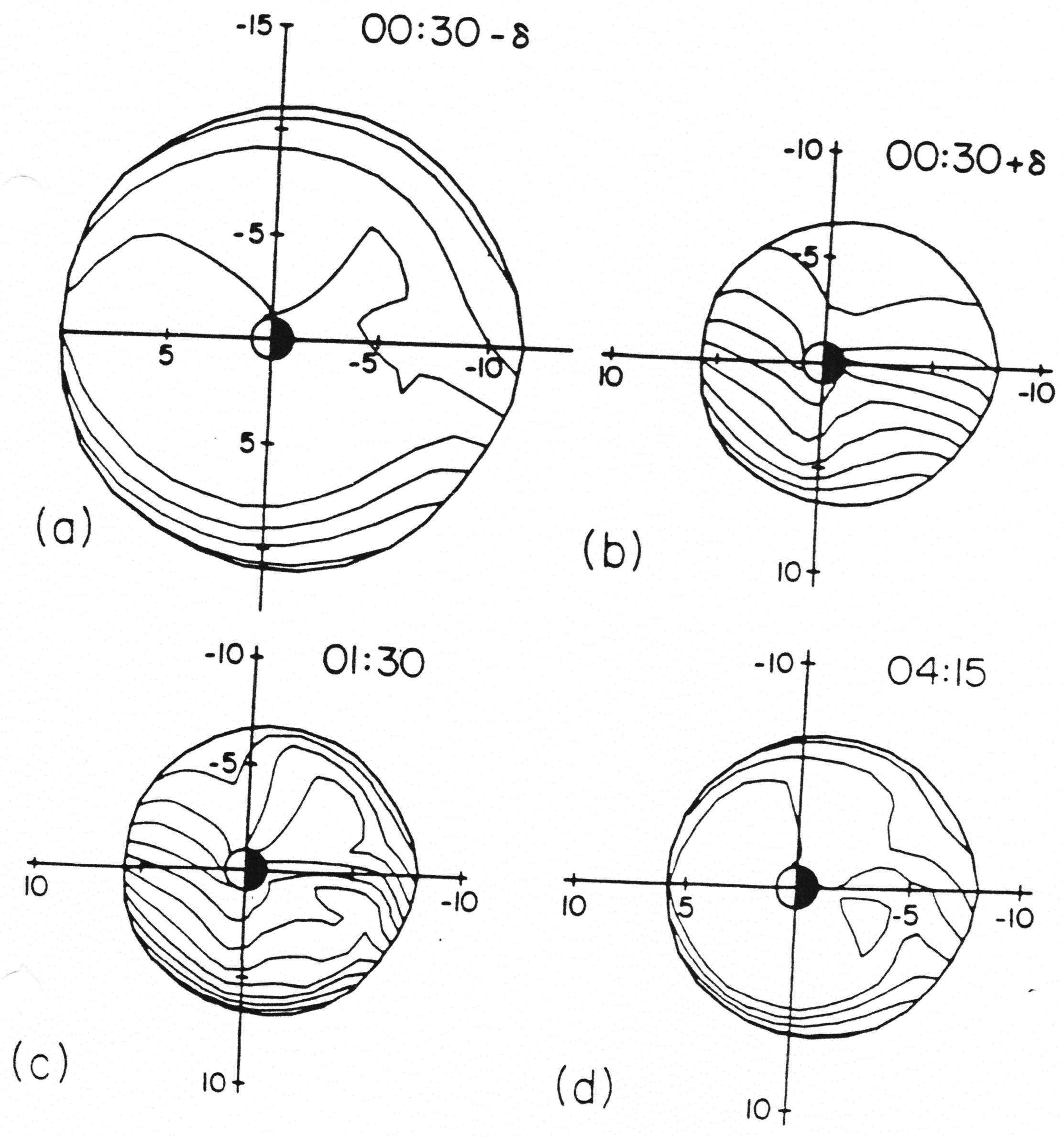
Figure 1


E


HOT-PARTICLE DISTRIBUTION AT OUTER BOUNDARY
HOT-PARTICLE DISTRIBUTION IN MAGNETOSPHERE
MAGNETIC-FIELD MODEL
PRECIPITATION LOSS OF HOT PARTICLES
FORMULA FOR GRAD./CURV. DRIFT
FORMULA FOR EXB/GRAD./CURV. DRIFT
GRADIENT/CURVATURE DRIFT CURRENT DISTRIBUTION
MAGNETOSPHERIC ELECTRIC FIELDS
$\nabla \cdot \tilde{j} = 0$
FIELD LINE TRACING
MODEL FOR FIELD-ALIGNED POTENTIAL DROP
DISTRIBUTION OF BIRKELAND CURRENT
$\nabla \cdot \tilde{j} = 0$
IONOSPHERIC POTENTIAL DISTRIBUTION
POTENTIAL DISTRIBUTION AT POLAR-CAP BOUNDARY
MODEL FOR NEUTRAL WINDS
MODEL FOR HEIGHT-INTEGRATED IONOSPHERIC CONDUCTIVITY

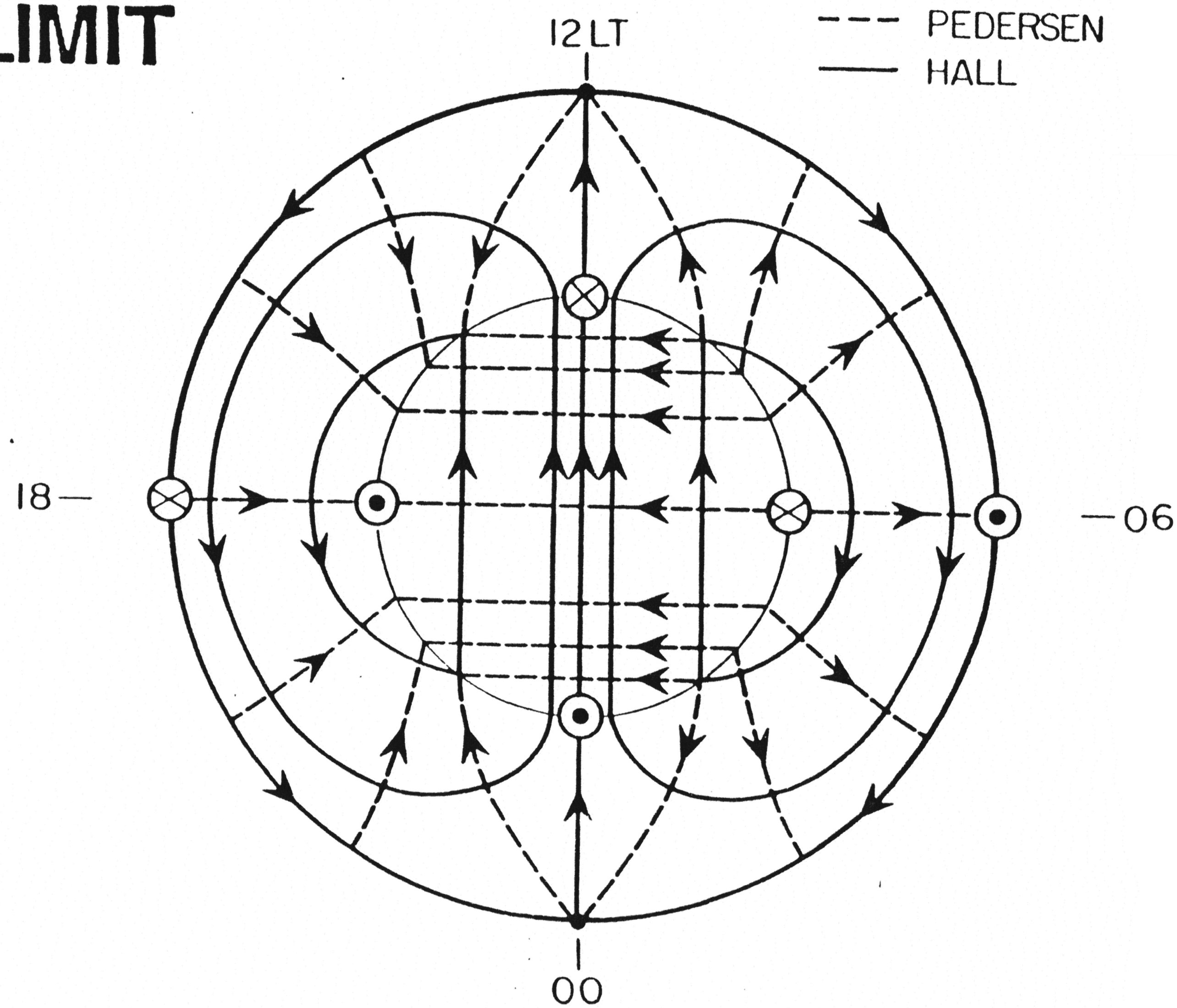


0300 UT
12
18
6
24
50°
60°
70°
DATA SUMMARY
(IIJIMA + POTEMRA)
THEORY
(WOLF et al.)
DOWNWARD CURRENT
UPWARD CURRENT



00:30 - δ
00:30 + δ
01:30
04:15
(a)
(b)
(c)
(d)

PERFECT SHIELDING LIMIT



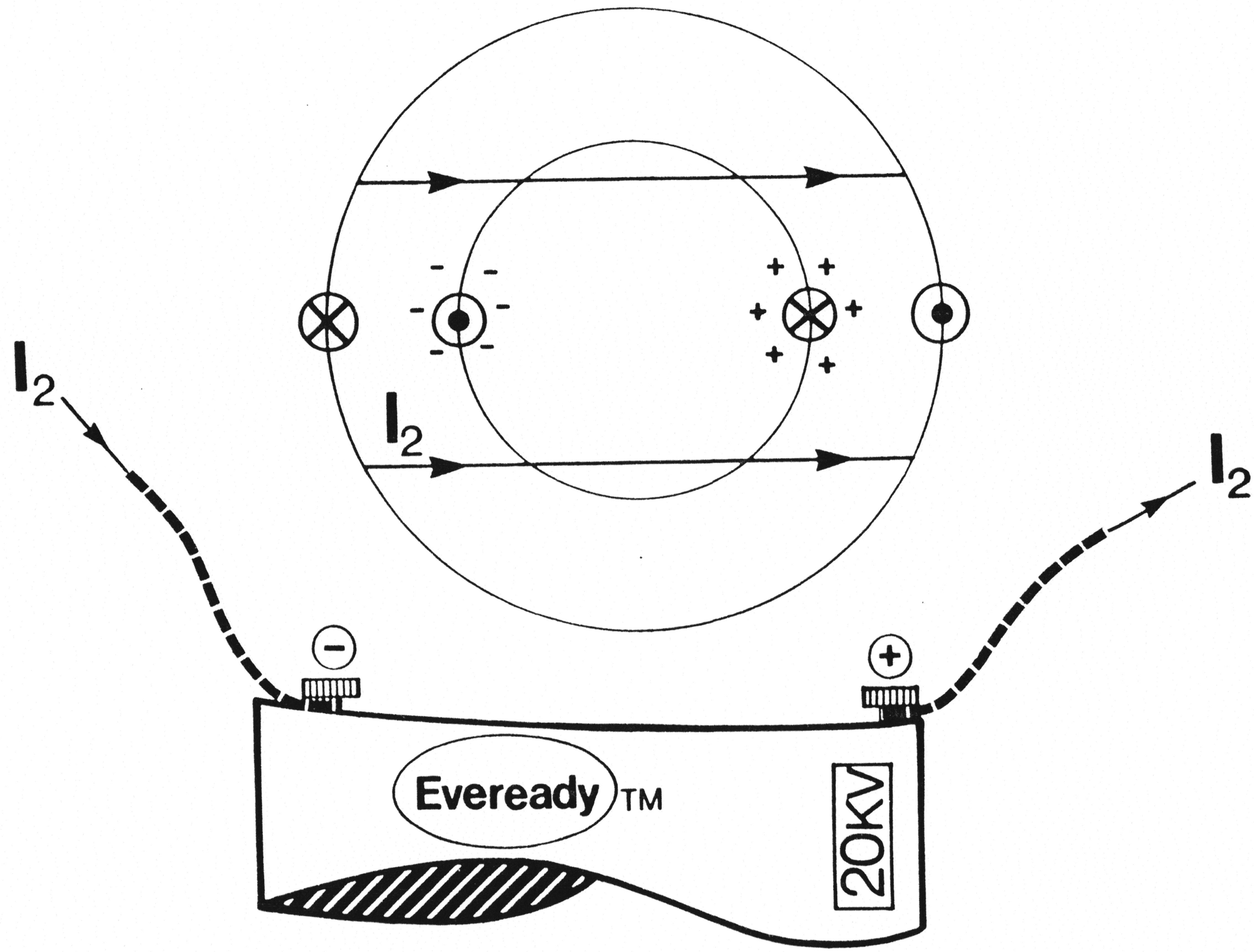
PERFECT SHIELDING LIMIT

$$I_1^P = \left(\frac{b^2+a^2}{b^2-a^2}\,\Sigma_A^P + \Sigma_e^P\right)\Phi$$

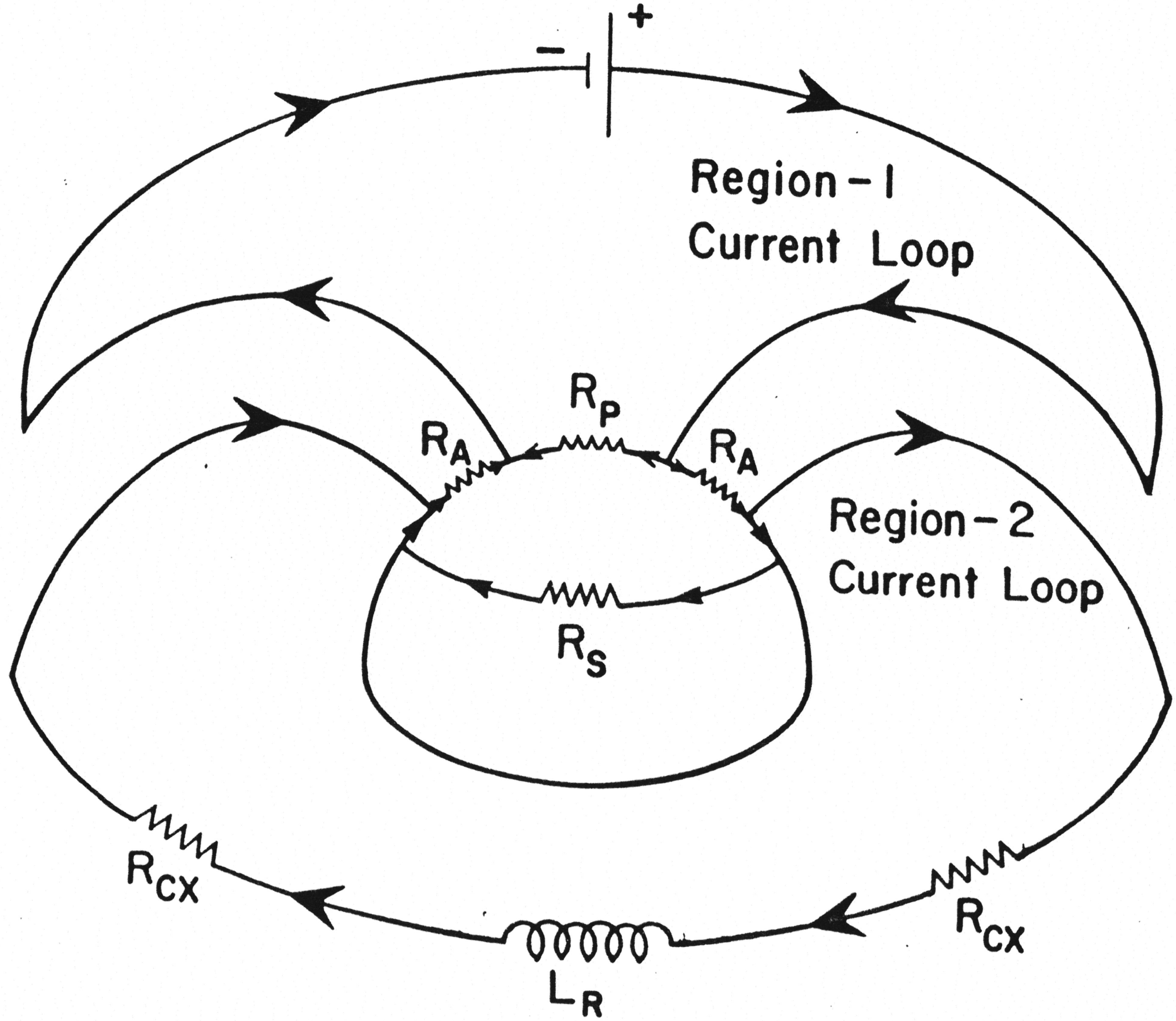
$$I_2^P = \frac{2\,ab}{b^2-a^2}\,\Sigma_A^P\,\Phi$$

1. BECAUSE OF REGION 2 CURRENTS, THE IONOSPHERE DRAWS 3 TO 5 TIMES MORE CURRENT FROM THE REGION 1 DYNAMO

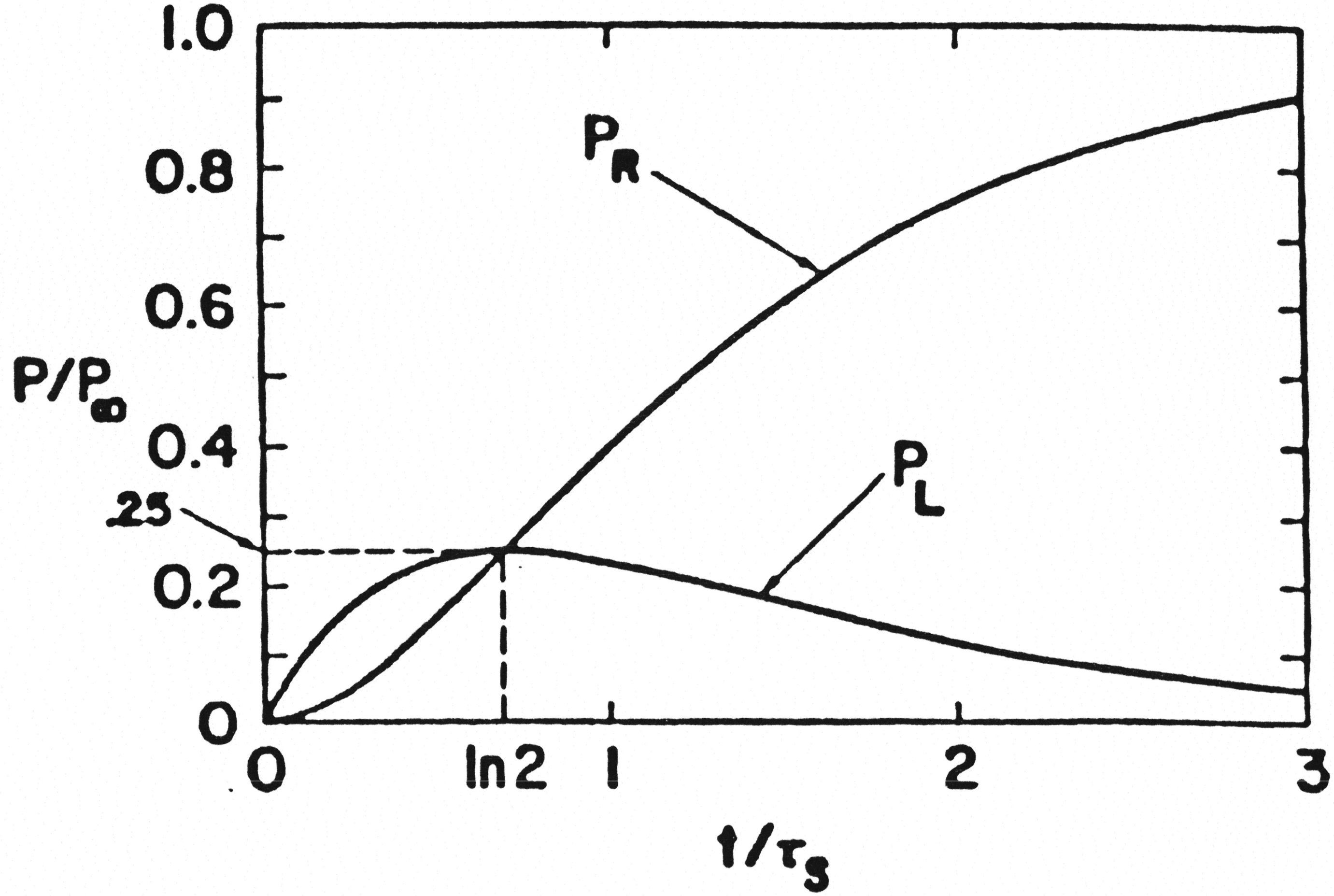
2. I_1 AND I_2 INCREASE AS THE ANNULAR WIDTH NARROWS

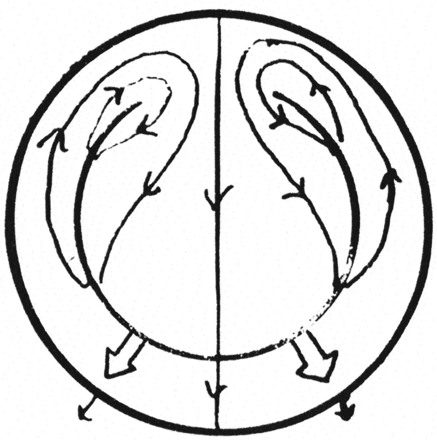


I2
I2
I2
Eveready TM
20KV



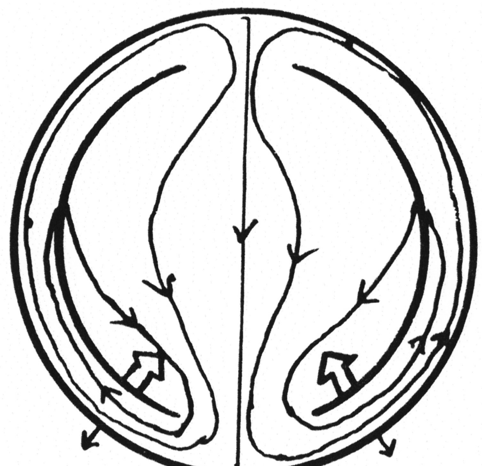
-
+
Region-1
Current Loop
R_P
R_A
R_A
Region-2
Current Loop
R_S
R_{CX}
R_{CX}
L_R


1.0
0.8
0.6
0.4
.25
0.2
0
P/P∞
P_R
P_L
0
ln2
1
2
3
t/τ_s



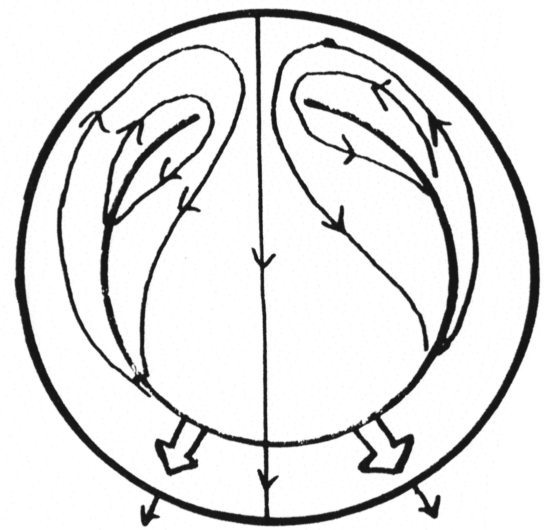
1

Growth Phase



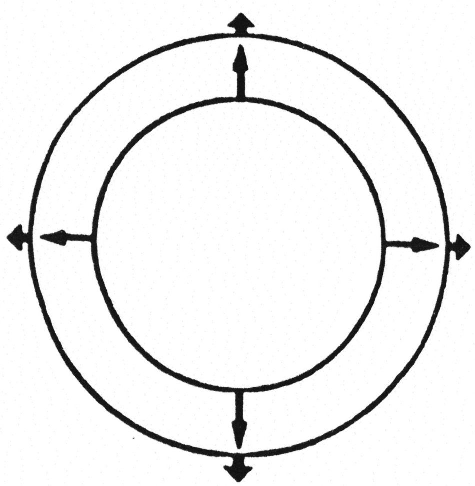
2

Expansion Phase

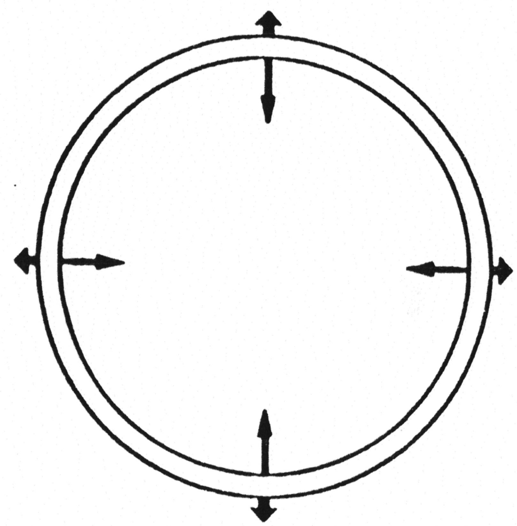


3

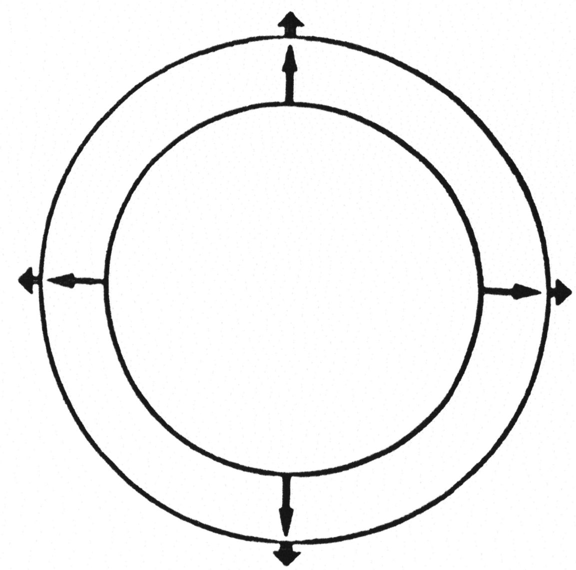
2nd Growth Phase



1



2



3

$$\frac{d}{dt}(\pi a^2 B_p) = \Phi$$

COMPARE $\frac{b}{R_e} = (A \frac{a}{b} \Phi)^{3/16}$

WE FIND $\frac{db/dt}{da/dt} \approx \frac{1}{16}$

AND $\frac{b-a}{da/dt} \approx 1$ HOUR

FURTHER IMPLICATIONS

1. D_{st} DIRECTLY DRIVEN BY Φ
2. SUBSTORMS INDIRECTLY

FURTHER IMPLICATIONS

1. $\frac{d}{dt} D_{st} \propto I_2 \frac{d\Phi}{dt} \propto \frac{d}{dt} \Phi^2$

$$\therefore D_{st} \propto \Phi^2 \propto (\text{IMF } B_z)^2$$

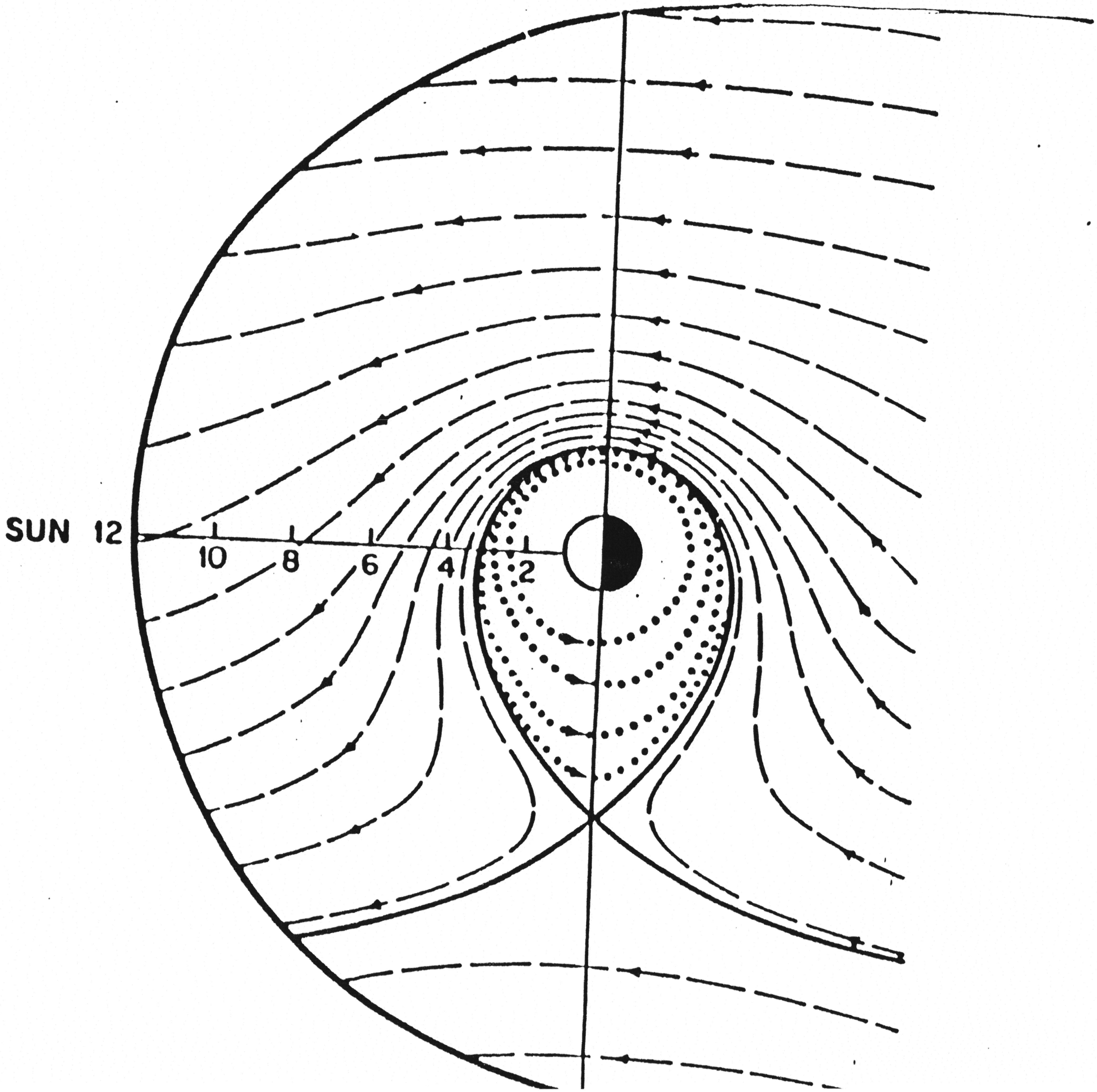
2. $AE \propto I_1 \propto \Phi \propto \text{IMF } B_2$

CONCLUDING WORDS

The physics of the magnetosphere-ionosphere coupling that takes place on closed , quasi-dipolar field lines is relatively well understood. With the Rice Convection Model (RCM), the subject is well into the computer implementation and application stage. Nonetheless, even here there are still some major and interesting problems. Ionospheric potentials at low latitudes are not what they are supposed to be. Neutral winds stirred by magnetospheric convection may play the dominant role in determining these. Magnetic fields and field aligned currents in the magnetosphere still have to be determined self - consistently. Inductive electric fields can be important and have to be added. But the RCM is now a powerful research tool that can be used to advance global theories and to aid in interpreting global observations.

Lumped circuit analogs of magnetosphere-ionosphere coupling can help understand the system's time dependent global behavior. The property of hot , trapped plasma to simulate an inductor in its interchange of thermal energy eliminates some of the objections to circuit analogs. This avenue should be explored beyond the simple example shown here to see where it goes.

The magnetosphere-ionosphere coupling models are only formulated for the closed field line, quasi-dipolar parts of the magnetosphere. A great but immensely important task is to include the tail. The ultimate task is to attach them to an ionosphere-magnetosphere-solar wind coupling model that spans the polar cap


SUN 12
10
8
6
4
2

CURRENT SYSTEM	REPRESENTATIVE TOTAL CURRENT (10^6 A)
Region 1 Birkeland	2.7
Region 2 Birkeland	2.2
Chapman - Ferraro	2.5
Tail	1.5 per 10 R_e
Cusp	0.2

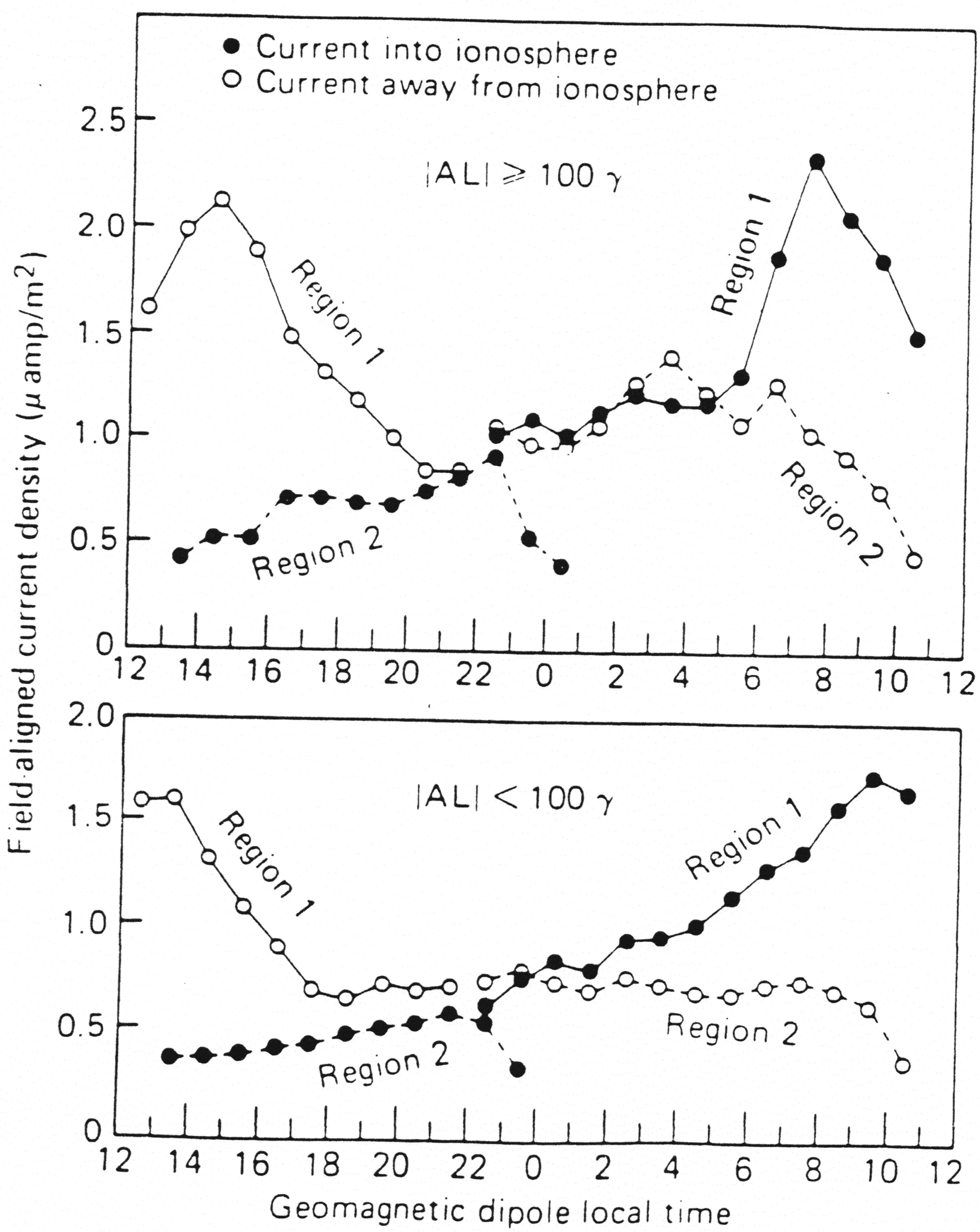
$$B \frac{\partial}{\partial S} \frac{J_{\parallel}}{B}$$

$$= 2 \frac{\vec{B}}{B^3} \cdot (\nabla p \times \nabla B)$$

PRESSURE TERM

$$+ \rho \vec{V} \cdot \nabla \frac{\Omega_{\parallel}}{B}$$

INERTIAL TERM



● Current into ionosphere
○ Current away from ionosphere
|AL| ≥ 100 γ
|AL| < 100 γ
Region 1
Region 2
Field-aligned current density (μ amp/m²)
2.5
2.0
1.5
1.0
0.5
0
12 14 16 18 20 22 0 2 4 6 8 10 12
Geomagnetic dipole local time