MI Coupling from a Magnetospheric Point of View

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Normal Stress

- Normal Stress
  - Normal stress is created by the impact of the solar wind on the Earth's dipole field
  - This interaction produces a sheet current that confines the field to a volume called the magnetosphere
- Shape of the magnetopause due to normal stress
  - The distance to the magnetopause at the stagnation point is called the standoff distance
- Effects of these currents near the Earth's surface
  - During a change in solar wind dynamic pressure the effects of the magnetopause current are transmitted to the Earth by Alfven waves and field-aligned currents
  - In steady state they produce a spatially varying field across the Earth
  - The force produced by the gradient in this field on the Earth's dipole moment transmits the force of the solar wind to the Earth

Image Dipole Model for Magnetopause

- Electrical currents are induced in the leading edge of an approaching solar wind stream
- These currents produce an image of Earth's dipole inside the solar wind
- The superposition of Earth's dipole and image dipole produce a field that vanishes upstream of a planar boundary

FIELD LINES OF A MAGNETIC DIPOLE
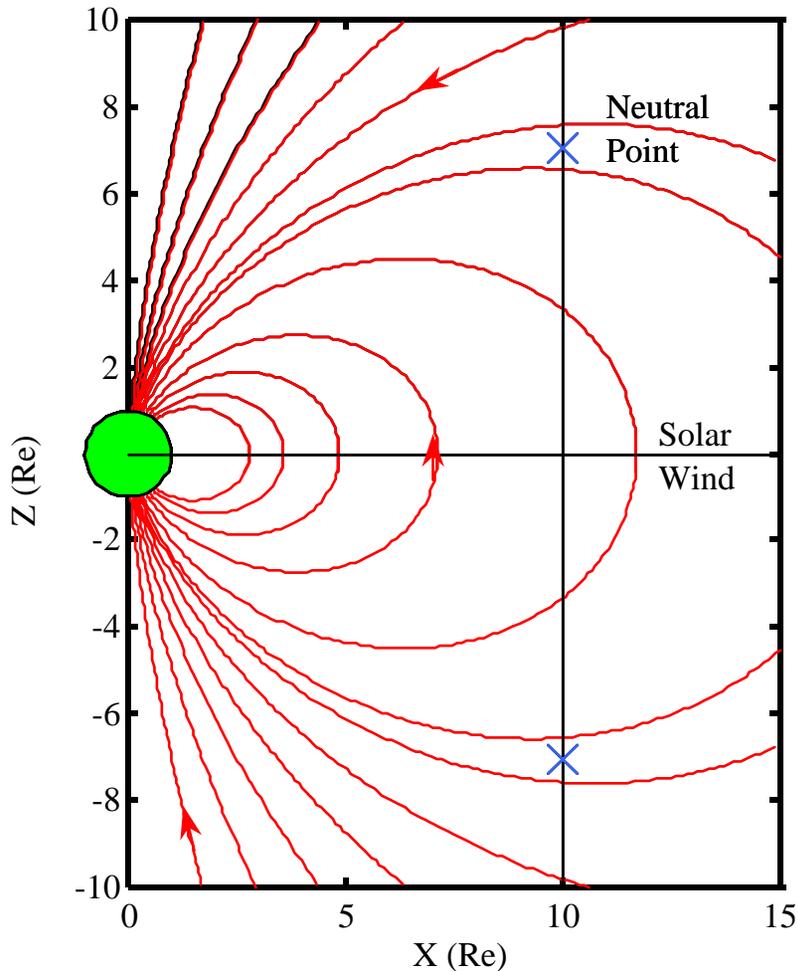
FIELD LINES OF A MAGNETIC DIPOLE AND ITS IMAGE

Neutral Point

Neutral Point

Solar Wind

Solar Wind

R_m
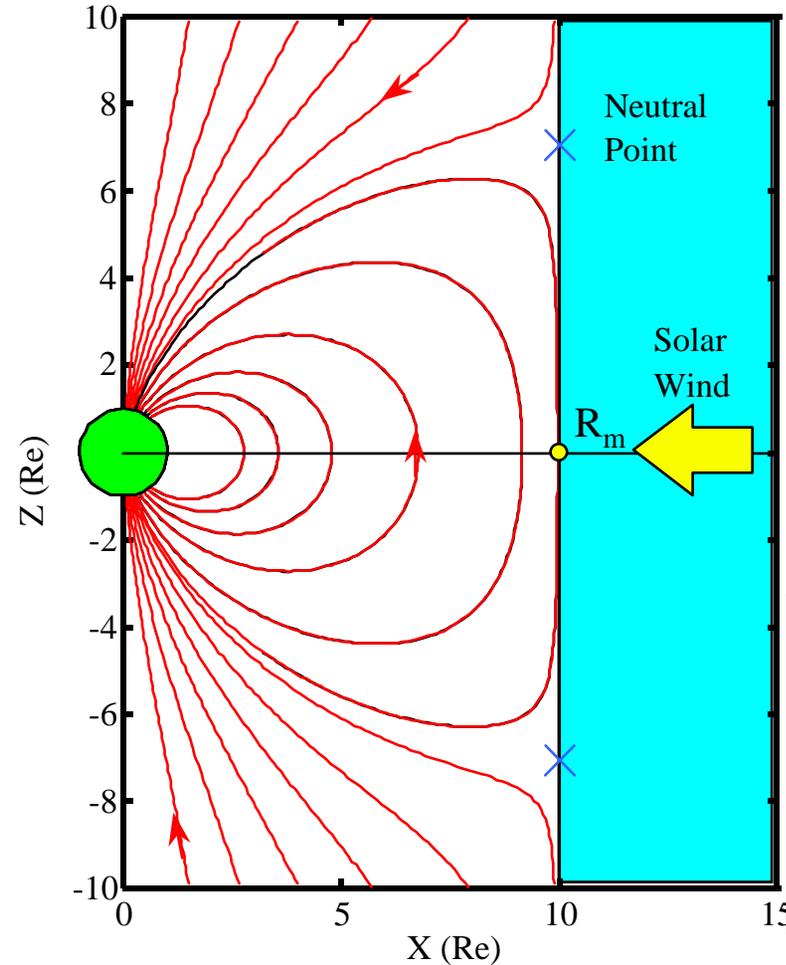
Chapman, S., and V.C.A. Ferraro, A new theory of magnetic storms. Part I. The initial phase, *Terrest. Magnetism Atmospheric Elec.*, *36*, 77-97, 1931.

Magnetopause Current System

- A sheet current flows on the magnetopause circulating around both the north and south neutral points

- This current cancels the Earth's field outside the current sheet and roughly doubles it inside

- Everywhere inside the current the magnetic field can be represented by a potential field expansion

McPherron, R.L., Physical Processes Producing Magnetospheric Substorms and Magnetic Storms, in *Geomagnetism*, edited by J. Jacobs, pp. 593-739, Academic Press, London, 1991.
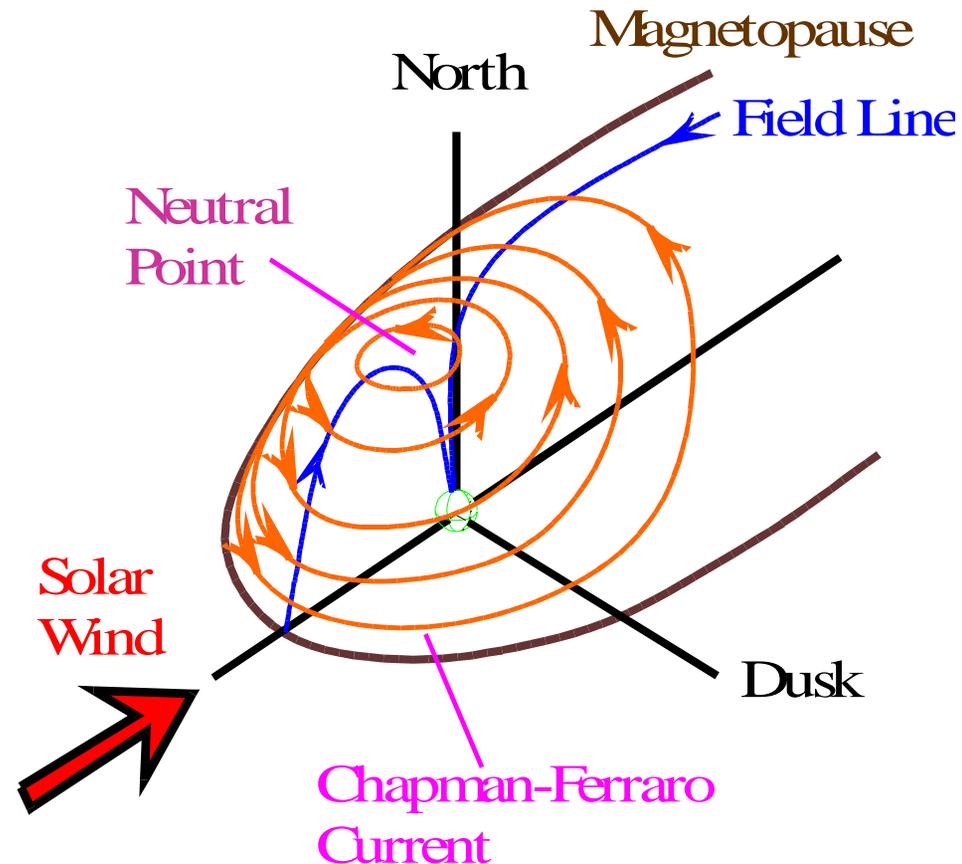
The Total Field of the Dipole and Magnetopause Current

- The magnetopause current confines the dipole field to the region inside the current sheet and increases the magnetic field everywhere

- Note that there is no current closing through the magnetosphere in this model

- All field lines cross the equator close to the Earth than they would in a pure dipole

- Normal stress does not produce a tail

- The polar cusps form around the neutral points and allow particles easy entry to ionosphere creating the dayside auroral oval

Polar Cusp


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---- PURE DIPOLE
—— DISTORTED DIPOLE
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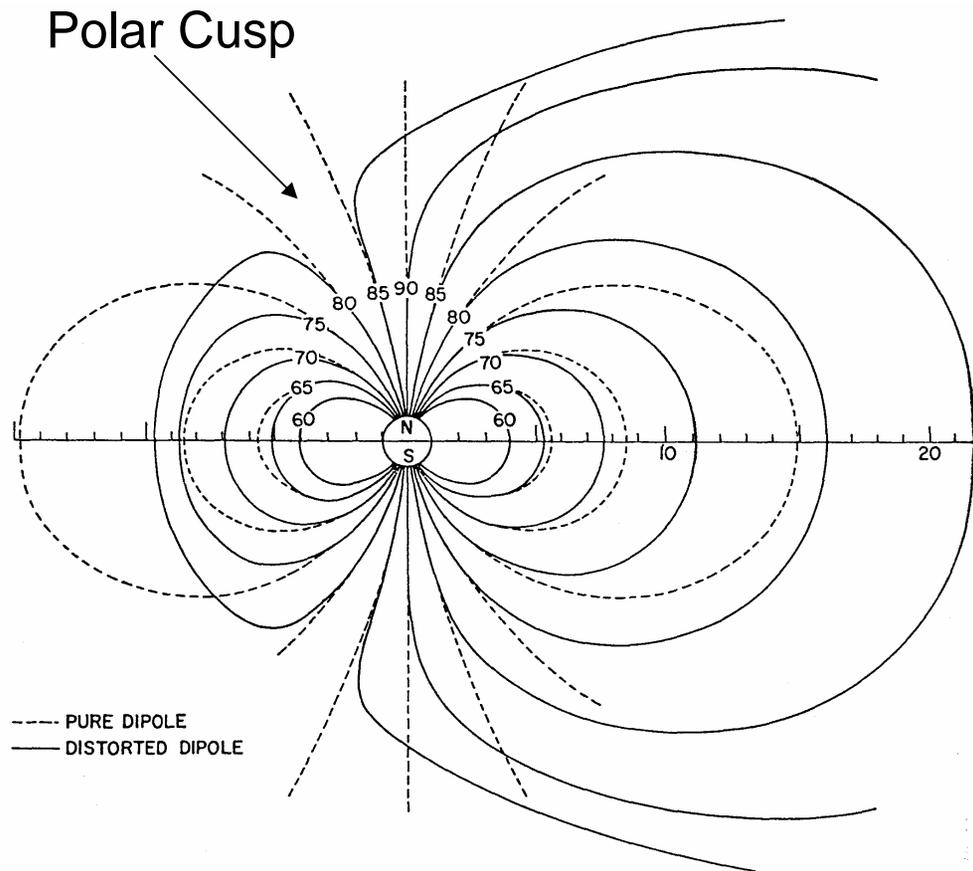
Mead, G.D., Deformation of the geomagnetic field by the solar wind, *Journal of Geophysical Research*, *69*(7), 1181-1195, 1964.

Ground Effects of Magnetopause Current

- The vertical magnetic perturbation of the magnetopause current along the x axis is given approximately by the relation at the right

$$B_z = -g_1^0 + \sqrt{3}g_2^1 x$$

$$g_1^0 = -2.515 \cdot 10^4 / r_b^3$$

$$g_2^1 = +1.215 \cdot 10^4 / r_b^4$$

$$r_b = r_0 (p_0/p)^{1/6}$$

- Bz is in nT and x is in Re

- *The reference pressure p_0 and reference distance r_0 are about 2.4 nPa and 11 Re producing a 20 nT effect at Earth (green)*

- *A storm sudden commencement (SSC) can increase pressure to 50 nPa moving the magnetopause inside synchronous orbit and causing a 60 nT increase (red)*

Effect of the Magnetopause Current
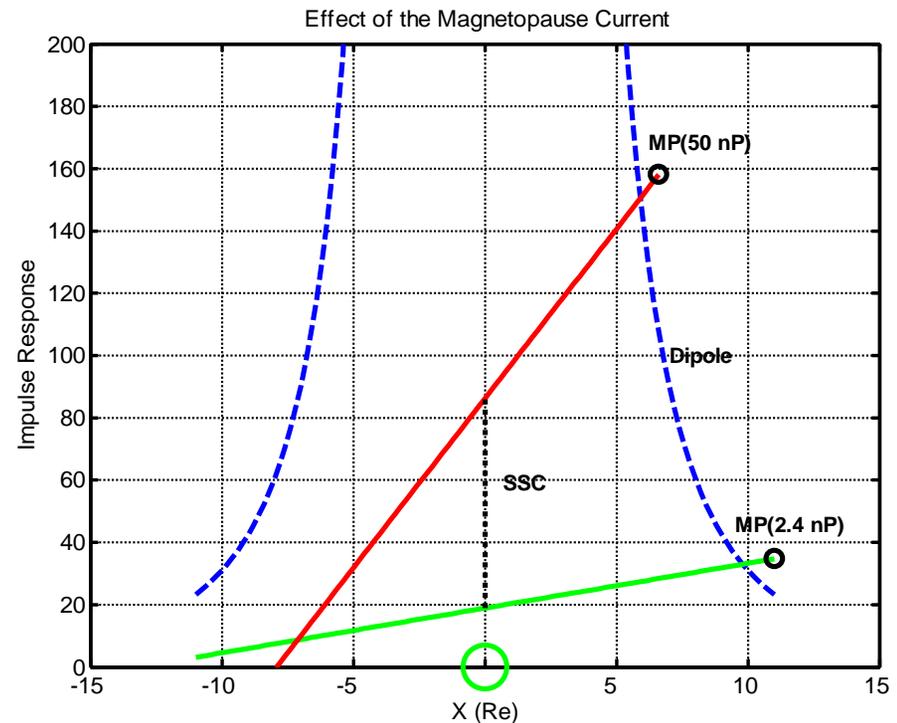
LOCATION OF THE SUBSOLAR MAGNETOPAUSE

- The standoff distance to the subsolar magnetopause is determined by a balance between the solar wind dynamic pressure and the magnetic field inside the boundary
- The collisions of particles with the boundary may not be completely elastic hence a factor k is introduced
- The magnetic field inside the boundary is the total field from dipole and boundary current. For an infinite planar sheet current the field would be exactly doubled. Inside a spherical boundary the multiplication factor is 3. The factor f must lie in this range .
- Equate and substitute for the dipole strength variation with distance
- Solve for the dimensionless standoff distance L_s. The ratio of the two constants is ~ 1

$$p_{dyn} = p_B \qquad kmnv^2 = \frac{f^2 B_d^2}{2\mu_0}$$

$$p_{dyn} = kmnv^2$$

$$p_B = \frac{(fB_D)^2}{2\mu_0} \qquad B_D = B_0 \left(\frac{R_e}{R_s} \right)^3$$

Where k is the elasticity of particle collisions and f is the factor by which the magnetospheric magnetic field is enhanced by the boundary current. R_s is the subsolar standoff distance

$$L_s = \left(\frac{R_s}{R_e} \right) = \left[\left(\frac{f^2}{2k} \right) \left(\frac{B_0^2}{2\mu_0 mnv^2} \right) \right]^{\frac{1}{6}}$$

Tangential Stress

- Viscous interaction
  - Solar wind momentum is transported across the magnetopause by particle scattering, wave propagation, and surface waves
  - Plasma in a thin boundary layer on each flank begins to move antisunward
  - Magnetic field lines are frozen in the moving plasma and are stretched away from the Sun
- Frozen flux
  - Plasma and field are frozen together via the Lorentz force and an extremely high electrical conductivity
  - Charges separate until the force of the induced electric field is equal and opposite to the Lorentz force $E = - V \times B$
  - Both charges drift with the same velocity $V = (E \times B)/B^2$
  - Since charges move together no current is produced

Two Forms of Tangential Drag on Magnetosphere

- Viscous interaction moves closed field lines antisunward in a boundary layer

- Magnetic reconnection connects dipole field lines to the IMF and moves open field lines across the poles

- Both open and closed field lines must return to the dayside else flux imbalance will occur
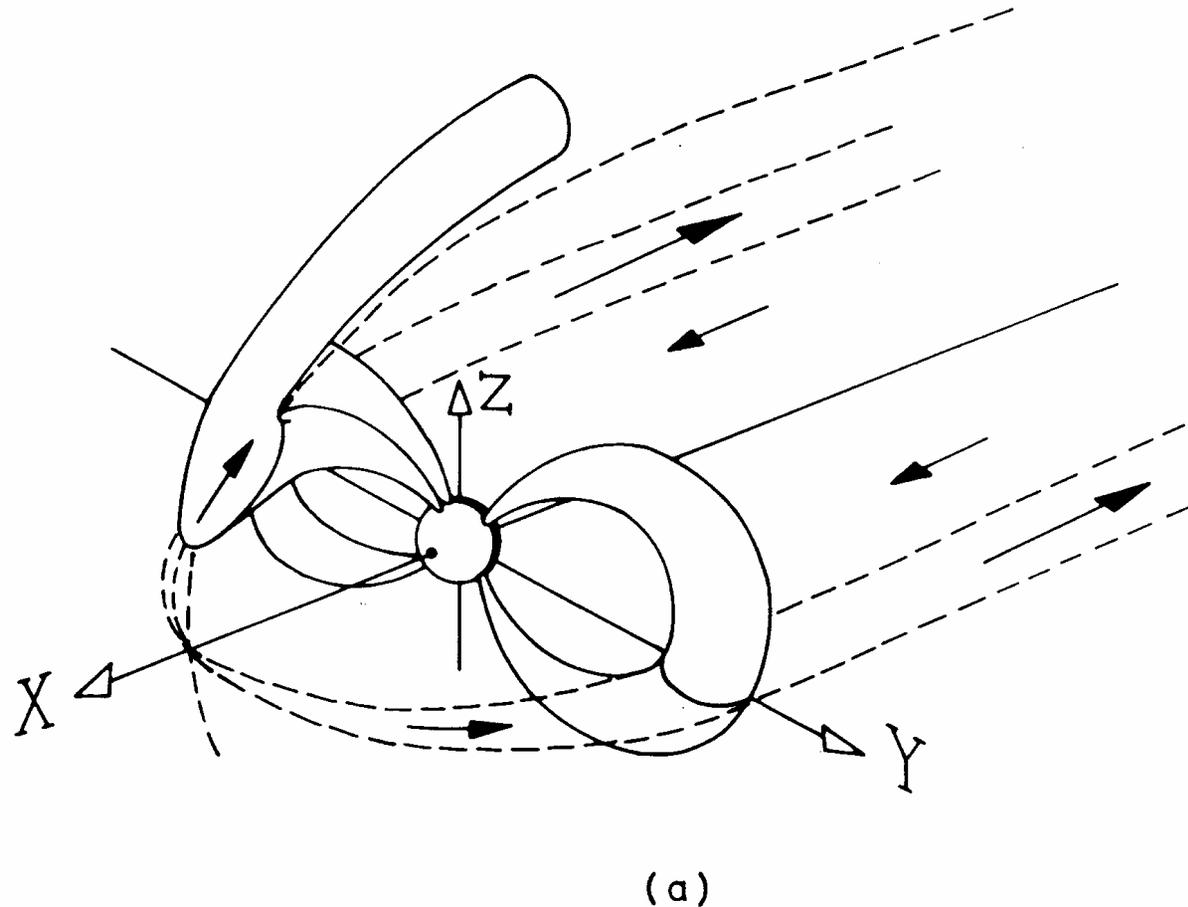
(a)

Cowley, S.W.H., The causes of convection in the earth's magnetosphere: A review of developments during the IMS, *Reviews of Geophysics and Space Physics*, *20*(3), 531-565, 1982.

Space Charge in MHD

- In a static magnetic field configuration the only source of electric field is electrical charges as derived from Poisson's equation
- In MHD we assume that the charge density is zero hence it would appear no electric field is possible
- However, other relations show that plasma drift in the presence of a magnetic field creates an electric field
- Suppose the velocity is zero on one side of a boundary layer of thickness 1/100 Re and is E~1 mV/m on the other side
- *This corresponds to a charge density of only 1 electron per cubic meter!*

$$\vec{\nabla} \cdot \vec{E} = \rho / \varepsilon_0 = eN / \varepsilon_0$$

$$\vec{E} = -\vec{V} \times \vec{B}$$

$$N \approx \frac{\varepsilon_0 \Delta E}{e \Delta l}$$

$$N \approx \frac{\left(8.85 \times 10^{-12}\right)\left(1 \times 10^{-3}\right)}{\left(1.6 \times 10^{-19}\right)\left(6.38 \times 10^{6}/100\right)}$$

$$N \approx 0.867 \text{ particles/m}^3$$

Frozen Flux and Induced Electric Field

- Move a slab of highly conducting plasma with velocity V through a magnetic field B

- Lorentz force $F = q(V \times B)$ separates positive and negative chages and polarizes the edges of the slab

- Charge builds up until the force of the electric field $F = qE$ balances the Lorentz force
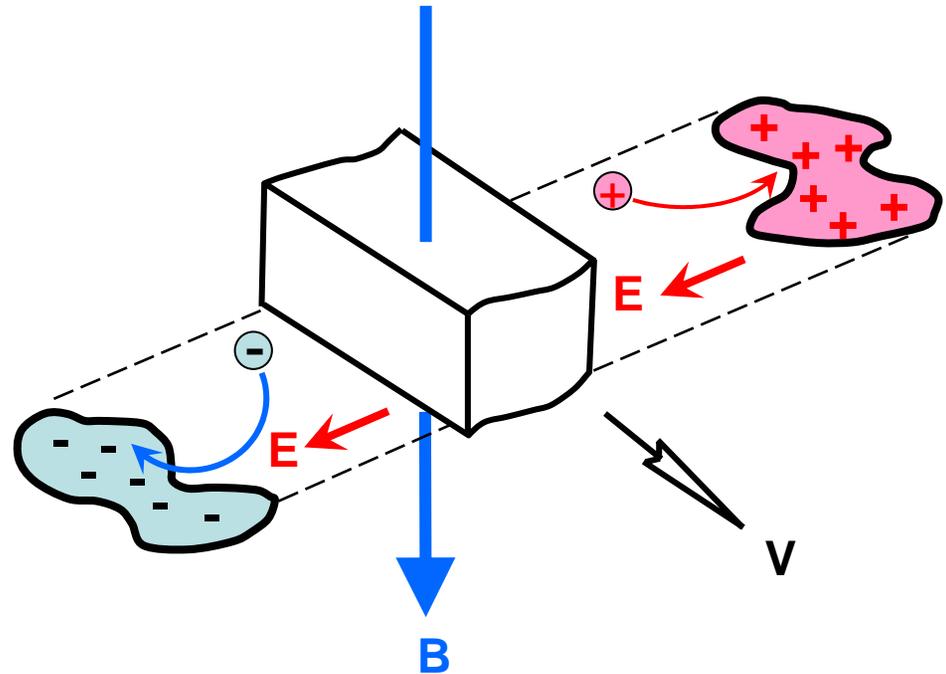
Generation of Region 1 Currents
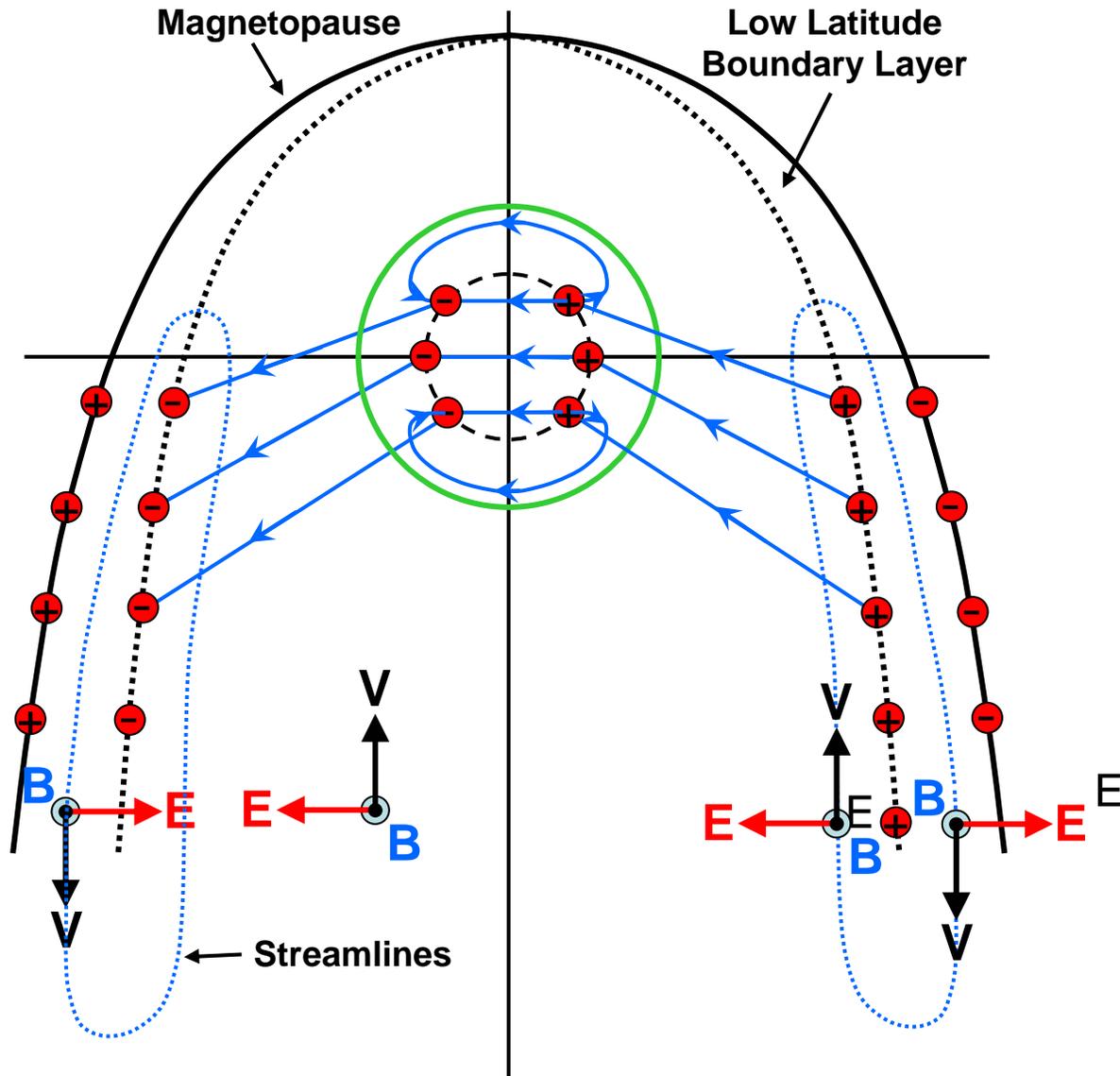
Relation of Magnetospheric Equipotentials and Cold Particle Drift

- The E x B drift velocity
- The electric field is derived from the potential
- Drift is perpendicular to B
- Field lines are nearly equipotentials
- Drift is perpendicular to E but E is the gradient of potential

- Therefore

- *Cold partilces drift in equipotential surfaces perpendicular to magnetic field*

$$V = \frac{E \times B}{B^2}$$

$$E = -\nabla\Phi$$

$$V = \frac{-\nabla\Phi \times B}{B^2}$$

Particle Drift

$$E = -\nabla V$$

Constant potential
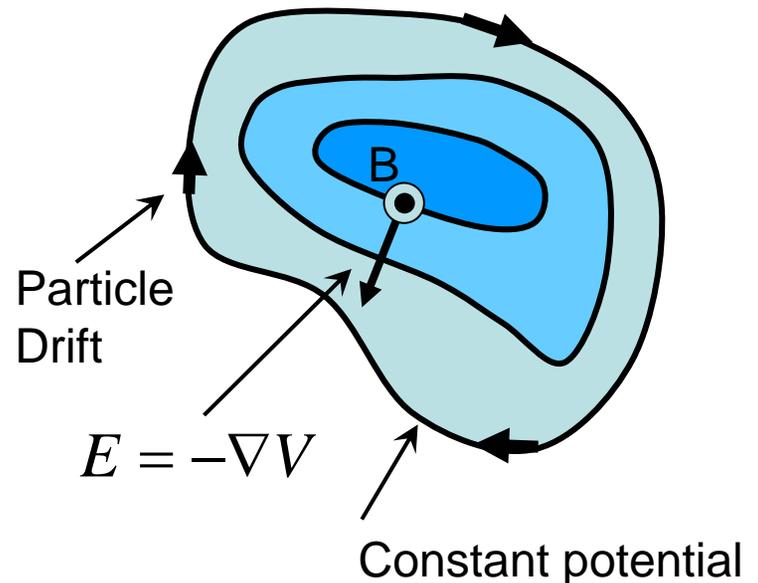
Magnetospheric Convection

- ● **Viscous Interaction**
  - – Tailward transport in the low latitude boundary layer
  - – Sunward transport in the plasma sheet
  - – Divergent electric fields along velocity shear
  - – Equipotentials of magnetospheric electric field are lines orthogonal to electric field
  - – Cold particles drift along the equipotentials

Axford, W.I., Viscous interaction between the solar wind and the earth's magnetosphere, *Planetary Space Science*, *12*, 45-53, 1964.
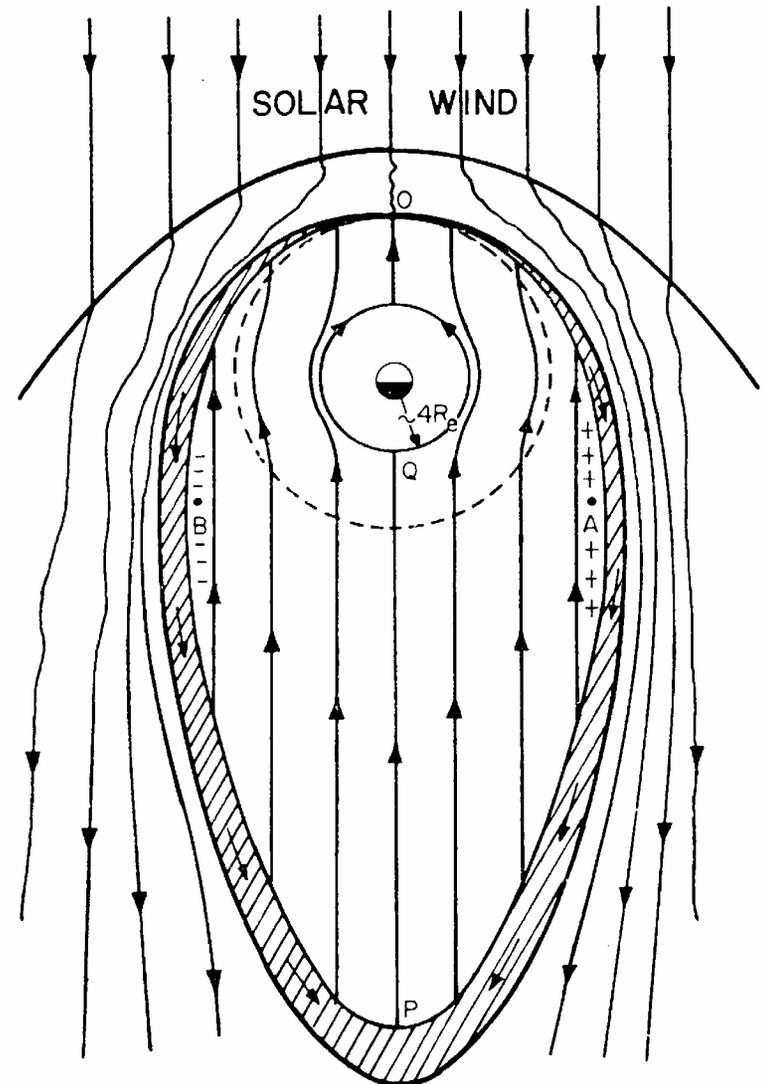
Ionospheric Convection

- Magnetospheric electric field is projected onto ionosphere via equipotential field lines

- The electric field drives a Pedersen current in the ionosphere

- Ionospheric plasma is accelerated by J_p x B force

- Charges E x B drift along equipotentials of the projected electric field

- The pattern of plasma drift is a 2-celled pattern with foci at the dawn and dusk projections of the inner edge of the velocity shear

Sun

12

18

06

B

J_P

J_P x B

00

Boundary Layer

Return Flow
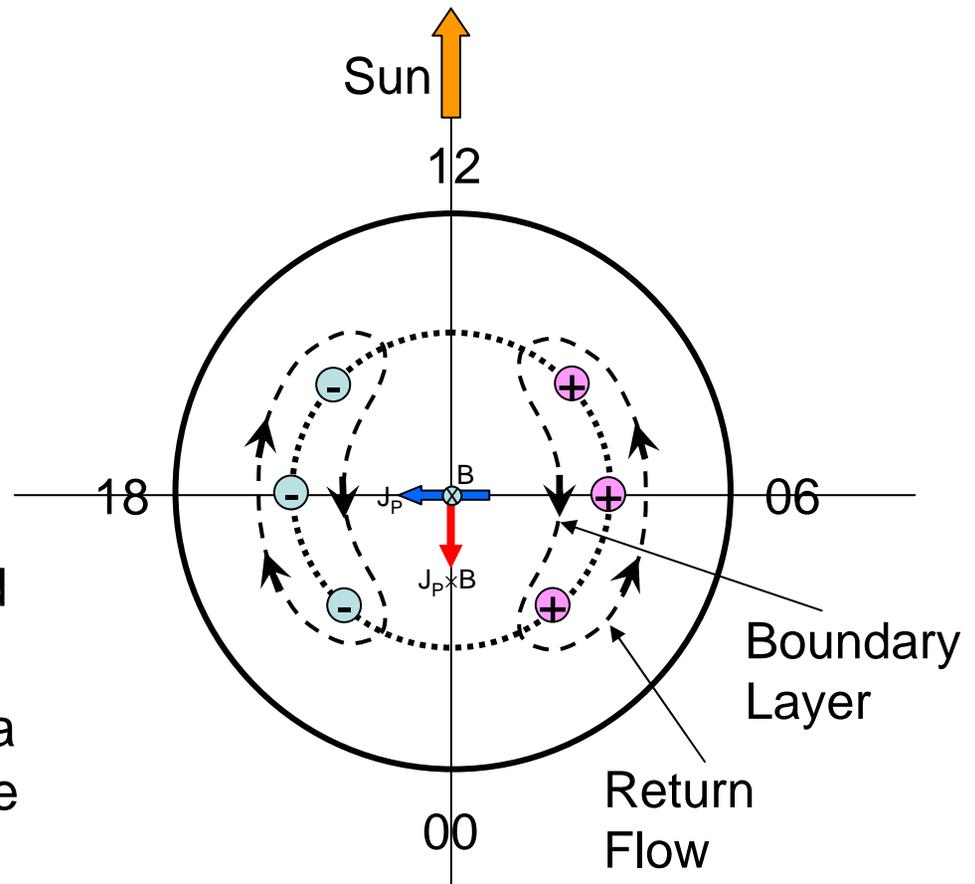
Generation of an Ionospheric Hall Current

- In the F-region ExB drift is unimpeded

- In the E-region the neutral density is much larger and the ion collision frequency with neutrals exceeds that of electron

- The collisions limit the ability of both charges to ExB drift thus allowing them to move along the electric field creating the Pedersen current

- Electrons ExB drift faster than ions producing a negative relative velocity and a current opposite to convection

(a) Collisional Case

(b) Collisionless Case

(c) Intermediate Case

$$J_P \propto \left(V_{i\parallel} - V_{e\parallel}\right)$$

$$J_H \propto \left(V_{i\perp} - V_{e\perp}\right)$$
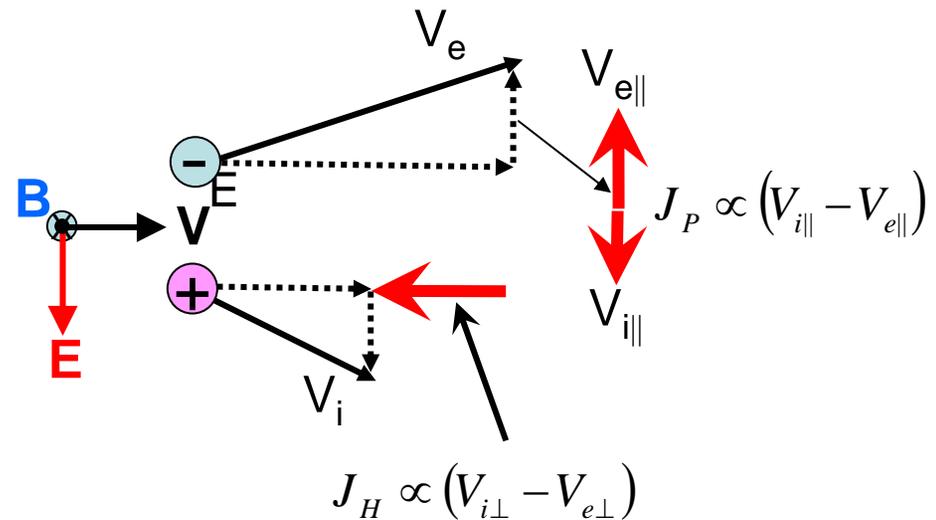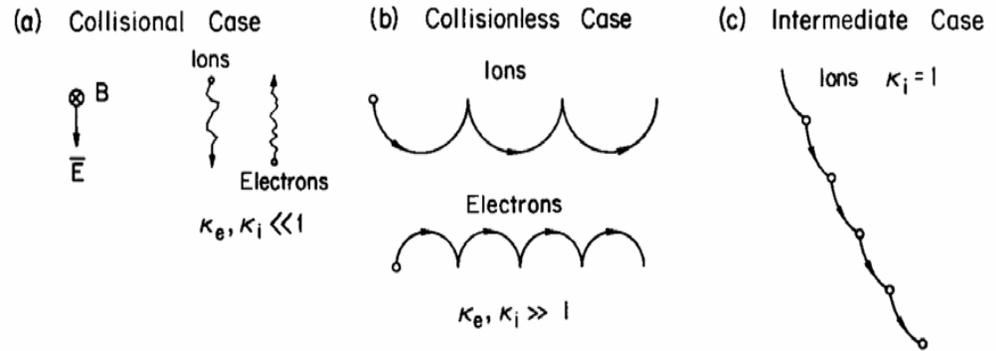
Fukushima's Theorem

- Vertical field-aligned current (FAC) enters uniform conducting ionosphere
- Current spreads radially to infinity
- Magnetic field from FAC is circular in clockwise manner seen from above
- Magnetic field from radial segments create an equal and opposite CCW perturbation
- The two magnetic fields cancel and the field-aligned current is invisible on the ground
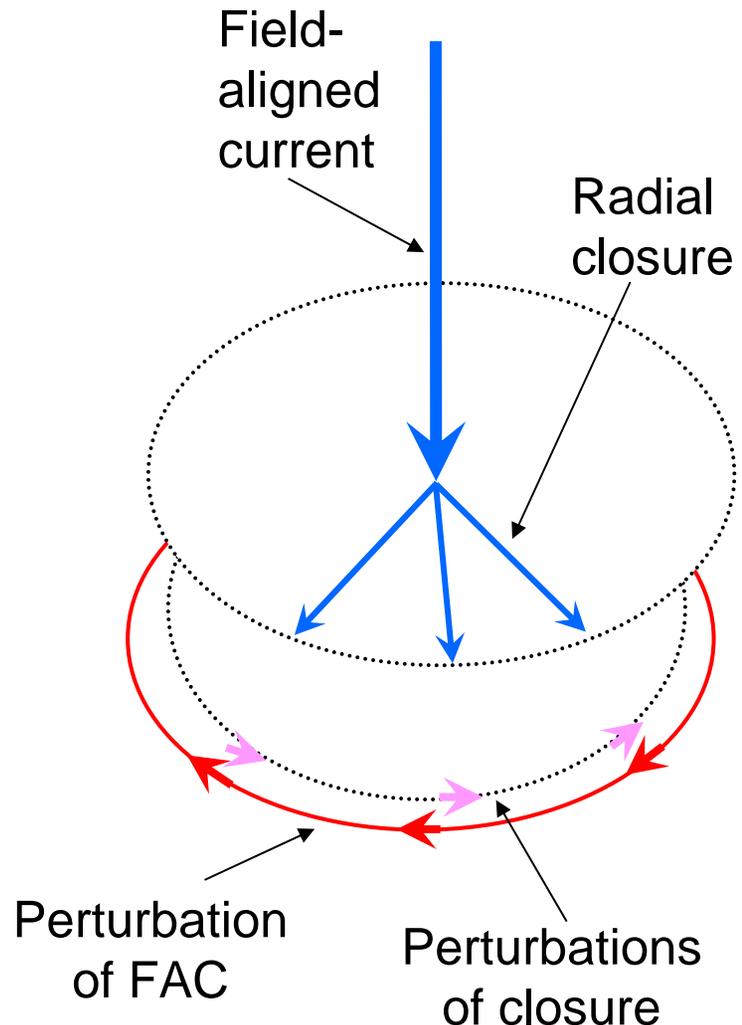
Fukushima, N., Ground magnetic effect of field-aligned currents connected with ionospheric currents: Fundamental theorems and their applications, in *Prospect and Retrospect in Studies of Geomagnetic Field Disturbances*, edited by A. Nishida, S. Kokubún, T. Iijima, Y. Kamide, and T. Tamao, pp. 11-19, Tokyo, 1985.

Field-aligned current

Radial closure

Perturbation of FAC

Perturbations of closure

The Equivalent Ionospheric Current

- The equivalent current pattern for steady convection as derived from ground magnetic data is called DP-2

- The pattern has two cells and is aligned around a line from 09-21 lt

- Most of the equivalent current is Hall current
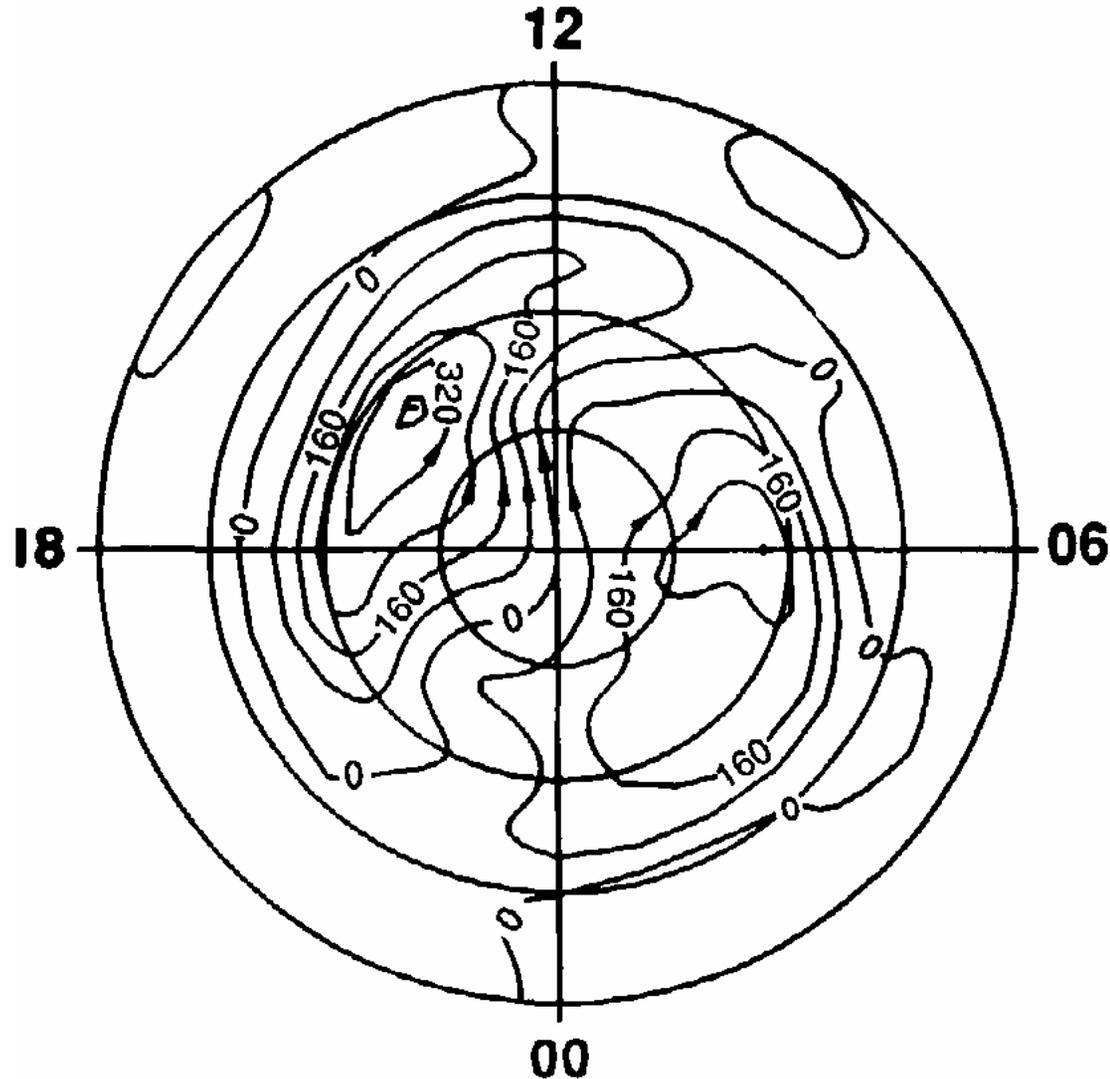
Divergent Ionospheric Currents

- Ionospheric current is related to electric field through a matrix conductivity
- The conductivity matrix in a field-aligned coordinate system has three independent elements:
  - Conductivity parallel to B (parallel)
  - Conductivity perpendicular to B in direction of E (Pedersen)
  - Conductivity perpendicular to both B and E (Hall)
- Any divergence of ionospheric current will produce a field-aligned current
- Parallel current arises from either the electric field or the conductivity

$$\Sigma_P = \int \sigma_P dz$$

$$\Sigma_H = \int \sigma_H dz$$

$$\vec{J}_\perp = \int \vec{j}_\perp dz$$

The integration is from top to bottom

$$\vec{J}_\perp = \Sigma_P \vec{E}_\perp - \Sigma_H \left(\vec{E}_\perp \times \hat{B} \right)$$

but $\nabla \cdot \vec{J} = 0$ so that

$$\frac{\partial j_\parallel}{ds} = -\nabla_\perp \cdot \vec{J}_\perp$$

Integrate this from top to bottom

$$j_\parallel = \left(\nabla_\perp \Sigma_P \right) \cdot \vec{E}_\perp - \left(\nabla_\perp \Sigma_H \right) \cdot \left(\vec{E}_\perp \times \hat{B} \right) + \Sigma_P \left(\nabla_\perp \cdot \vec{E}_\perp \right)$$

Baumjohann, W., and R.A. Treumann, *Basic Space Plasma Physics*, 329 pp., Imperial College Press, London, 1996.

Corotation and the Magnetospheric Potential

- Corotation of magnetospheric plasma
  - Electric field of the rotating Earth
  - Magnetospheric equipotentials from rotation
- Superposition of convection and corotation potentials
  - The electric field sepratrix
  - Dynamics of the sepratrix
- Cold plasma drift in the magnetosphere
  - Equivalence of equipotentials and cold plasma stream lines
  - The plasmasphere and plasmapause
  - The plasma trough

Corotation Electric Field

- The Earth is a conductor rotating through its own magnetic field

- The Lorentz force on charges in the Earth creates a positive space charge along the rotation axis and negative charge on the surface

- This charge distribution creates a quadrapolar electric field in space

- Charges flow along the magnetic field until a space charge distribution is created that makes the total electric field orthogonal to the magnetic field

- This field causes magnetospheric plasma to corotate with the Earth

- At the equator the electric field is radially inward

$$\vec{E} = -\vec{V} \times \vec{B}$$

$$\vec{V} = \vec{\Omega} \times \vec{r}$$

$$E = r\Omega B = \frac{\Omega a^3 B_0}{r^2}$$

$$\Phi_c = \frac{-91\,\text{keV}}{(r/a)}$$

McPherron, R.L., Physical Processes Producing Magnetospheric Substorms and Magnetic Storms, in *Geomagnetism*, edited by J. Jacobs, pp. 593-739, Academic Press, London, 1991.
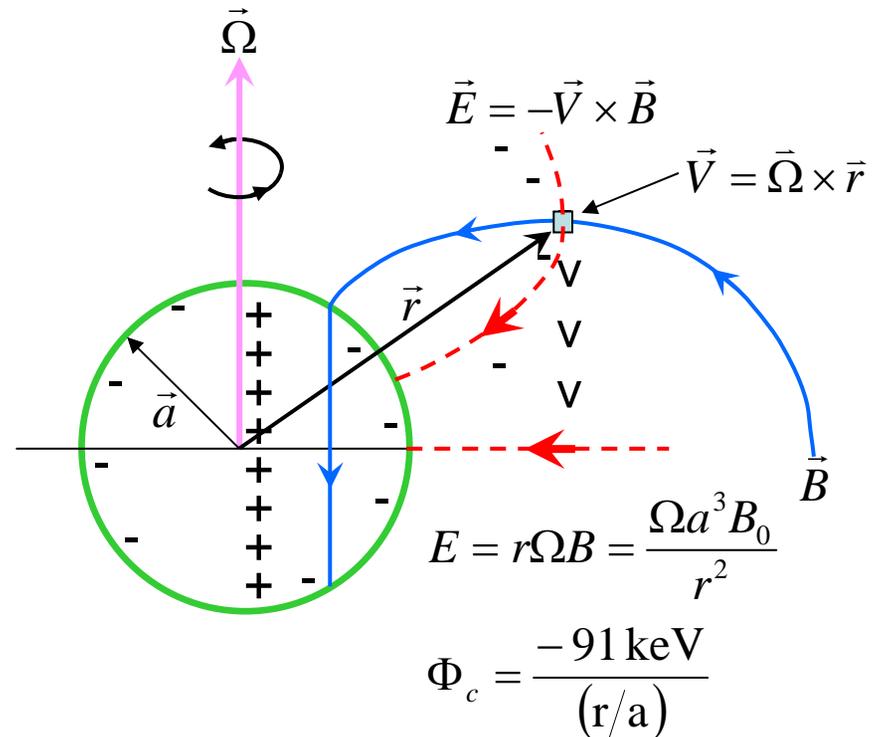
Total Magnetospheric Potential

- Contours of the electric field produced by the return flow of convection are lines parallel to the X-axis
- Contours of the corotation electric field are circles around the Earth
- The total potential consists of both types of contour lines separated by a separatrix
- The separatrix bulges outward at dusk because the corotation and convection are oppositely directed here
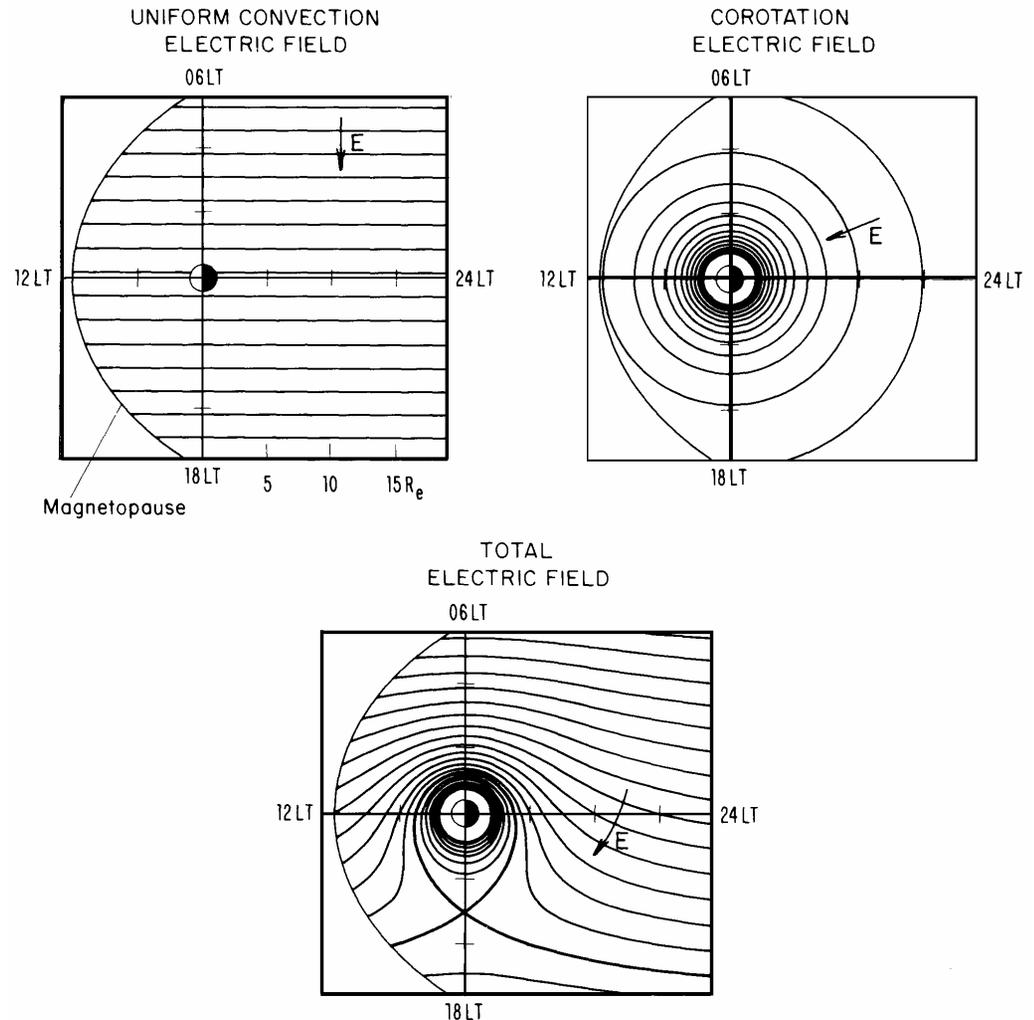
Lyons, L.R., and D.J. Williams, *Quantitative Aspects of Magnetospheric Physics*, D. Reidel Pub. Co., New York, 1984.

Hot Particle Drifts

- Energetic particles are subject to gradient and curvature drift

- For equatorially mirroring particles the gradient drift can be represented by a potential

- The electron separatrix is further from the Earth on the duskside while the ion separatrix is further on the dawnside

- These separatrices move Earthward with increasing strength of the convection electric field

Kavanagh, L.D.J., J.W. Freeman, and A.J. Chen, Plasma flow in the magnetosphere, *Journal of Geophysical Research*, *73*(17), 5511-5519, 1968.

ELECTRONS $\gamma\mu = .05$ keV/γ
E = 0.3 mv/m
PLASMASPHERE TO R=4

DRIFT PATHS   ENERGY CONTOURS (keV)

PLASMA FLOW

PROTONS $\gamma\mu = .05$ keV/γ
E = 0.3 mv/m
PLASMASPHERE TO R=4

DRIFT PATHS   ENERGY CONTOURS (keV)

Space Charge Shielding of Plasmasphere

- The drift of energetic charges creates a space charge distribution with positive charges at dusk and negative charges at dawn

- A shielding electric field points from dusk to dawn canceling the convection electric field inside the plasmasphere
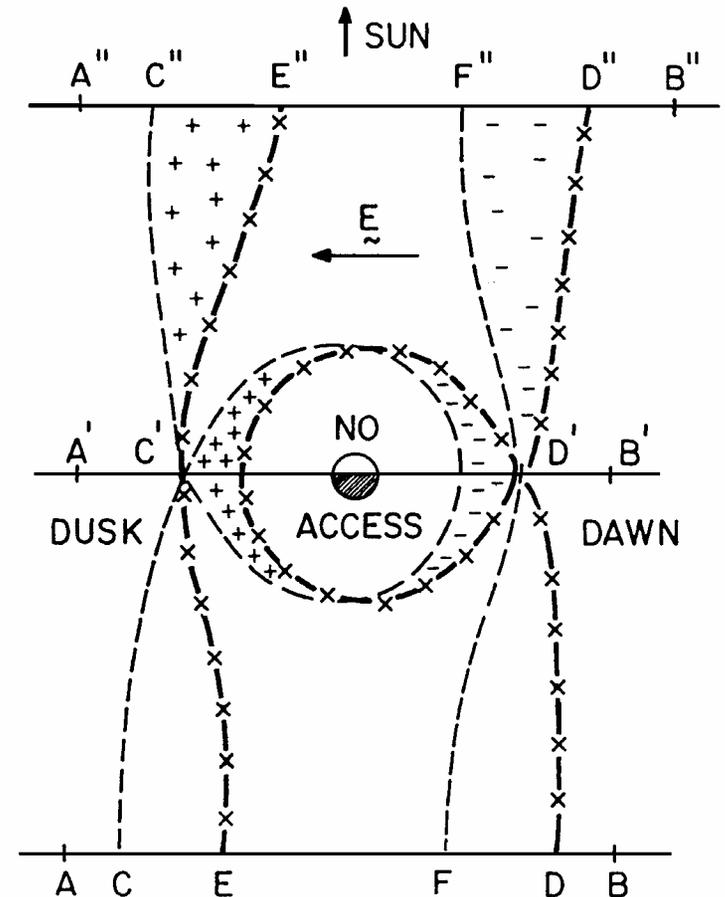
Schield, M.A., J.W. Freeman, and A.J. Dessler, A source for field-aligned currents at auroral latitudes, *Journal of Geophysical Research*, *74*(1), 247-255, 1969.

Region 2 Current From Shielding Region

- The magnetospheric electric field is projected on ionosphere

- In the ionosphere the projected fields drives a Pedersen current

- On the dawn side this current is divergent from the projected inner edge of low latitude boundary layer

- No current can flow into the shielded ionosphere because E = 0

- This current is divergent upward along field lines as the Region 2 current

Low latitude boundary layer

R1

?

E

R2

$E = 0$

Return flow

E   E
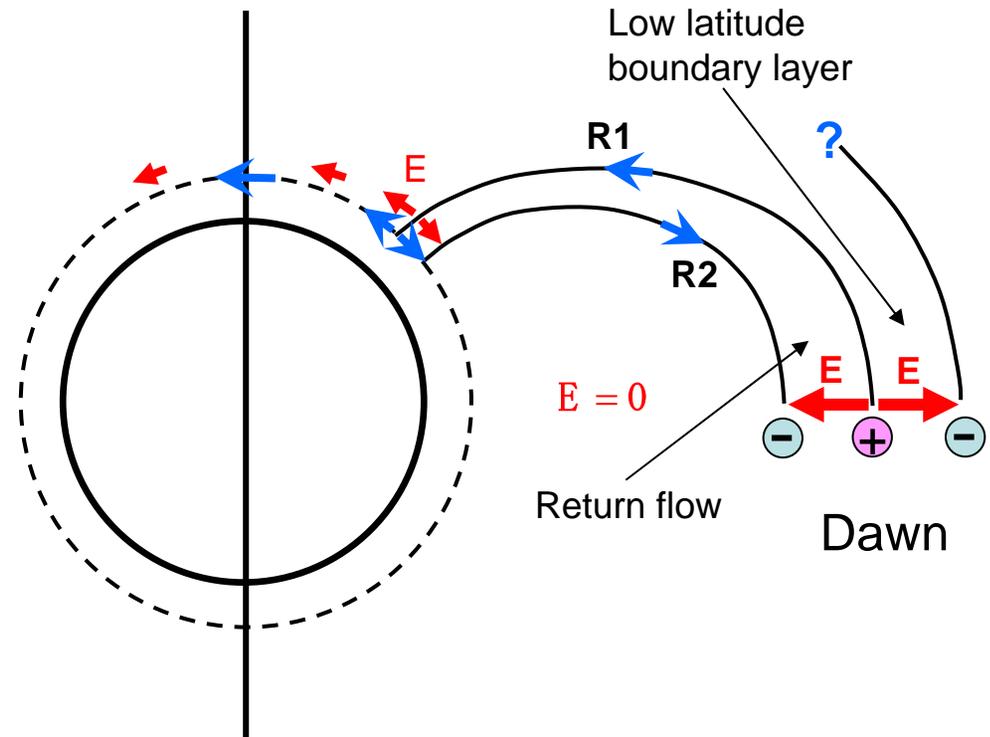
Dawn

The Currents Produced by M-I Coupling

- On the dawn side Region 1 current flows downward from the inner edge of the low latitude boundary region

- R1 current splits with some flowing over the polar cap and the rest equatorward

- At the shielding layer current flows upward as Region 2 current

- This current flows westward in the equatorial plane through gradient and curvature drift

- On the dusk side the current flows downward as R1 current

- It then flows poleward meeting current flowing over the polar cap

- The currents combine and flow outward to the inner edge of the dusk boundary layer

- Closure from the outer edges of the boundary layers is unknown, but could be through the polar cusp or through the solar wind
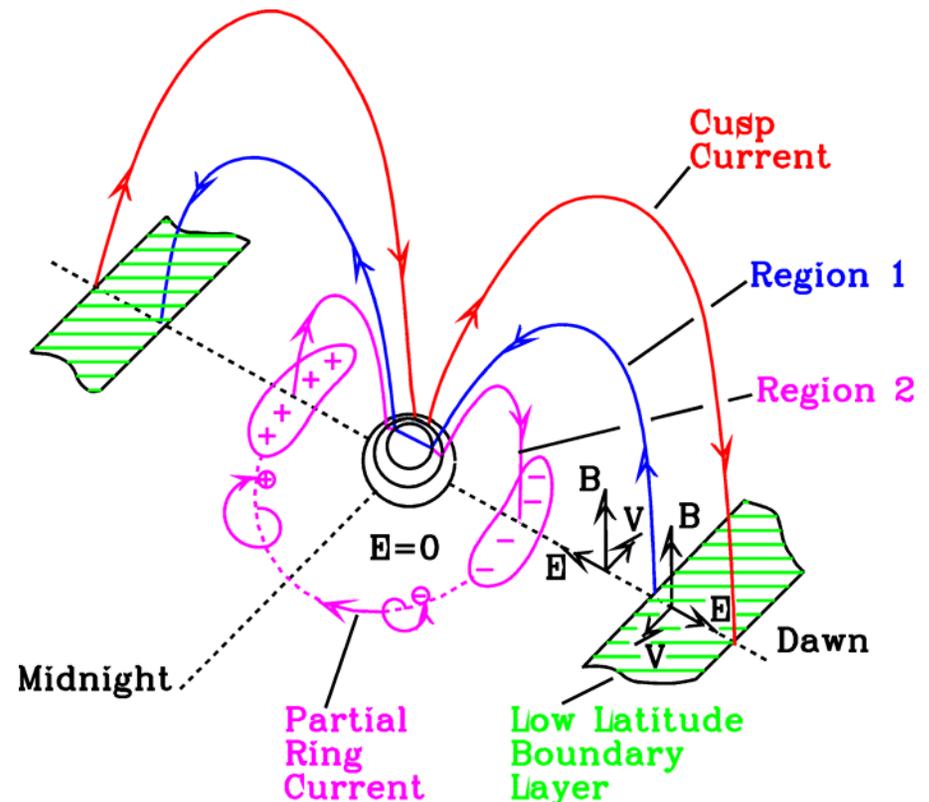
McPherron, R.L., Physical Processes Producing Magnetospheric Substorms and Magnetic Storms, in *Geomagnetism*, edited by J. Jacobs, pp. 593-739, Academic Press, London, 1991.

Ionospheric Pedersen and Hall Currents

- Pedersen current circuit
  - The polar cap Pedersen current is fed by downward R1 FAC at dawn and drained by upward R1 FAC at dusk
  - The equatorward Pedersen current at dawn is drained by the upward R2 FAC
  - The poleward Pedersen current at dusk is fed by a downward R2 FAC and drained by the upward R1 FAC

- Hall current circuit
  - The polar cap Hall current flows from midnight to noon
  - From noon the Hall current spits flowing both around the dusk and dawn side

- Unbalanced ionospheric current
  - Some Pedersen and Hall current flows upward as FAC at midnight
  - This current reenters the ionosphere at noon
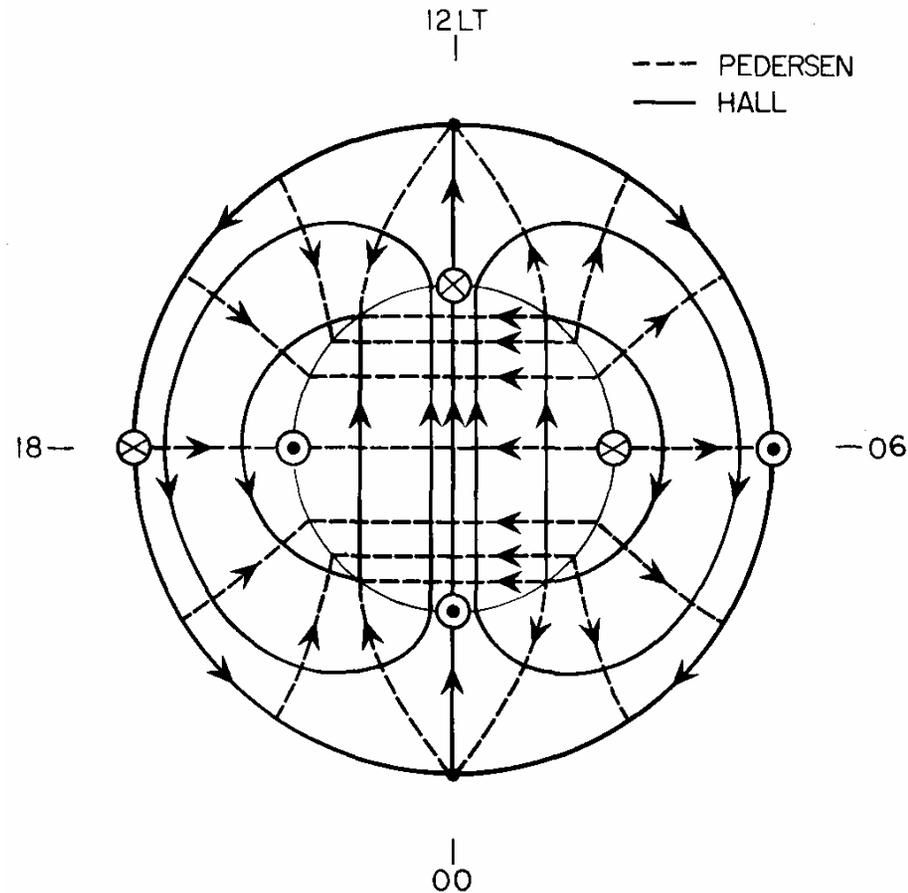
Crooker, N.U., G.L. Siscoe, M.A. Doyle, and W.J. Burke, Ring coupling model: Implications for the ground state of the magnetosphere, *Journal of Geophysical Research*, submitted, 1983.

Magnetic Reconnection

- A second and more important form of tangential drag is caused by magnetic reconnection
- Interplanetary magnetic field lines merge with dipole field lines at the subsolar point and are carried over the polar caps as open field lines by the solar wind
- The field lines are stretched into a long tail and pressed together in two lobes of antiparallel magnetic field separated by a current sheet
- The field lines reconnect at a second X-line in the tail and then move Sunward as closed field lines in the plasma sheet
- The electric field of the solar wind is projected onto the polar caps pointing in the same direction as the electric field produced by the viscous interaction

Interplanetary Field Southward
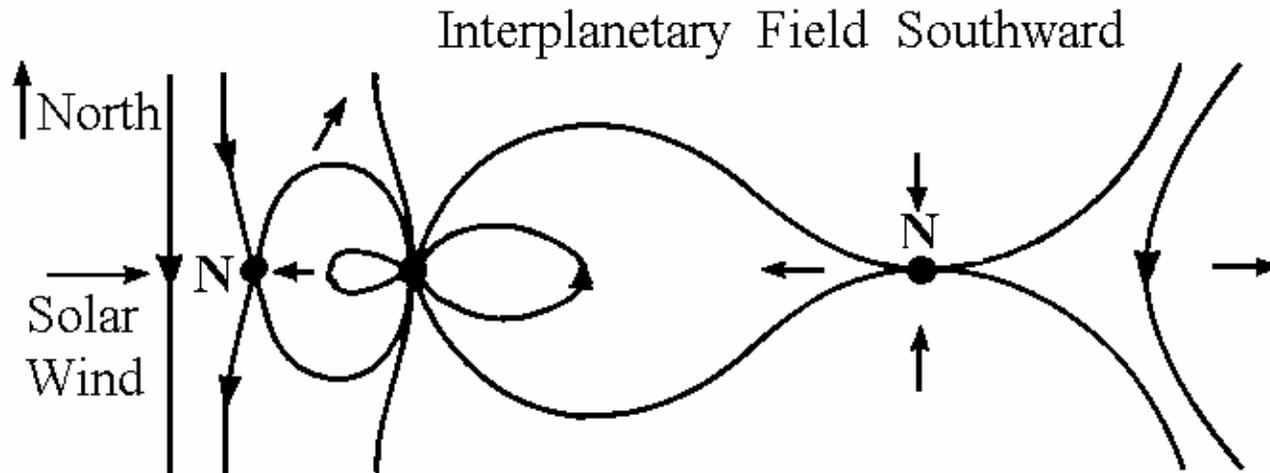
Dungey, J.W., Interplanetary magnetic field and the auroral zones, *Phys. Res. Letters*, *6*, 47-48, 1961.

The Plasma Sheet and Auroral Oval

- The distant X-line produces the plasma sheet
- Open field lines are devoid of plasma
- Closed field lines contain plasma
- The closed field lines project onto the ionosphere as the auroral oval
- The inner edge of the plasma sheet corresponds to the shielding region

McPherron, R.L., C.T. Russell, and M. Aubry, Satellite studies of magnetospheric substorms on August 15, 1978, 9. Phenomenological model for substorms, *Journal of Geophysical Research*, *78*(16), 3131-3149, 1973.
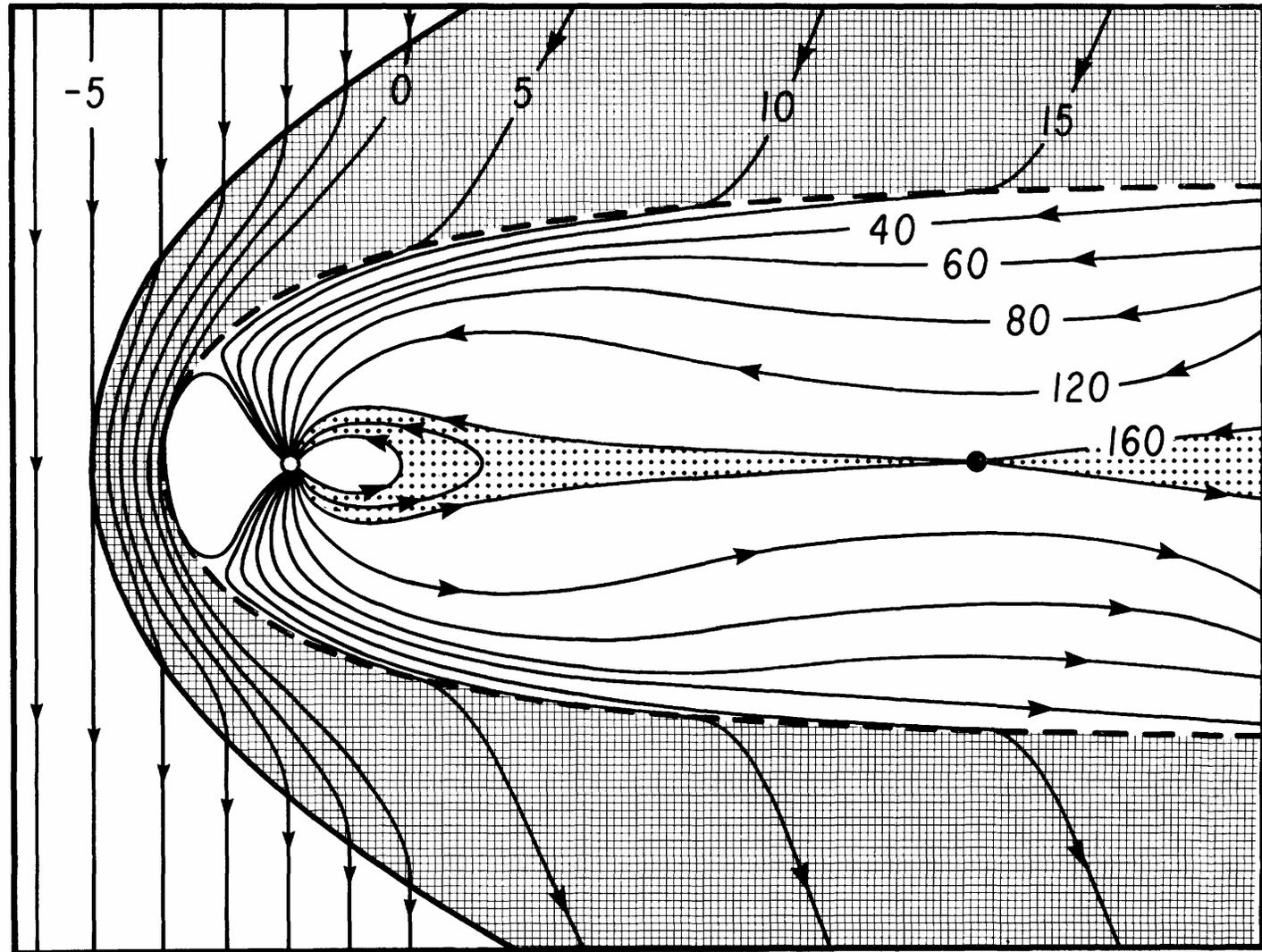
Flow from Tail Reconnection

- Tail reconnection occurs at the center of the tail and sends closed field lines Earthward

- This flow is confined between two regions of return flow from viscous interaction (cross hatched region)

Cowley, S.W.H., The causes of convection in the earth's magnetosphere: A review of developments during the IMS, *Reviews of Geophysics and Space Physics*, *20*(3), 531-565, 1982.

- The cross section of the plasma sheet contains several identifiable regions:
    - Low latitude boundary layer
    - Return flow from boundary layer
    - Return flow from tail X-line
    - Plasma sheet boundary layer

- The open field region of tail contain two parts
    - Polar mantle
    - Lobes of tail
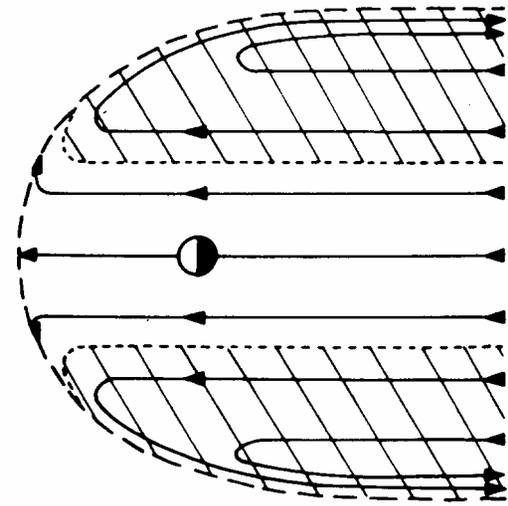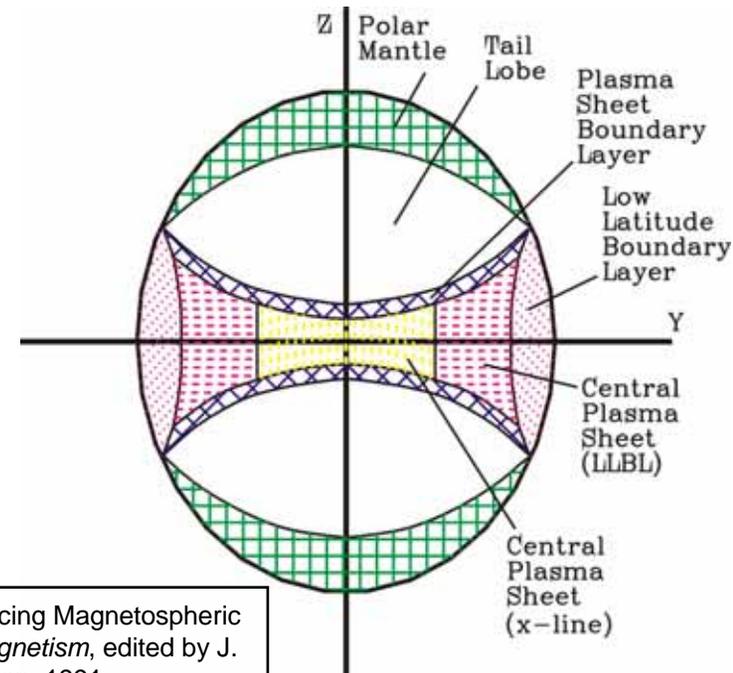
McPherron, R.L., Physical Processes Producing Magnetospheric Substorms and Magnetic Storms, in *Geomagnetism*, edited by J. Jacobs, pp. 593-739, Academic Press, London, 1991.

Particle Precipitation and Ionospheric Conductivity

- As particles convect closer to the nightside of Earth the loss cone increases, the flight time to the ionosphere decreases, and wave particle scattering increases

- All of these changes produce a region of unstructured electron precipitation on the night side that causes diffuse aurora (no arcs)

- The precipitation is bounded toward the pole by the last closed field lines connected to the distant X-line and toward the equator by the Alfven layers. This region is the nightside auroral oval.

- The precipitation also enhances conductivity within the oval relative to the ionosphere in the polar cap and the plasmasphere

- The region of high conductivity channels the DP-2 current into the eastward and westward electrojets

Ionospheric Space Charge and Rotation of the Polar Cap Potential

- If the ionosphere had uniform Hall conductivity the electrojets would close across the polar cap

- But if oval conductivity is high compared to polar cap conductivity positive space charge accumulates at nightside polar cap boundary and negative charge at the dayside boundary

- This produces a midnight to noon electric field

- Superposition of the two fields rotates the polar cap potential clockwise viewed from above north pole
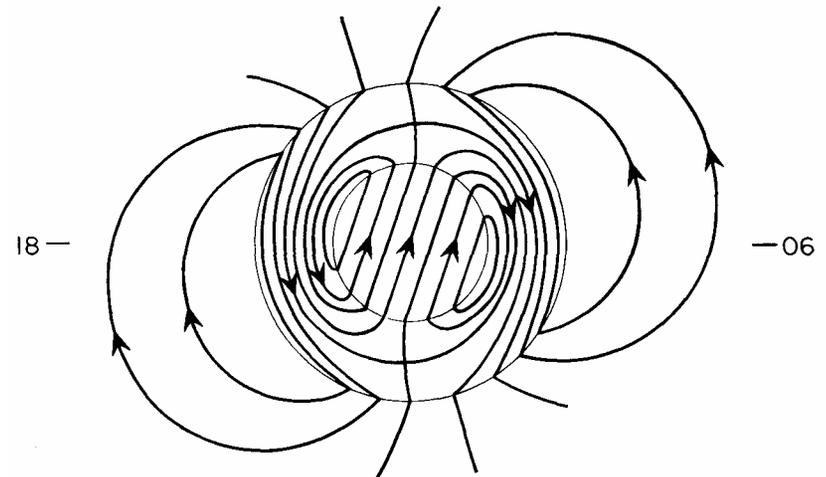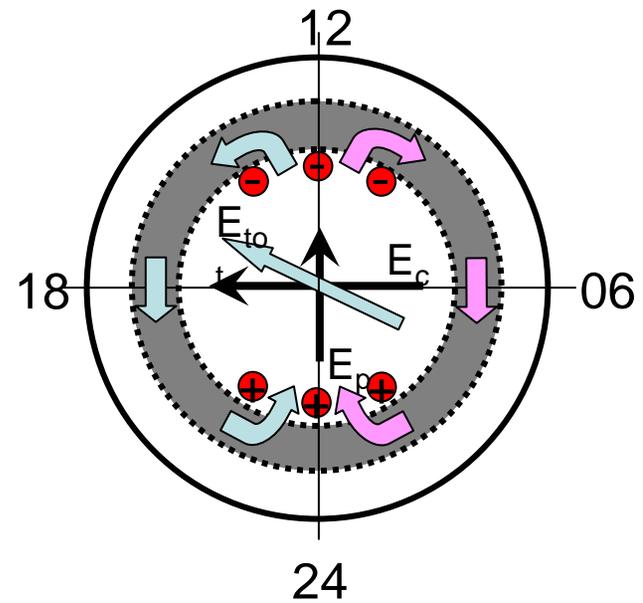
Crooker, N.U., and G.L. Siscoe, Birkeland currents as the cause of the low-latitude asymmetric disturbance field, *Journal of Geophysical Research*, *86*(A13), 11201-11210, 1981.

The Harang Discontinuity

- The ionospheric electric field pattern is skewed near midnight producing the Harang discontinuity which separates the eastward and westward Hall currents

- R1 Pedersen currents from pre and post midnight regions flow toward the Harang discontinuity and diverge upward

- Some Hall current diverges upward also because the oval conductivity is higher than the polar cap conductivity
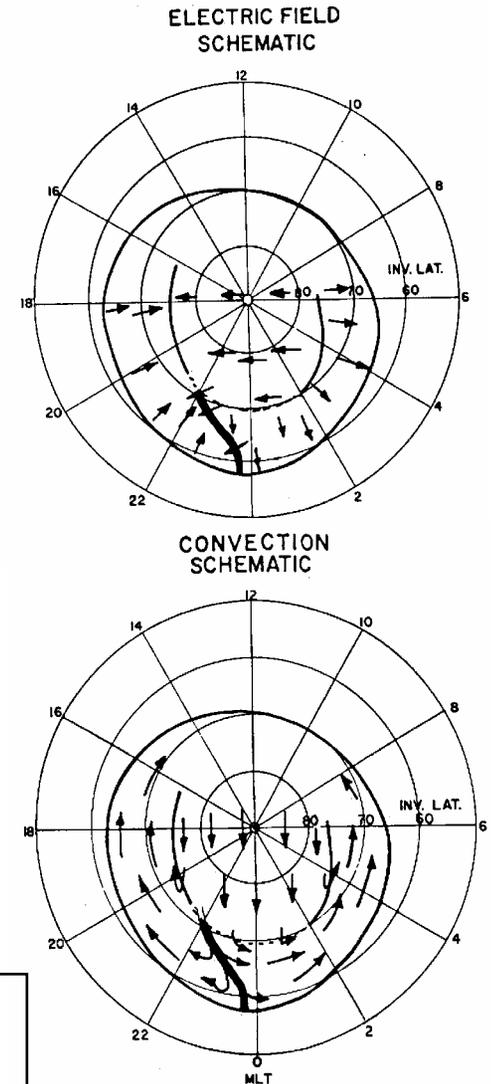
Maynard, N.C., Electric field measurements across the Harang discontinuity, *Journal of Geophysical Research*, *79*(31), 4620-31, 1974.

Formation of the Harang Discontinuity

- For reasons unclear to me the equipotentials in the midnight equatorial plane are tilted towards dawn
- Stream lines east of the stagnation line turn and pass the dawn meridian
- Stream lines west of the stagnation lines suddenly turn and pass the dusk meridian
- The locus of the discontinuity of the tangent to the stream lines is the equatorial manifestation of the Harang discontinuity

McPherron, R.L., Physical Processes Producing Magnetospheric Substorms and Magnetic Storms, in *Geomagnetism*, edited by J. Jacobs, pp. 593-739, Academic Press, London, 1991.
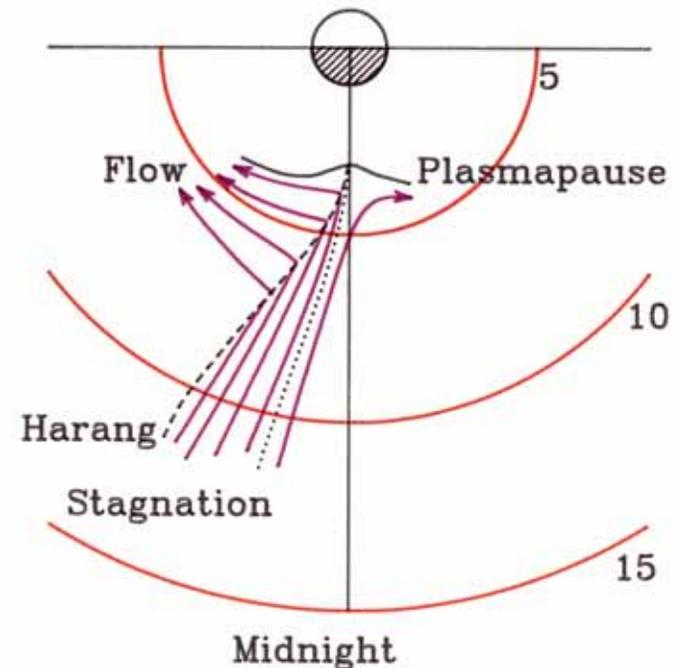
Electrodynamics of the Harang Discontinuity

- When polar cap conductance is low the Hall currents must close via field-aligned currents in the Harang discontinuity

- Also the Pedersen currents coverge at the HD and must close via field-aligned currents

Koskinen, H.E.J., and T.I. Pulkkinen, Midnight velocity shear zone and the concept of Harang discontinuity, *Journal of Geophysical Research*, *100*(A6), 9539-47, 1995.
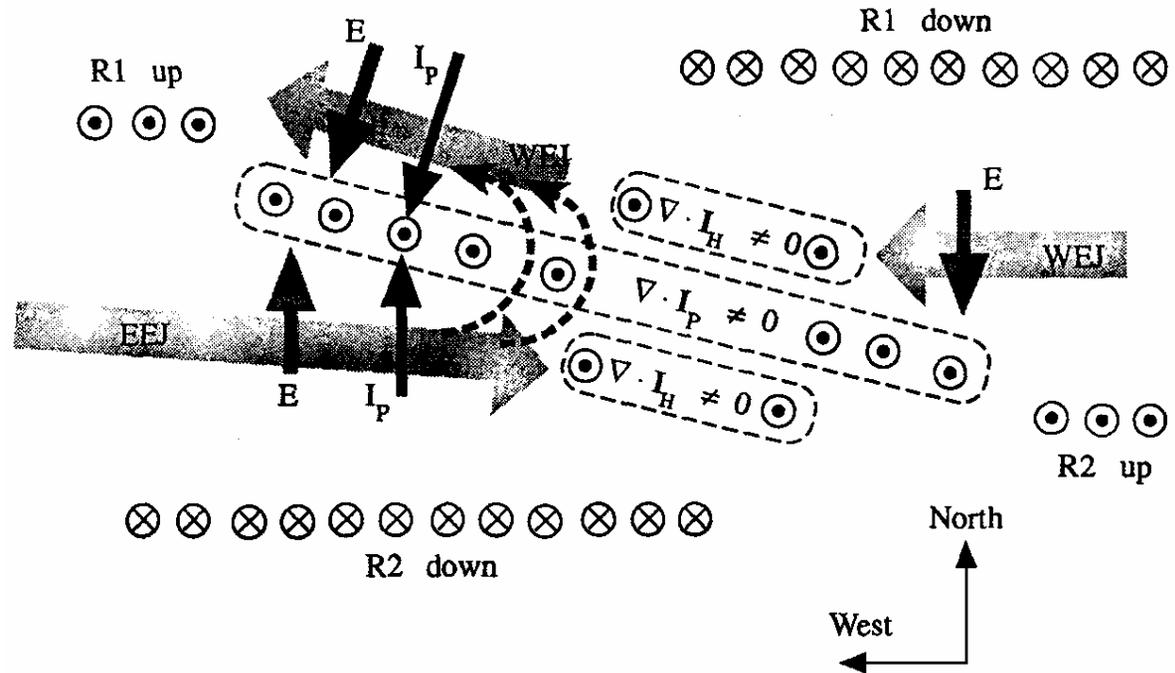
Discrete auroral arcs

- Discrete auroral arcs are formed near the Harang discontinuity by E-W sheets of more energetic (1-10 keV) electron precipitation

- They are created by field-aligned potential drops along field lines carrying outward current from the HD

- The potential drops are needed to accelerate the available magnetospheric electrons to sufficient velocity to carry the outward current

- The onset of an auroral substorm occurs on the most equatorward arc in this region
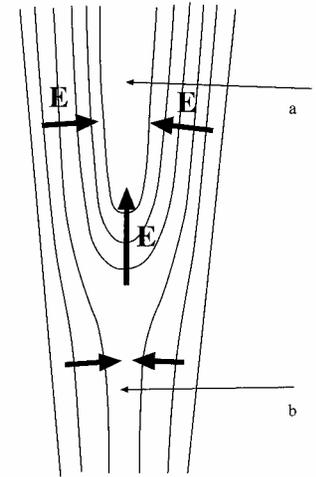
Input Data

- Top left panel shows electric field measurements

- Top right panel contains ground magnetic data

- Bottom left panels shows a model of Pedersen conductance

- Bottom right panel shows model of Hall conductance

Richmond, et al., Global measures of ionospheric electrodynamic activity inferred from combined incoherent scatter radar and ground magnetometer observations, *Journal of Geophysical Research*, *95*(A2), 1061-1071, 1990.
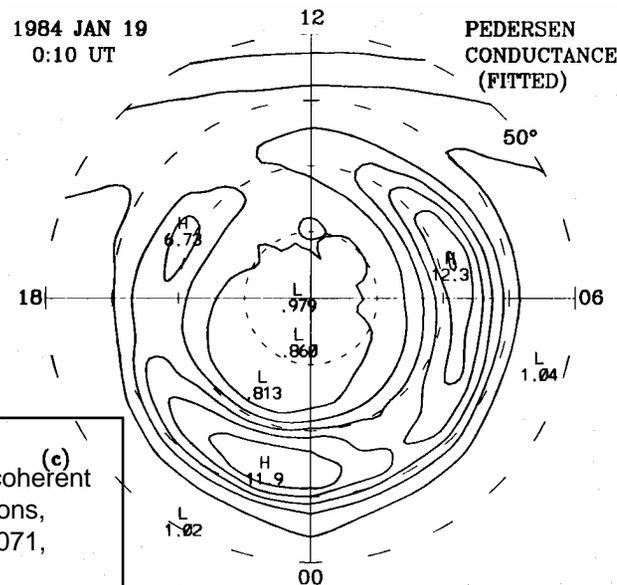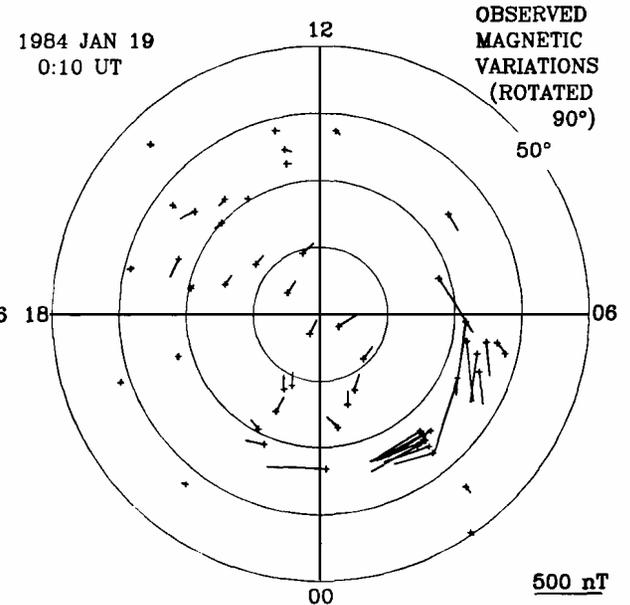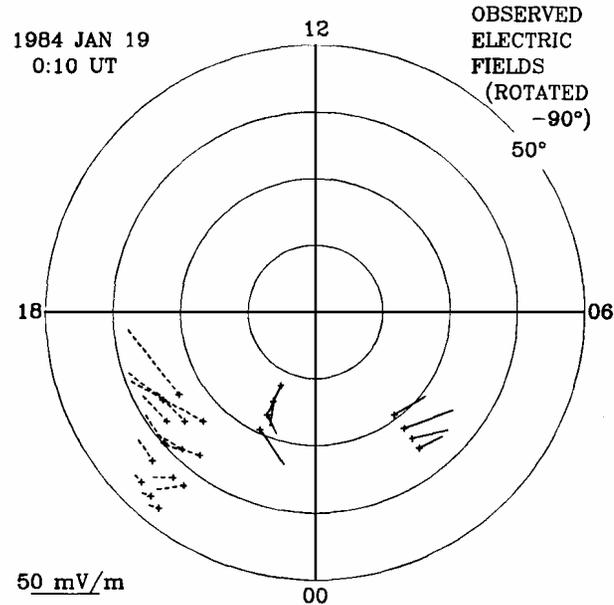
AMIE E Field and Potential

- Ground magnetic observations are inverted to obtain equivalent ionospheric current
- A conductance model is assumed
- The current and conductance are converted to an electric potential pattern
- The electric field derived from the potential
- Dashed lines are portion of pattern mainly derived from statistical information modified to be consistent with available data

- The electric Harang discontinuity (HD) is defined as the velocity shear near midnight
- It is not known how this relates to the high latitude dusk shear

1984 JAN 19
0:10 UT

ELECTRIC
FIELD
(FITTED)

50°

18 — 06

(c)

0.1 V/m

00

1984 JAN 19
0:10 UT
ΔΦ = 106.3 kV

ELECTRIC
POTENTIAL
(FITTED)

50°

18 — 06

(b)

?

Harang
Discontinuity

00
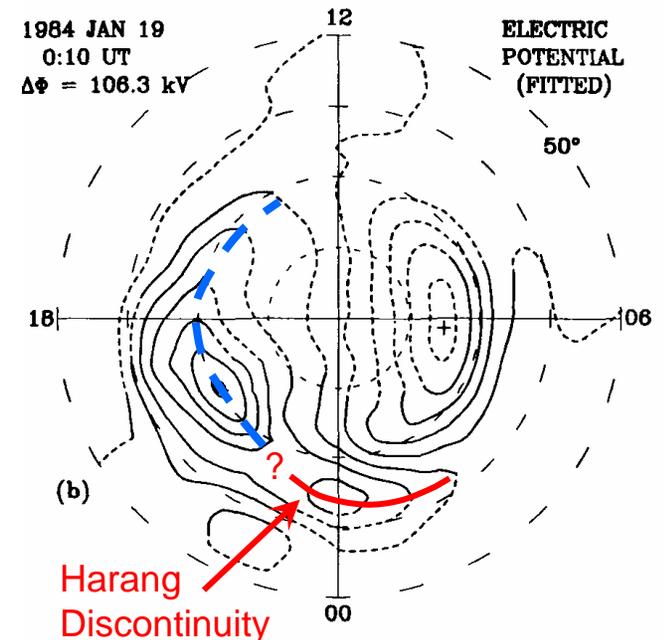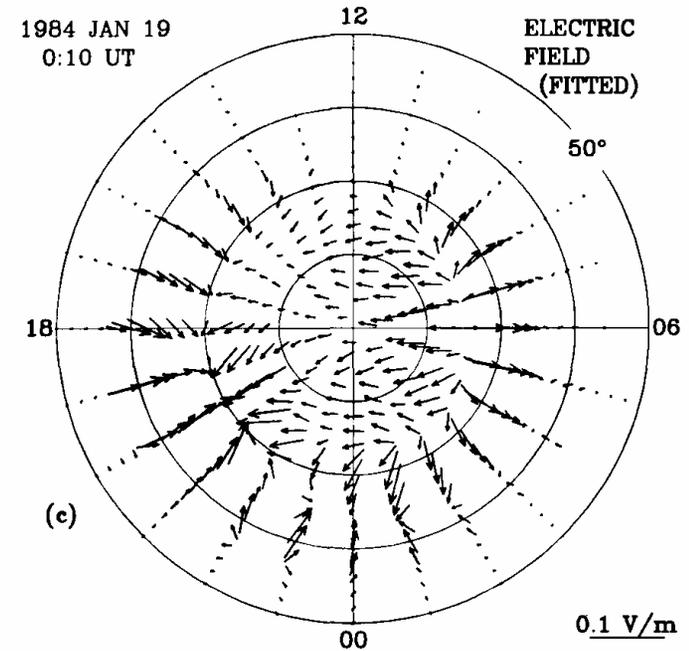
Horizontal and Field-Aligned Currents

- Panel (a) shows vectors of the height-integrated ionospheric current

- Panel (b) shows stream lines of the current (ψ)

- Panel (c) shows potential whose Laplacian gives the field aligned currents (τ)

- Panel (d) presents the field-aligned current pattern obtained from I

$$\vec{I} = \hat{r} \times \nabla \psi - \nabla \tau$$

$$J_\parallel = \nabla \cdot I = \nabla^2 \tau$$

1984 JAN 19 0:10 UT   HORIZONTAL 1984 JAN 19   0:10 UT $\Delta\psi = 683$ kA   CURRENT (FITTED)   EQUIVALENT CURRENT FUNCTION (FITTED)

50°

18   06 18   06

(a)   (b)

1 A/m   00

1984 JAN 19 0:10 UT $\Delta\tau = 742$ kA   CURRENT POTENTIAL (FITTED)   1984 JAN 19 0:10 UT $I_\parallel = 5.97$ MA   FIELD-ALIGNED CURRENT (FITTED)

50°

18   06 18   06

(c)   (d)

00   00
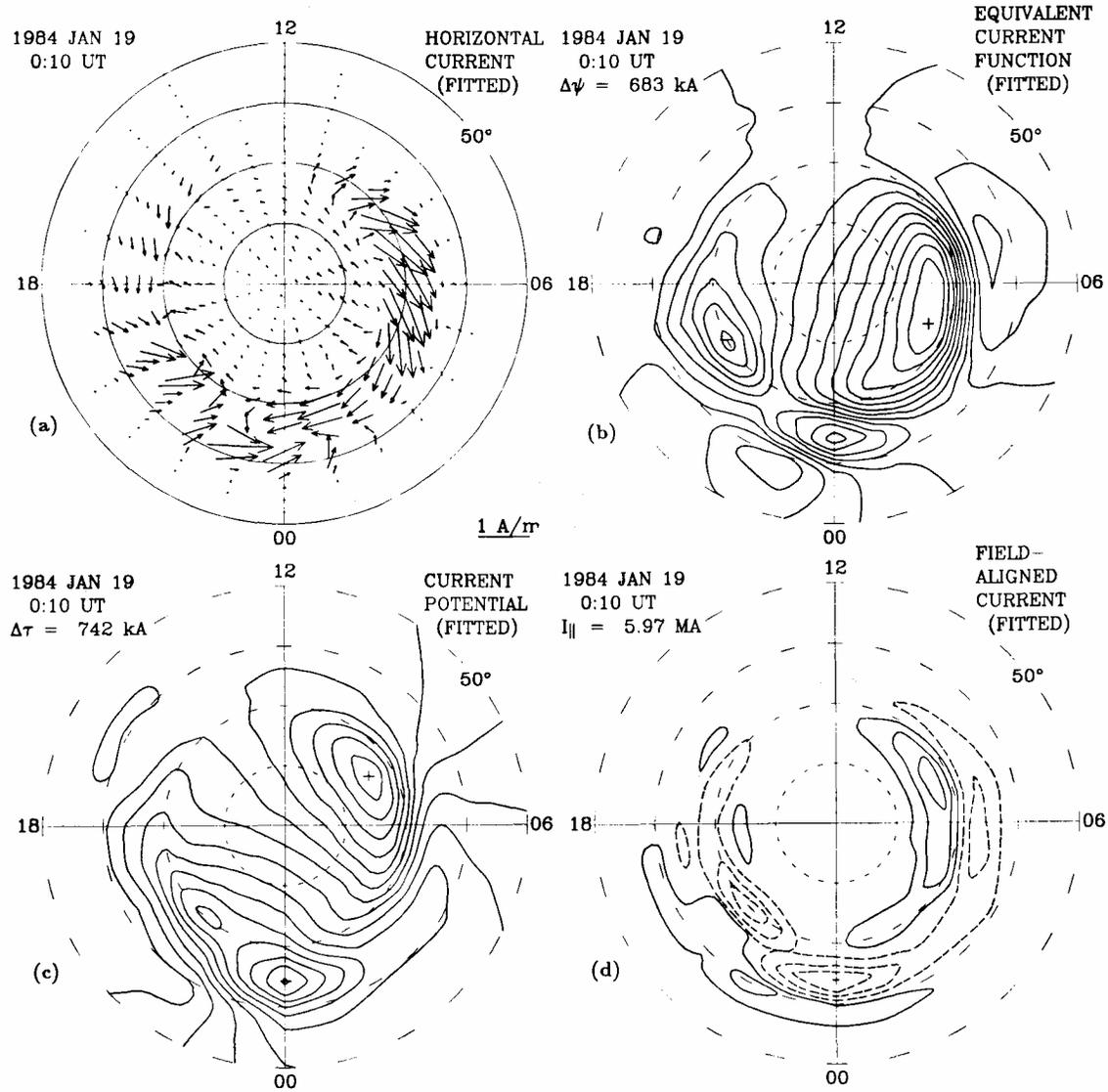
Electrodynamics of the Auroral Bulge

- Bulge is highly conducting
- Neglect conductivity outside
- Primary field E_{py} is westward
- Primary field drives westward J_P
- J_P closes by FAC at E-W ends
- Primary field drives northward J_H
- A fraction α_p of J_H is not discharged by FAC
- Polarization charges accumulate at N-S boundaries creating a southward secondary field E_{sx}
- E_{sx} drives southward Pedersen current that cancels the fraction of northward Hall not closed by FAC
- E_{sx} also drives a westward Hall current
- The total westward current is sum of primary Pedersen and secondary Hall currents
- For ap ~1/2 and Σ_H/Σ_P~4 we get J_y ~ 9 $\Sigma_P E_{py}$
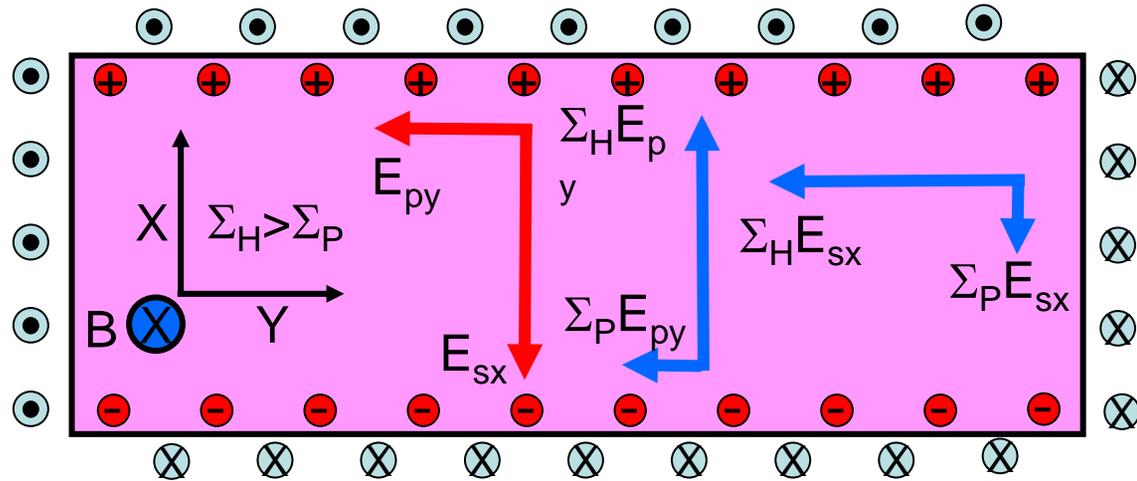
$$\alpha_p \Sigma_H E_{py} - \Sigma_P E_{sx} = 0$$

$$\therefore \; E_{sx} = \alpha_p \frac{\Sigma_H}{\Sigma_P} E_{py}$$

$$J_y = \Sigma_P E_{py} + \Sigma_H E_{sx}$$

$$\therefore \; J_y = \left(\Sigma_P + \alpha_p \frac{\Sigma_H^2}{\Sigma_P} \right) E_{py}$$

Current Systems in the Magnetosphere

- Magnetopause current at equator and above polar cusp
- Region 1 field-aligned current
- Region 2 field-aligned current
- The symmetric ring current
- The partial ring current
- The plasma sheet current
- The substorm current wedge

- Currents NOT SHOWN:
  - Closure of plasma sheet current
  - Currents in the polar cusp
  - Closure of boundary layer current

McPherron, R.L., Physical Processes Producing Magnetospheric Substorms and Magnetic Storms, in *Geomagnetism*, edited by J. Jacobs, pp. 593-739, Academic Press, London, 1991.

The End