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School on the Physics of Equatorial Atmosphere

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External Current Systems

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EXTERNAL CURRENT SYSTEMS

Jeffrey M. Forbes, University of Colorado

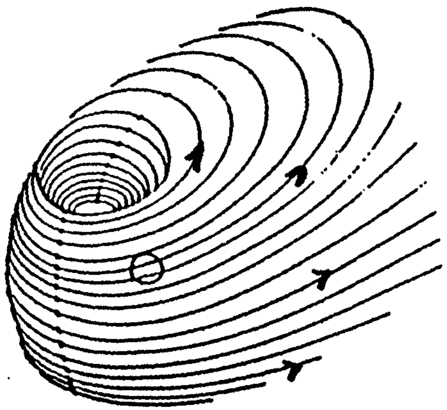
- **Magnetospheric Currents: Magnetopause, Tail, Ring, Birkeland**
- **Sq Ionospheric Currents**
- **Disturbance Variations and Magnetic Indices**
- **E-Region Dynamo Theory**
- **Equatorial Electrojet**
- **Electrodynamic Coupling of the Equator with High Latitudes**

<u>MAGNETOSPHERIC CURRENTS</u>

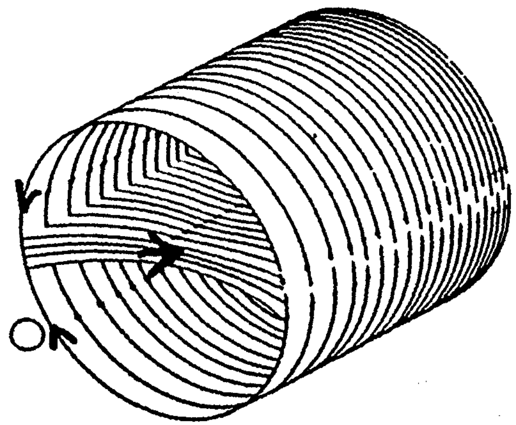
The combination of plasma and electric fields in the magnetosphere allows electric current to flow. Several <u>current systems</u> have been identified:

- magnetopause current (A)
- tail current (B)
- ring current (C)
- Birkeland (field-aligned) currents

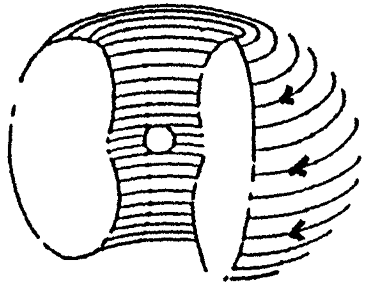
A

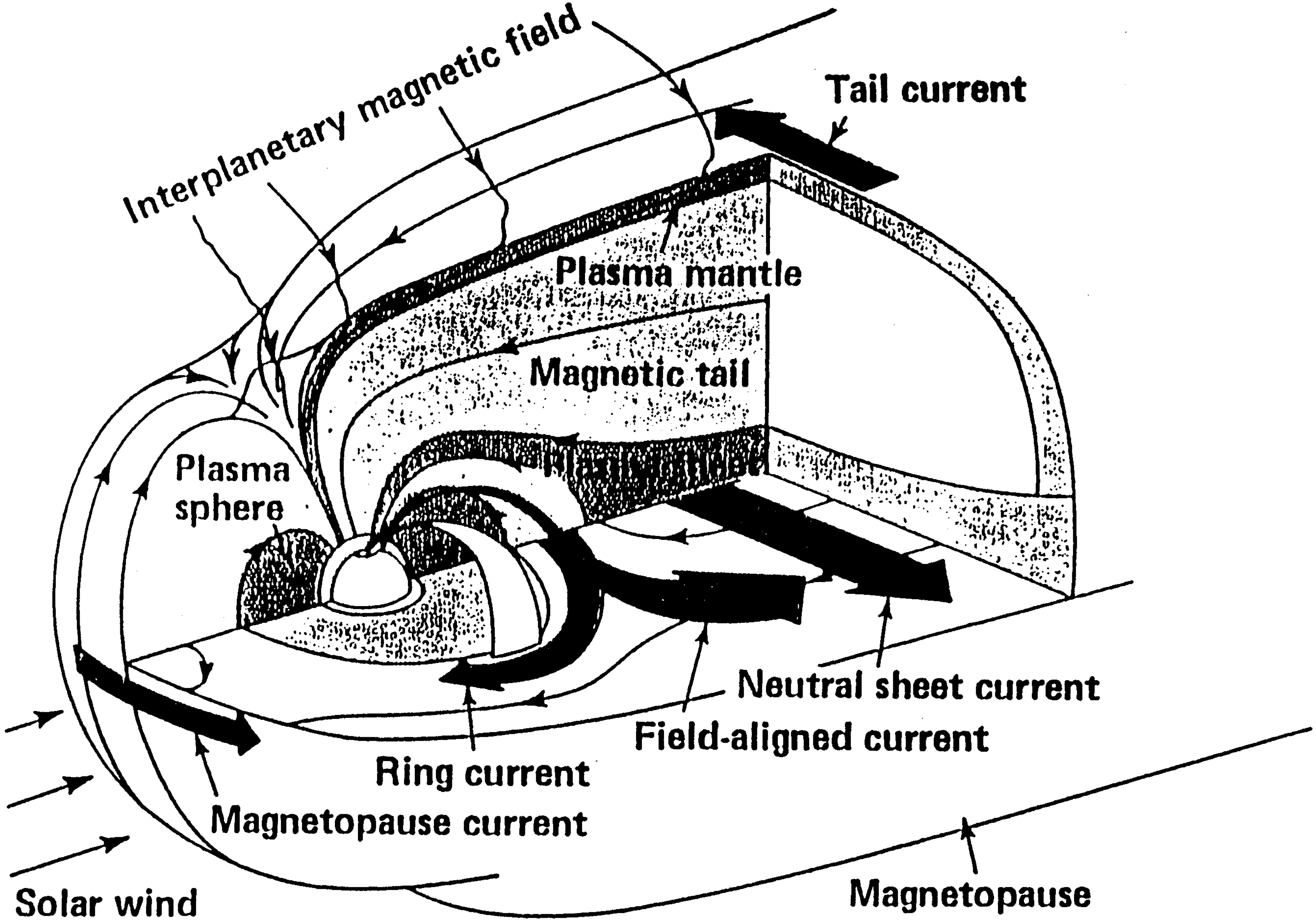


B



C





Plasma populations and current systems of the magnetosphere. (T. A. Potemra, *Johns Hopkins APL Tech. Digest* 4, 276, 1983)

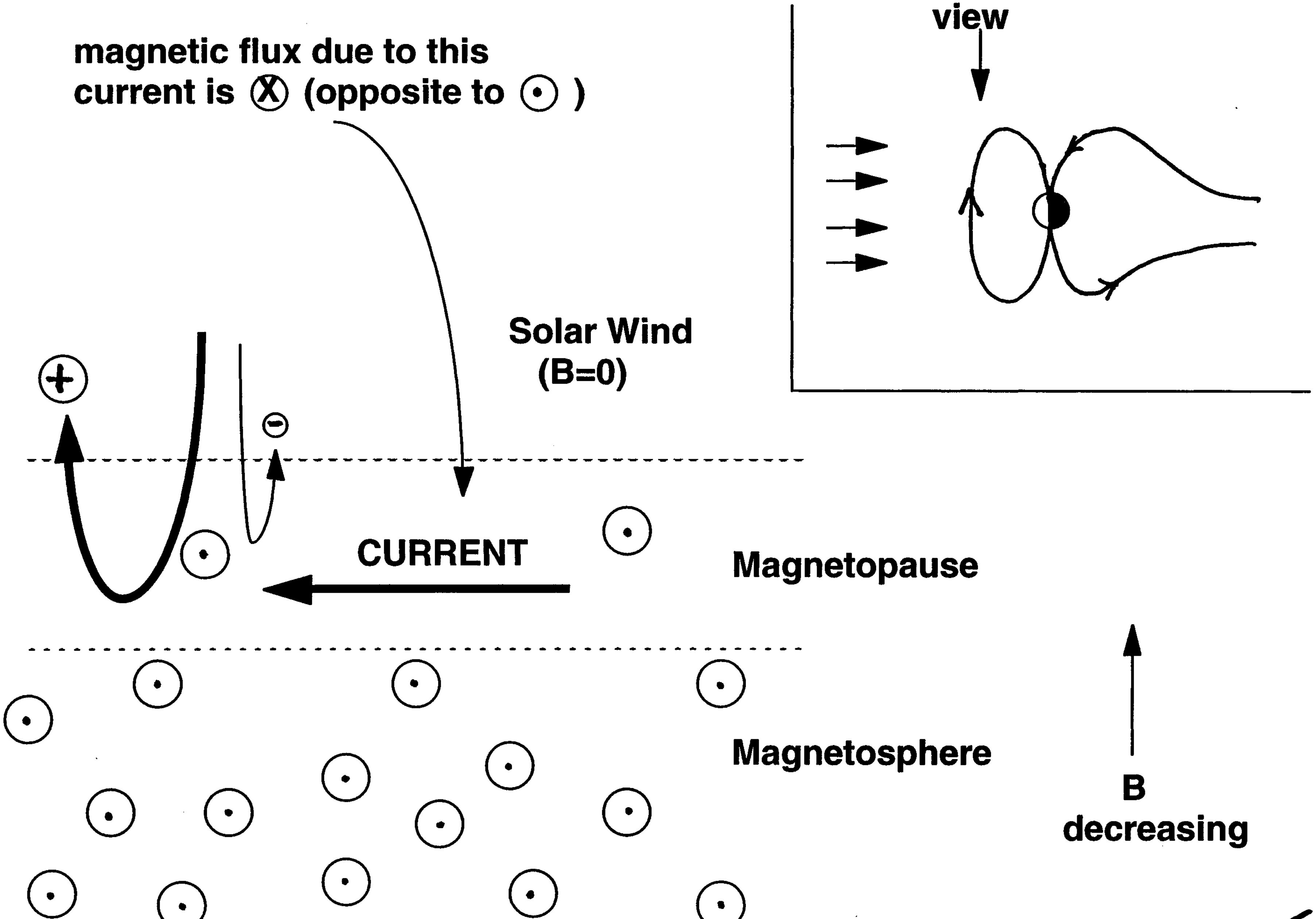
- The strong deviations of the magnetosphere from a dipole shape are in fact due to the first three of the above current systems. These are now discussed in turn.

MAGNETOPAUSE CURRENT

If we ignore any magnetic or electric field in the solar wind, the origin of the magnetopause current and the corresponding modifications of the magnetic field can be grossly understood as follows:

- Consider a small section of the dayside magnetopause with the solar wind normal to it (see following figure). The ions are deflected one way and the electrons the other, causing a current to flow (consisting mostly of ions due to their greater penetration depth). The current flow at the magnetopause is such that its magnetic field cancels the *geomagnetic* field outside the boundary.

CURRENTS AND FIELDS AT THE MAGNETOPAUSE BOUNDARY



• Similarly, earthward of the boundary the field strength is doubled -- this is essentially the "compression" of the dayside magnetosphere that we have alluded to before.

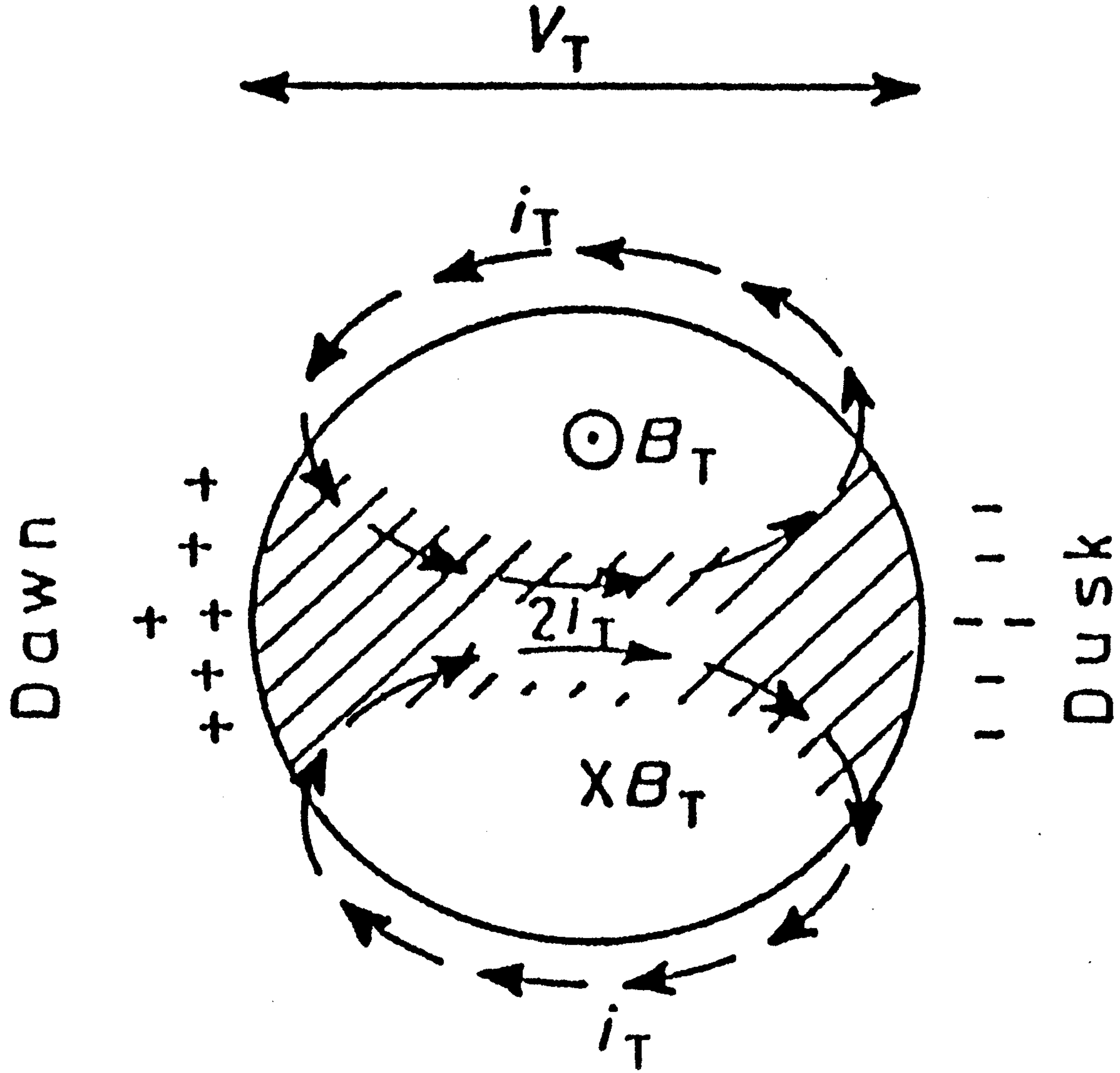
• It turns out that the force produced by this current (the so-called Lorentz or J X B force) balances the momentum force of the solar wind, which is another way of stating the "dynamic pressure" vs. "magnetic pressure" balance we discussed before.

• When the solar wind intensifies, the magnetopause current is increased:

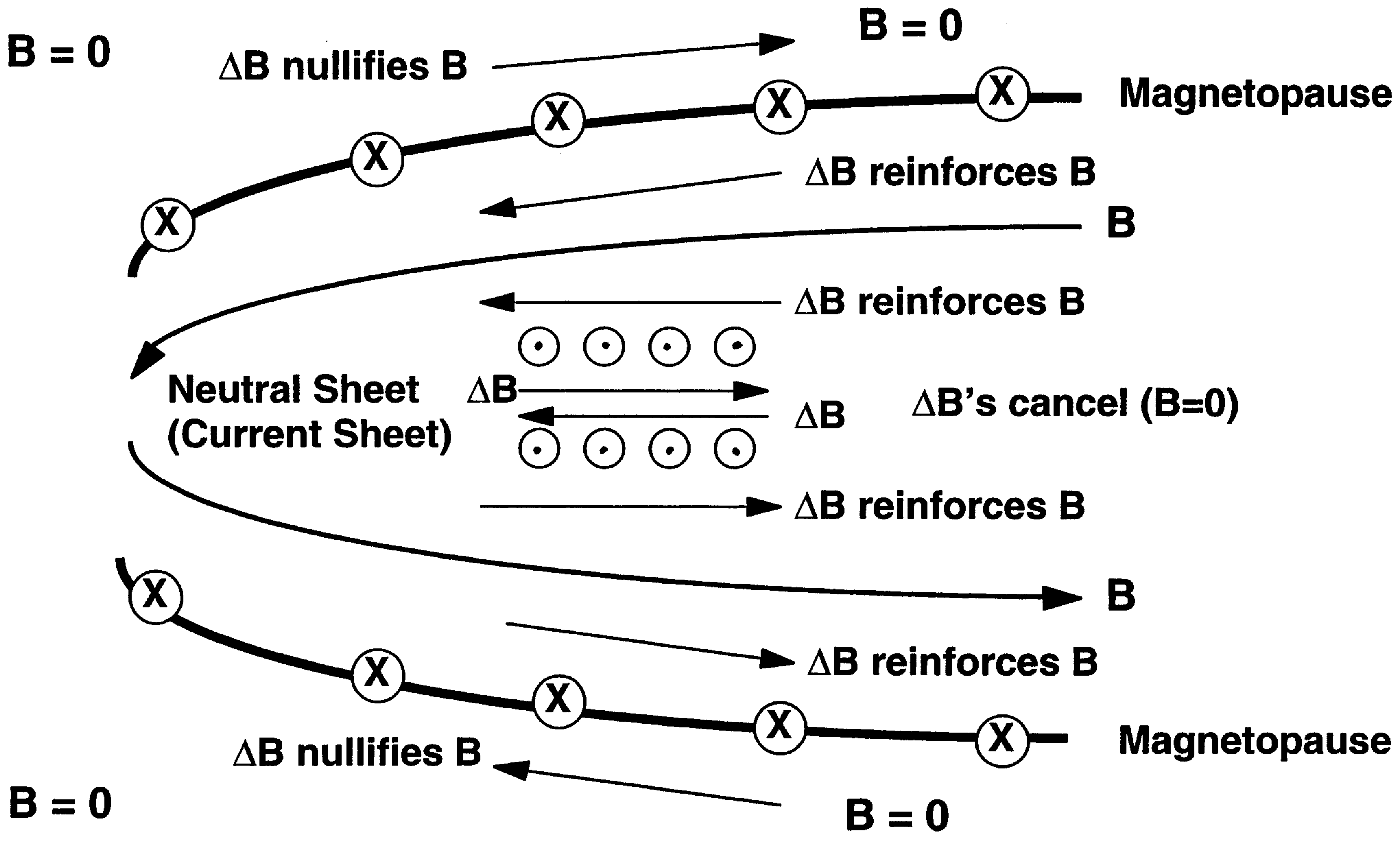
- -- This further "compresses" the dayside magnetosphere;
- -- The ground magnetic signature of this sudden compression is called a "sudden impulse" (SI), or if it is connected with the beginning of a storm, it is called a "sudden storm commencement" (SSC).

TAIL CURRENT

The down-wind extension of the magnetosphere into a tail indicates the presence of a current system as follows:



CURRENTS AND MAGNETIC FIELDS IN THE GEOTAIL



RING CURRENT

• Under magnetic storm conditions the magnetic field of the earth at low latitudes may be depressed ~ 1-2% for a day or two (main phase). This is due to a westward ring current which we have already discussed in relation to particle drift (gradient drift) on curved field lines with the magnitude of B increasing towards the earth.

• Recall that the gradient drift depends on the particle "magnetic dipole moment"

$$v_g = \mu \frac{\vec{B} \times \nabla B}{eB^2} \qquad \mu = \frac{1}{2} \frac{m v_\perp^2}{B}$$

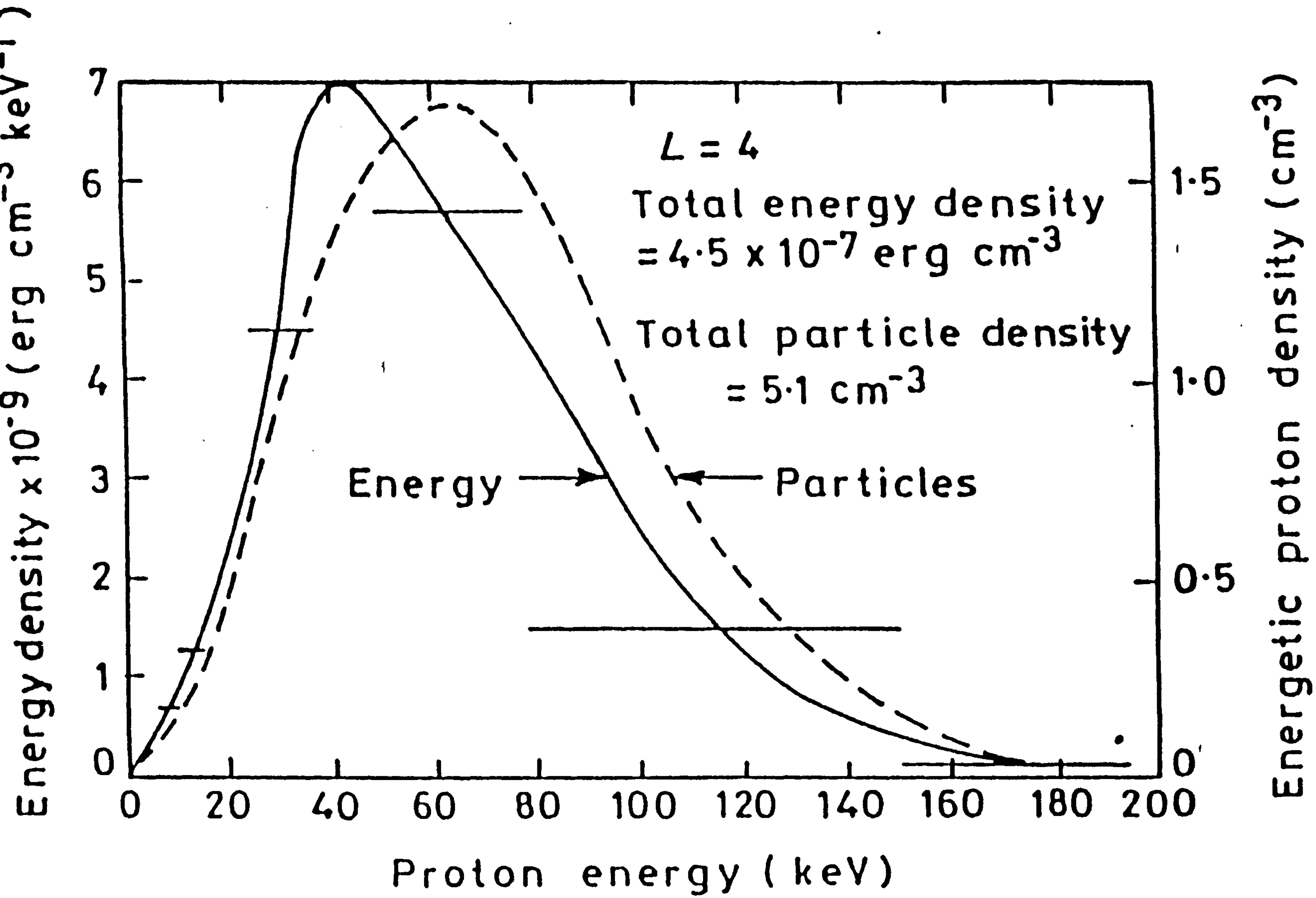
-- hence gradient drift is not important for "cold" particles like those populating the ionosphere and plasmasphere; these particles co-rotate.

- However, it is also true that it is <u>not</u> the energetic Van Allen particles that are the <u>main</u> contributors to the ring current. The fluxes of these particles are too small. the main ring current particles are protons of 20 - 100 keV (see following figure).

- The ring current is located between 4 and 6 R_E, close to the inner edge of the plasma sheet and and <u>outer edge of the trapping zone</u>.

- Where do the ring current particles come from?

-- magnetospheric convection after reconnection accelerates particles inward, but they eventually <u>mirror</u> in the stronger field near the earth, and this is where the inner edge of the plasma sheet forms.



Energy and number spectra of protons in the ring current at L = 4 during a magnetic storm. (M. H. Rees and R. G. Roble, *Rev. Geophys. Space Phys.* **13**, 201, 1975, copyright by the American Geophysical Union)

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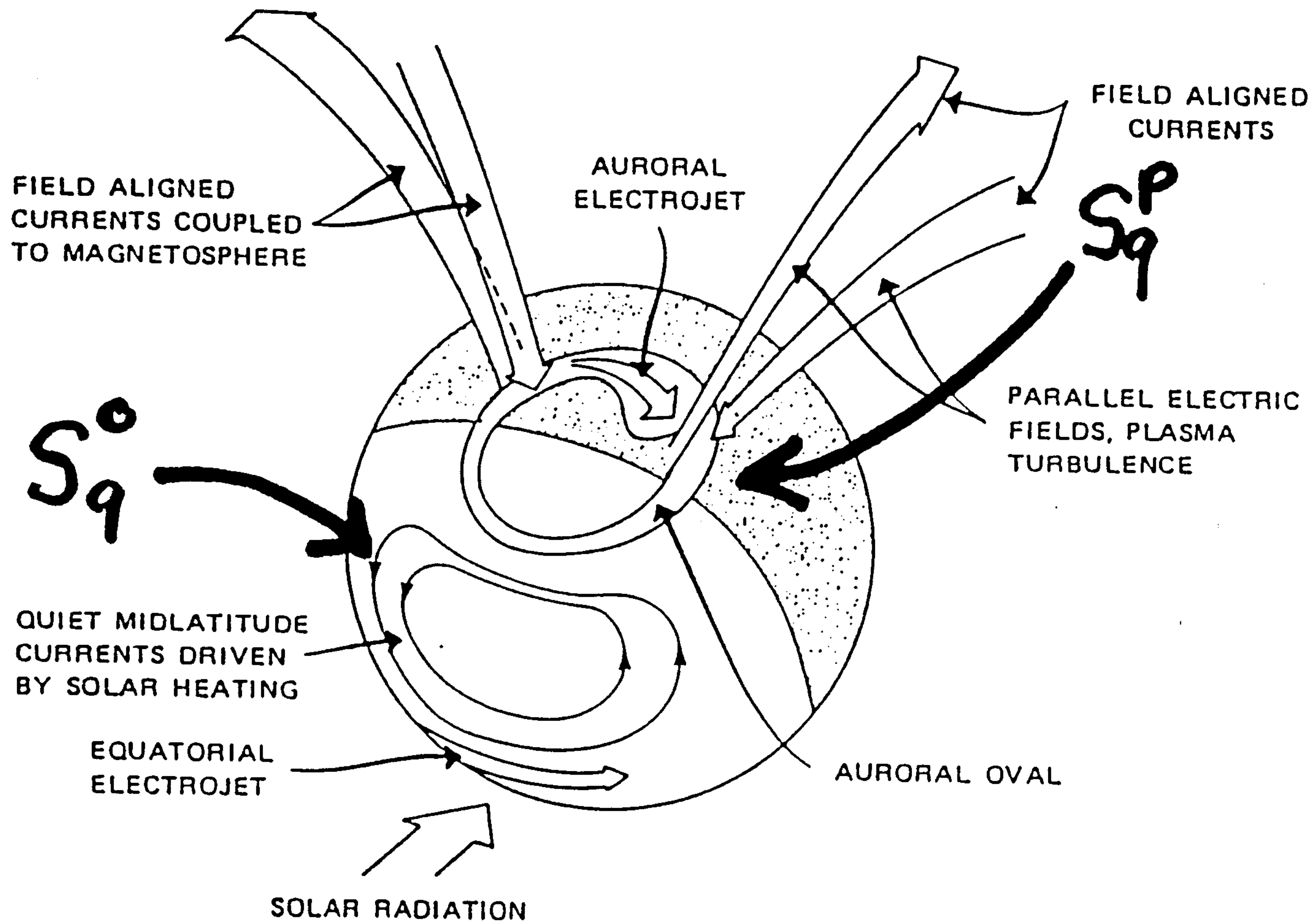
IONOSPHERIC CURRENTS



- Currents flowing in the ionosphere and magnetosphere also induce magnetic field variations on the ground. These field variations generally fall into the categories of "quiet" and "disturbed".

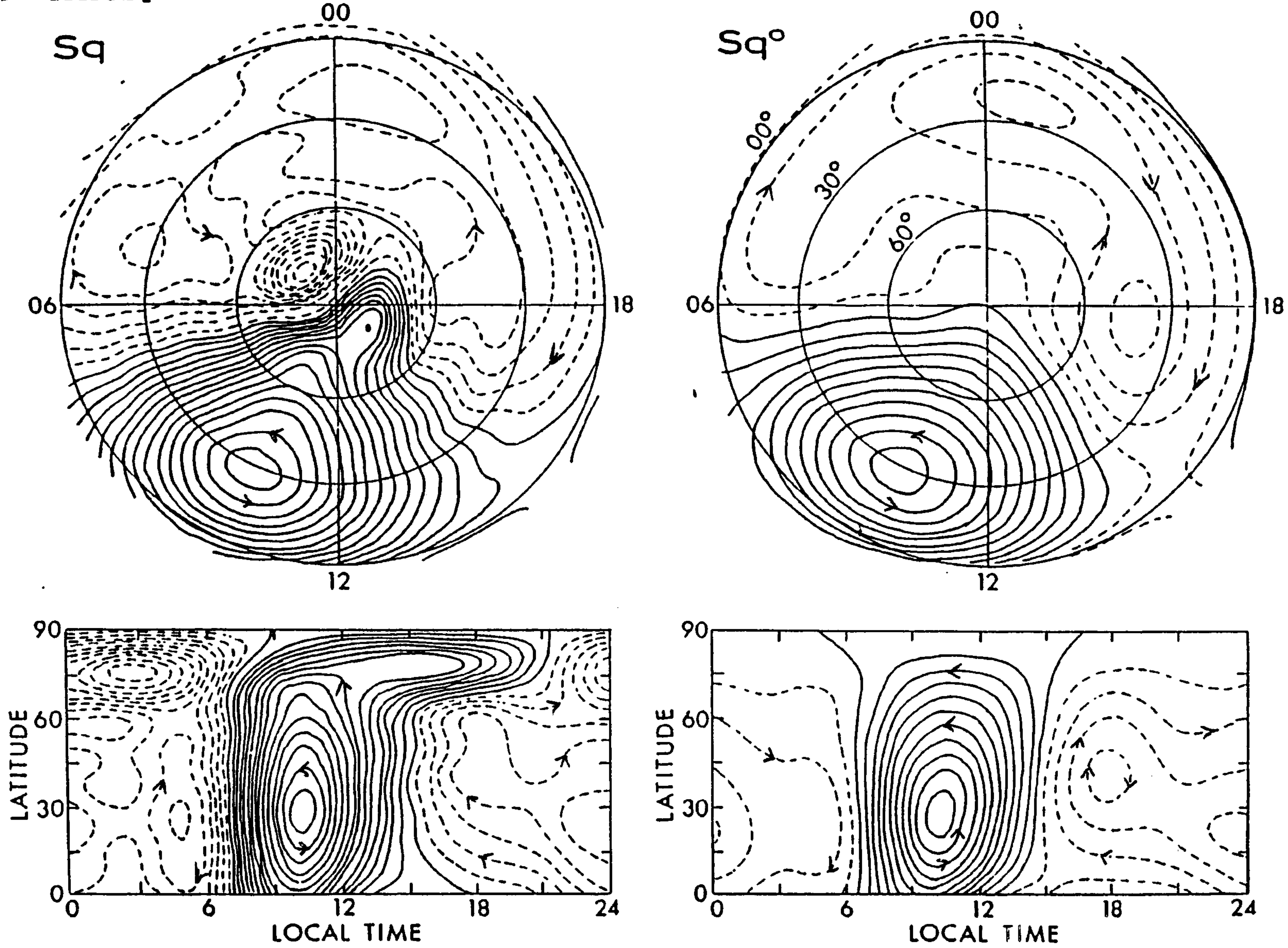
- In the previous figure the connection to the magnetosphere is by the high latitude field-aligned currents.

- Within the ionosphere, the convection electric fields drive currents that are fed by the field-aligned currents flowing downward on the dawn side and upward on the dusk side of the polar cap.

- Notice also that equatorward of the auroral oval, the field-aligned currents change direction, upward on the dawn side and downward on the dusk side of the auroral oval.

- The solar quiet daily variation (Sq) results principally from currents flowing in the electrically-conducting E-layer of the ionosphere.

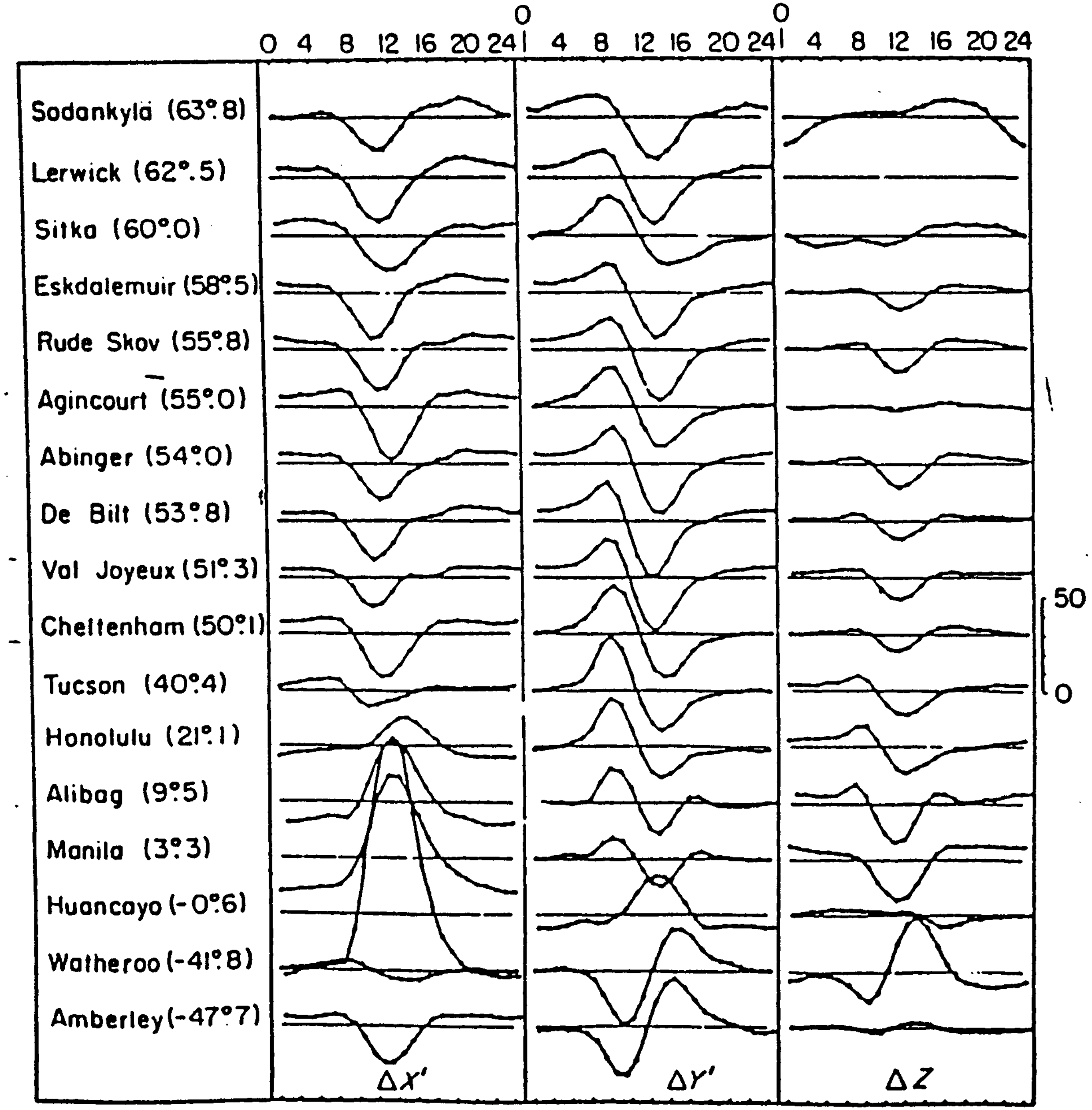
Sq consists of 2 parts: S_q^o , due to the dynamo action of tidal winds; and S_q^p, due to current exhange between the high-latitude ionosphere and the magnetosphere along field lines.



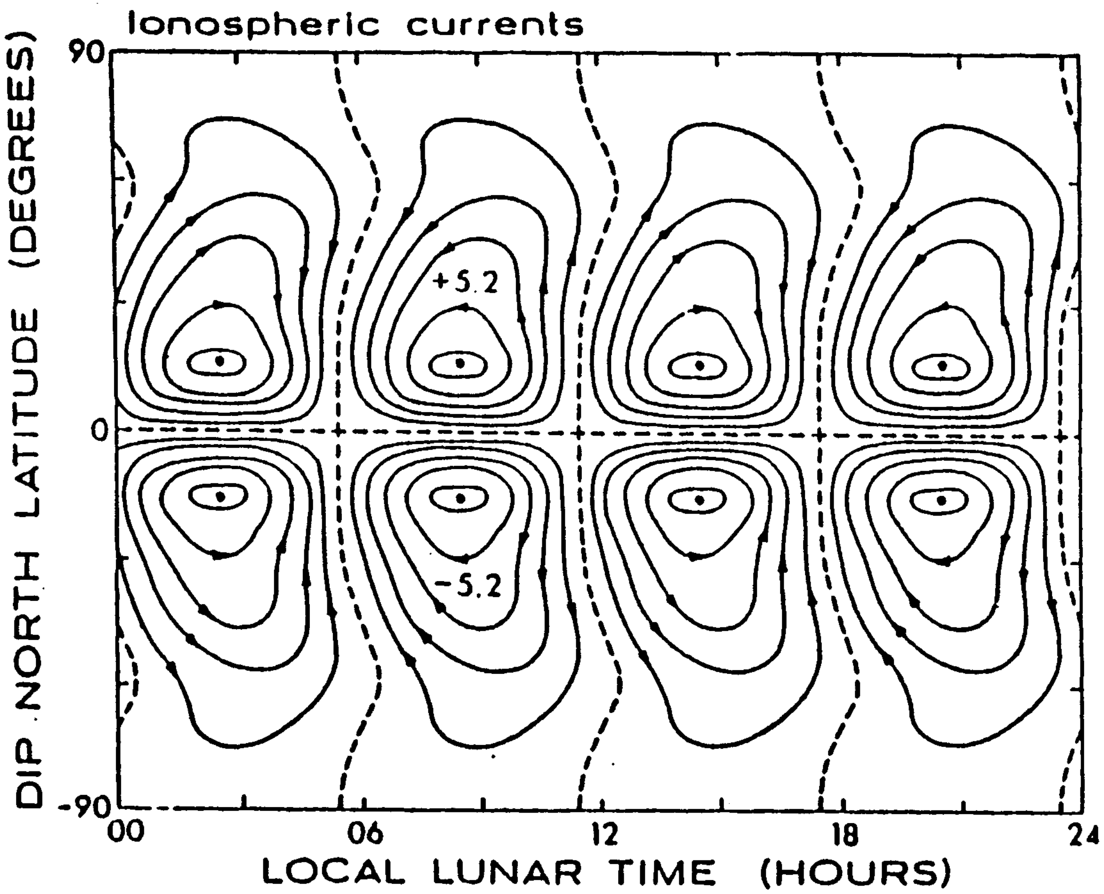
• The following figure illustrates the Sq variation in the magnetic components X,Y,Z at various latitudes from equinox data.

[Note: according to Ampere's law, a current will induce a magnetic field, and conversely a time-changing magnetic field will induce a current to flow in a conductor. Currents flowing in the ionosphere induce a magnetic field variation in the ground .... this is the "external" source we referred to before. But, some of this changing magnetic flux links the conducting earth, causing currents to flow there. These, in turn, induce a changing magnetic field on the ground which is also measured by ground magnetometers. These induced earth currents contribute about 25-30% of the total measured Sq field.]

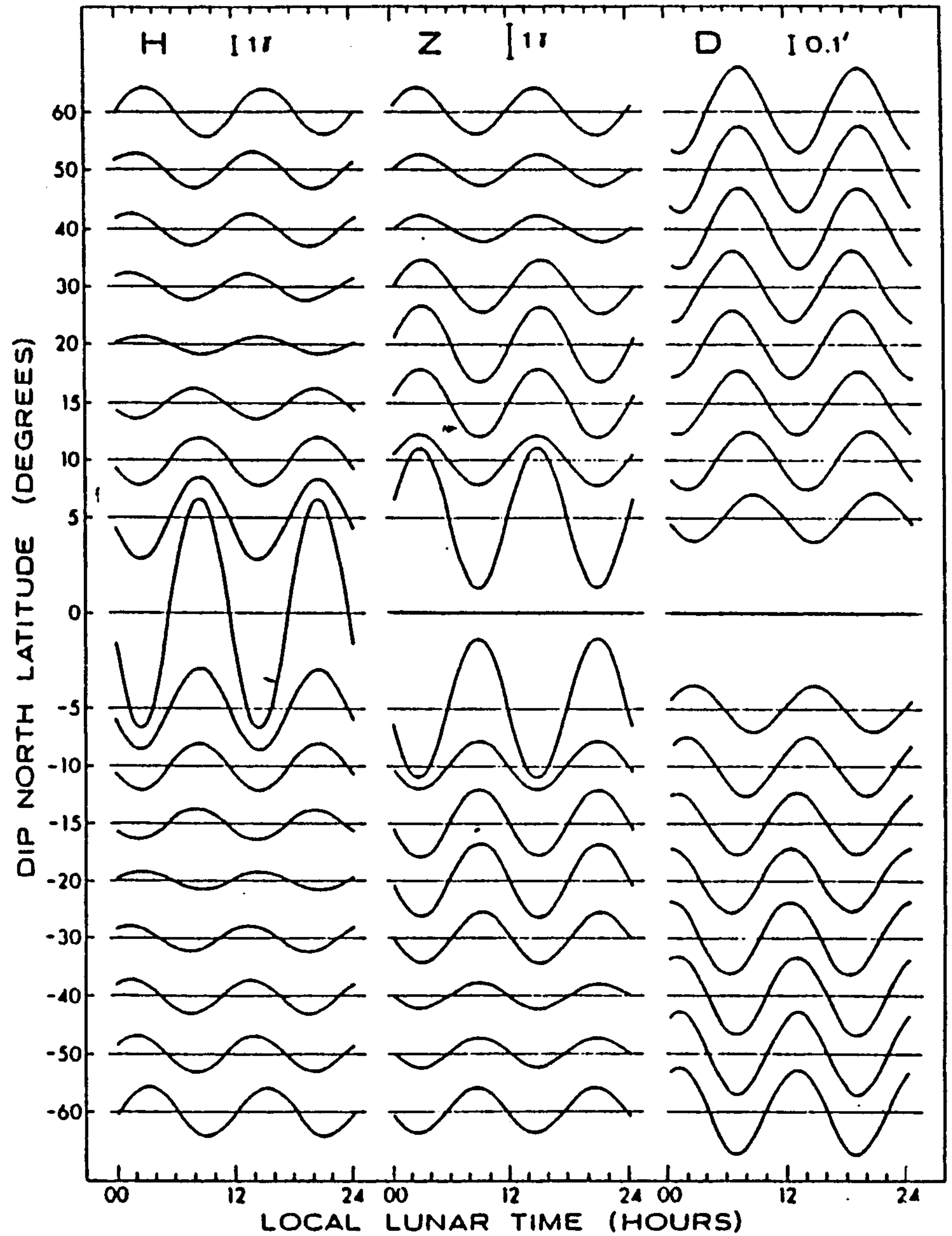
The above mutual feedback is very much like "mutual inductance"



The Sq variation in the magnetic components X,Y,Z at various latitudes from equinox data. The scale at the right indicates a range of 50γ . Note: the deviations ΔX', ΔY' are measured with respect to *geomagnetic* north and east, respectively.



• Another quiet current system, the lunar daily variation, L, exists similarly because of lunar tidal winds in the ionospheric E-region. These are gravitational tides, as opposed to solar-driven (thermally-driven) atmospheric tidal oscillations. The L variation is about 10-15% of the Sq variations.



Lunar semidiurnal variation near the time of equinox.

DISTURBANCE VARIATIONS

• In addition to Sq and L variations, the geomagnetic field often undergoes irregular or <u>disturbance variations</u> connected with solar disturbances. Severe magnetic disturbances are called <u>magnetic storms</u>.

• Storms often begin with a <u>sudden storm commencement</u> (<u>SSC</u>), after which a repeatable pattern of behavior ensues.

<u>disturbed value of a magnetic element</u> (X, Y, H, etc.)

disturbed field $\quad \Delta X = X_{obs} - X_q$ "quiet"

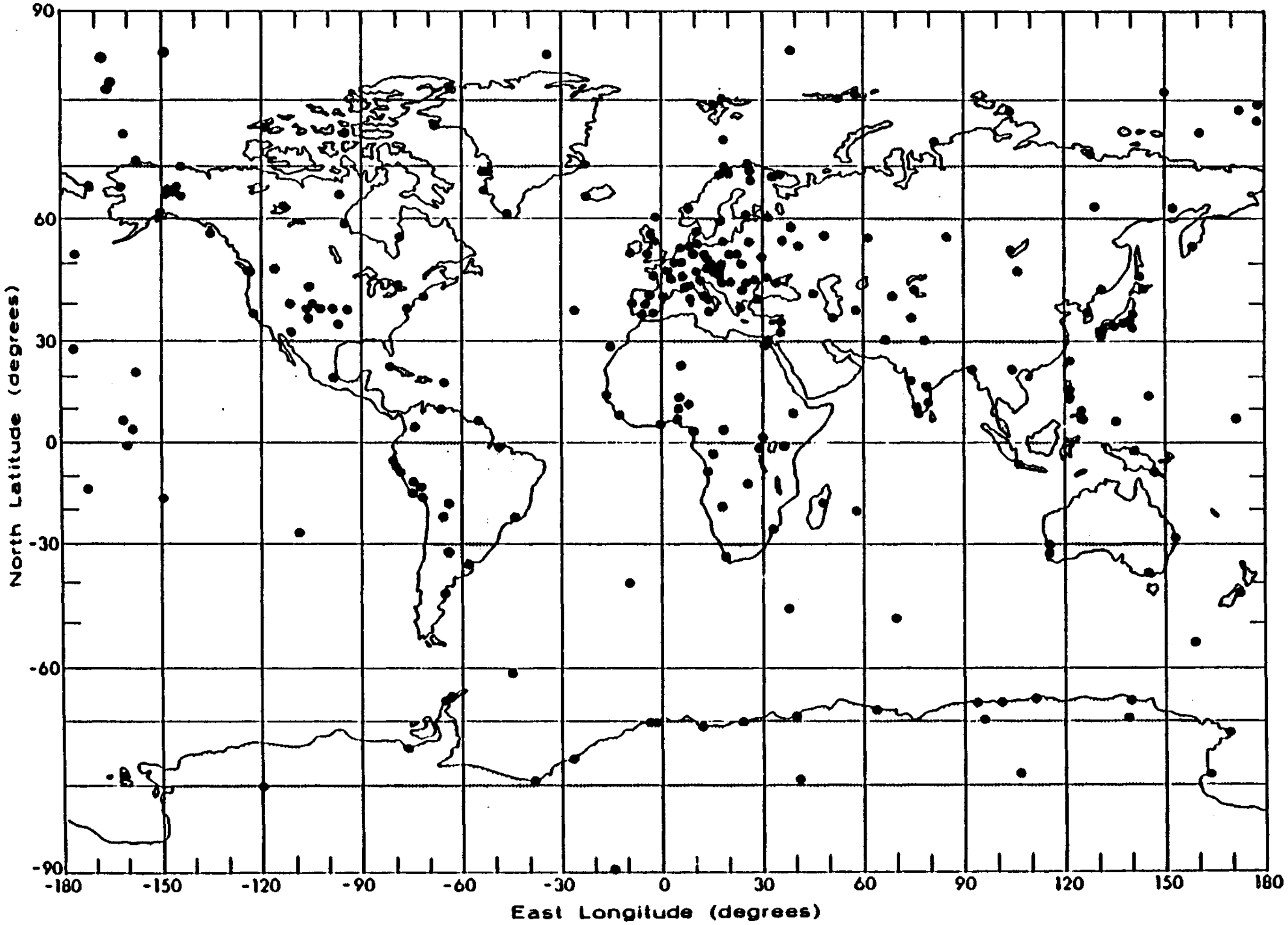
$$= D_{st}(\tau) + DS(\tau)$$

τ = storm time (time elapsed from SSC)

storm-time variation, the average of ΔX around a circle of constant latitude

disturbance local time inequality ("snapshot" of the ΔX variation with longitude at a particular latitude).

Geographical distribution of magnetic observatories



Typical Magnetic Storm:

- SSC followed by an "initial" or "positive" phase lasting a few hours. During this phase the geomagnetic field intensity is increased, probably due to solar wind compression; this is reflected in $D_{st}(h) > 0$ (see figure, following page).

- During the main phase $D_{st}(H) < 0$ and the field remains depressed for a day or two. The $D_{st}(H) < 0$ is due to a "westward ring current" around the earth, reaching its maximum value about 24 hours after SSC.

- During recovery phase after ~ 24 hours, Dst slowly returns to ~ 0 (time scale ~ 24 hours).

- Generally D_{st} is maximum at low latitudes

  DS is maximum at high latitudes

Various indices of activity have been defined to describe the degree of magnetic variability.

For any station, the range (highest and lowest deviation from regular daily variation) of X, Y, Z, H, etc. is measured (after Sq and L are removed); the greatest of these is called the "amplitude" for a given station during a 3-hour period. The average of these values for 12 selected observatories is the a_p index.

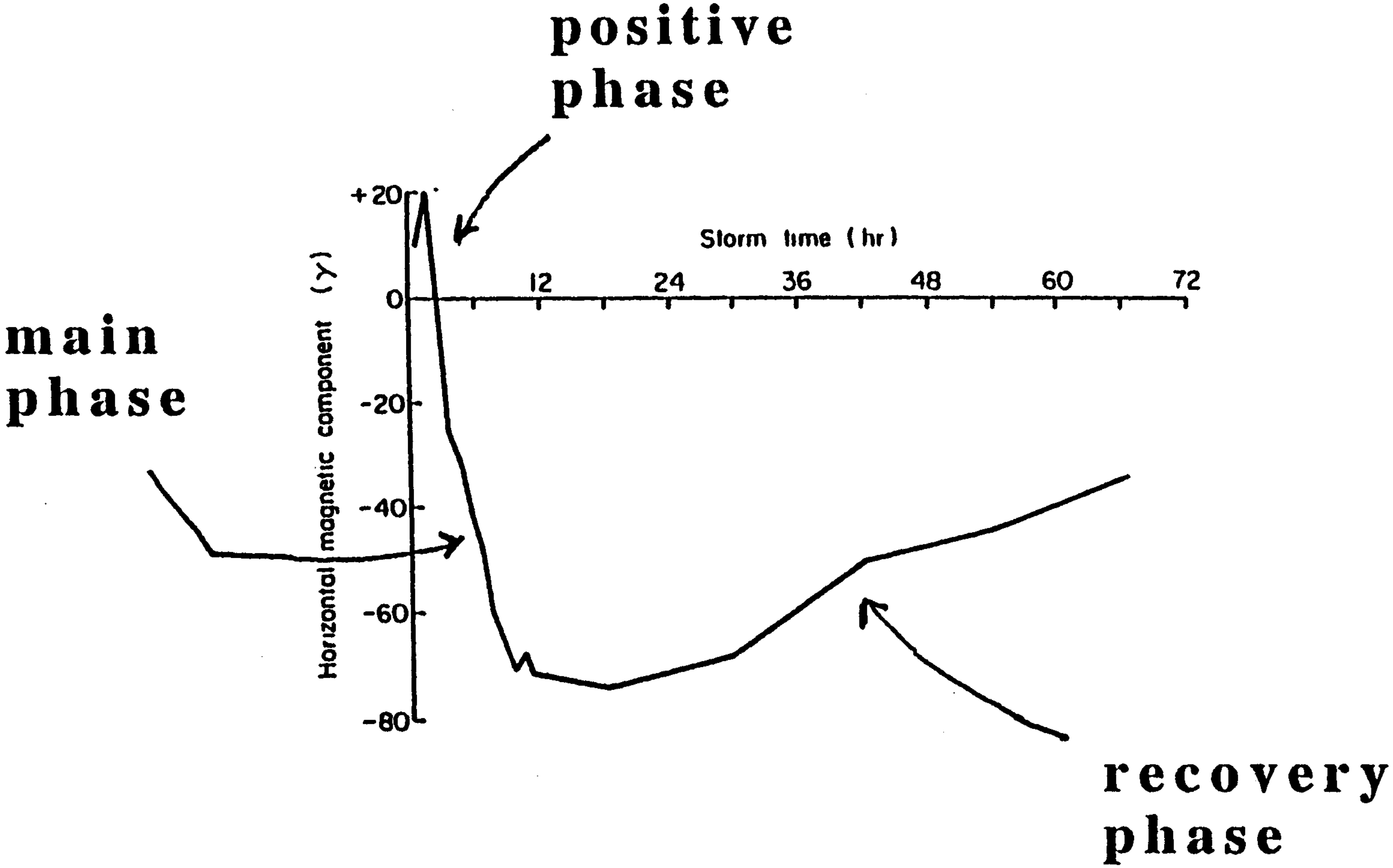
The K_p index is the quasi-logarithmic equivalent of the a_p index. The conversion is as follows:

Value of the ap index for a given value of Kp.

If Kp=	0o	0+	1−	1o	1+	2−	2o	2+	3−	3o	3+	4−	4o	4+
then ap=	0	2	3	4	5	6	7	9	12	15	18	22	27	32
If Kp=	5−	5o	5+	6−	6o	6+	7−	7o	7+	8−	8o	8+	9−	9o
then ap=	39	49	56	67	80	94	111	132	154	179	207	236	300	400

The daily A_p index, for a given day, is defined as

$$A_p = \sum_{n=1}^{8} a_p$$



Average magnetic Dst variations of the horizontal component of the magnetic field for great storms at stations around 42° latitude.

E-REGION DYNAMO THEORY

$$\nabla \times \vec{H} = \frac{4\pi}{c}\vec{J} \quad \Rightarrow \quad \nabla \cdot \vec{J} = 0 \qquad\qquad \vec{J} = Ne\left(\vec{V}_i - \vec{V}_e\right)$$

$$0 = -\frac{1}{N_i}\underline{\nabla} N_i k T_i \; + \; m_i \vec{g} \; + \; e\left(\vec{E} \; + \; \vec{V}_i \times \vec{B}\right) \; - \; m_i \upsilon_{in}\left(\vec{V}_i - \vec{U}\right)$$

Pressure Gradient — **Gravity** — **Electric Field** — **Lorentz** — **Collisions with Neutrals**

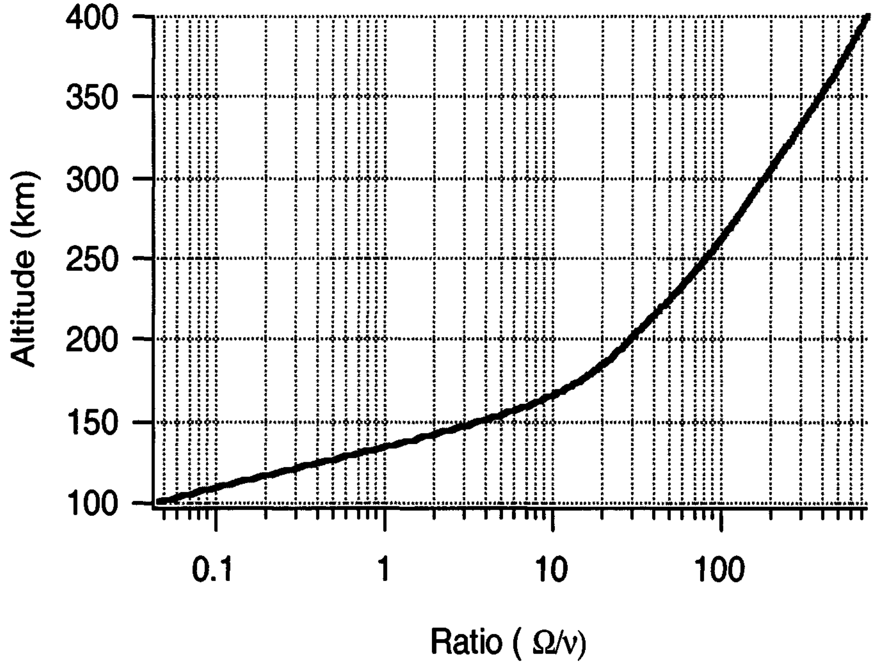
$$0 = \underbrace{-\frac{1}{N_i m_i \upsilon_{in}}\underline{\nabla} N_i k T_i \; + \; \frac{1}{\upsilon_{in}}\vec{g} \; + \; \frac{e}{m_i \upsilon_{in}}\vec{E} \; + \; \vec{U}}_{\textbf{Velocity Independent Forces } \vec{F}} \; + \; \frac{\Omega_i}{\upsilon_{in}}\vec{V}_i \times \hat{b} \; - \; \vec{V}_i$$

$$\Omega = \frac{eB}{m}, \quad \hat{b} = \frac{\vec{B}}{B}$$

Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

$$V_i^{\|} = F_i^{\|}$$

$$\vec{V}_i^{\perp} = \frac{1}{1+\left(\Omega/\upsilon_{in}\right)^2}\left[\vec{F} + \Omega/\upsilon_{in}\,\vec{F}\times\hat{b}\right]$$



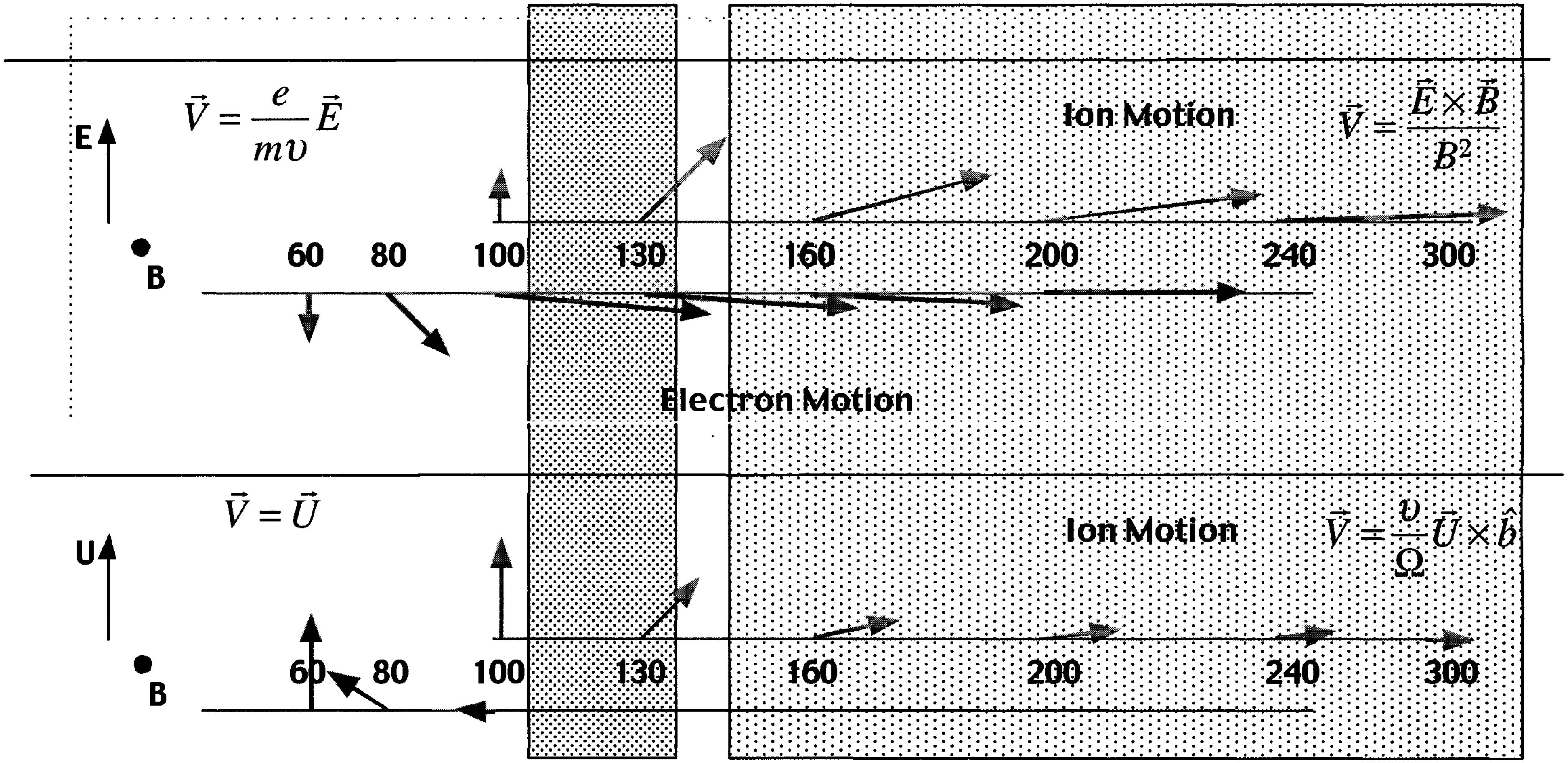
Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

Charged particle Motions Perpendicular to B

With Neutral Collisions

$\Omega / \upsilon_{in} < 1 \quad \vec{V}_i^{\perp} \approx \vec{F}^{\perp}$

$\Omega / \upsilon_{in} > 1 \quad \vec{V}_i^{\perp} \approx \upsilon_{in} / \Omega \, \vec{F} \times \hat{b}$



Electron Motion

Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

Hall, Pedersen and Longitudinal Conductivities and Currents

$$\vec{J} = Ne\left(\vec{V}_i - \vec{V}_e\right) = \sigma \cdot \vec{E}$$

Hall: σ_H or σ_1 $\perp\vec{B}, \perp\vec{E}$

Pedersen: σ_P or σ_2 $\perp\vec{B}, \parallel\vec{E}$

Direct: σ_0 $\parallel\vec{B}, \parallel\vec{E}$

$$J_1 = \sigma_1 E_1 + \sigma_2 E_2$$
$$J_2 = -\sigma_2 E_1 + \sigma_1 E_2$$
$$J_0 = \sigma_0 E_0$$

$$\sigma_1 = Ne^2\left[\frac{1}{m_e}\frac{\upsilon_e}{\left(\upsilon_e^2 + \Omega_e^2\right)} + \frac{1}{m_i}\frac{\upsilon_i}{\left(\upsilon_i^2 + \Omega_i^2\right)}\right]$$

$$\approx \frac{Ne^2}{m_i}\frac{\upsilon_i}{\left(\upsilon_i^2 + \Omega_i^2\right)}$$

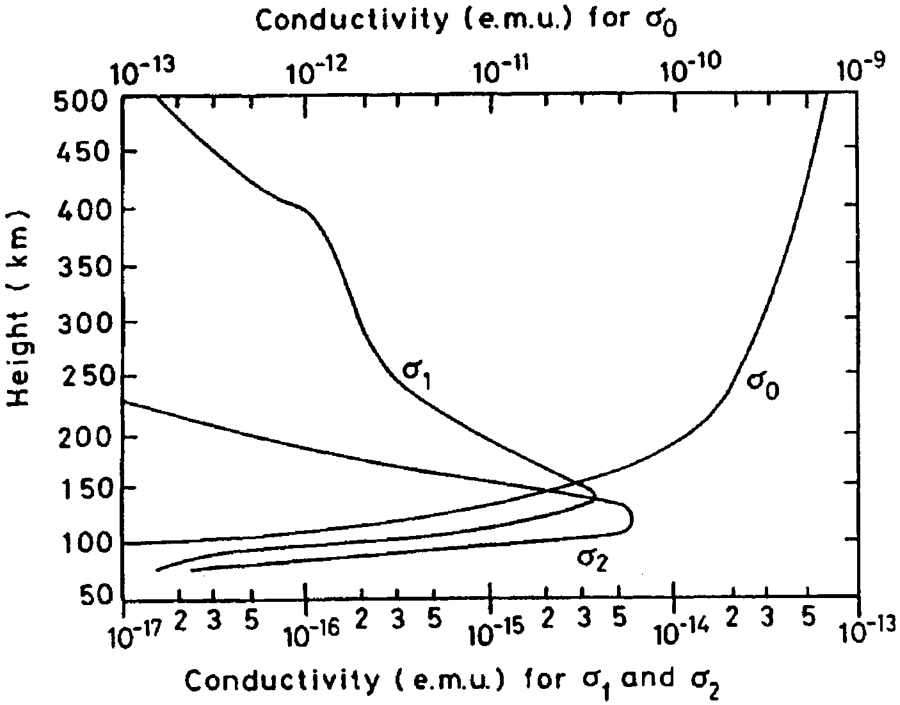
$$\sigma_0 = \frac{Ne^2}{m_e\upsilon_e} + \frac{Ne^2}{m_i\upsilon_i} \approx \frac{Ne^2}{m_e\upsilon_e}$$

$$\sigma_2 = Ne^2\left[\frac{1}{m_i}\frac{\Omega_i}{\left(\upsilon_i^2 + \Omega_i^2\right)} - \frac{1}{m_e}\frac{\Omega_e}{\left(\upsilon_e^2 + \Omega_e^2\right)}\right]$$

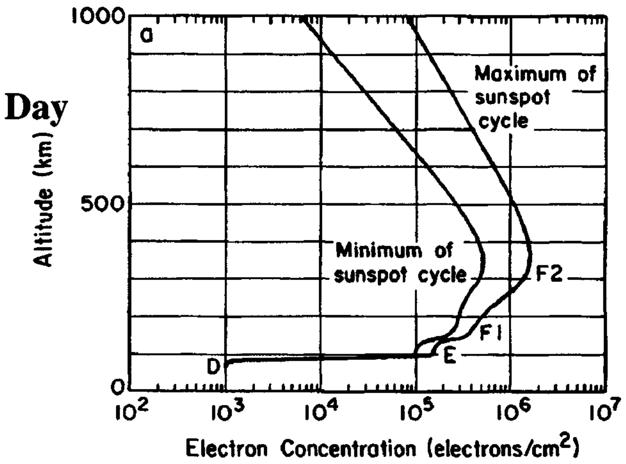
*** Ion and Electron Terms Cancel at high altitudes**

Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

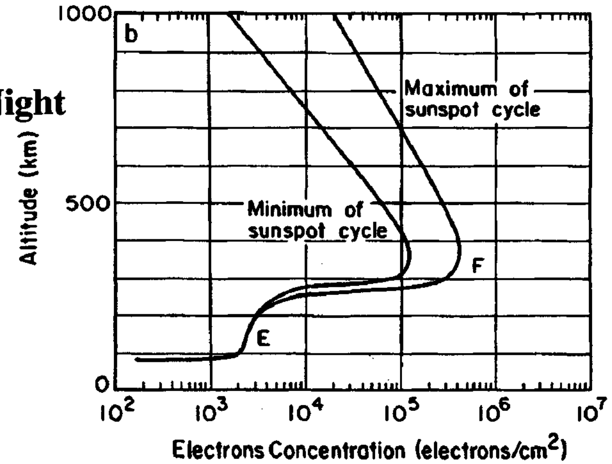
Ion Concentration and Conductivity



Day



Night

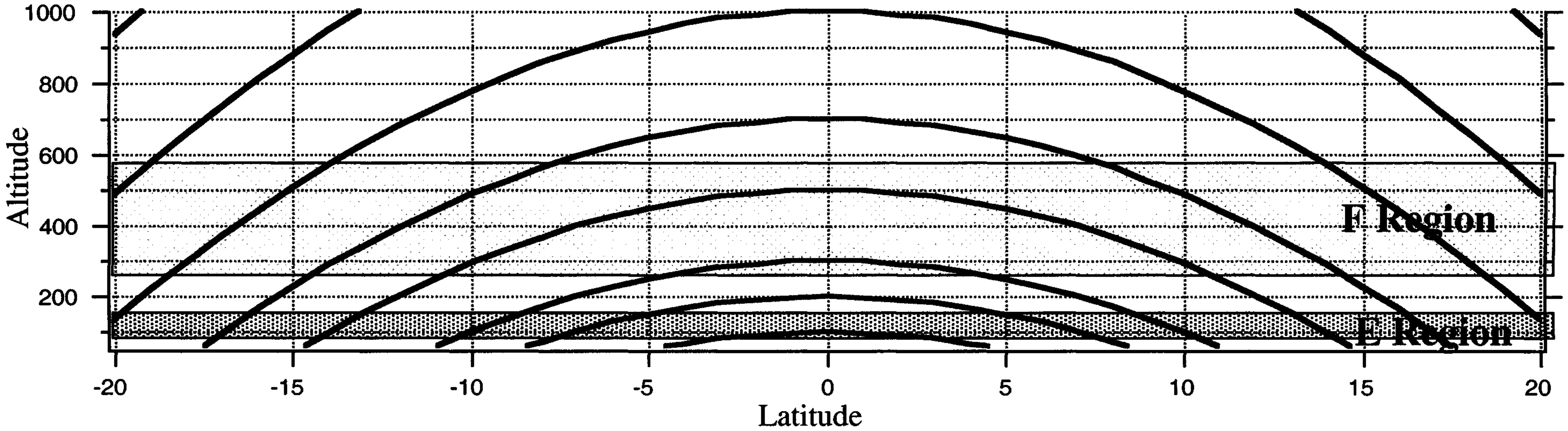


- **Hall conductivity in a layer near 120 km**
  Essentially removed at night
- **Pedersen conductivity distributed in two regions**
  E-region much greater than F-region during the daytime
  F region much greater than E region at night.
- **Direct conductivity much greater than transverse conductivities everywhere above 90 km.**
  For spatial scales larger than 10 km magnetic field lines are almost electric equipotentials even though field-aligned currents flow.

Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

Electric field depends on flux-tube integrated drivers and conductivity.

$$\vec{J} = Ne\left(\vec{V}_i - \vec{V}_e\right) \qquad \nabla \bullet \mathrm{J} = 0 \qquad \frac{\partial \vec{J}^{\perp}}{\partial \perp} + \frac{\partial \vec{J}^{\parallel}}{\partial \parallel} = 0$$

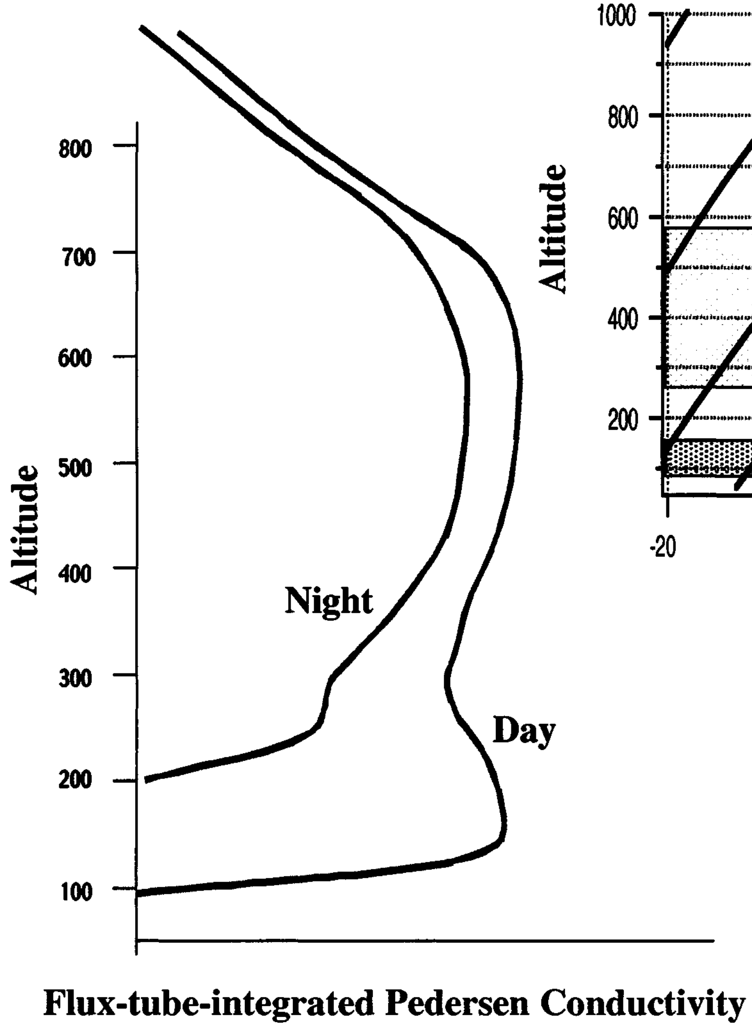


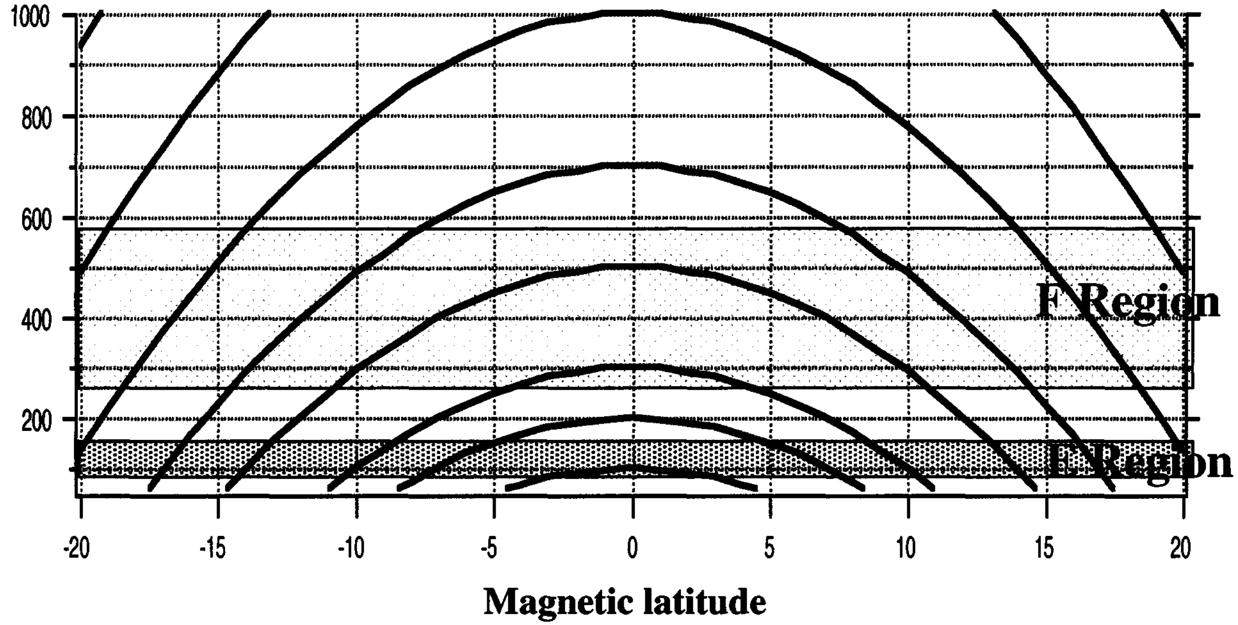
We assume that no current flows out of the bottom of the region and that above some altitude say 1000 km, the perpendicular current is negligible.

$$\int_{\text{other end}}^{\text{one end}} \frac{\partial \vec{J}^{\perp}}{\partial \perp} ds = 0 \qquad \int_{\text{other end}}^{\text{one end}} \left.\frac{\partial \vec{J}^{\perp}}{\partial \perp}\right|_{driver} ds + \int_{\text{other end}}^{\text{one end}} \left.\frac{\partial \overline{\sigma} \vec{E}^{\perp}}{\partial \perp}\right| ds = 0$$

Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

Electric field depends on flux-tube integrated drivers and conductivity.





Polarization charges produced in one region within latitudes/apex heights of 10-15 deg/250-800 km can be removed by high conductivity in another.

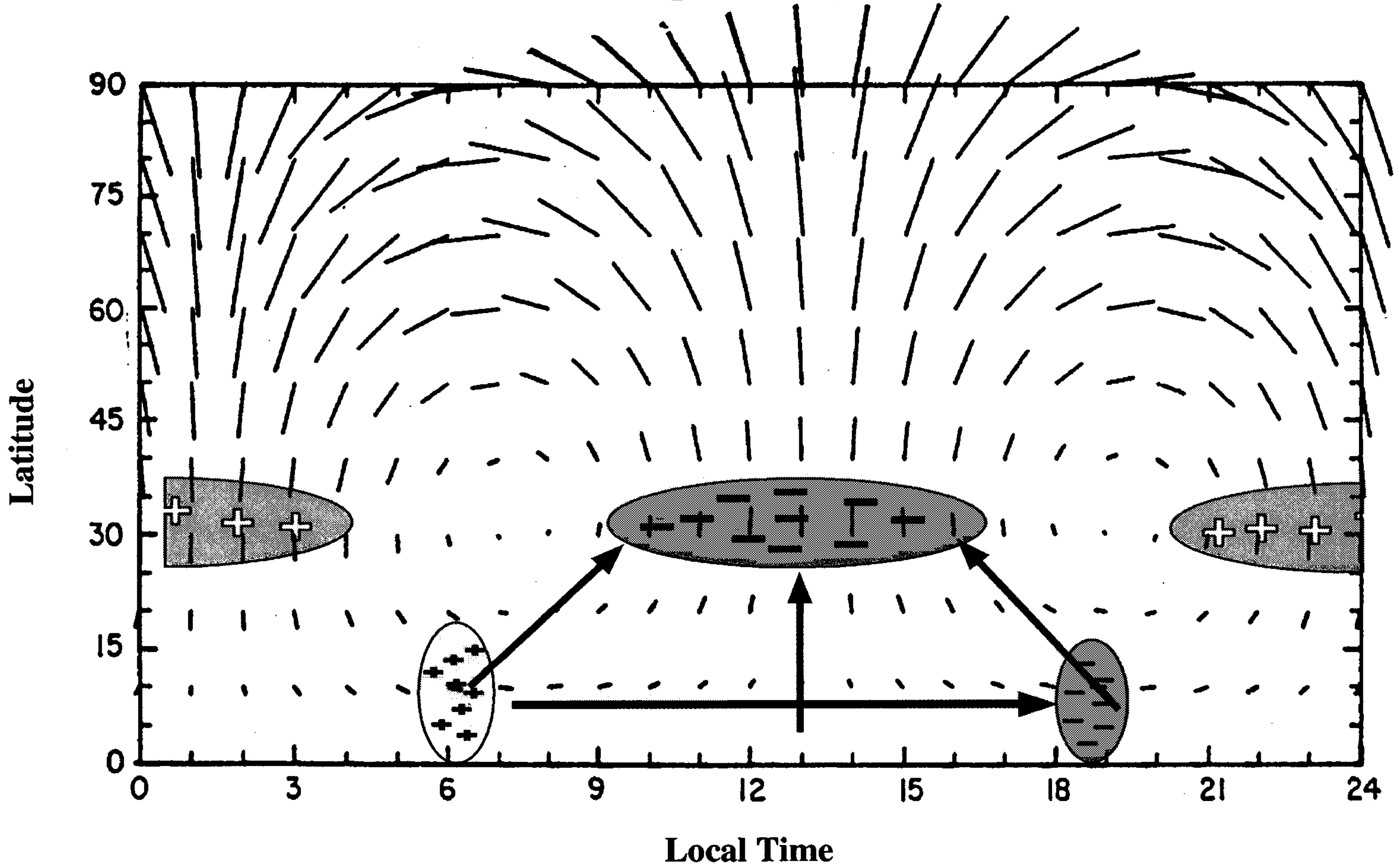
Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

E-Region Dynamo

Neutral circulation transports ions away from local noon at mid latitudes.

UxB drift of ions produces charge accumulation at the terminators.

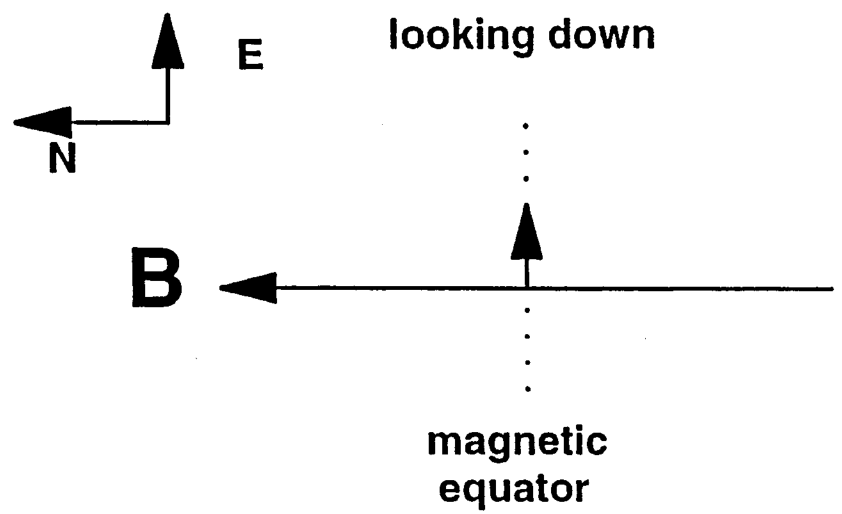
Zonal and Meridional electric fields map to F-region.



Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

An interesting phenomenon, the <u>equatorial electrojet</u>, occurs at the magnetic equator:

E_λ, eastward electric field induced by dynamo action



$$J_\lambda = \sigma_1 E_\lambda + \sigma_2 E_z$$
$$J_z = -\sigma_2 E_\lambda + \sigma_1 E_z$$

(1) Charge separation due to $-\sigma_2 E_\lambda$ (downward Hall current, upward e-)

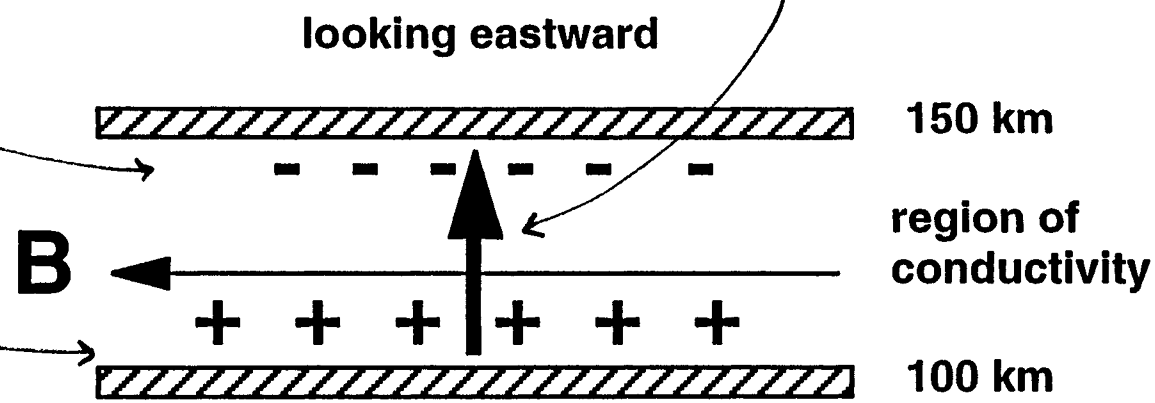
(2) E_z compensating vertical field to maintain $J_z = 0$. (no vertical currents due to insulating boundaries).

$$J_\lambda = \overset{(1)}{\sigma_1 E_\lambda} + \overset{(3)}{\sigma_2 E_z}$$

$$J_z = \overset{(1)}{-\sigma_2 E_\lambda} + \overset{(2)}{\sigma_1 E_z}$$

(1) Charge separation due to $-\sigma_2 E_\lambda$ (downward Hall current, upward e-)

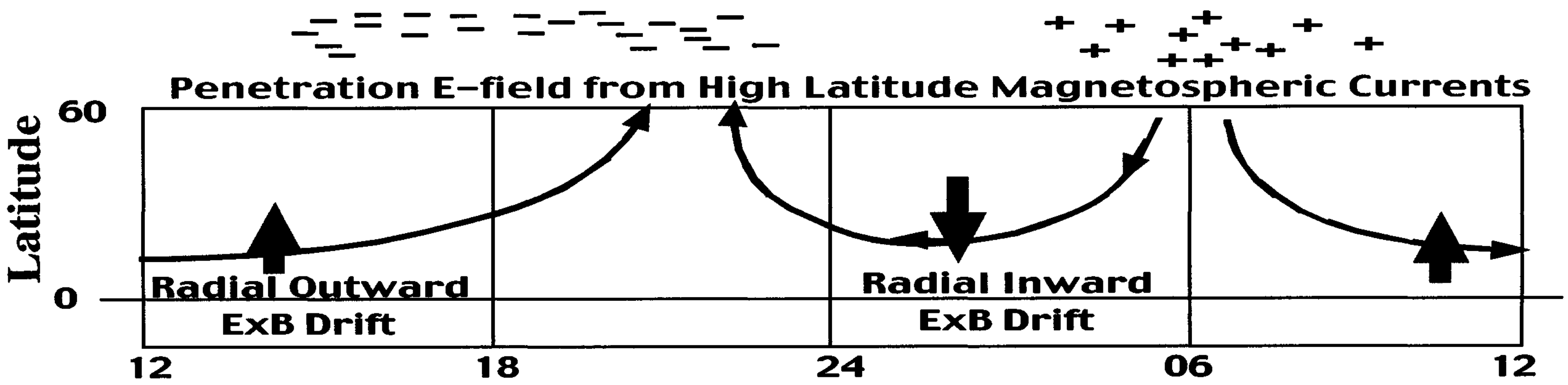
(2) E_z compensating vertical field to maintain J_z = 0. (no vertical currents due to insulating boundaries).



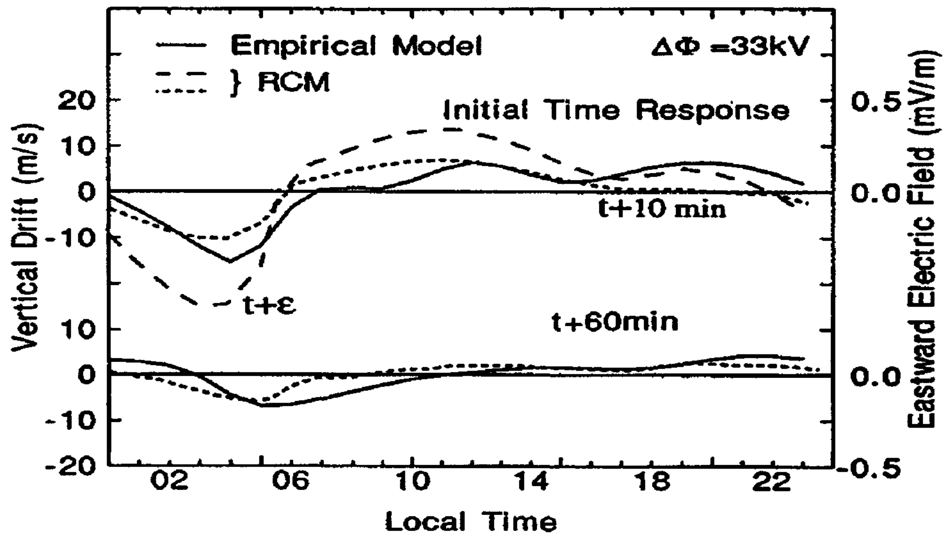
(3) $\sigma_2 E_z$ is an intense eastward current (the <u>equatorial electrojet</u>) driven by the vertical polarization field.

External Influences -- Electric Field Penetration/Current Leakage From High to Low latitudes

The high latitude potential distribution can penetrate to lower latitudes when the cross-polar cap potential and internal magnetospheric potentials are not matched.



Detailed local time distribution depends upon high latitude current distribution and middle and low latitude conductivity distribution.

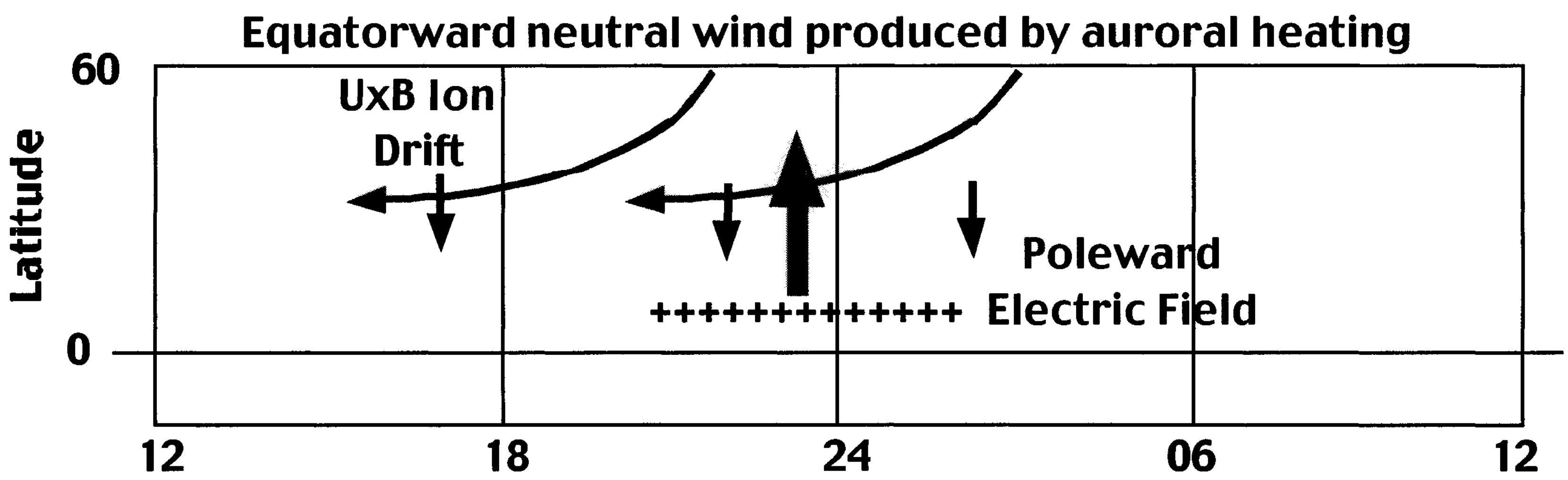


Fejer and Scherliess, Geophys. Res. Lett., *22*, 851, 1985

Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001

External Influences -- "Disturbance Dynamo"

- Auroral heating from energetic particles and Joule heating produces equatorward wind.
- Conservation of momentum produces westward and equatorward neutral winds.
- UxB ion current maximizes at middle latitudes.
- Poleward polarization field produces westward ExB drift in the F region
- Local time distribution depends on details of auroral heating.



Courtesy Dr. Rod Heelis, UTDallas, CEDAR 2001