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Ionoshpere-Thermosphere Basics: Magnetosphere-Ionosphere Coupling

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Ionosphere-Thermosphere Basics V

Magnetosphere Ionosphere Coupling

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Ionosphere-Thermosphere Basics V

Magnetosphere Ionosphere Coupling

1. Field-Aligned Currents in the Ionosphere
   - Connection to drivers in the magnetosphere and magnetosheath
   - Dependencies on the IMF Bz and By
   - Current carriers and auroral precipitation

2. Ionospheric conductivity at high latitudes
   - contributions from euv and precipitation

3. Electric field distributions at high latitudes
   - Dependencies on IMF
   - Plasma transport paths with addition of corotation
   - ` Effects of offset magnetic pole

4. Plasma transport
   - tongue of ionization
   - mid-latitude trough
   - polar hole

5. Joule Heating
   - Effects on Chemistry
   - Feedback on neutral-ion coupling

Ionosphere-Thermosphere Basics V

Magnetosphere Ionosphere Coupling

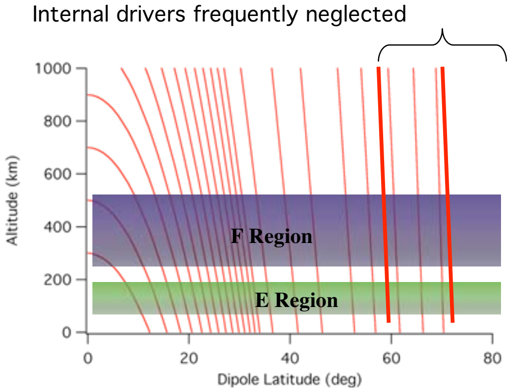
6. Momentum exchange
   Neutral-ion collision time constants as a function of altitude

7. Effects of magnetic activity
   Shielding fields below the auroral zone
   Expansion of the convection pattern to middle latitudes
   Disturbance dynamo effects

The Dynamo Equation at High Latitudes

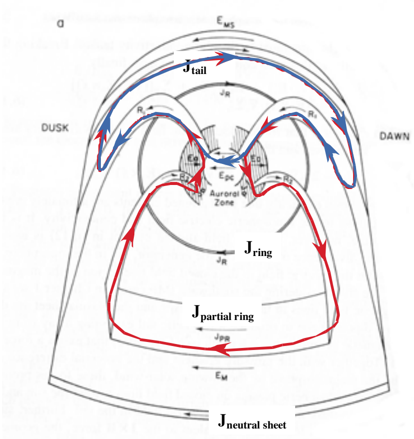
$$\int_{other\ end}^{one\ end} \nabla_\perp \vec{J}^{\perp}\Big|_{driver} ds - \int_{other\ end}^{one\ end} \nabla_\perp\left(\tilde{\sigma}_\perp \nabla_\perp \Phi\right) ds = \vec{J}^{\| one\ end} - \vec{J}^{\| other\ end}$$

Magnetic field terminates at the lower boundary and upper boundary.
No field-aligned current can flow at lower boundary but is continuous with magnetosphere current at upper boundary
No contribution to the integrals above 1000 km
Internal drivers frequently neglected



$$\int_{bottom}^{top} \nabla_\perp\left(\tilde{\sigma}_\perp \nabla_\perp \Phi\right) ds = -\vec{J}^{\| top}$$

Field-Aligned Current Systems



All currents must flow in closed loops.

$$\nabla \cdot \vec{J} = 0 \Rightarrow \nabla_{\perp} \cdot J_{\perp} + \nabla_{\parallel} \cdot \vec{J}_{\parallel}$$

A divergence in the horizontal current must be accompanied by a change in the field-aligned currents.

If this condition cannot be satisfied by the original driver then a polarization electric field is established to modify the current.

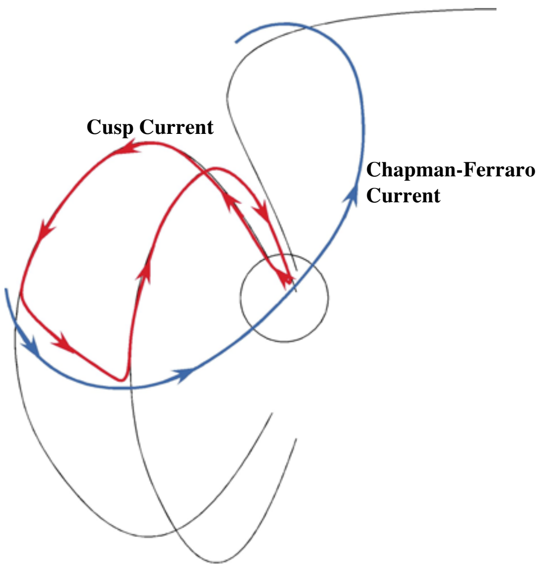
In the magnetosphere the requirement for closed loop flows demands that field-aligned currents flow into and out of the ionosphere.

The partial ring current gradients come from the gradient and curvature drifts only.

Field-Aligned currents originate

1) near the equatorial edge of the magnetopause	**the Region-1 currents**
2) in the plasma sheet where the ring current has a divergence	**the Region-2 currents**
3) at the magnetopause at high latitudes on the dayside	**the cusp currents**

Field-Aligned Current Systems



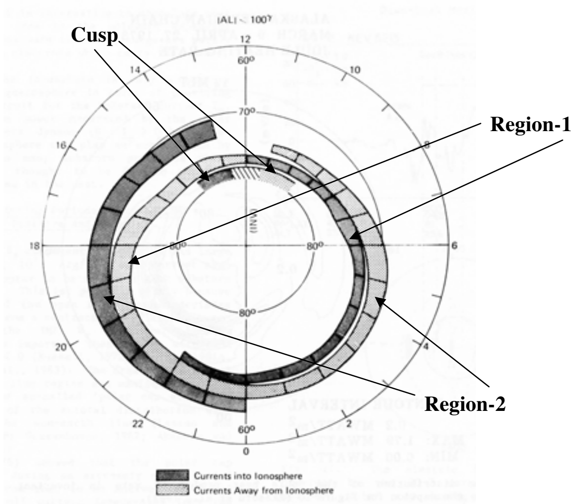
The cusp current is the signature of the dayside interaction of the interplanetary magnetic field with the geomagnetic field.

A variation in the configuration of the cusp currents is strongly dependent on IMF By.

The closure path for the cusp current is still an active research topic.

Field-Aligned Current Systems - Southward IMF

On the dayside, the distinction between the Region-1 and the cusp currents is not as clear as shown in the figure. Rather the cusp currents blend continuously with the Region-1 currents. These currents are the signature of the dayside interaction of the geomagnetic field with the interplanetary magnetic field where open magnetic flux is created from closed magnetic flux



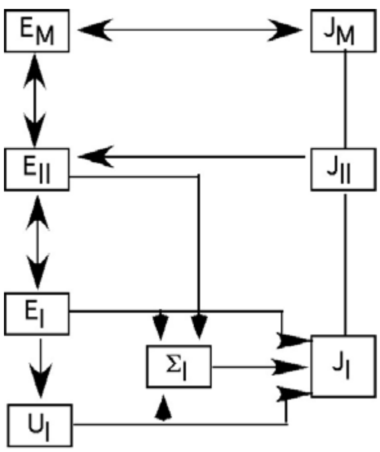
Magnetosphere Ionosphere Coupling

Particle Energy

Field-Aligned currents carried by electrons.

Upward currents …precipitating electrons from the magnetosphere

Downward currents … upward flowing ionospheric electrons.



Electric fields and perpendicular currents in the magnetosphere demand a field-aligned current to the ionosphere

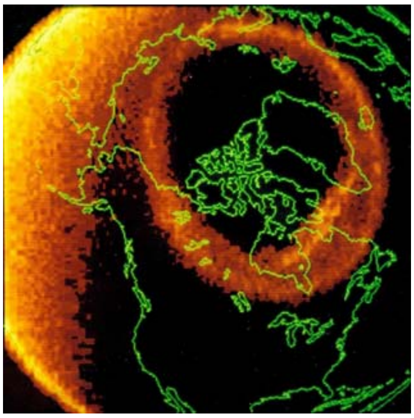
For field-aligned currents carried by magnetospheric electrons the needed flux may require acceleration along B.

The electric field in the ionosphere is modified by field-aligned potential drops .

The conductivity in the ionosphere is modified by precipitating electrons and ions .

The resulting perpendicular current must require the same field-aligned current .

Field-Aligned Current Carriers
The Aurora



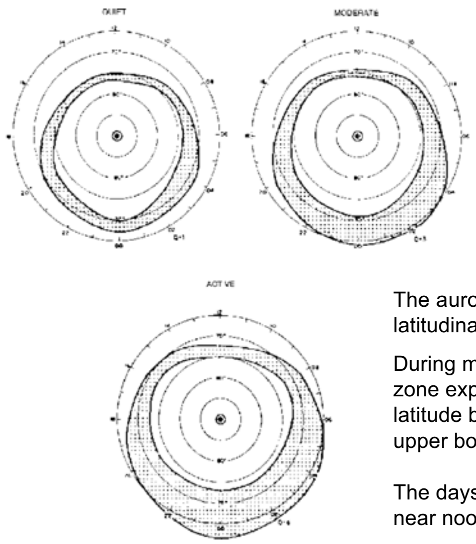
The currents in the magnetosphere must be balanced by field-aligned currents that flow into and out of the ionosphere and must be consistent with the horizontal current in that region.

The field-aligned currents are carried by electrons since their mobility is so high compared to ions. Thus the field-aligned current must itself be consistent with the precipitating electron flux.

The aurora is the most visible manifestation of the precipitating electron flux

The visible emissions that we see come from excited states of the neutral gases in the atmosphere. The neutral gases are excited by impact with energetic electrons and ions.

The Aurora



The auroral region changes location and latitudinal width depending on magnetic activity.

During magnetically active times the auroral zone expands across midnight so that the lower latitude boundary is lower than usual and the upper boundary is higher than usual.

The dayside region expands to lower latitudes near noon.

The Aurora

There are three persistent regions of precipitation.

1) The dayside cusp.
   In this region the precipitating electrons appear at highest latitudes near local noon. The electrons have energies near 100 eV that penetrate the atmosphere above 250 km. They produce red emissions but the intensity is usually sub-visual.

2) The discrete aurora
   This is a latitudinally narrow region at the poleward edge of the auroral zone. The precipitating electrons occur in spatially narrow bands. They are temporally variable and electrons show evidence for acceleration parallel to the magnetic field to energies in excess of 1 keV.
   The region of the discrete aurora corresponds roughly to the region occupied by the region-1 currents and maps to the outer edge of the plasma sheet (near the magnetopause and the boundary layer)

3) The diffuse aurora
   This is a latitudinally wider region that fills the region between the equatorward limit of the auroral zone and the discrete aurora. The precipitating electrons have high energies between 1 and 10 keV but are not preferentially accelerated along the magnetic field.
   The region of the diffuse aurora corresponds roughly to the region occupied by the region-2 currents and maps to the inner region of the magnetosphere corresponding to the plasma sheet.

High Latitude Ionospheric Conductivity

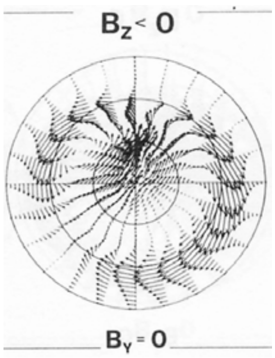
Precipitating energetic electrons produce additional ionization and thus the ionospheric conductivity is enhanced in a regions of electron precipitation.

In particular there is a band of enhanced conductivity in the auroral E region.

Given the distribution of field-aligned currents and ionospheric conductivity it is straightforward to derive the distribution of electric potential and horizontal current at high latitudes.

The auroral zone currents are in the direction -ExB and are referred to as the *auroral electrojets*.

Electric Potential

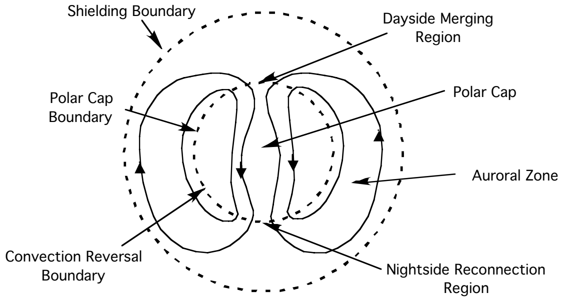


Horizontal Current

High Latitude Ionospheric Convection Pattern

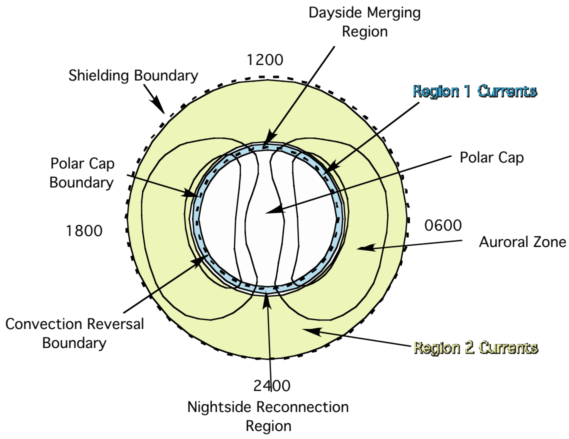
A two cell convection pattern describes a region at highest latitudes where the flow is antisunward.
This region is approximately circular and is called **“the polar cap”.**
In an open magnetosphere at high latitudes the Earth’s magnetic field is connected to the interplanetary magnetic field across the magnetosheath. The polar cap is a region of open magnetic field lines.

At lower latitudes between the **polar cap boundary** and the **shielding boundary** the charged particles participate in a return flow from the the nightside to the dayside. This region is approximately an annulus and is called **“the auroral zone”.** The auroral zone is a region of closed magnetic field lines.
The polar cap boundary also known as the **convection reversal boundary.**
The plasma flows from sunward to antisunward across the polar cap boundary in **the dayside merging region.**
The plasma flows from antisunward to sunward across the polar cap boundary in **the nightside reconnection region**

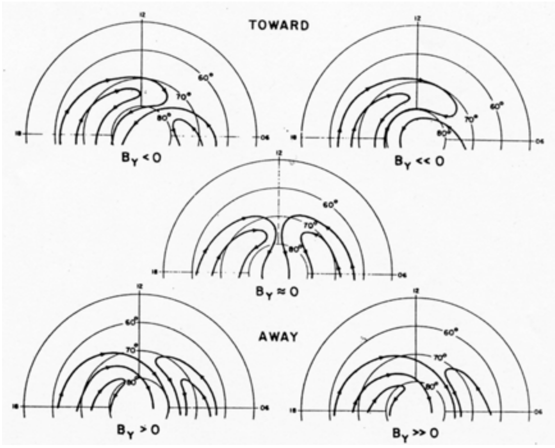


High Latitude Ionospheric Convection Pattern

The polar cap boundary is “region” where the **Region 1 field aligned currents** enter and leave the ionosphere.
The maximum electric potential is on the dawnside near 0600 local time
The minimum electric potential is on the duskside near 1800 local time
The auroral zone is a region where the **Region 2 field aligned currents** enter and leave the ionosphere. They occupy the region between the polar cap boundary and the shielding boundary.

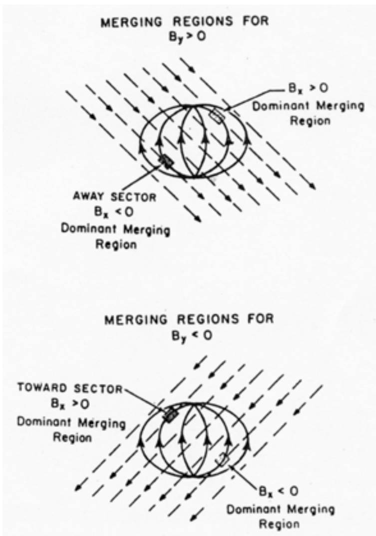


High Latitude Ionospheric Convection Pattern



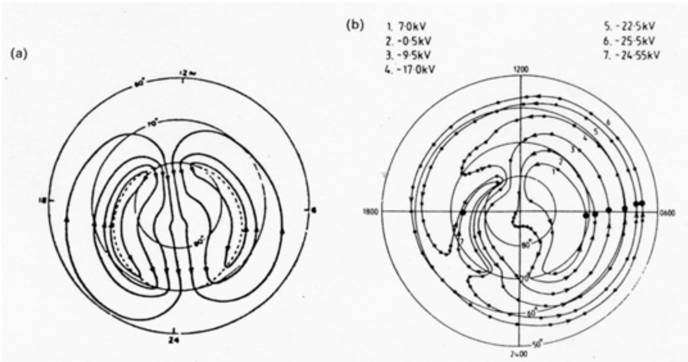
The orientation of ionospheric convection pattern on the dayside changes in accord with changes in the y-component of the IMF.

High Latitude Ionospheric Convection Pattern



An explanation for the By dependence in the convection pattern can be obtained by considering where the most efficient connection between the Earth's magnetic field and the interplanetary magnetic field is made.

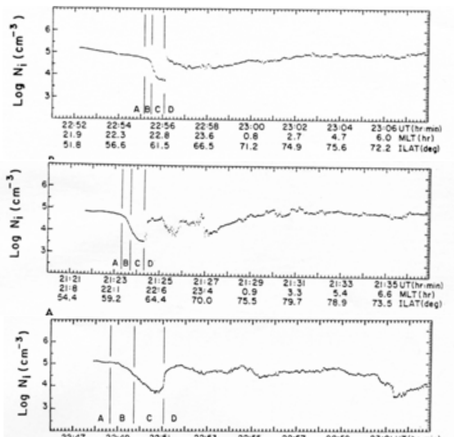
High Latitude Ionospheric Plasma Transport



At latitudes above the shielding boundary the charged particles in the ionosphere mimic the circulation of particles in the magnetosphere and the magnetosheath in a well-understood two-cell convection pattern. In addition to moving under the action of the electric field from the magnetosphere and magnetosheath, the ionospheric charged particles also corotate.

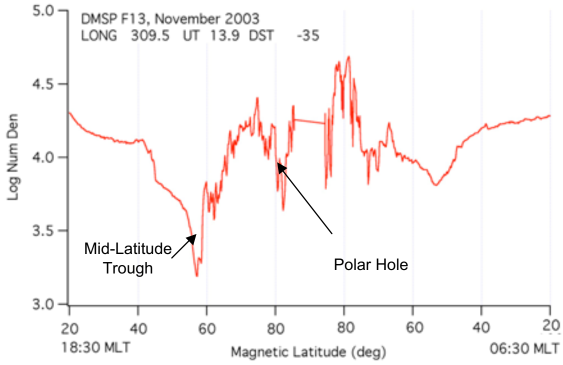
The motion of the charged particles is described by expressing the electric field in terms of the electric potential. $\nabla \times \mathbf{E} = 0 \Rightarrow \mathbf{E} = -\nabla\Phi$
Then the electric equipotentials represent the flow of the plasma
On the left panel dots are placed every hour for a convecting plasma packet

Plasma Transport at High Latitudes
The Mid-latitude Trough



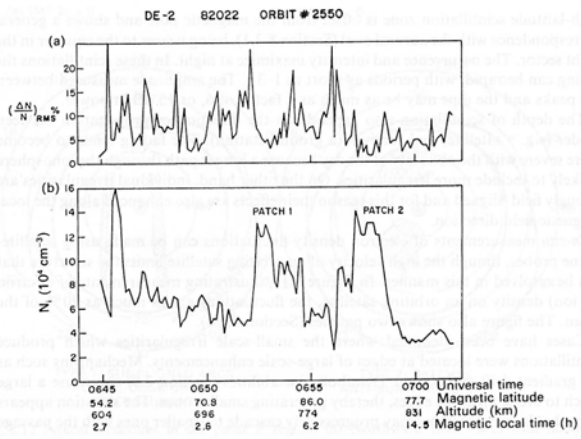
In the evening sector, at the equatorward edge of the auroral zone the corotation flow opposes the westward auroral flows and the plasma stagnates in darkness. A reduction in the ion number density is marked by a steep poleward gradient resulting from production by auroral electrons.

Plasma Transport at High Latitudes
The Polar Hole



In addition to stagnation at the equatorward edge of the auroral zone the plasma may also stagnate in the nighttime winter polar cap. This stagnation produces a local number density minimum called the “polar hole”

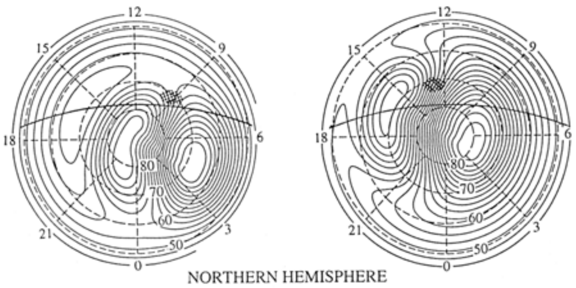
Plasma Transport at High Latitudes
Plasma Patches



During periods of southward IMF patches of enhanced plasma density are frequently observed to convect antisunward across the polar cap.
The large horizontal density gradients associated with patches can be unstable to the gradient drift instability. Which edges will be unstable ?

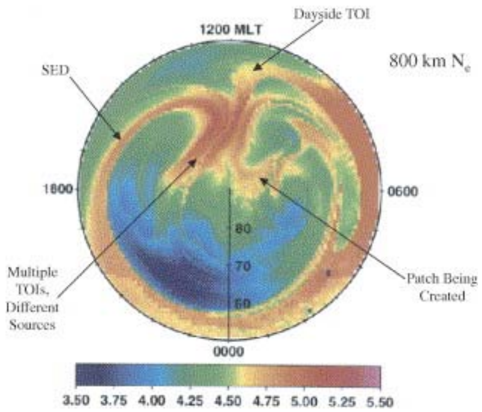
Convection and Corotation

Be aware that the convection pattern is referenced to the magnetic field.
The polar cap is a circular region about 15 degrees in radius with center displaced about 5 degrees toward midnight with respect to the magnetic pole.
The magnetic pole is displaced from the geographic pole.
Tilted dipole locations are 79N 71W and 79S 109E
IGRF pole locations are 79N 105W and 65S 139E
The main consequences of these offsets are that stagnation regions do not always occur in darkness. Thus **the density minimum features not only depend on local time but also on universal time**



a) 12:00 UT b) 18:00 UT

High Latitude Tongue of Ionization



The UT wobble of the magnetic pole about the geographic pole means that at any given location the plasma arrives from different places depending on the UT.

In addition the convection pattern will expand and contract as conditions in the solar wind change.

Plasma features such as the so-called

"tongue of ionization"

"plasma patches"

are produced by these UT variations

Ion-Neutral Coupling
Momentum Balance

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

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

$$0 = -\frac{1}{\rho}\underline{\nabla} p_n \;+\; \vec{g} \;-\; \upsilon_{ni}\left(\vec{U} - \vec{V}_i\right) - 2\vec{\Omega}\times\vec{U} - \left(\vec{U}\cdot\underline{\nabla}\right)\vec{U} \;+\; F_n$$

Pressure Gradient | **Gravity** | **Collisions with Neutrals** | **Coriolis Force** | **Advection** | **Other Forces**

The exchange of momentum between the ion and neutral gases acts to encourage a quasi-steady state wherein the ion and neutral velocities are coupled.

In the F-region ionosphere this relationship is such that the neutral gas mimics the ion gas motion with velocities that are usually smaller.

The time constants are very different so that the neutral gas motion takes longer to adjust to a new condition (1 hour in F-region) than the ions (few minutes)

Ion-Neutral Coupling
Energy Balance

Collisions between the ion and neutral gas also exchange energy leading to and equilibrium temperature for the ions that depends upon the square of the relative velocity between the ion and neutral gases.
Heating due to collisions between the ion and neutral gases is called
Joule Heating

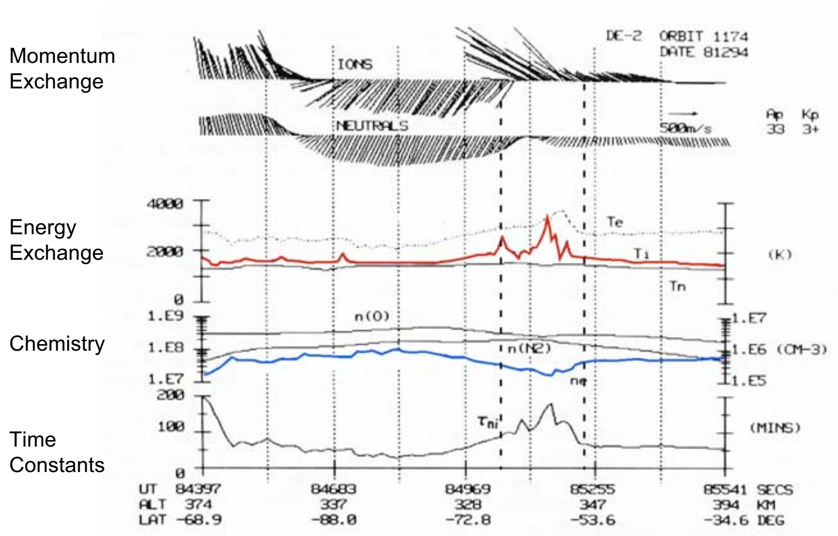
$$T_i = T_n\left(\frac{\upsilon_{in}}{\upsilon_{in}+\upsilon_{ie}}\right) + T_e\left(\frac{2\upsilon_{ie}}{\upsilon_{in}+\upsilon_{ie}}\right) + \left(\frac{2\upsilon_{in} m_n}{3k\left(\upsilon_{in}+\upsilon_{ie}\right)}\right)\left(\vec{V}_i - \vec{U}\right)^2$$

Remember that the temperature influences the scale height of the ionosphere so and the field-aligned plasma motions.

Temperature also influences the major ion chemistry because the reaction rates are temperature dependent.

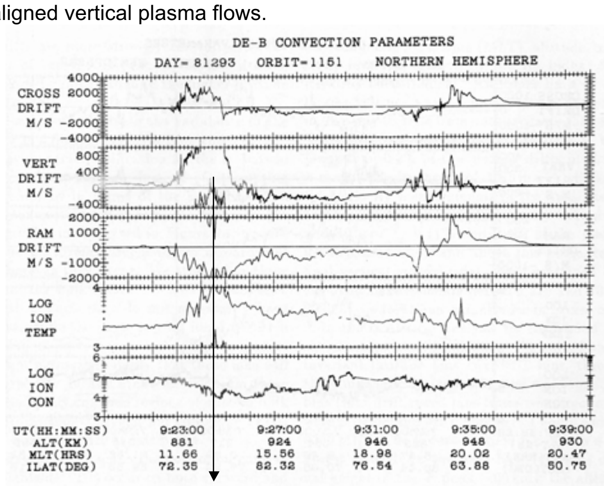
$$O^+ + N_2 \Rightarrow NO^+ + N \quad k = 2.73\times10^{-12} - 1.15\times10^{-12}\left(T/300\right) + 1.4\times10^{-13}\left(T/300\right)^2$$

Energy Momentum and Chemistry



Joule Heating and Plasma Expansion

Enhancements in the ion temperature will change the plasma pressure resulting in field-aligned vertical plasma flows.



Peak Ion Fluxes order $10^9 \, cm^{-2} s^{-1}$

More on Magnetosphere Ionosphere Coupling

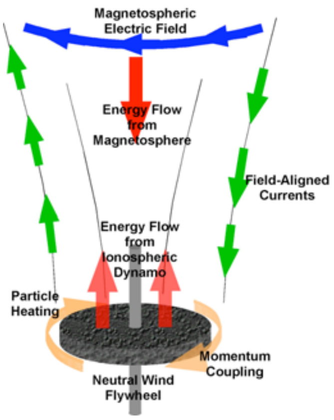
Cusp Currents, Region-1, Currents, Region-2 Currents, Substorm Current Wedge
- All these current systems flow through the ionosphere.
- The divergence in the E + UxB current must be consistent with the field-aligned current

The ExB drift motion of the plasma is coupled to the neutral gas through collisions.
The changing ionosphere and thermosphere change the conductivity.

Precipitating particles carrying field-aligned currents change the ionosphere number density.

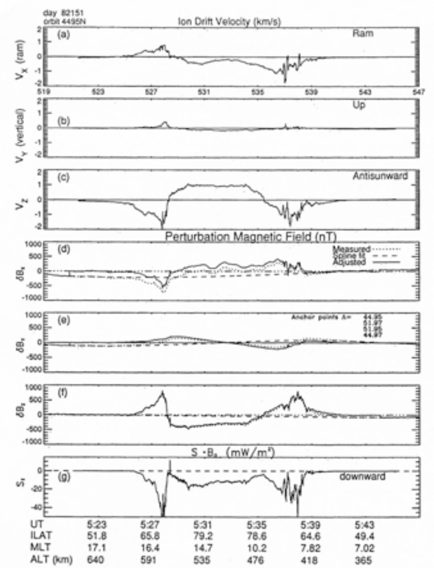
Thus the E+UxB current is modified.

The ionosphere-thermosphere is an active element in the circuit. It is both a source and a sink in the circuit.



Magnetosphere Ionosphere Coupling

Poynting Vector



$$\frac{\partial W}{\partial T} = \nabla \cdot \left(\frac{1}{\mu_0} \vec{E} \times \vec{B} \right) + \vec{J} \cdot \vec{E}$$

Field-Aligned Currents provide channels for the Poynting flux

Field-Aligned Poynting Flux is equal to the energy dissipation rate in the volume below the measurement.

At high latitudes the Poynting flux is predominantly downward in the auroral zones and polar cap.

There is a net electromagnetic energy flux to the ionosphere from the magnetosphere.

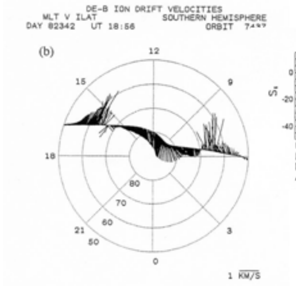
This energy flux is modulate by the ionosphere, reducing the magnitude of the flux when the neutral wind conforms to the ion drift.

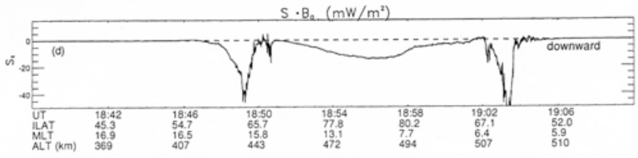
Momentum Exchange rate $\propto \left(\vec{V} - \vec{U}\right)$

Joule Heating rate $\propto \left(\vec{V} - \vec{U}\right)^2$

Magnetosphere Ionosphere Coupling

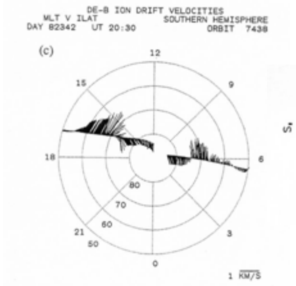
Poynting Vector

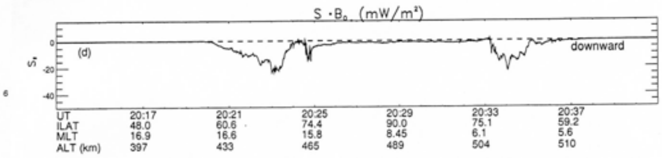




Large electric fields in the polar cap force the neutral gas antisunward requiring a downward Poynting flux

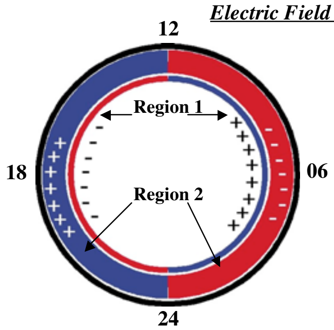
Reduced electric fields in the following pass show antisunward ion drift in the absence of a downward Poynting flux. Why ?





Current Drivers in the Ionosphere

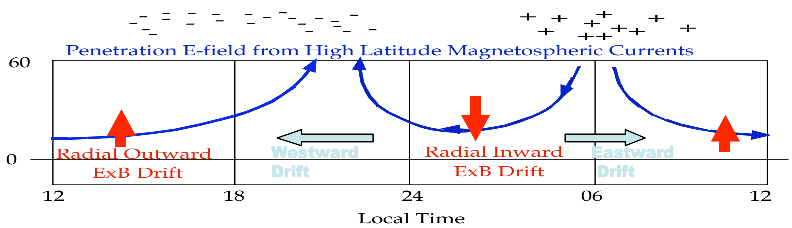
Electric Field Currents at Middle Latitudes



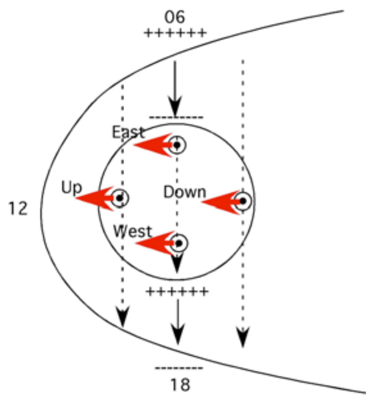
Potentials applied to the high latitude region by Region 1 and Region 2 field-aligned currents.

Imbalances in these currents can produce a potential variation around the equatorward edge of the region-2 currents (the equatorward edges of the auroral zone)

The resulting electric field and horizontal current at middle latitudes depends on the ionospheric conductivity.

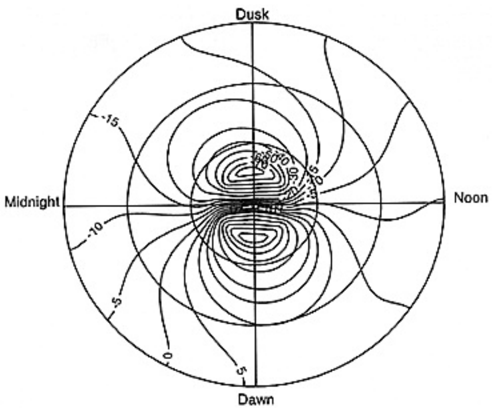


Connections to Lower Latitudes



This simple schematic illustrates how an increase in the potential across the magnetosphere produces drifts that are down at night and up during the day and west and east at dusk and dawn respectively.

Connections to Lower Latitudes



Rothwell and Jasperse, JGR, 2006.

In the absence of R-2 currents of sufficient intensity, the electrostatic potential applied at the magnetopause will produce electric fields that penetrate all the way to the equator.

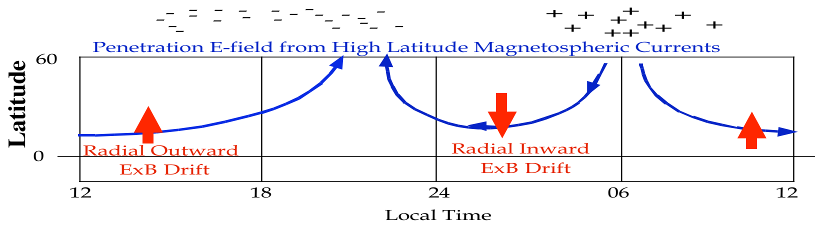
The potential distribution depends upon the ionospheric conductivity.
ExB drifts from this source are both

Up/down (vertical) and

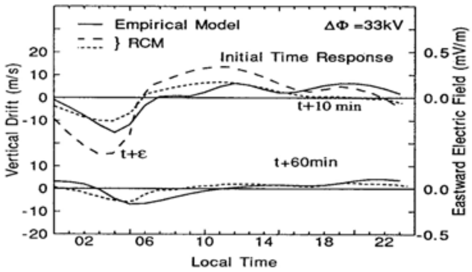
East/west (zonal)

Zonal Plasma Drifts at the Equator

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

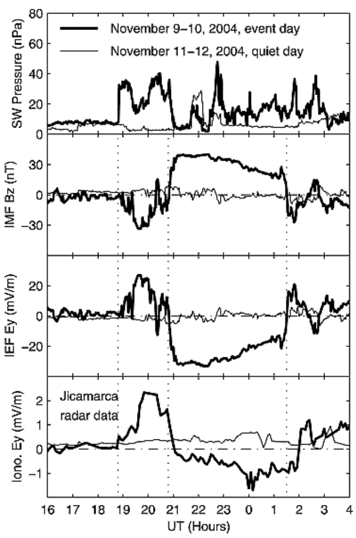


Detailed local time distribution depends upon high latitude current distribution and middle and low latitude conductivity distribution.



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

Penetration Electric Fields at Lower Latitudes

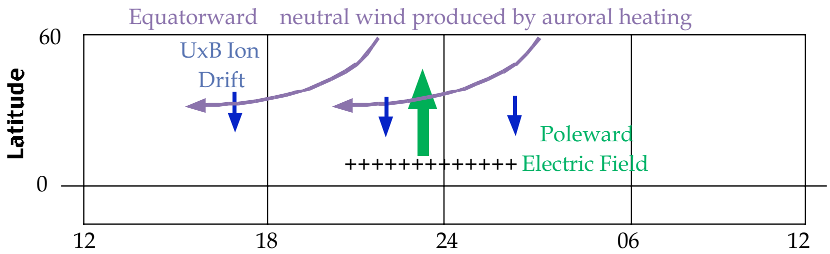


The potential across the magnetosphere is driven predominantly by the interplanetary electric field.

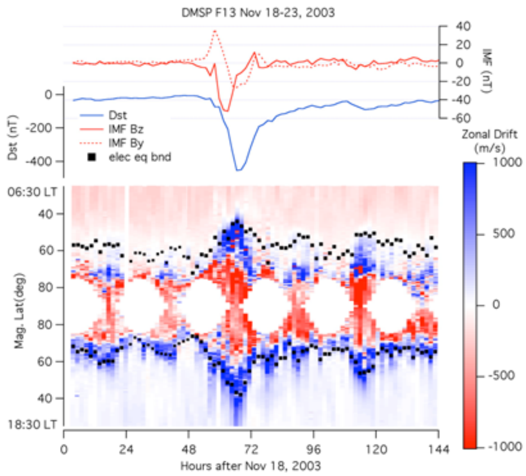
The vertical ion drift at the equator is well correlated with changes in this parameter.

External Influences

- 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.



Influences at Low and Middle Latitudes



Increases in magnetic activity produce increases not only the magnitude of the convection velocity but also the spatial extent over which it is applied.
Here the red to blue transition marks the convection reversal boundary and the black dots mark the equatorward edge of the auroral zone.
Boththese boundaries move to lower latitudes during period of magnetic activity.

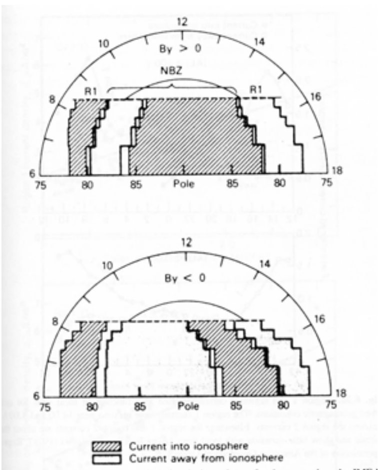
Influences at Low and Middle Latitudes

Middle and High Latitudes should not be defined just by a number.

Remember that 45 degrees magnetic latitude can be
- Inside the plasmasphere at middle latitudes or
- Inside the auroral zone

Electric fields at middle and low latitudes may be influenced by
- the wind dynamo
- the high latitude potential distribution.

Ionosphere-Magnetosphere Coupling
Northward IMF



Observations of field-aligned currents during times of northward IMF show that a broad regions of field-aligned current occupy what is normally the polar cap.

Remember that this region is normally void of field-aligned currents when the IMF is southward.

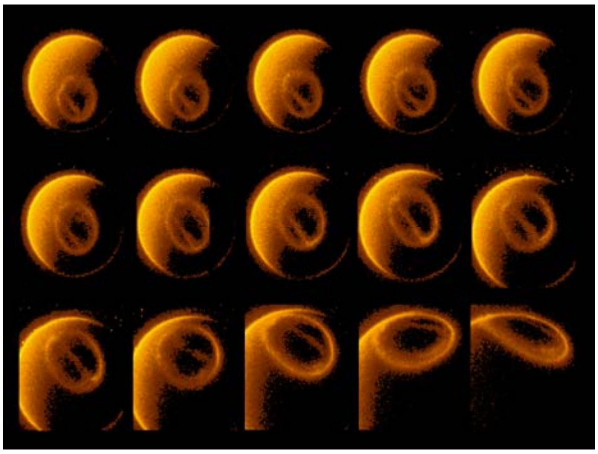
This field-aligned current system is called the northward Bz current system (NBZ)

The spatial extent of the NBZ currents are dependent on the y-component of the IMF in a manner consistent with the observed electric field.

The region 1 currents are still observed but are usually less intense than those observed during times of southward IMF.

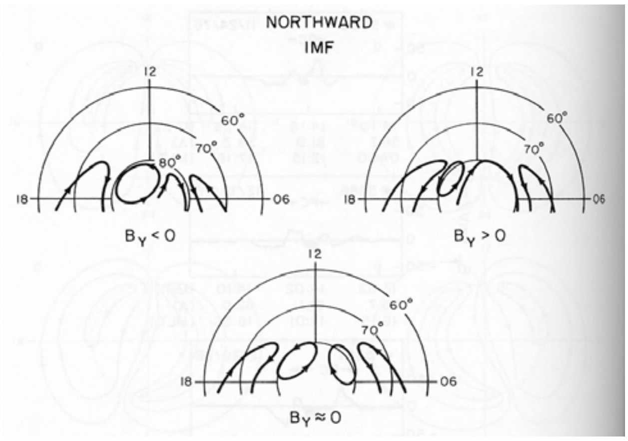
Ionosphere-Magnetosphere Coupling
Northward IMF

During times of northward IMF the auroral oval is always smaller than the oval seen during times of southward IMF.
Many times as the polar cap fills in a bright edge forms and is sometimes isolated.

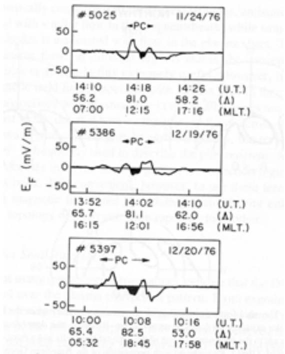


Ionosphere-Magnetosphere Coupling
Northward IMF

Evidence for connection to the IMF comes from a dependence of the convection pattern on the y-component of the IMF



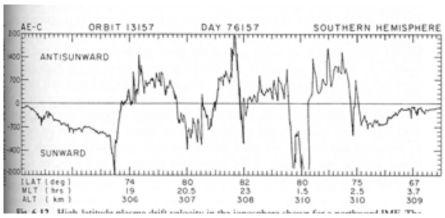
Ionosphere-Magnetosphere Coupling
Northward IMF



The electric field observed in the ionosphere and magnetosphere frequently shows a four-cell pattern.

A two-cell pattern at highest latitudes is attributed to connection with interplanetary magnetic field.

The outer two-cell convection pattern has the same sense as we would expect for southward IMF and we assume it is driven by "viscous interaction"



However there are many occasions when the electric field shows many reversals and appears to be very disorganized.