Magnetosphere Ionosphere Coupling: Ionospheric Perspective

Outline

- **Current Systems Connecting the Ionosphere and Magnetosphere**
- **Electromagnetic Energy Inputs**
  Joule Heating, Momentum Coupling, Poynting Vector
- **Particle Energy Inputs**
  Electrical Coupling, Particle Acceleration
- **Ionospheric Plasma Outflow**
- **Alfven Waves**

Magnetosphere Ionosphere Coupling

Magnetospheric Currents Perpendicular to B produced plasma pressure gradients and magnetic field stresses.

Ionospheric Currents Perpendicular to B produced by electric fields and neutral winds.

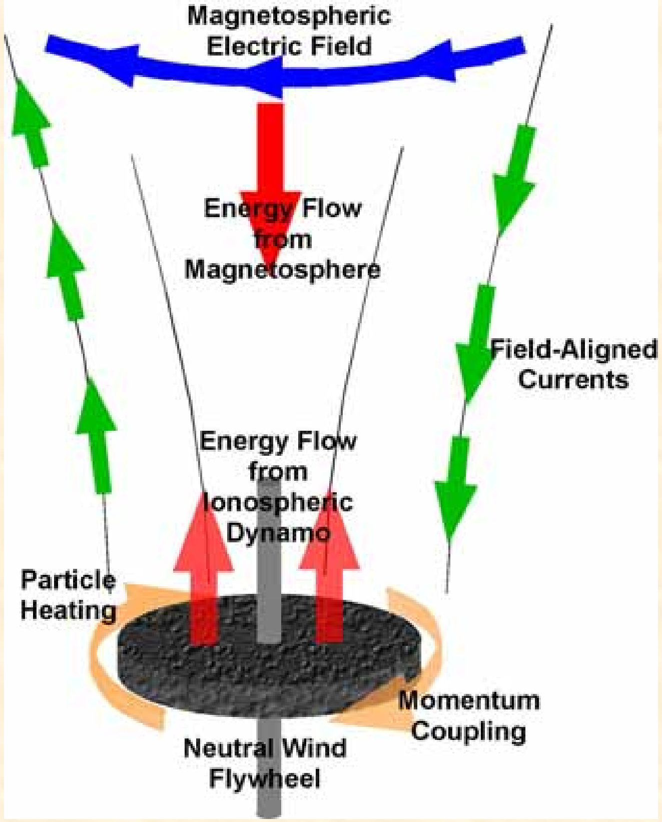
Gradients in these currents require field aligned currents that must be consistent.

Electric fields produced in the magnetosphere and ionosphere will modify the horizontal currents (directly in the ionosphere ; indirectly in the magnetosphere) to make the field-aligned currents consistent.

In the ionosphere 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 ionospheric conductivity. 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.



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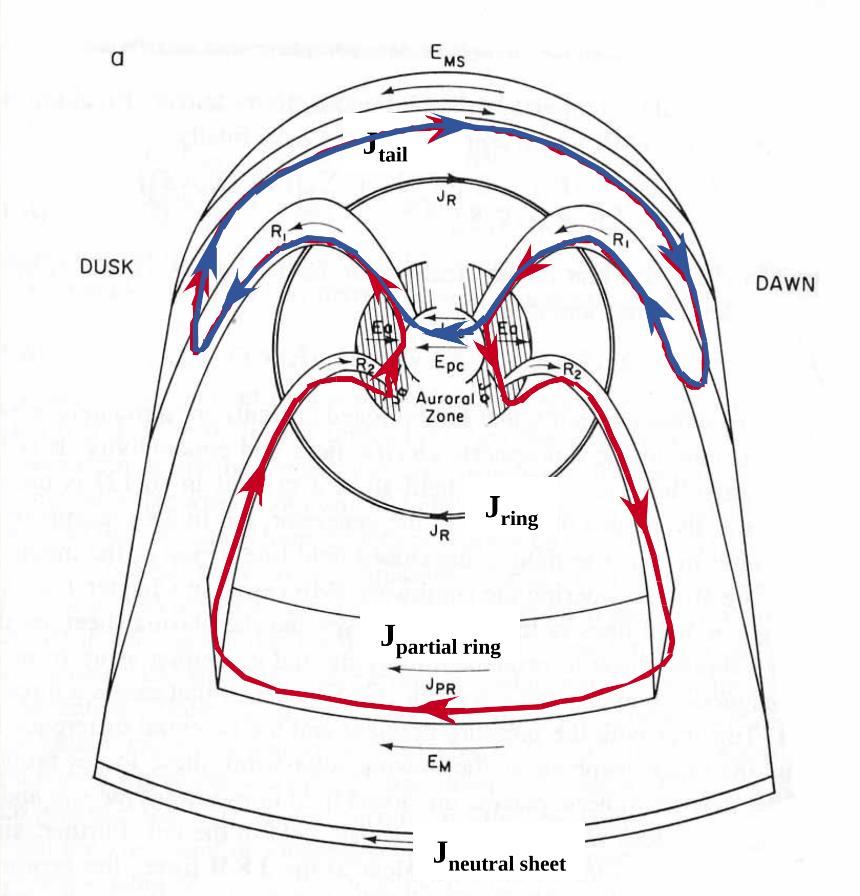

All currents must flow in closed loops.

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

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.

Note that 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**

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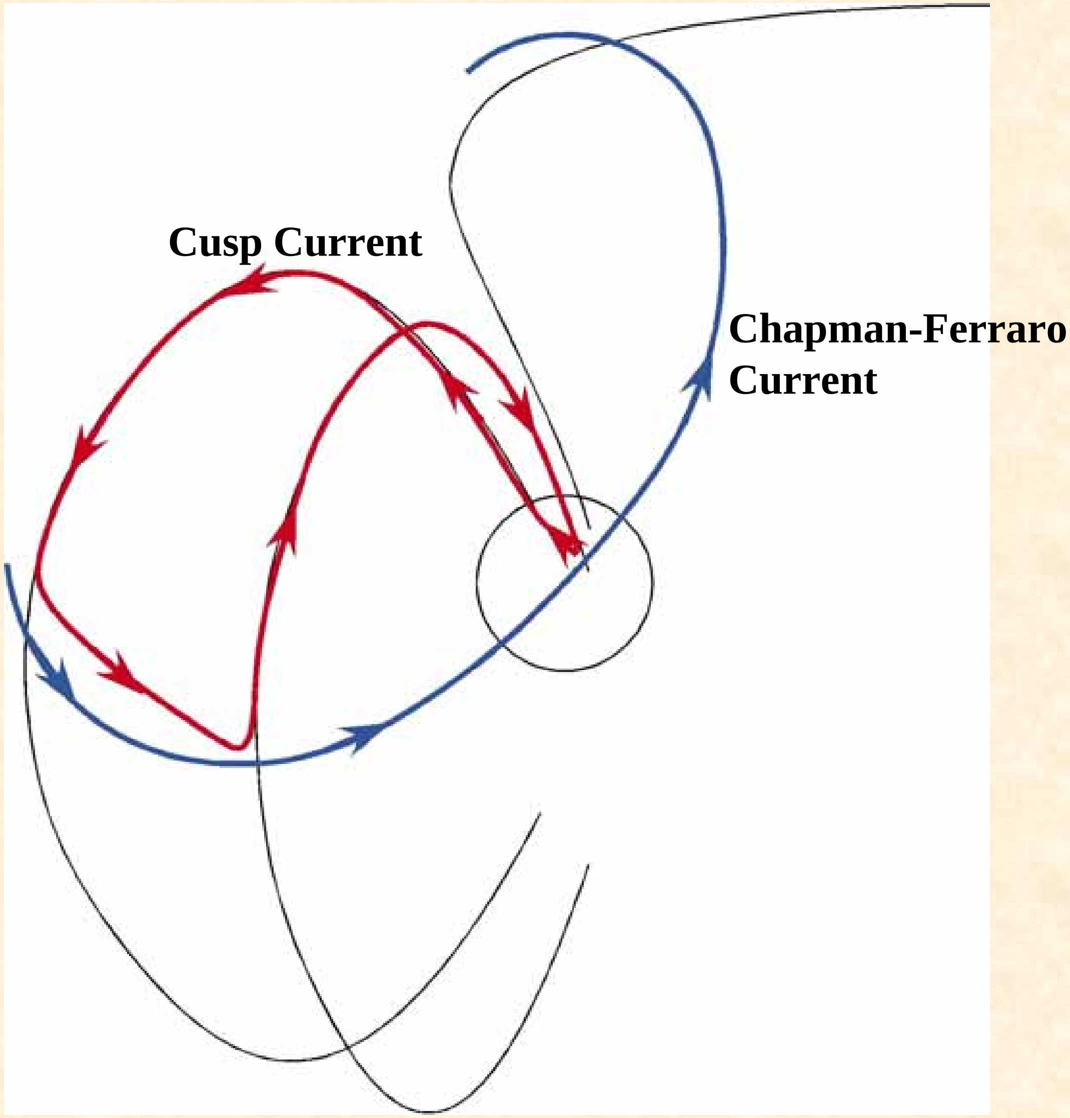

The cusp current is the signature of the dayside interaction of the interplanetary magnetic field with the geomagnetic field.

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

Cusp currents decrease the C-F current at high latitudes where it is replaced by the Region 1 current closure path .

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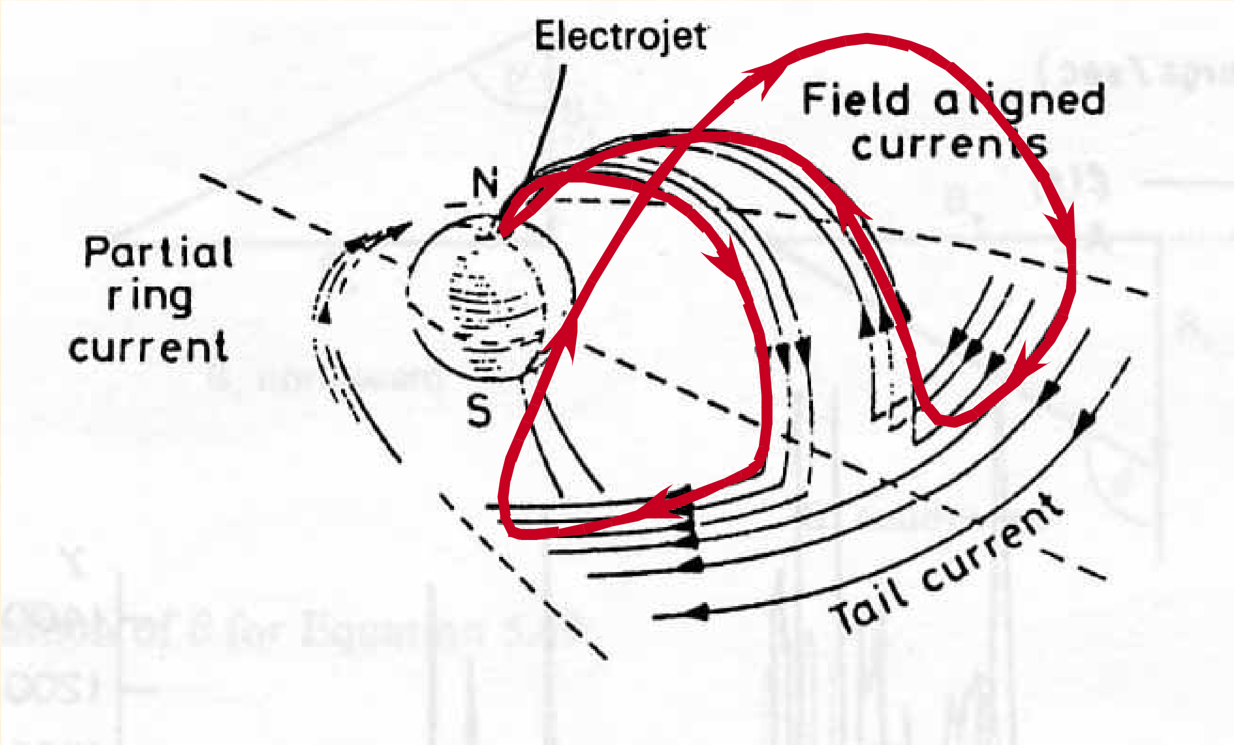

Plasma sheet thinning can be associated with a diversion of some portion of the neutral sheet current through the ionosphere.

This process occurs during a "magnetic substorm" and the current loop is called a "*substorm current wedge*"

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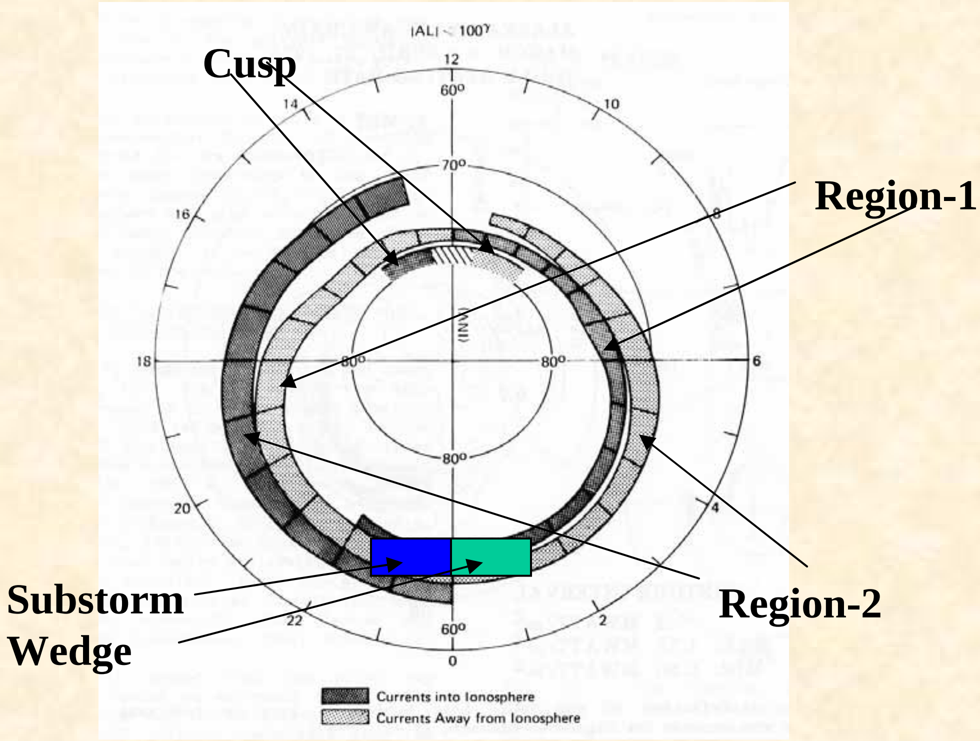

The ionosphere is itself a generator of current and the same principles apply.
Thus the ionosphere may demand that field-aligned currents flow
into and out of the magnetosphere.
Agreement is reached between the ionosphere and magnetosphere by modifications of the electric field and conductivity in the regions.
Temporal changes are transmitted between the regions by Alfven waves.

Steady state is represented by field-aligned currents.

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Steady State Features

Energy Input to Ionosphere has two flavors "electromagnetic" and "particle"
"electromagnetic" exceeds "particle" by about a factor of 4 (Lu et al, JGR,10,19643,1995)

These energy inputs are frequently anticorrelated in space.

Electromagnetic energy **is divided into**

Joule Heating Rate (>90%) and Momentum Exchange Rate(<10%)

$$\vec{J}_{\perp} \cdot \vec{E}' \qquad + \qquad \vec{U} \cdot \left(\vec{J} \times \vec{B} \right)$$

Joule Heating - Raises the neutral and plasma temperatures
Changes the neutral pressure and associated wind field
Raises the plasma scale height and imparts outward field-aligned plasma flows.

Momentum Exchange - Imparts ion motion to neutral gas.
Pressure gradients, Coriolis Forces and Viscosity also modify the neutral wind.

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Joule Heating Rate -

$$\vec{J}_\perp \cdot \vec{E}' = \underbrace{\sigma_p E^2}_{\text{E-field effect}} + \underbrace{\sigma_p \left|\vec{U} \times \vec{B}\right|^2 - 2\sigma_p \vec{U} \cdot \left(\vec{E} \times \vec{B}\right)}_{\text{Neutral Wind effect}}$$

Is modified by changes in

Pedersen Conductivity

Electric Field mapped from the magnetosphere

Neutral wind modified by ion drag and gas heating.

Modifications in the Joule Heating Rate must result in a change in the field-aligned current and/or the electric field.

Momentum Exchange Rate -

$$\vec{U} \cdot \left(\vec{J} \times \vec{B}\right)$$

Is modified by changes in

Pedersen Conductivity

Electric Field mapped from the magnetosphere

Neutral wind modified by ion drag and gas heating.

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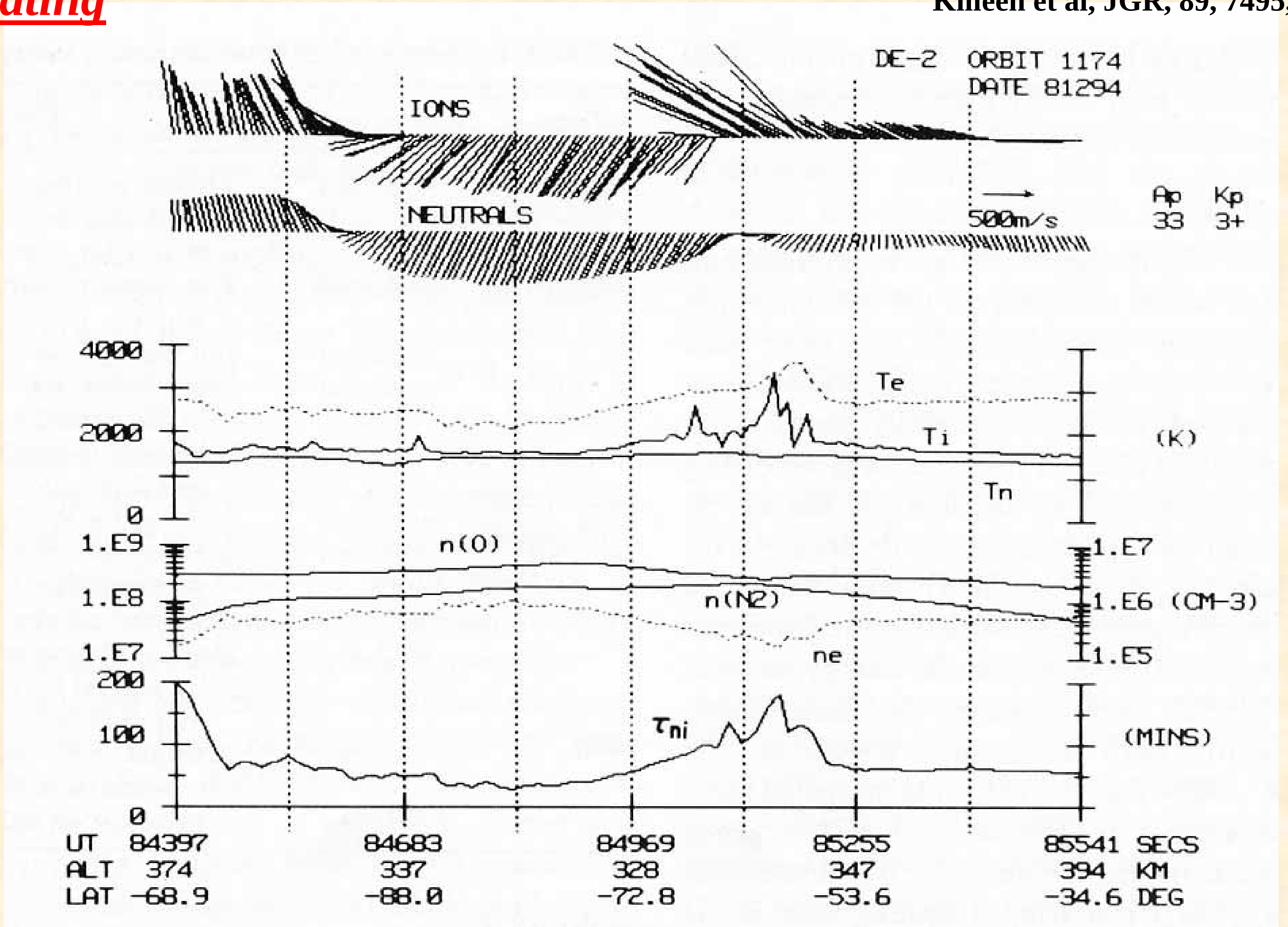
Joule Heating

Killeen et al, JGR, 89, 7495, 1984.



In regions where the ion and neutral velocity differ significantly the ions will be frictionally heated.

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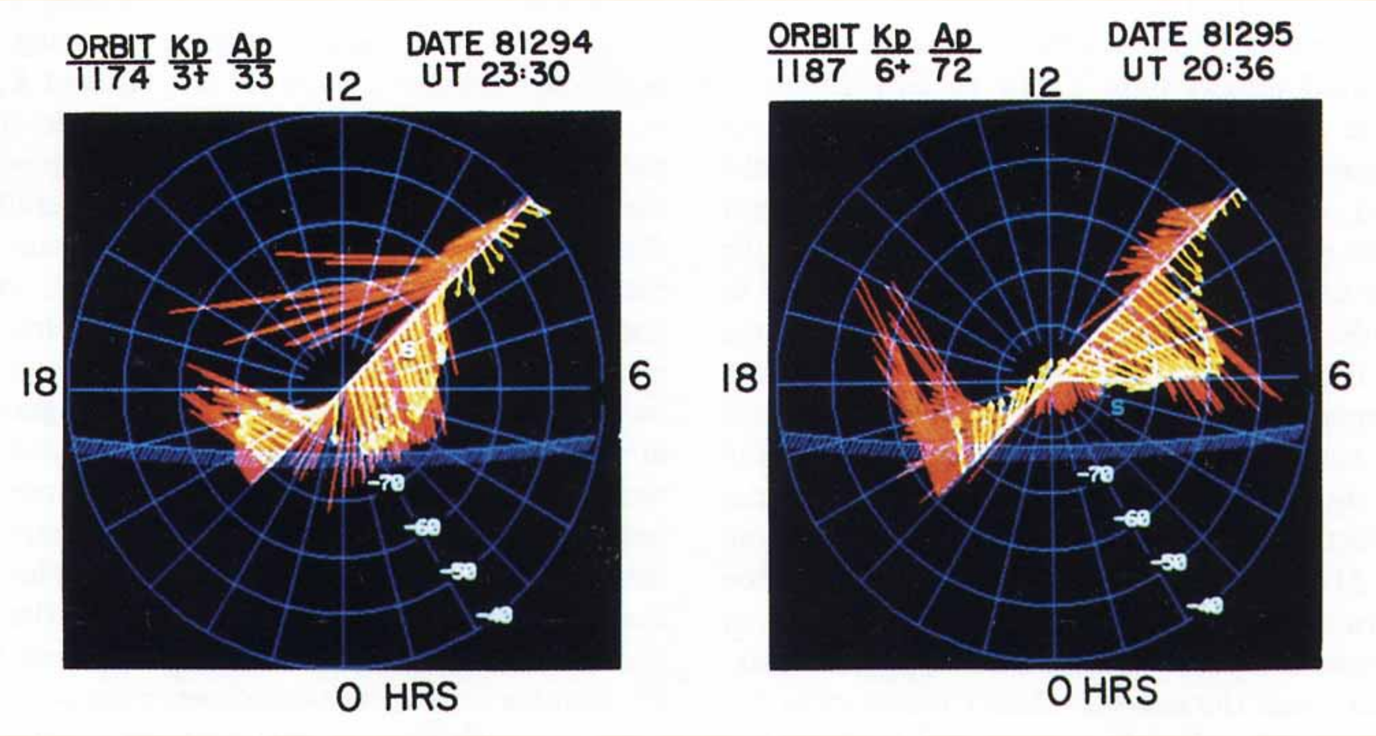
Joule Heating

Under steady state conditions ion-neutral collisions will impose the convective motion of the ions upon the neutrals



Day to night pressure gradients tend to assist the neutrals to flow antisunward.

Sunward flow in the neutrals in the auroral zone is harder to achieve.
Most of the Joule heating occurs in the auroral zones.

Why more in the dawnside than the dusk side ?

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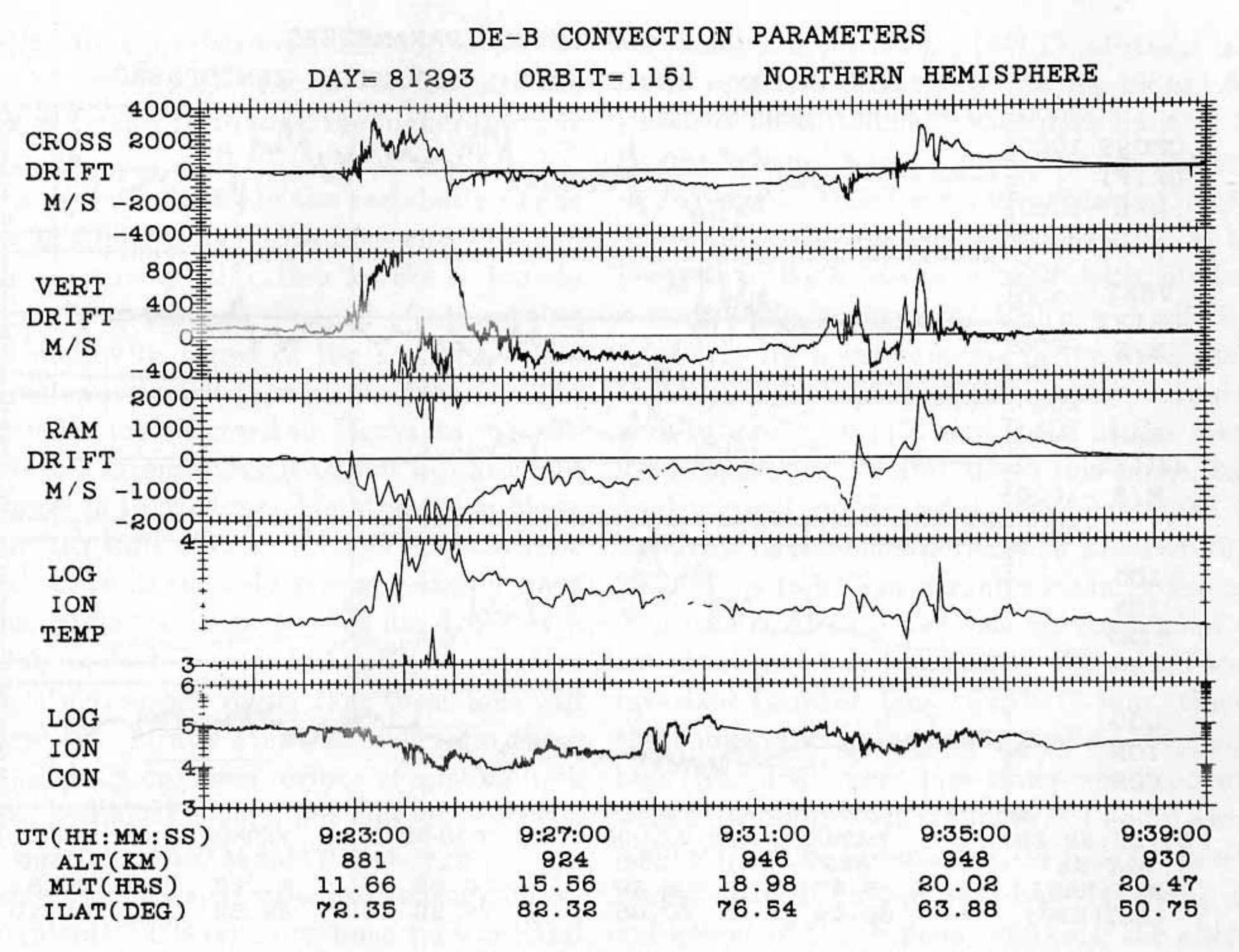
Joule Heating

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



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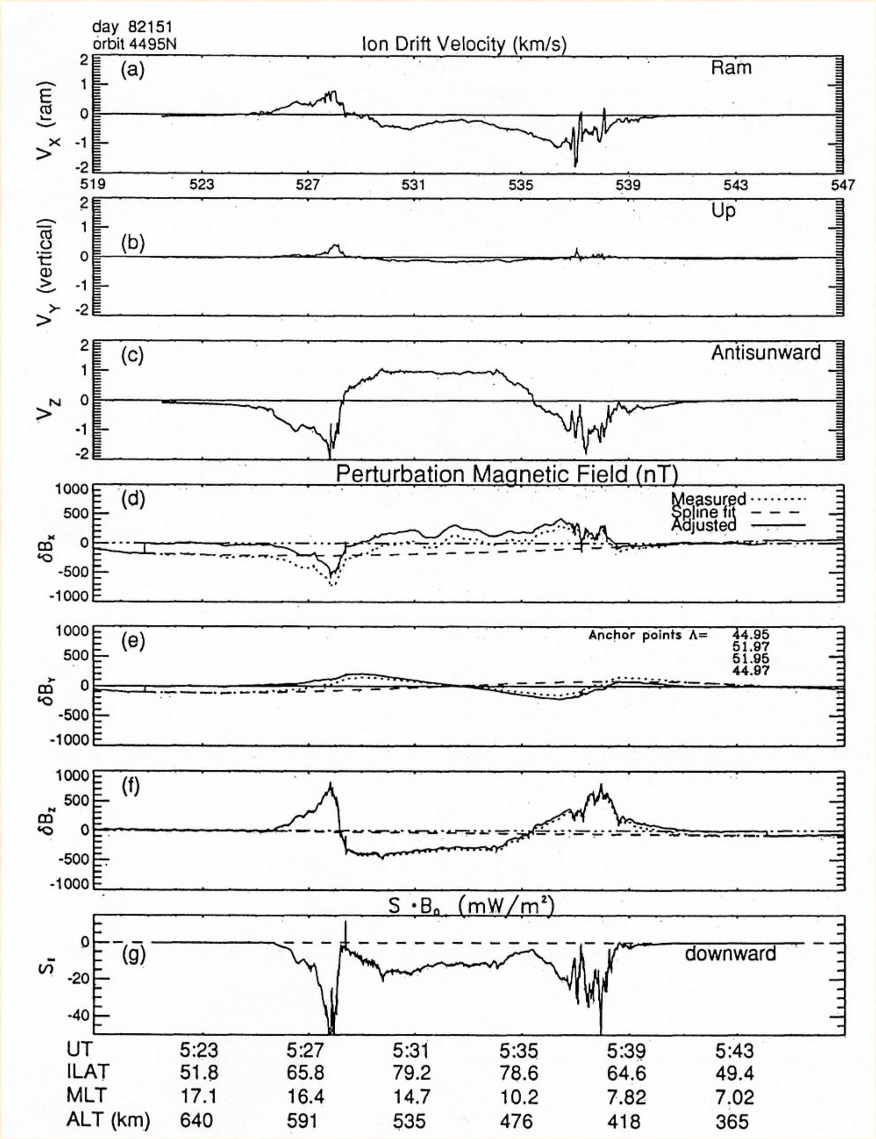
Poynting Flux



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

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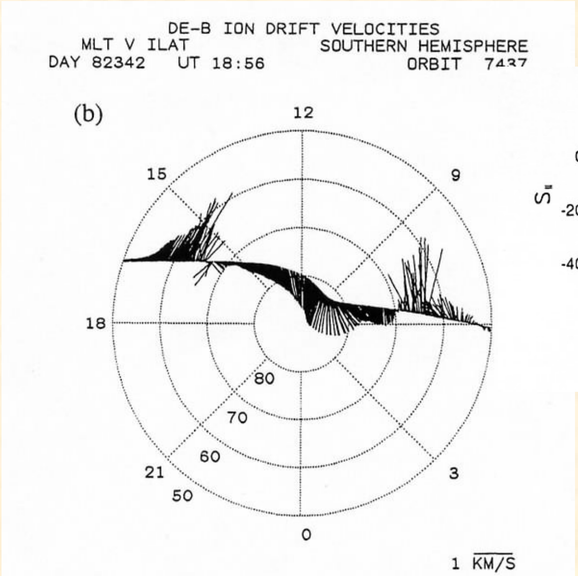
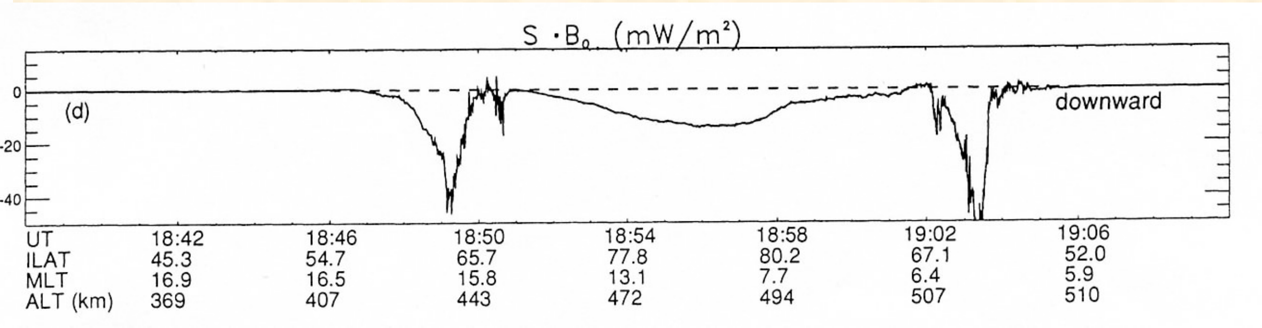
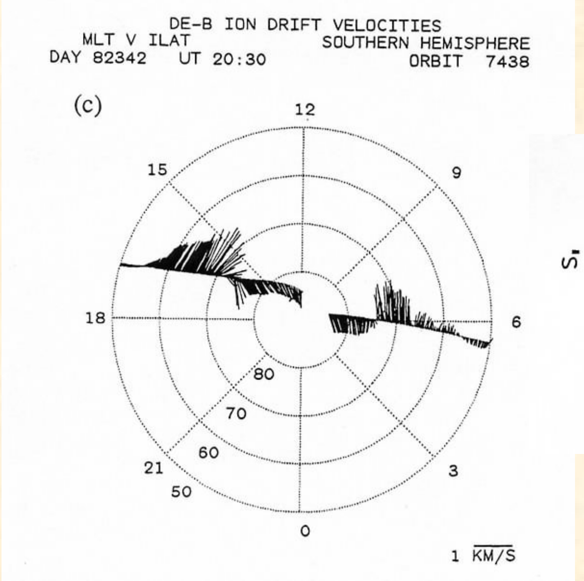
Poynting Flux

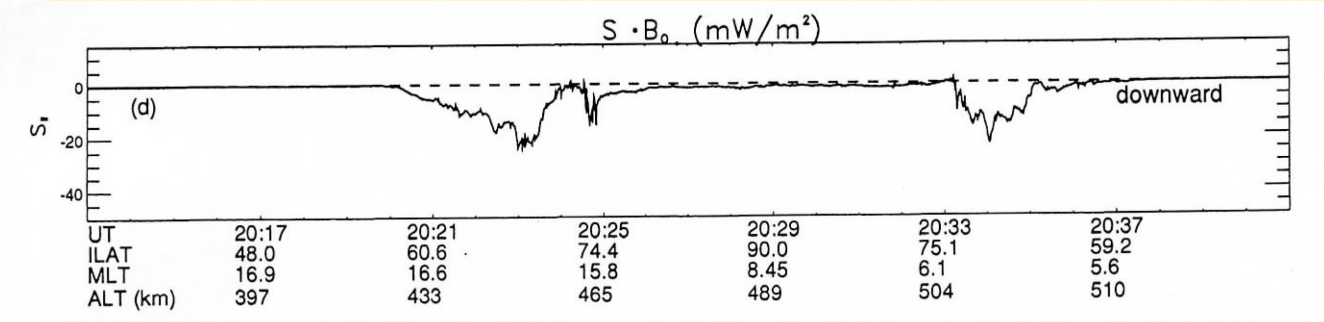




Large electric fields in the polar cap force the neutral gas antisunward requiring a downward Poynting flux

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





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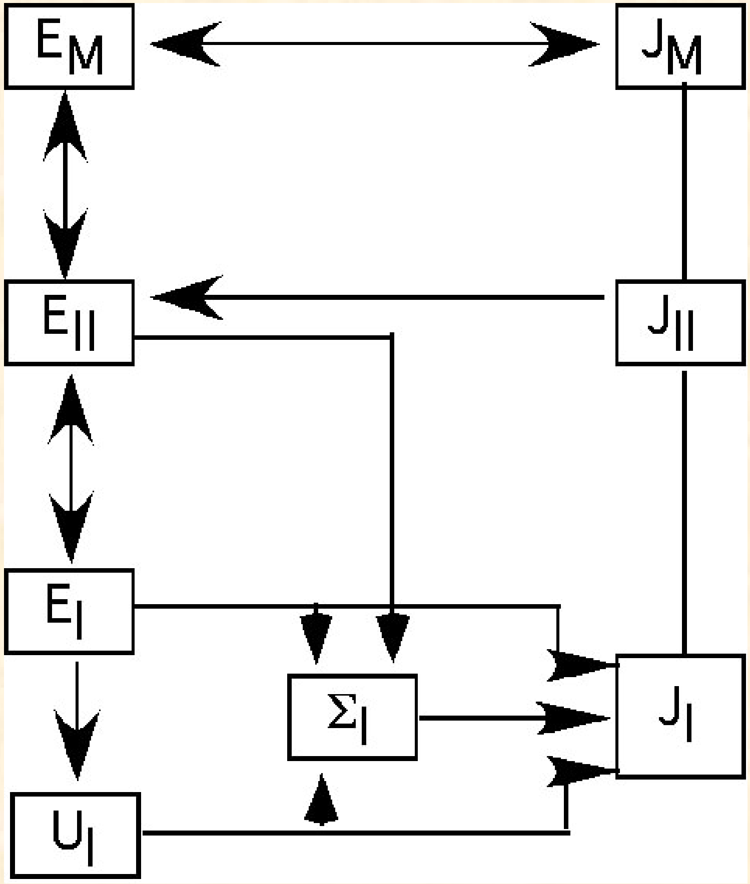
Particle energy

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 provided 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 .

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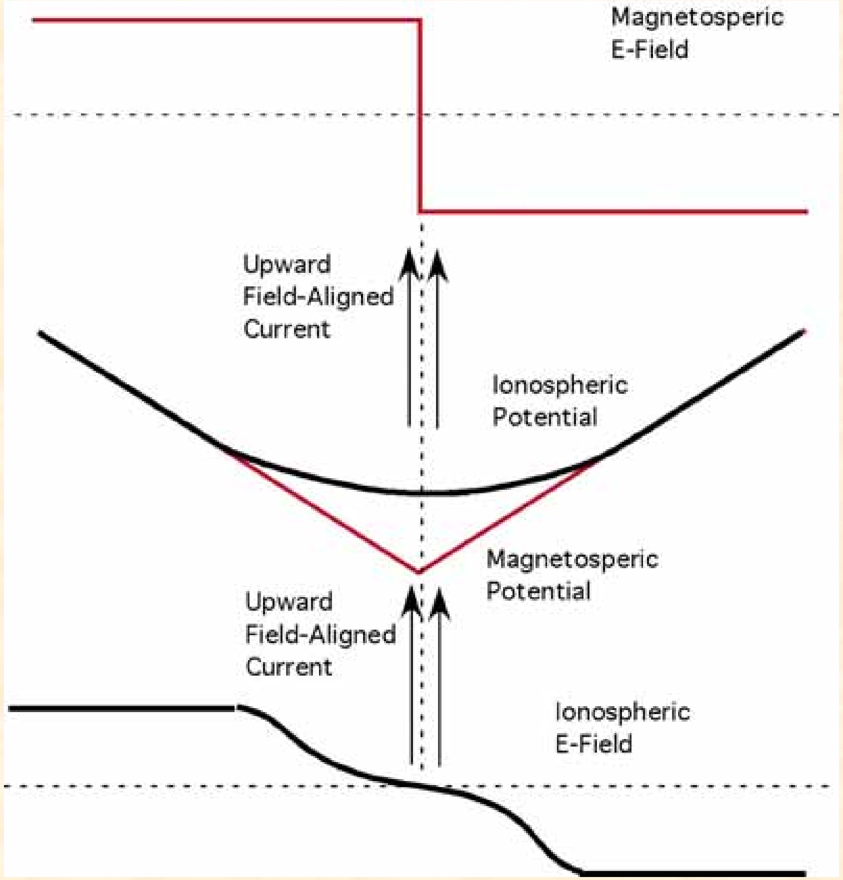
Particle energy

When an isotropic Maxwellian distribution with a given energy and number density is accelerated to carry a current the acceleration potential drop is related to the field-aligned current density [Knight, Planet Space Sci., 21, 741,1973.]



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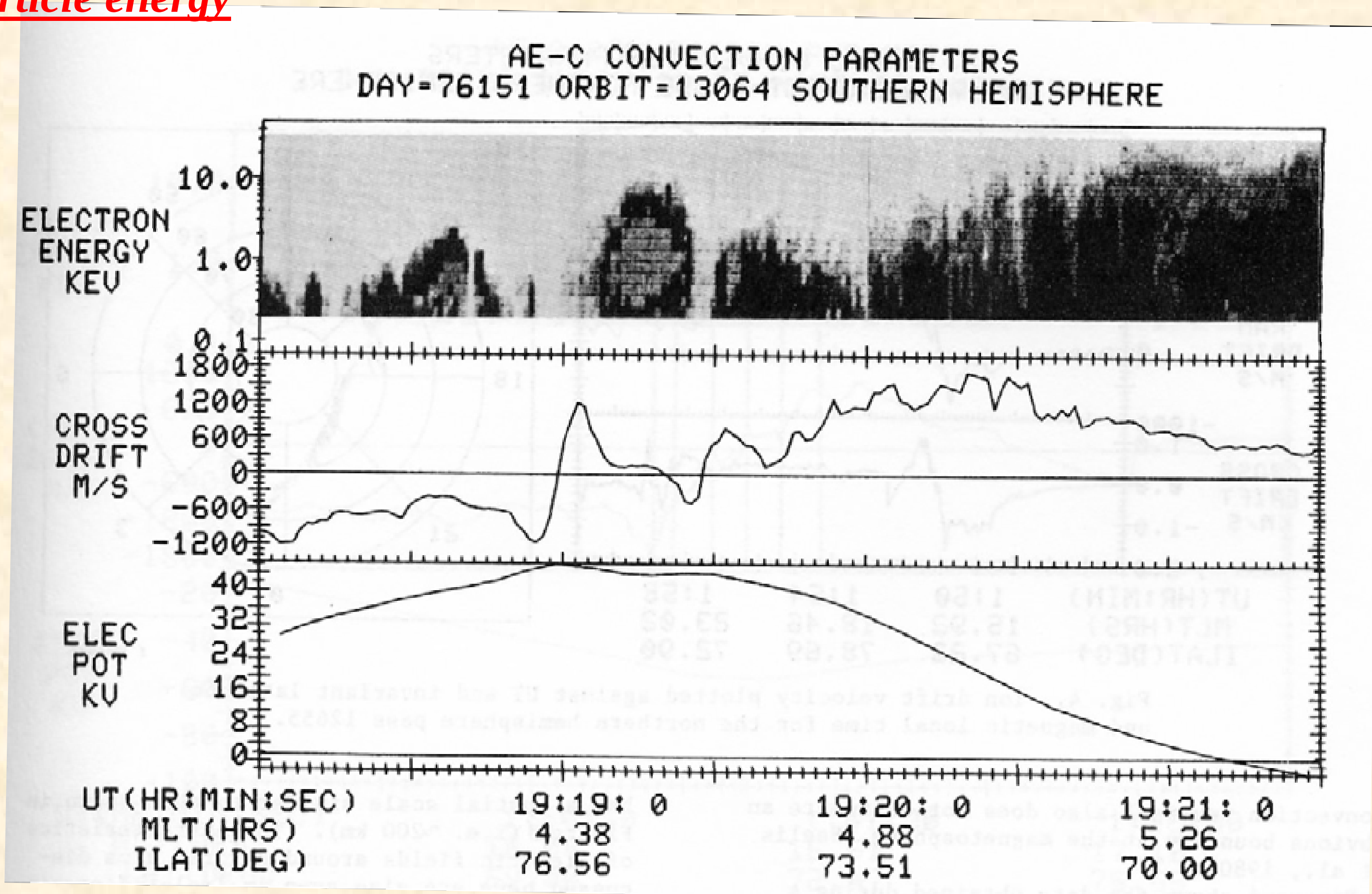
Particle energy



Notice that the peak electric fields bound the particle precipitation region so that the joule heating is adjacent to the particle heating.

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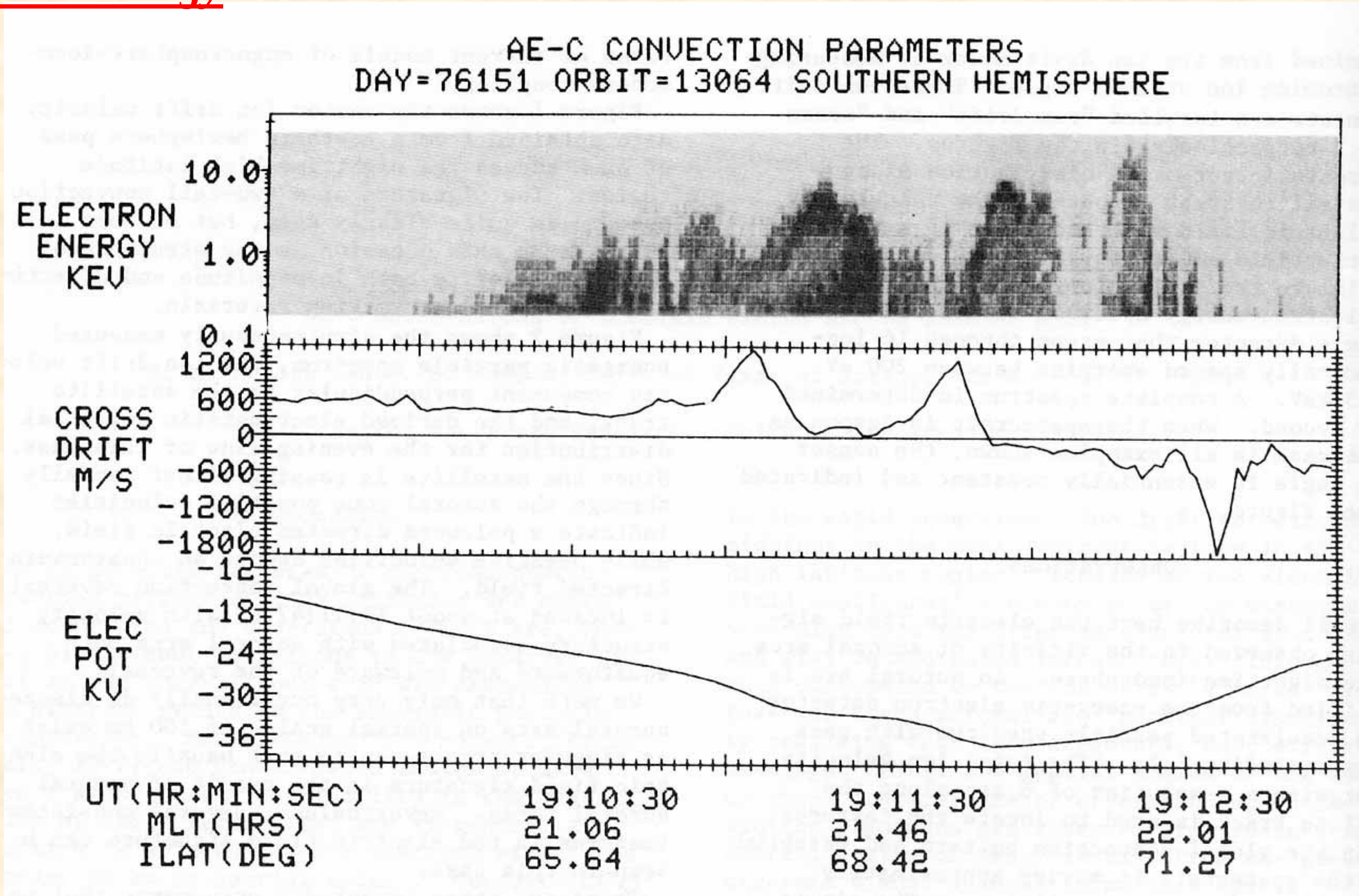
Particle energy



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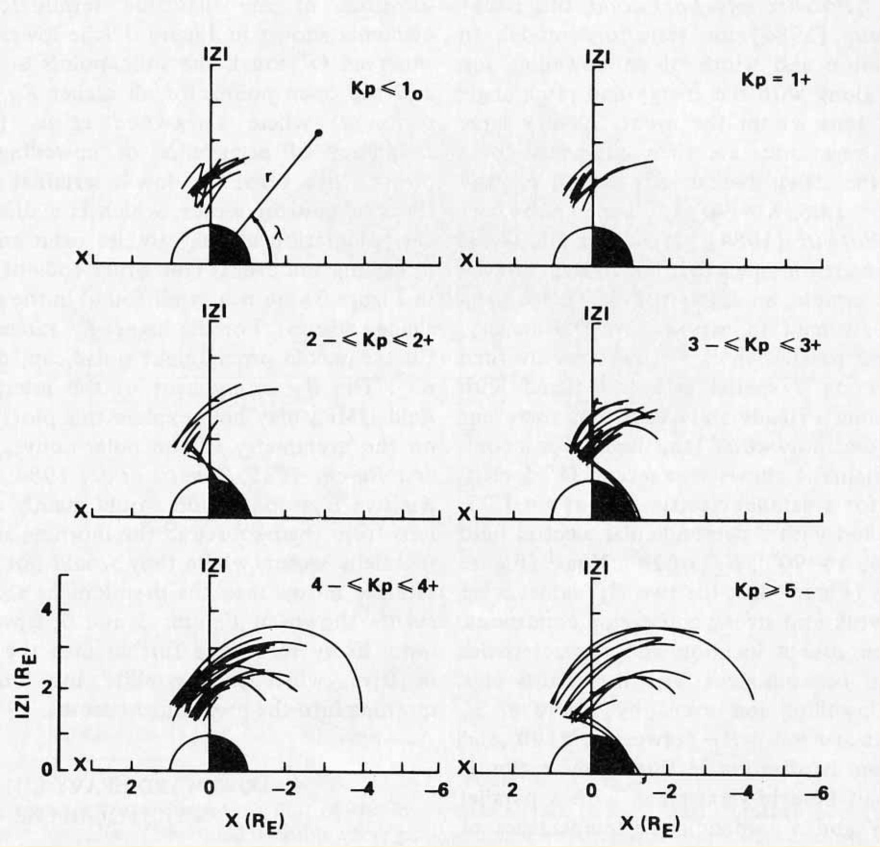
Plasma Outflow



The vertical ion flows resulting from frictional heating and particle heating provide significant outward fluxes toward the magnetosphere.

The observed field-aligned velocities in the ionosphere are insufficient to provide enough energy to overcome the gravitational potential.

However, there exist acceleration mechanisms at altitudes above 2000 km that provide this energy.

The ionosphere is a dominant source of plasma to the magnetosphere.

Lockwood et al., JGR, 90, 936, 1985.

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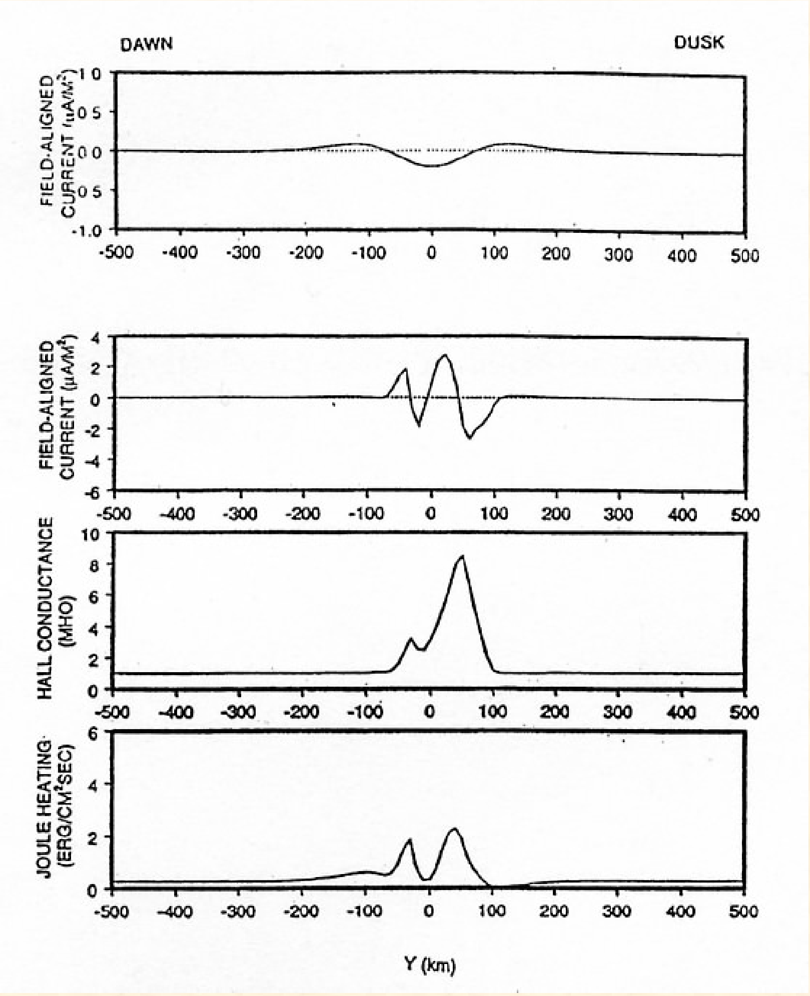
Alfven Waves

All the previous discussion assumed a quasi steady state.
There are many occasions when this is not the case.
A shear in the electric field delivered to the ionosphere will launch an Alfven wave toward the magnetosphere to impose a simple pattern of field-aligned current.
This wave will be reflected and modify the field-aligned current.

A single structure can form into multiple structures due to this process.

Lysak and Song, JGR, 107, 101029, 2002



Zhu et al., GRL, 21, 649, 1994

Summary

Electric Fields are imposed on the ionosphere from the magnetosphere.
These fields require field-aligned current loops.
Electric fields and field-aligned currents produce Joule and particle heating at high latitudes.
Electric fields also transfer momentum to the neutral atmosphere.

Joule Heating and Momentum Transfer modify the electric fields produced by dynamo action of the neutral wind.

Electric fields and particles change the ionospheric conductivity and thus the horizontal current distribution in the ionosphere.

The horizontal current in the ionosphere must be consistent with the field-aligned current that is delivering electromagnetic and particle energy to the the ionosphere from the magnetosphere.

Joule and particle heating change the plasma pressure in the ionosphere and impart upward field-aligned motions to the plasma.
The outward ionospheric ion fluxes are further accelerated into the magnetosphere where they serve as a dominant source of plasma to the inner magnetosphere.

Changes in time are communicated between the regions as Alfven waves. The propagation properties of these waves can produce multiple spatial structures from a single driving feature

Research Areas

In the ionosphere above 300 km the ions ExB drift but below this altitude the do not. Thus the motion imposed on the neutrals is a strong function of altitude.

How is the Joule heating and momentum transfer distributed in altitude ?

It is customary to think of the magnetic field lines as electric equipotentials but the field-aligned current is closed in the ionosphere so this cannot be the case in the lower ionosphere.

What are the current closure paths in the lower ionosphere ?

Under steady state conditions we think of Poynting flux delivered to the ionosphere as the electric field drives the neutral atmosphere. If the electric field is subsequently reduced the neutral wind could in principle drive the ions.

Are there conditions under which electromagnetic energy is delivered from the ionosphere to the magnetosphere ?

There exist a wide variety of spatial and temporal scales for the electric field and field-aligned current in the ionosphere.

Which spatial and temporal scales are most effective in delivering electromagnetic energy to the ionosphere ?