

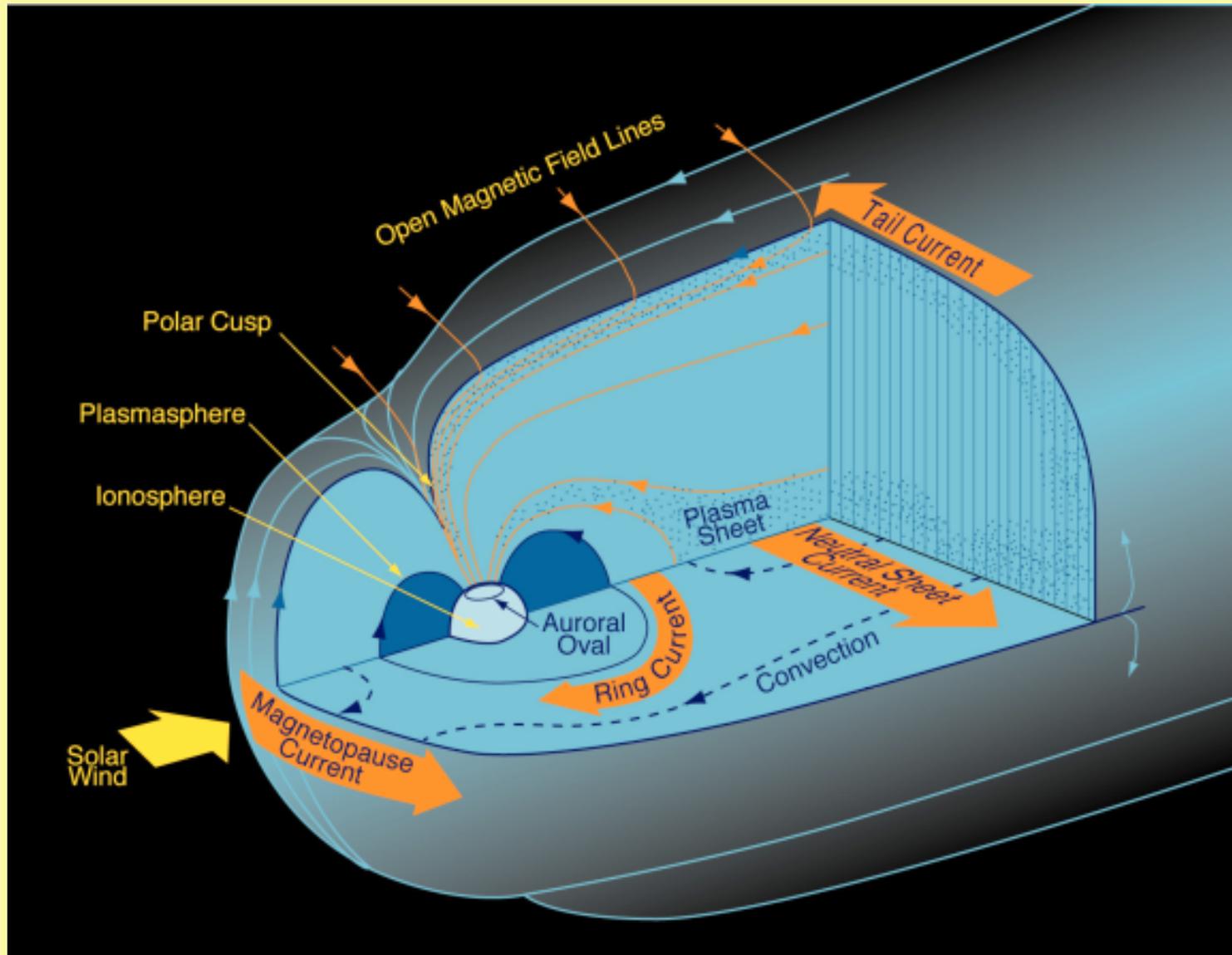
# **Sub-Auroral Electric Fields: An Inner Magnetosphere Perspective**

Bob Spiro  
*Rice University*

# Introduction/Outline

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- Importance of Sub-Auroral  $E$ -Fields
- Early Models of Sub-Auroral Electric Fields
- Sub-Auroral Electric Field Structures - SAID/PJ/SAPS
- Modeling the Inner Magnetosphere - RCM
- Physics of Inner Magnetosphere Shielding
- Inner Magnetosphere Explanation of SAID/PJ/SAPS
- How Well Do Models Represent Observed Features?
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# Magnetosphere Regions



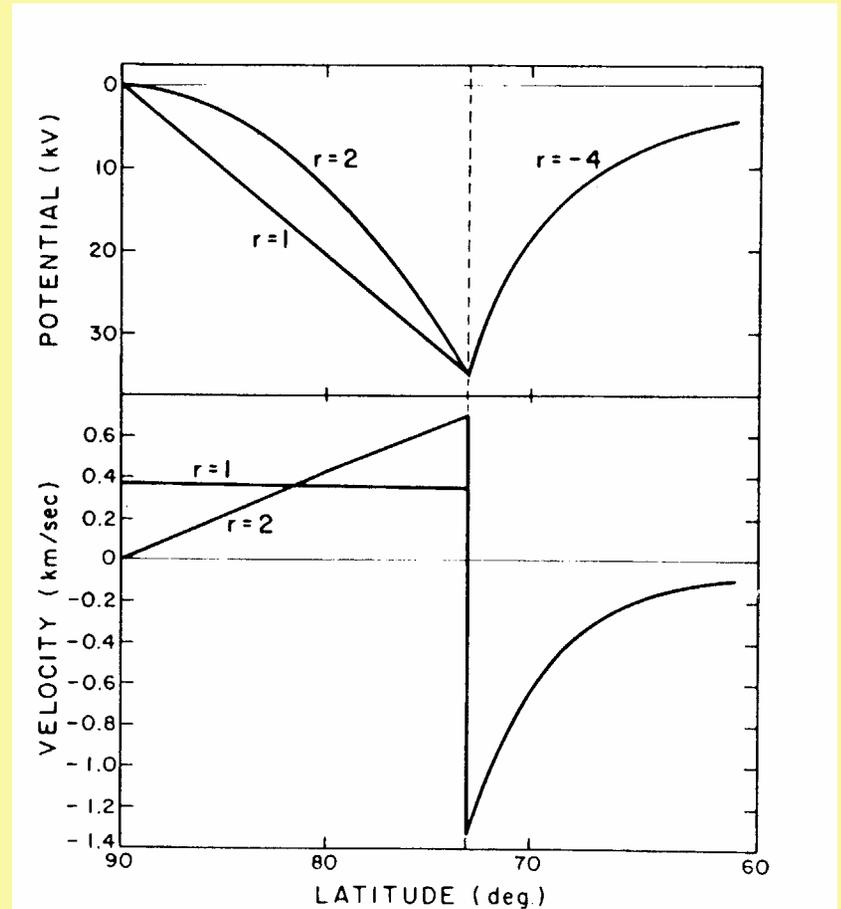
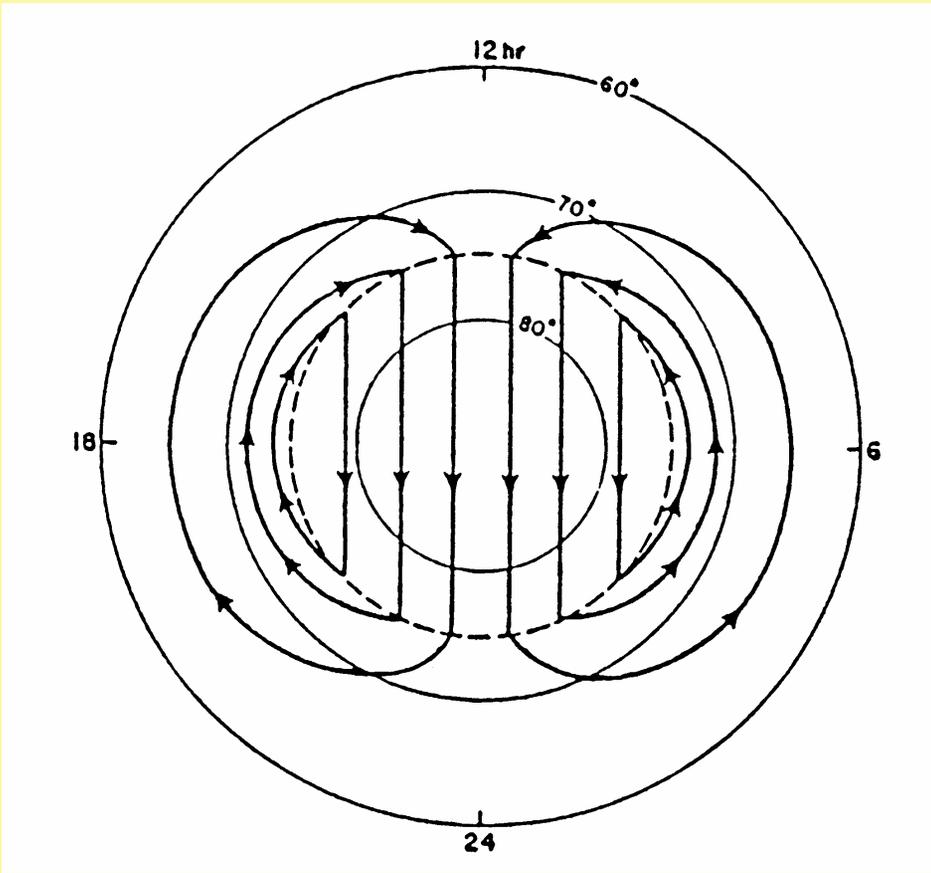
# Importance of Inner Magnetosphere/Sub-Auroral *E*-Field for Magnetosphere/Ionosphere System

- Ionosphere - plasma transport
  - Mid-latitude trough
  - Storm-associated changes in global ionosphere
  - Electrical conductivity changes
  - Penetration field effects on equatorial ionosphere (e.g., Spread-F and scintillation)
- Plasmasphere
  - Formation process
  - Plasmapause erosion and plumes
- Ring Current formation
- Radiation belts

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# Volland/Stern $E$ -Field



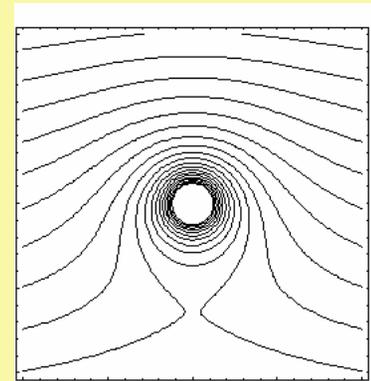
# Simple Representations of Inner-Magnetospheric Electric Fields

Simplest approximation: Uniform dawn-dusk E + corotation

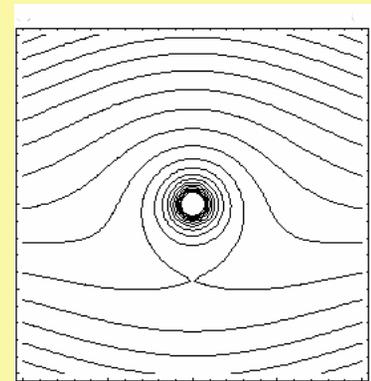
$$\Phi = -E_0 y - \frac{B_0 \omega_E R_E^3}{r}$$

Uniform dawn-dusk field

Corotation



Next simplest approximation—Stern-Volland + corotation



- Neither of these simple models captures the complexity of the real system.

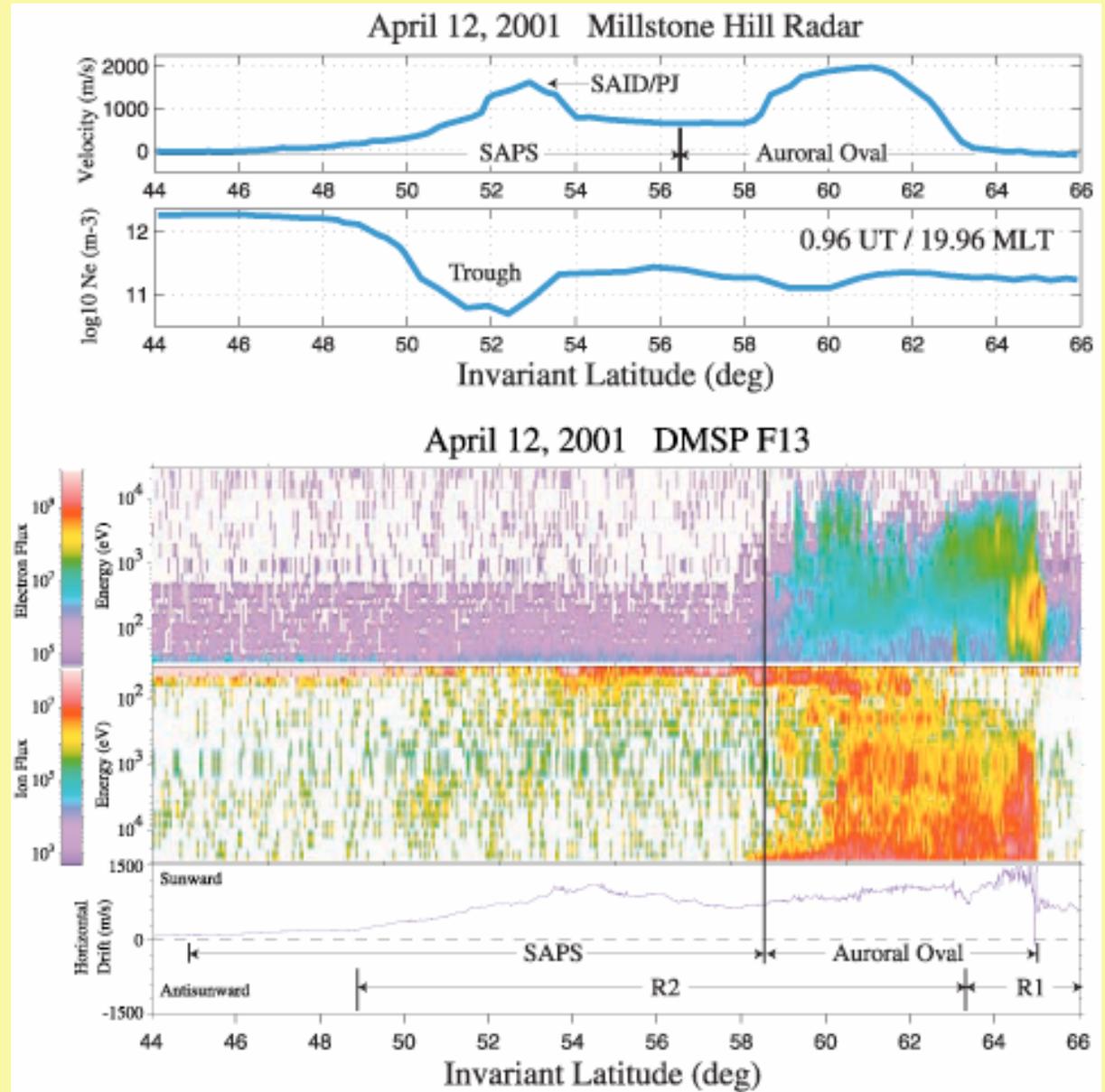
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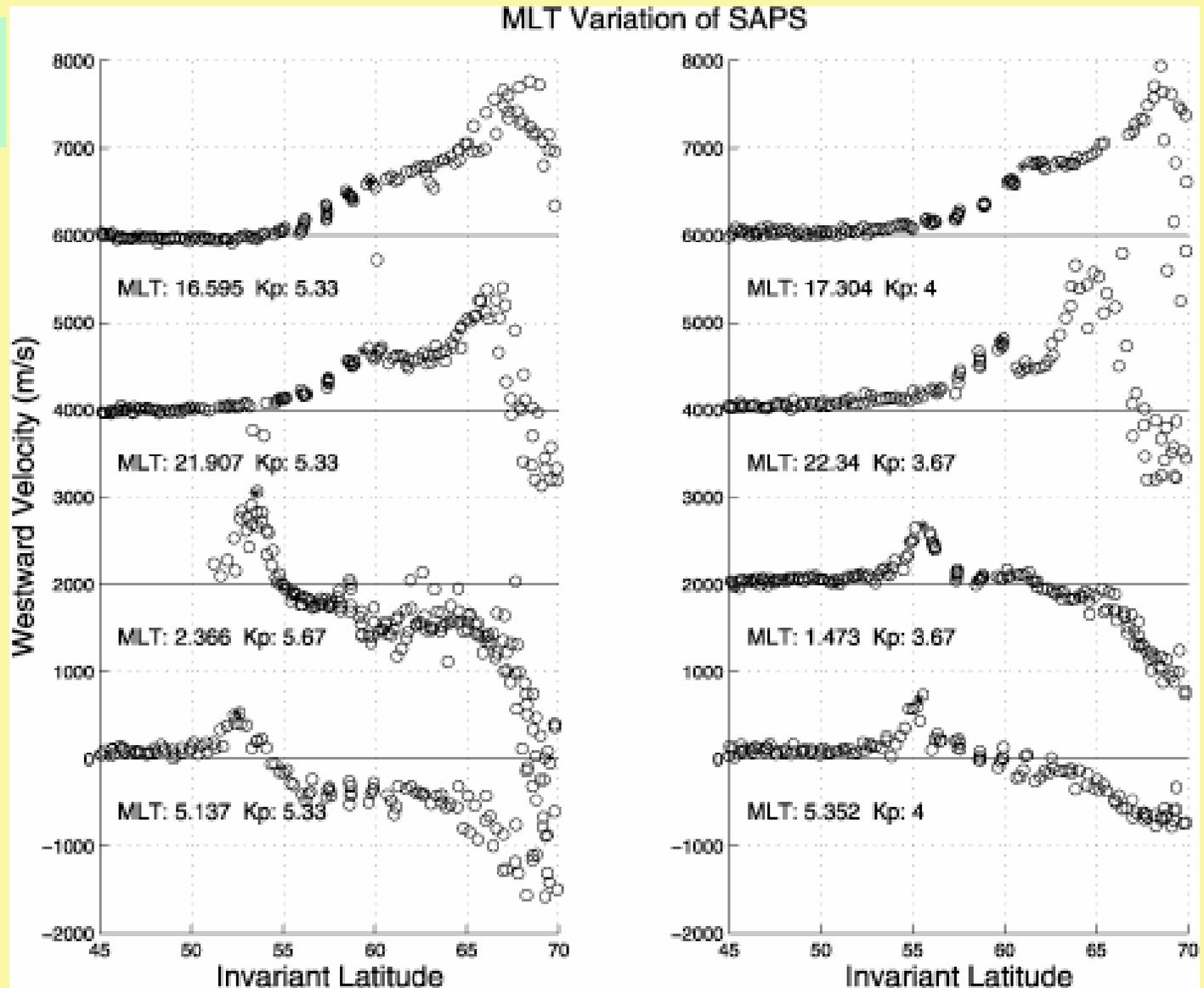
# Sub-Auroral Electric Field Structures

- Satellite and radar measurements have revealed that, especially during active periods, the early *E*-field models fail to capture the complexity of the system.
- Two effects that I will be concentrating on are:
  - Sub-Auroral Polarization Stream (SAPS) E-field structures
  - Shielding/overshielding/undershielding (Penetration E-fields)

# SAPS Observed From Millstone Hill (Foster & Vo, JGR, 2002)



# Millstone Hill (Foster & Vo, 2002)

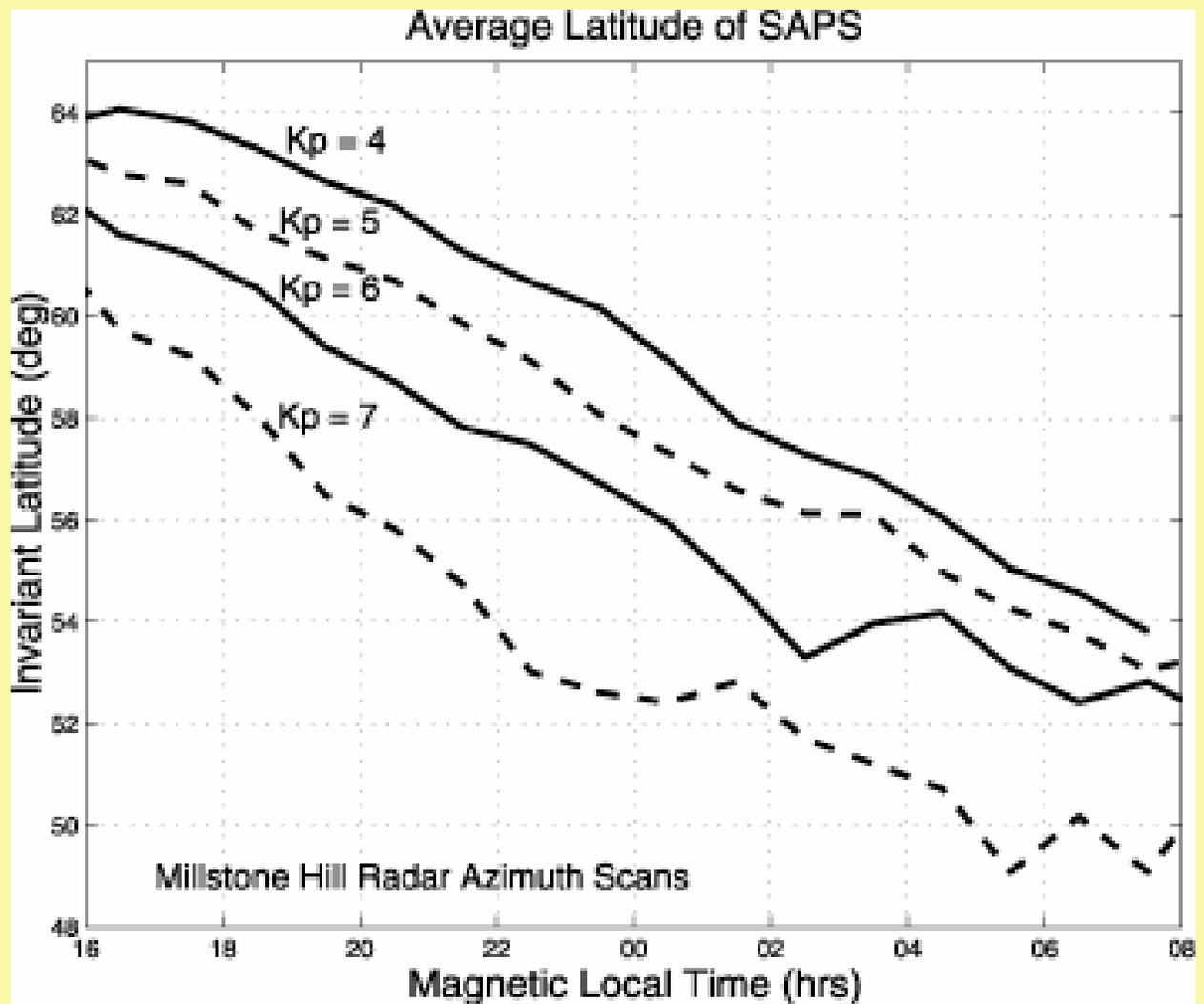


# Dependence of SAPS location on Kp & MLT

(Foster & Vo, 2002)

~ .7 deg/hr MLT

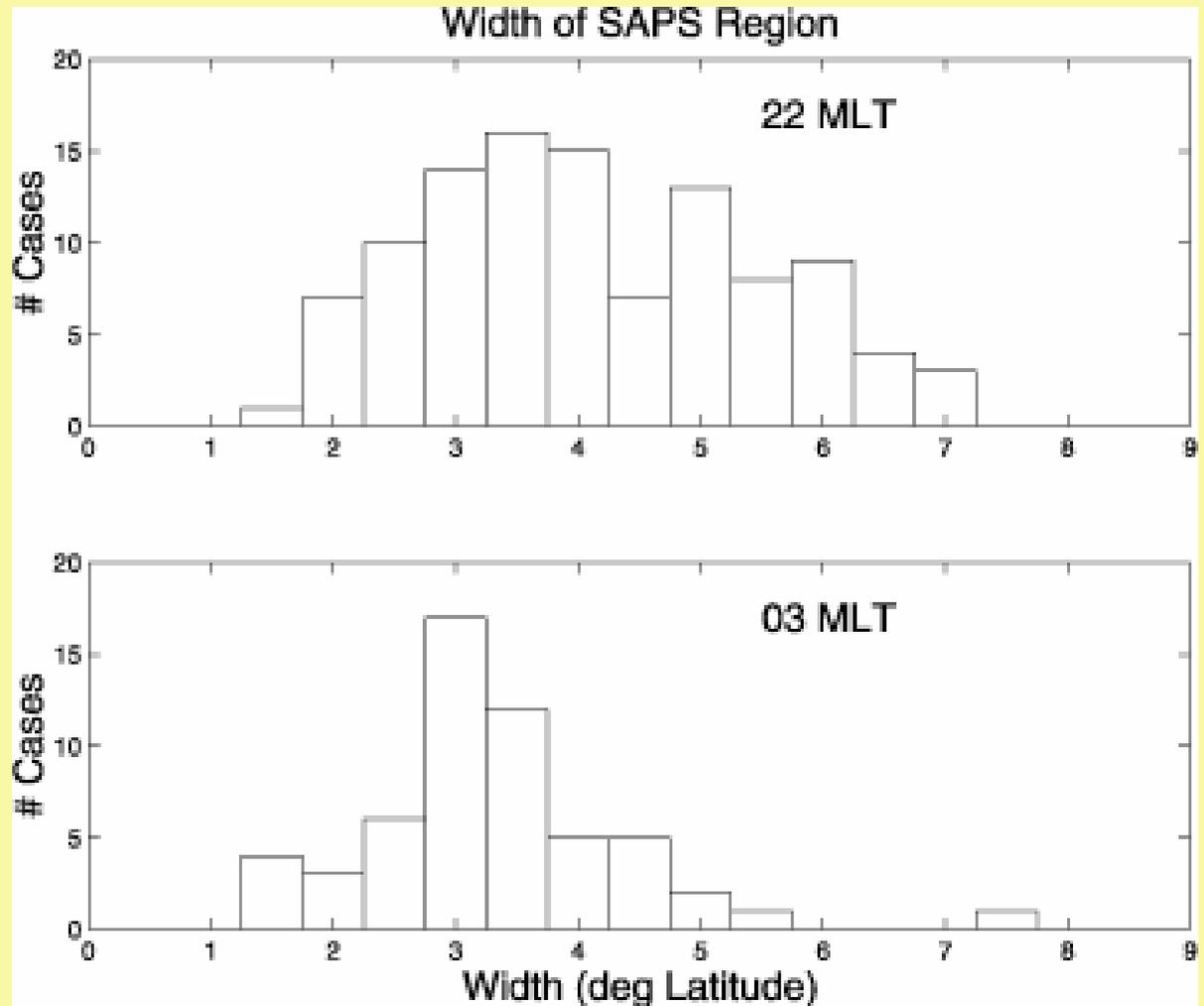
~ 1-2 deg/unit Kp



Location of SAPS peak moves equatorward with increasing MLT and increasing magnetic activity

# SAPS Latitudinal Width

(Foster & Vo, 2002)



SAPS are typically a few degrees wide.

# DMSP Observation of Sub-Auroral $E$ -Field Structures

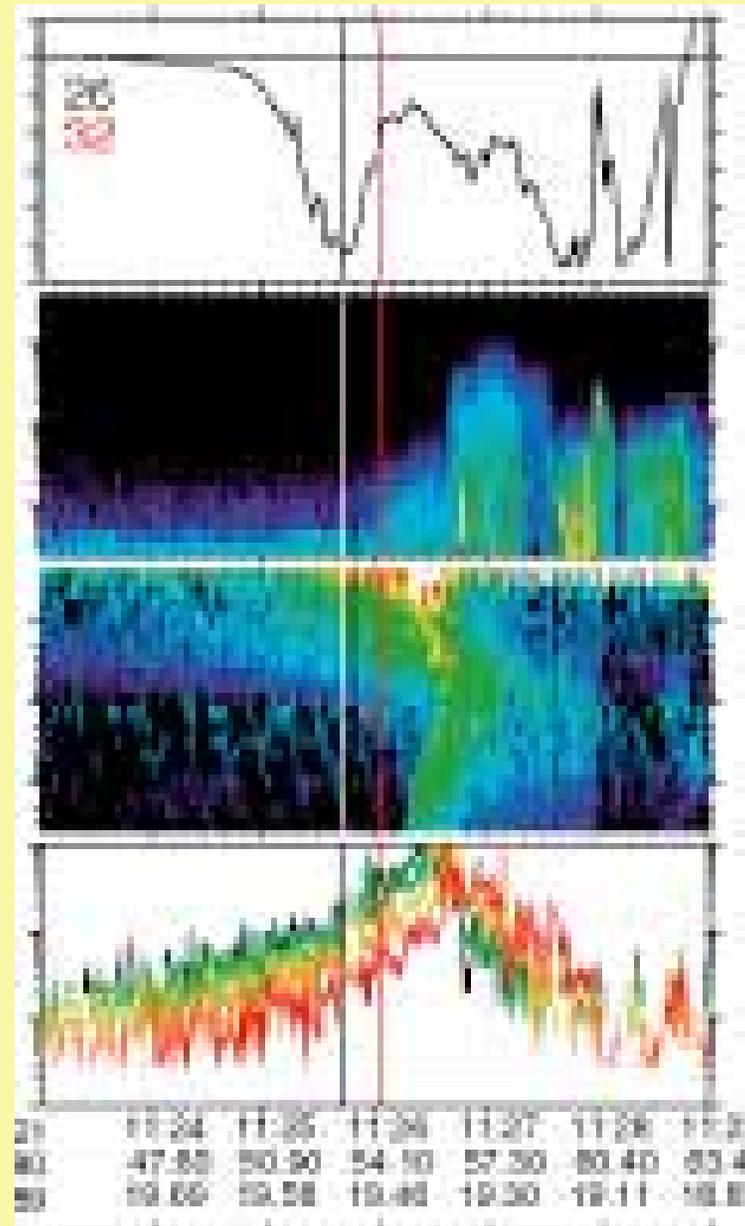
(Anderson et al., JGR, 2001)

Ion drift velocity

Precipitating electron number flux

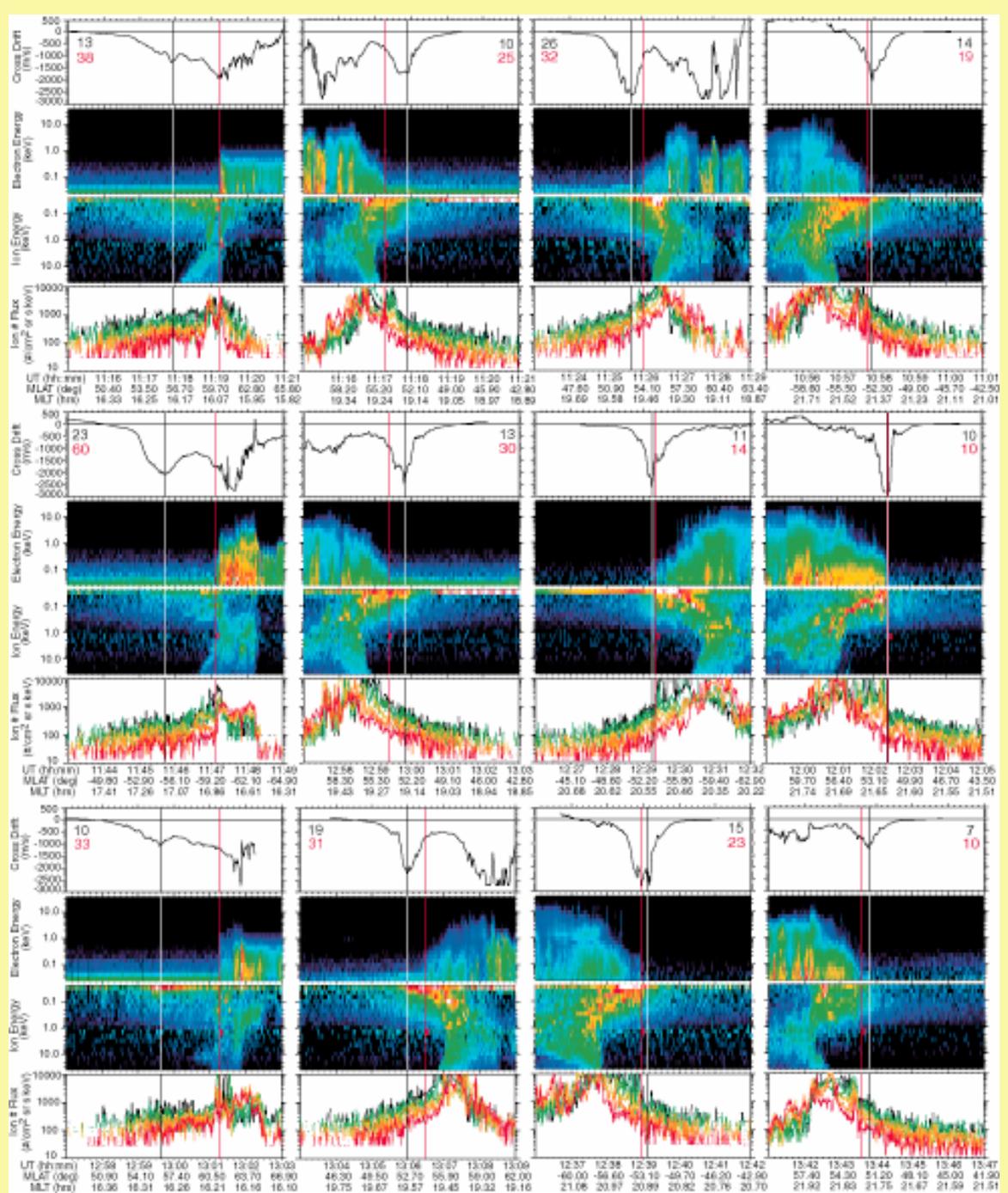
Precipitating ion number flux

Ion number fluxes



# DMSP Observations

(Anderson et al., JGR, 2001)



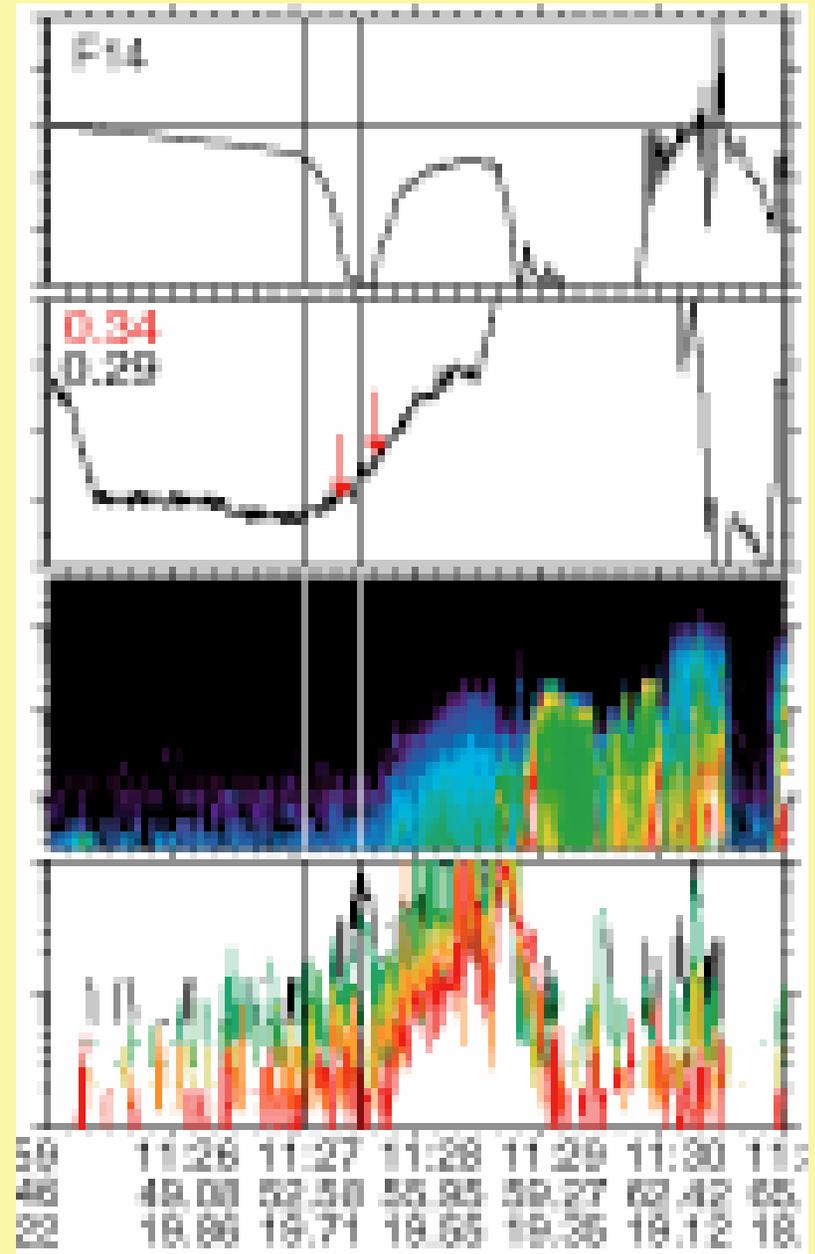
# DMSP Observations [with magnetometer data] (Anderson et al., JGR,2001)

Ion drift velocity

Magnetic perturbation

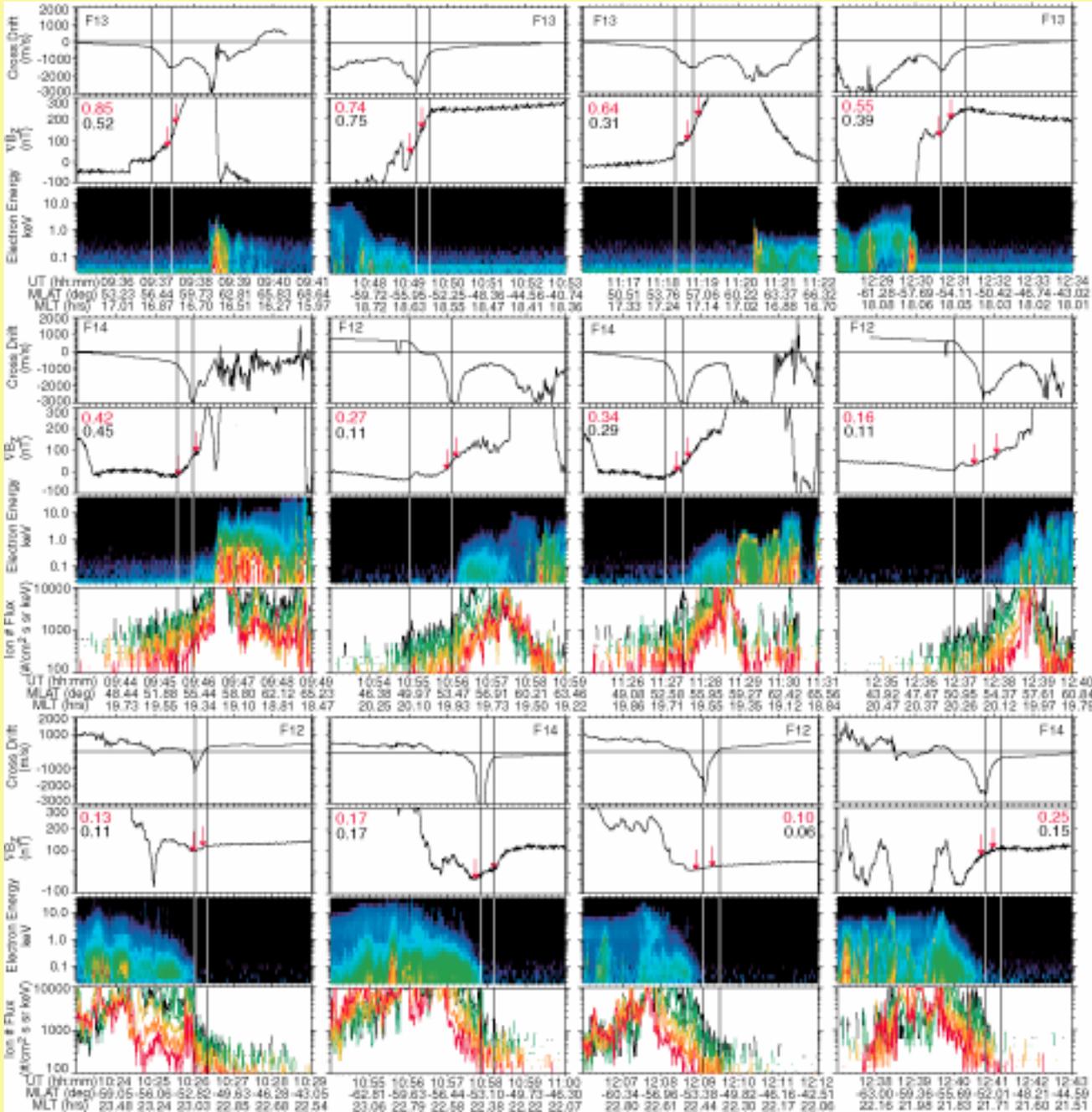
Precipitating electron number flux

Ion number fluxes



# DMSP Observations of SAPS [with magnetometer data]

(Anderson et al., JGR, 2001)



# Nomenclature

- *Polarization Jet (PJ)* - Term used by Galperin(1973) to describe narrow, intense poleward-directed electric field structures observed just equatorward of the nighttime auroral region by Soviet spacecraft.
- *Sub-Auroral Ion Drift (SAID)* - term introduced by Spiro et al. (1978) to describe essentially the same phenomena on the basis of Atmosphere Explorer ion drift measurements.
- *Sub-Auroral Polarization Stream* - term introduced by John Foster to include somewhat broader and less intense regions of sub-auroral, poleward-directed electric field.

## Observational Summary of Sub-Auroral *E*-Field Structures

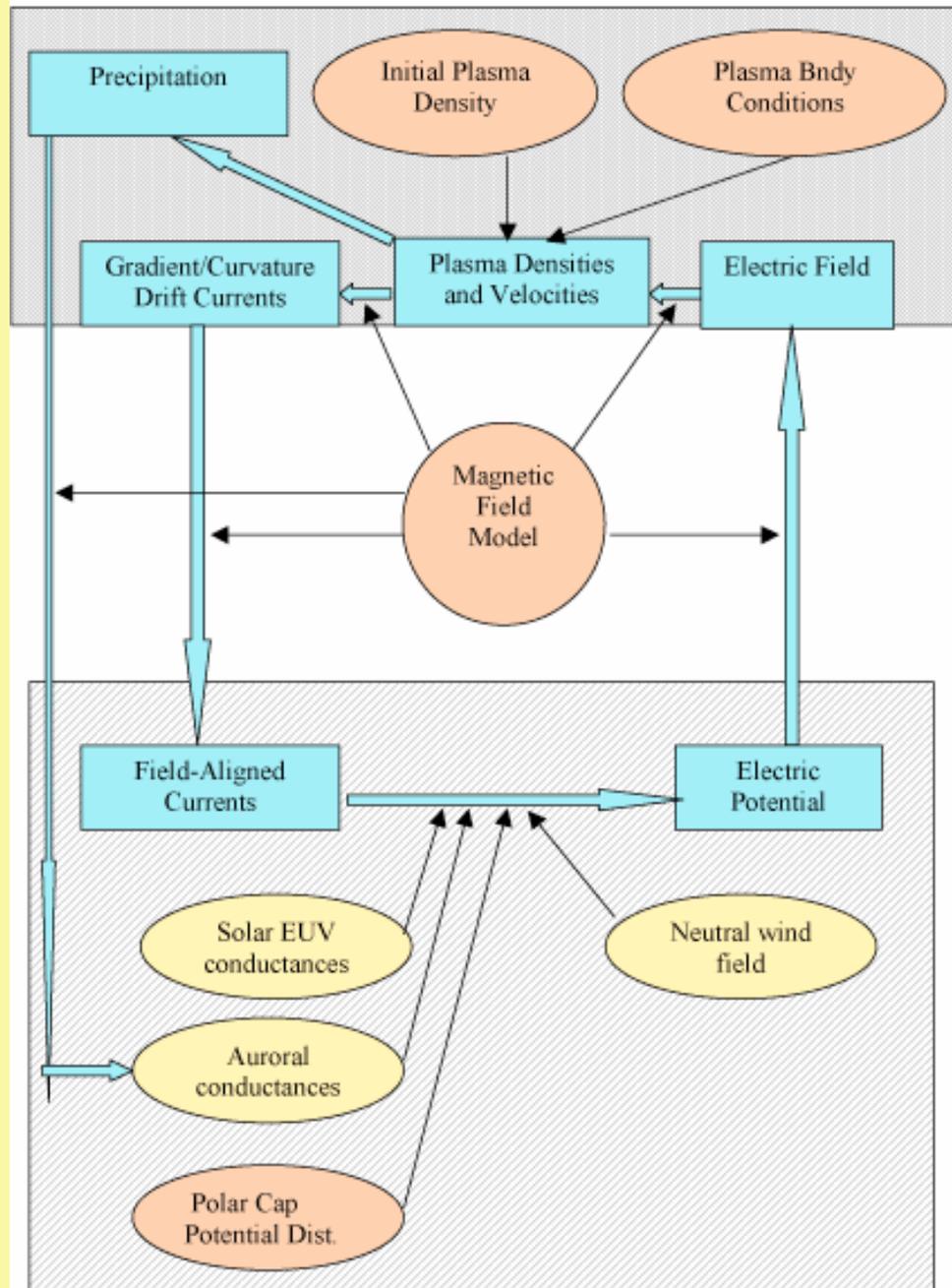
- SAPS - clearly defineable region of westward ion convection velocity at or equatorward of the low-latitude edge of the diffuse aurora
- SAPS peak often separated from the auroral westward (premidnight) or eastward (postmidnight) two cell region.
- Mean latitude of polarization stream moves equatorward  $\sim 0.7$  deg per hour of local time. [Note: roughly corresponds to observed dependence of mid-latitude trough location (e.g., Rycroft and Burrell, 1968).
- SAPS peak moves equatorward by a degree or two per unit change in  $K_p$
- Typical latitudinal width is  $\sim 3 - 5$  degrees

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# Modeling the Inner Magnetosphere With the RCM (Rice Convection Model)

# RCM Conceptual Diagram



# What Determines the Inner Magnetospheric $\mathbf{E}$ ?: Governing Equations

- Equation relating field-aligned currents to inner magnetosphere pressure gradients (Vasyliunas, )

$$\frac{J_{\parallel in} - J_{\parallel is}}{B_i} = \frac{\hat{\mathbf{b}} \cdot \vec{\nabla} V \times \vec{\nabla} p}{B} \quad (1)$$

- where *in* and *is* mean northern and southern ionosphere, we have assumed the magnetic field strength is the same at either end of the field line,

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

- and the right side of (1) can be evaluated anywhere on a field line.
- The form (1) assumes isotropic pressure, but it can be generalized.

# Equations

- Ohm's law for ionosphere:

$$\mathbf{J}_h = \vec{\Sigma} \cdot (-\vec{\nabla}\Phi) + (\vec{\Sigma} \cdot \vec{v}_n) \times \vec{B} \quad (2)$$

Field-line-integrated current  
(includes both hemispheres)

Field-line-integrated  
Conductivity (both hemispheres)

Field-line integrals of products of  
Hall and Pedersen conductivities and  
neutral winds

- Conservation of ionospheric current:

$$\vec{\nabla} \cdot \mathbf{J}_h = J_{\parallel} \sin(I) \quad (3)$$

- Substituting (2) and (3) in (1), and neglecting winds, gives the “Fundamental equation of ionosphere-magnetosphere coupling”:

$$\vec{\nabla}_i \cdot [\vec{\Sigma} \cdot (-\vec{\nabla}_i \Phi)] = \hat{\mathbf{b}} \cdot \vec{\nabla}_i V \times \vec{\nabla}_i p \sin(I)$$

# Evolution of Magnetospheric Particle Population

- For simplicity, assume that the particle distribution is isotropic
- “Isotropic energy invariant”  $\lambda$  is conserved:

$$W_K = \lambda V^{-2/3}$$

where  $W_K$ =kinetic energy

# Evolution of Magnetospheric Particle Population

- Equation for evolution of the particle distribution:

$$\left( \frac{\partial}{\partial t} + \vec{v}_d \cdot \vec{\nabla} \right) \eta_s = S - L$$

where  $\eta_s$  = number of particles per unit magnetic flux with certain chemical species and certain range in  $\lambda$ .  $S$  and  $L$  are sources and losses.

- $\eta_s$  is proportional to the distribution function.

$$pV^{5/3} = \frac{2}{3} \sum \eta_s \lambda_s$$

- Bounce-averaged drift equation:

$$\vec{v}_d = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{\lambda \vec{B} \times \vec{\nabla} V^{-2/3}}{qB^2}$$

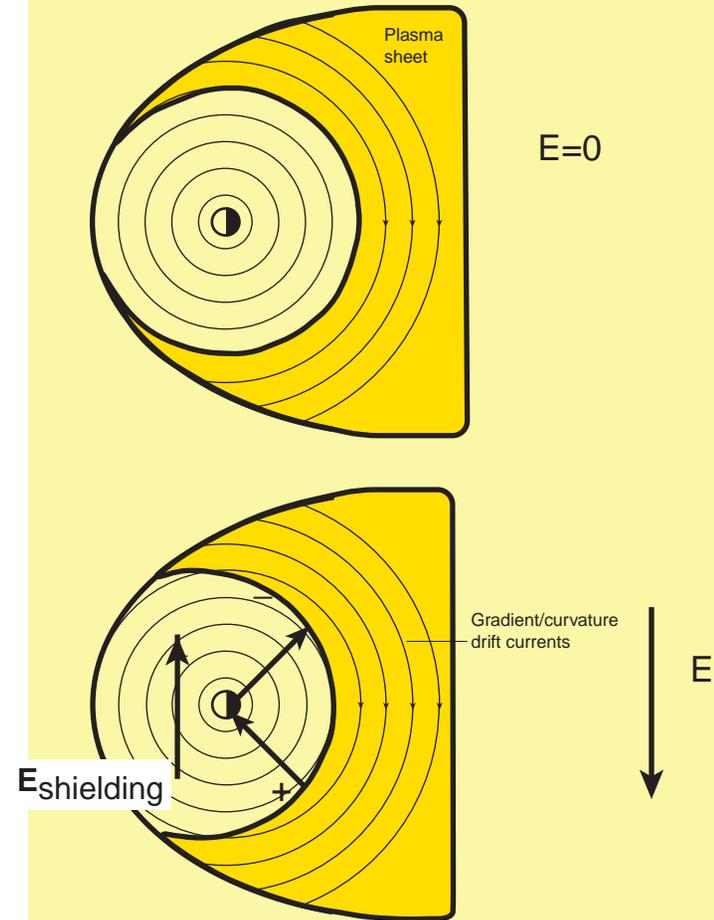
- Reference: Wolf, in *Solar-Terrestrial Physics*, ed. Carovillano and Forbes, 1983.

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# Magnetospheric Effects: Shielding

- Top diagram shows equilibrium condition no convection, with plasma-sheet edge aligned with contours of constant  $V$ .
  - Particles gradient/curvature drift along contours of constant  $V$
- Effect of applying cross-tail  $E$  (bottom) is to move edge sunward
  - Causes a partial westward ring across night side
  - Dusk side of edge charges +, dawn side –.
    - Charging occurs near eq. plane and in ionosphere
  - Currents flow up from dawnside ionosphere near inner edge, down to dusk side.
    - Those are the region-2 currents.
- They tend to shield the near-Earth region from the dawn-dusk  $E$ . Dusk-dawn polarization  $E$  opposes convection in the inner magnetosphere.



$$\vec{v}_d = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{\lambda \vec{B} \times \vec{\nabla} V^{-2/3}}{qB^2}$$

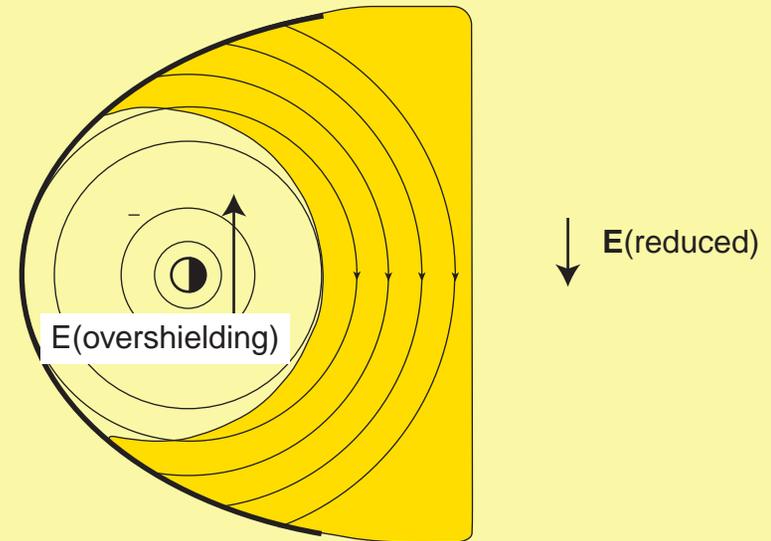
$$\frac{J_{||in} - J_{||is}}{B_i} = \frac{\hat{b} \cdot \vec{\nabla} V \times \vec{\nabla} p}{B}$$

## How Effective is Shielding in Steady State, for Typical Conditions?

- Answer: It's not clear.
- Shielding is often pretty good in Rice Convection Model simulations, but it is also often marginal.
- Main theoretical uncertainty is the value of  $PV^\gamma$  at the outer boundary of the RCM calculation.
- In RCM, efficiency of shielding is sensitive to plasma-sheet temperature, with higher temperature giving weaker shielding.

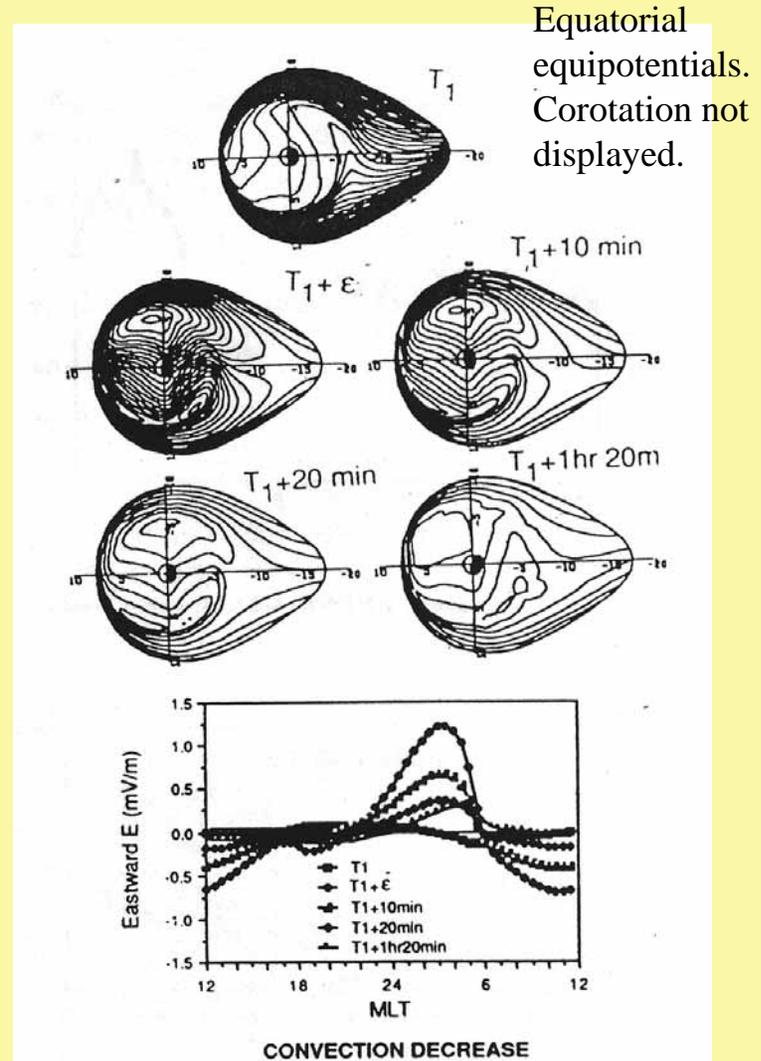
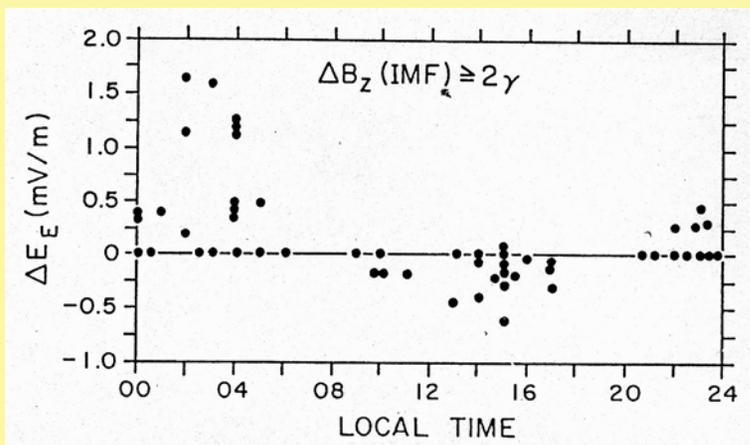
# Overshielding: The Idea

- If the shielding layer is configured to shield the inner magnetosphere from a strong convection field, and the driving convection field suddenly decreases, due to a northward turning of the IMF, the result will be a backwards  $\mathbf{E}$  field (dusk to dawn) across the inner magnetosphere, until the shielding layer readjusts.
- Originally seen in Jicamarca data by Kelley et al. (*GRL*, 6, 301, 1977)
  - Observations were interpreted in terms of overshielding picture



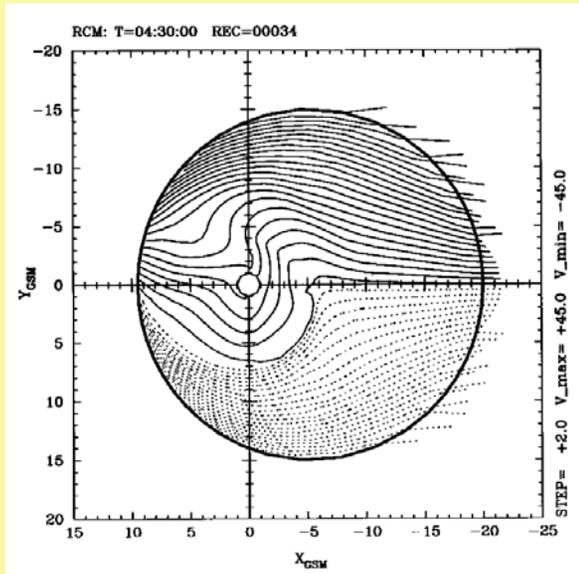
# Overshielding: Pattern Detail

- RCM (Spiro et al., *Ann. Geophys.*, 6, 39, 1988) indicated that the eastward penetration field was not spread uniformly across the night side but was concentrated in the midnight-dawn sector, particularly at low  $L$ . Senior and Blanc model (*JGR*, 89, 261, 1984) also showed similar results.
- Agreed with earlier observations of equatorial  $E$  in response to northward turning of IMF (Fejer, in *Solar-Wind Magnetosphere Coupling*, 1986)

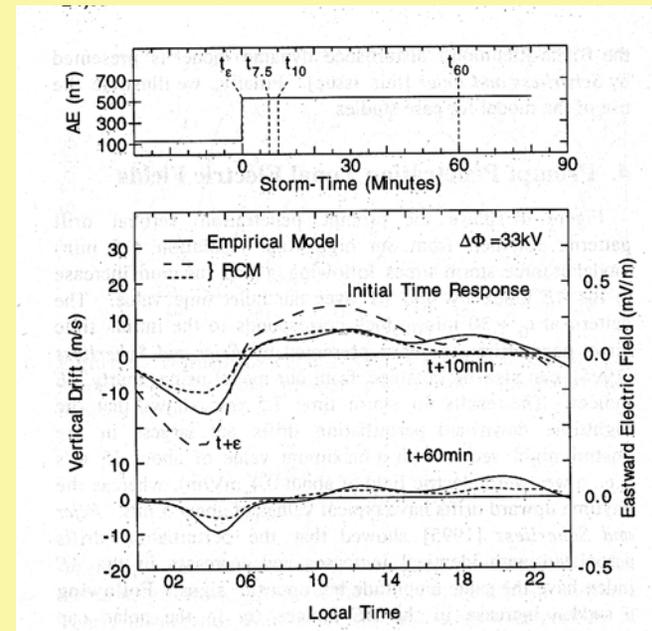


# Undershielding

- Undershielding is temporary penetration of dawn-dusk electric field in times of increasing convection.
- Pattern at low  $L$  is much the same as for overshielding, but the field is reversed: westward penetration electric field post-midnight.



From Sazykin Ph.D thesis, Utah State, 2000.



Equatorial ionospheric  $\mathbf{E}$  from Fejer and Scherliess (*JGR*, 102, 24047, 1997).

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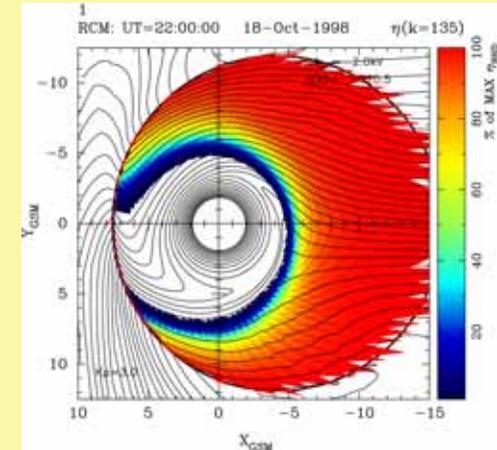
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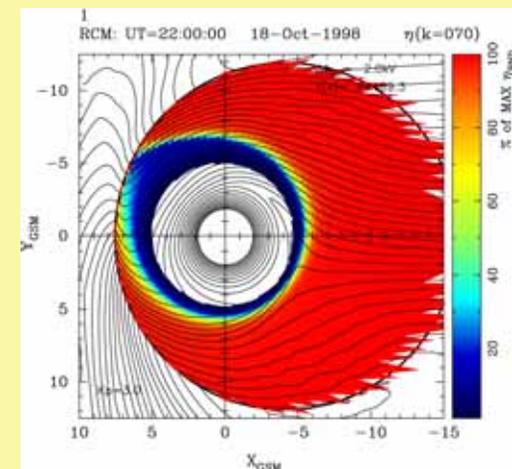
# Physical Interpretation of SAPS

- In the pre-midnight sector, gradient/curvature drift causes plasma-sheet ions to penetrate closer to Earth than electrons.
- Precipitating electrons mostly control auroral conductance.
- Therefore, in the premidnight sector, the inner edge of the plasma-sheet ions lies at lower  $L$  than the auroral conductance enhancement.
- Most of the shielding (region-2) current is driven by ion pressure gradients, because they carry most of the pressure.
- Thus, some region-2 current flows into the nightside low-conductance, sub-auroral ionosphere. That is what causes SAPS in the RCM.
- This interpretation was first advanced by Southwood and Wolf [JGR, 1978] to explain the existence of large sub-auroral electric fields.

Electrons

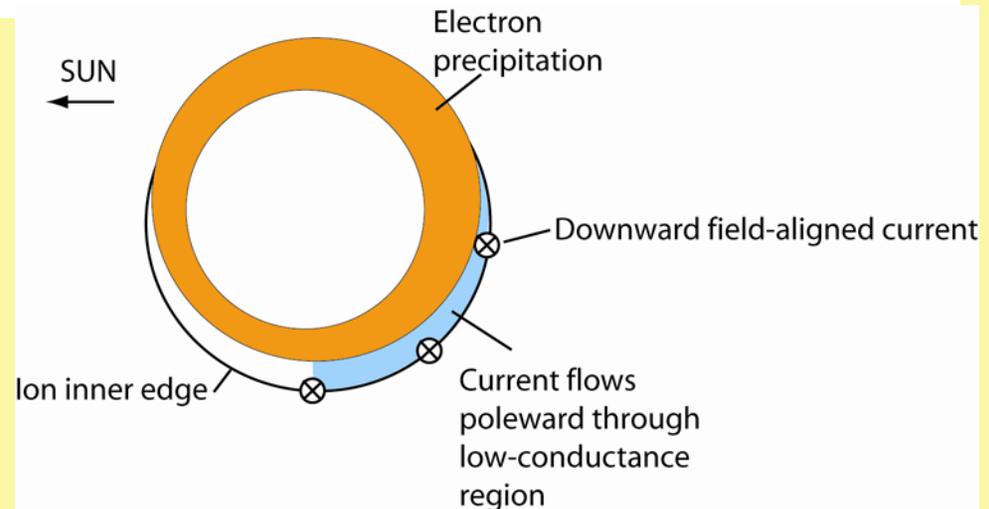
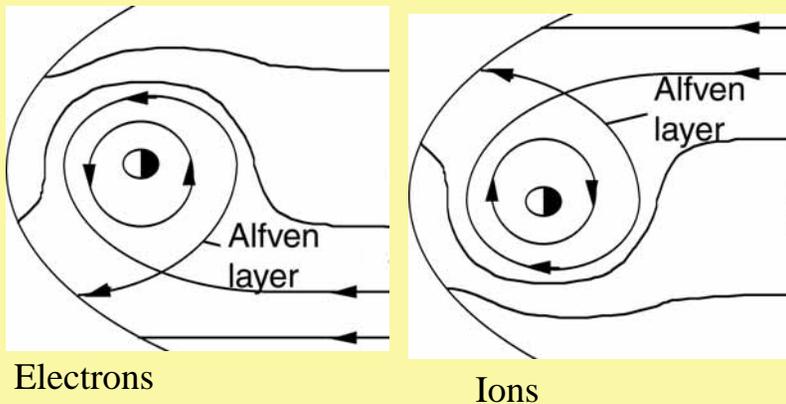


Ions

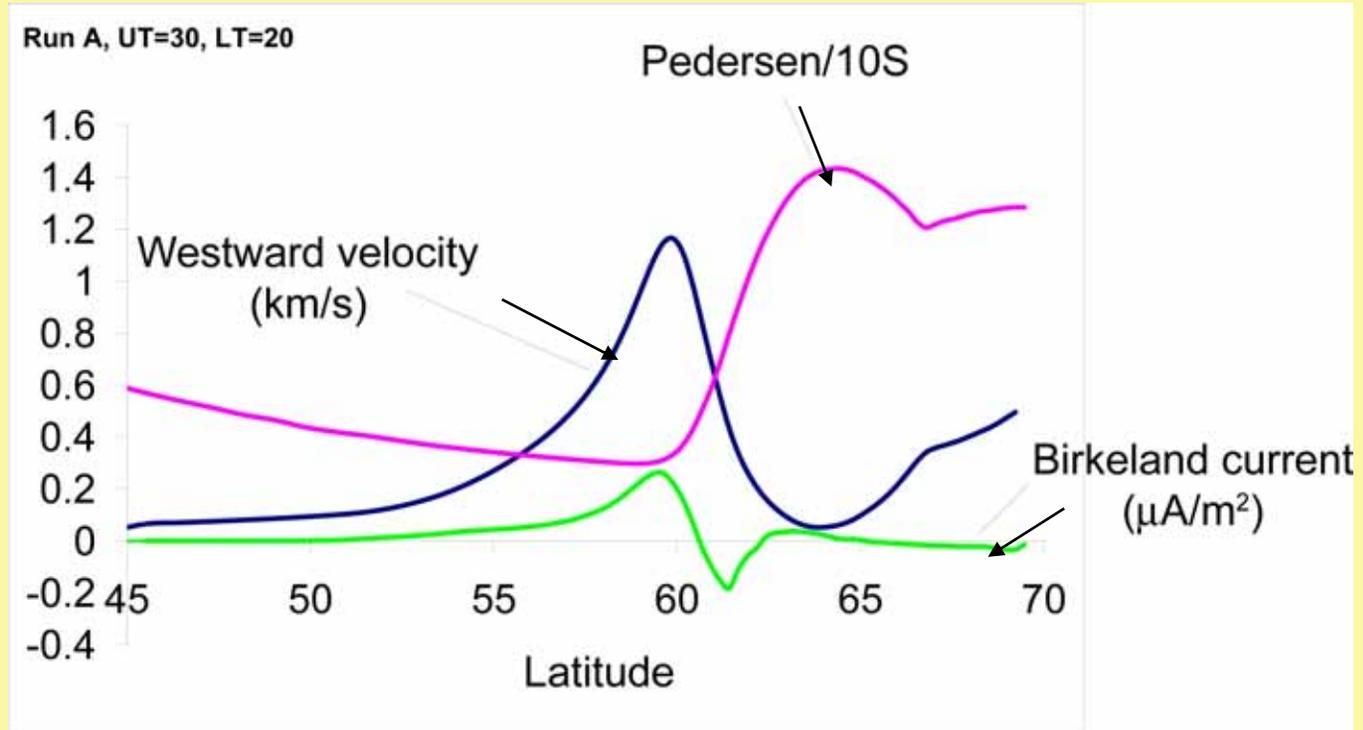


# Physical Interpretation of SAPS

- In pre-midnight sector, plasma-sheet ions drift closer to Earth than electrons.
- Electrons mostly control auroral conductance.
- Therefore, in the pre-midnight sector, the inner edge of the plasma-sheet ions lies at lower  $L$  than the auroral conductance enhancement.
- Most of region-2 current is driven by ions (they carry  $\sim 85\%$  of pressure).
- Therefore, some region-2 current flows into low-conductance, subauroral ionospheric region in the pre-midnight sector.
- This gap between these two regions becomes larger in great storms, because precipitation erodes the electron inner edge.



# Latitudinal Cut Through a SAPS

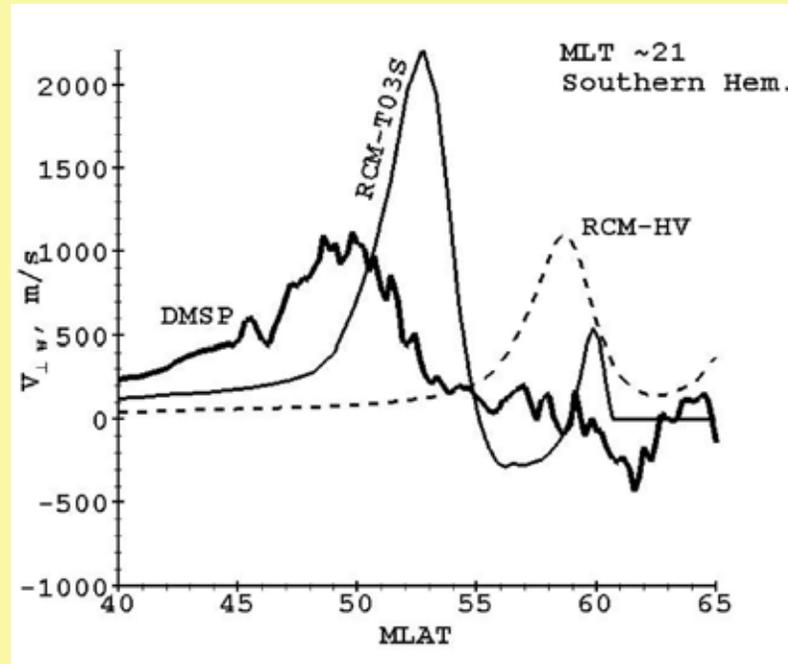


- In the RCM, SAPS typically lie on the equatorward edge of the diffuse-auroral conductance enhancement.
- Equatorward part of SAPS lies in a region of weak downward current.

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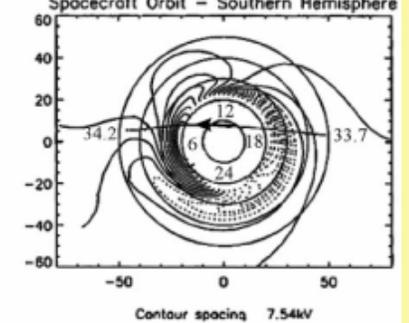
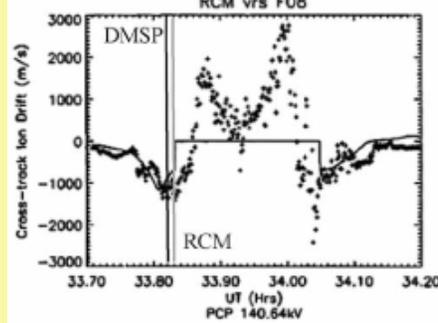
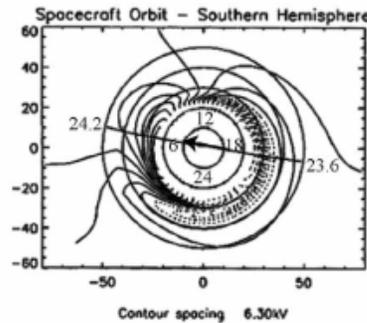
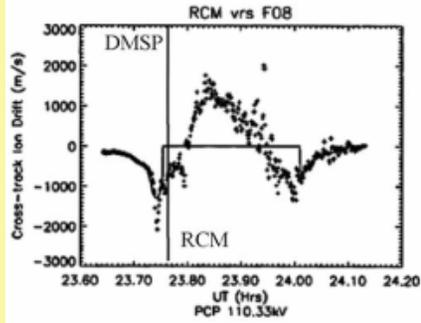
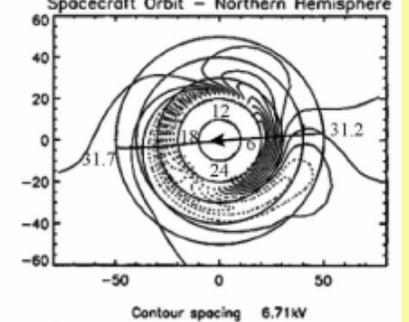
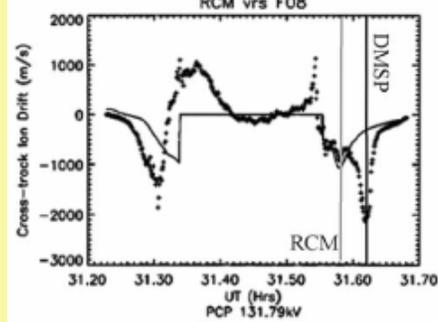
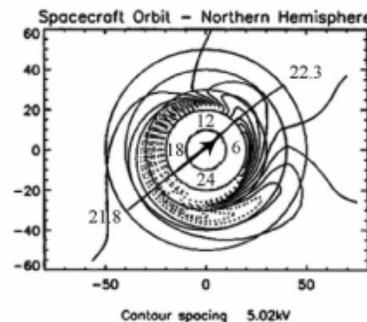
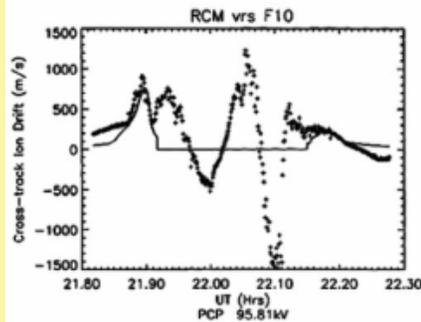
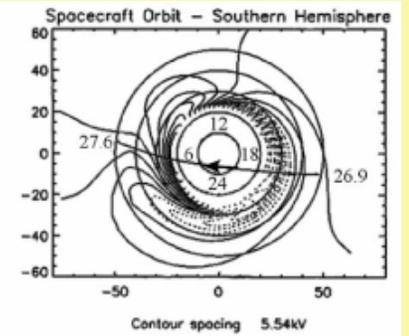
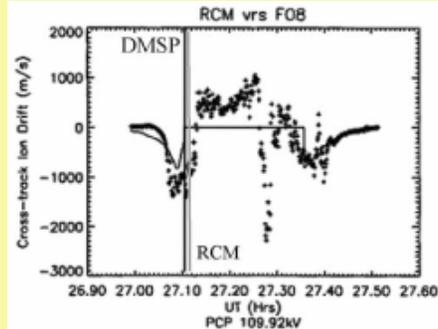
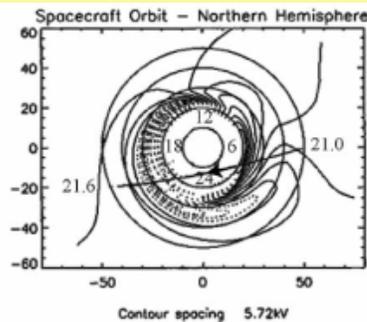
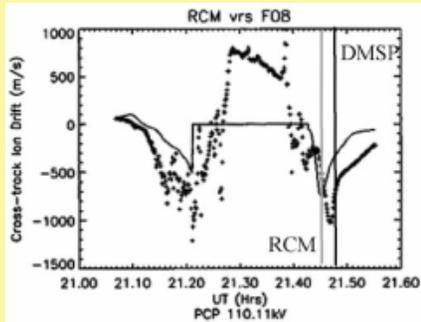
# How Well Does RCM Fit SAPS Observations?



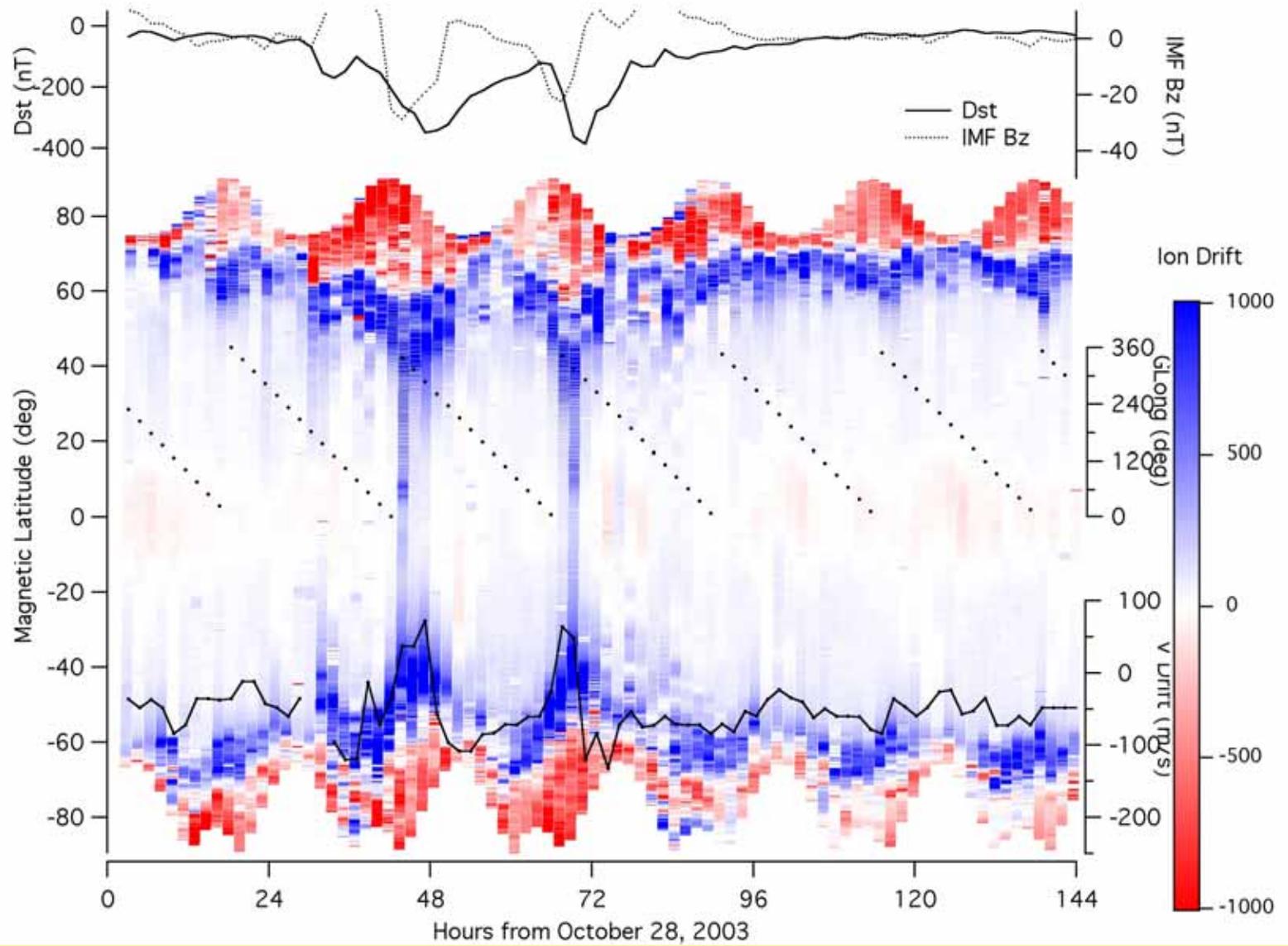
Westward ion flow velocity measured by DMSP about 16 UT on March 31, 2001. The peak velocities lie equatorward of diffuse electron aurora. “HV” and “T03S” refer to RCM runs using the *Hilmer-Voigt* (1995) and *Tsyganenko* (2003S) magnetic fields models. From *Sazykin et al.* (in *Physics and Modeling of Inner Magnetosphere*, 2004). (For more examples, see *Garner et al.* (JGR, 2004).)

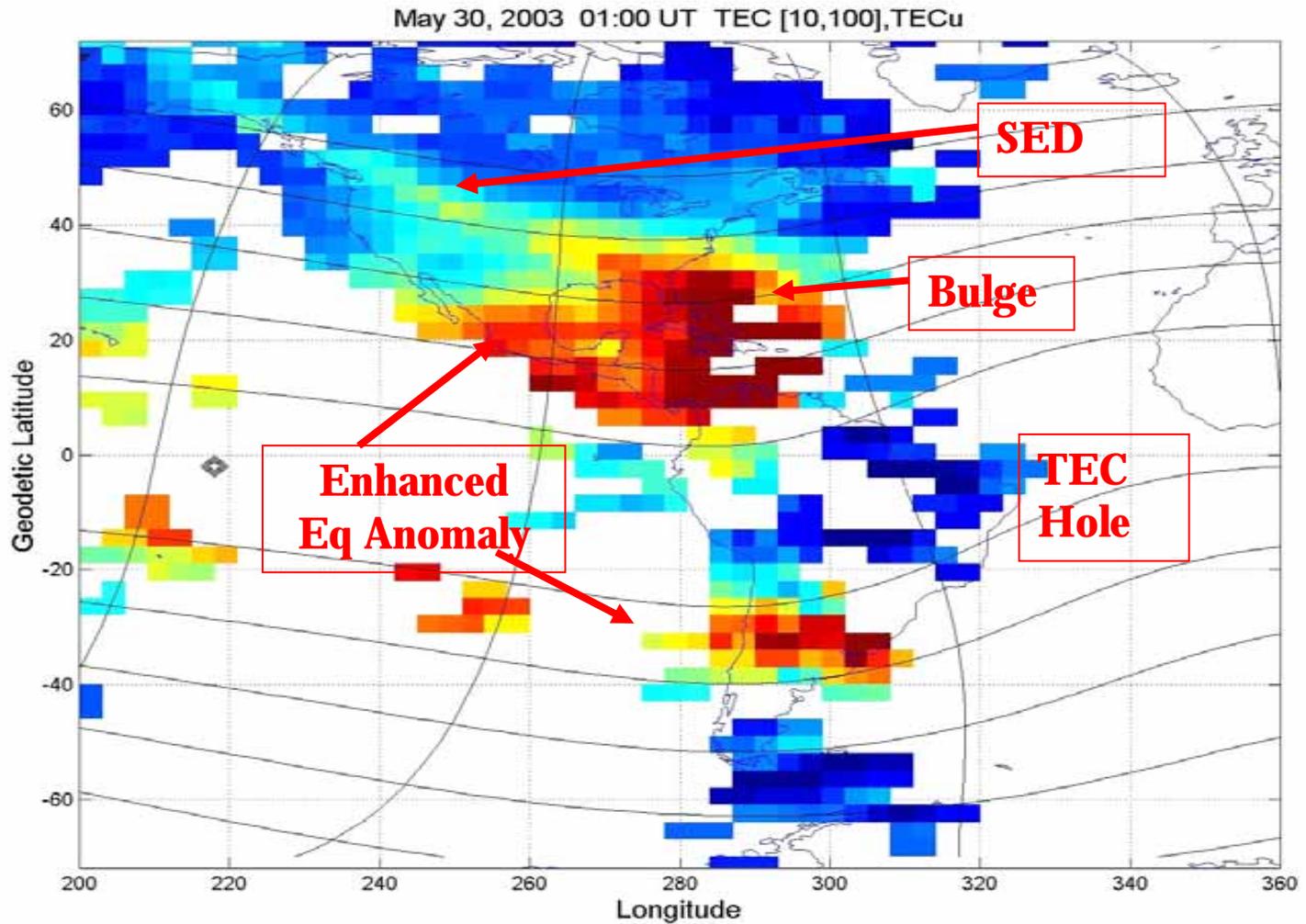
# RCM/DMSP Comparison

(Garner et al., 2004)



DMSF F13 Oct 28 - Nov 2, 2003 ~18:30 LT





*Courtesy of John Foster*

# Summary

- Rice Convection Model has been able to capture the phenomenology of many observed sub-auroral electric field features, including:
  - Overshielding and Undershielding: Model results generally agree with data as to conditions of occurrence, location, and magnitude.
  - SAPS: Model is able to produce typical features as to location, width, and magnitude.
- Model is less good at getting quantitatively accurate electric fields at a given place at a given time. Ability to accurately model extreme events unproven.
- What is currently missing in RCM?
  - Realistic neutral wind model
  - Ion precipitation
  - Reliable knowledge of outer plasma boundary condition
  - Self-consistent ionospheric conductance model
  - Self-consistent magnetic field model
  - Realistic internal magnetic field model. RCM currently uses a dipole aligned with the spin axis.
- Need for coupled models of magnetosphere/ionosphere/thermosphere.

The End