Conductance: An essential element in MI Coupling

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With thanks to O. Amm, J. W. Gjerloev, W. Lotko, J. G. Lyon, V. G. Merkin, S. Milan, C. L. Waters, B. Zhang

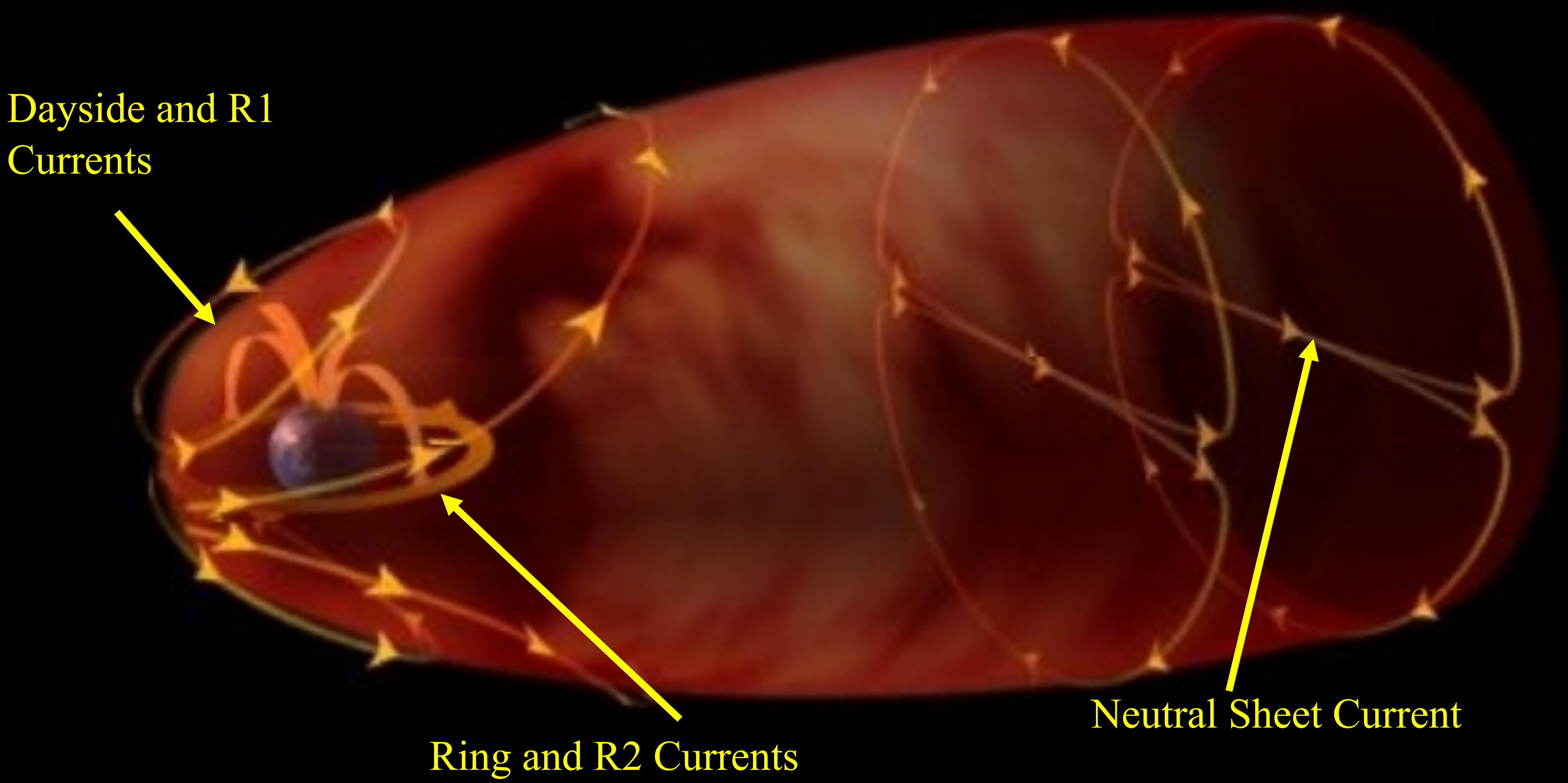
Motivation

- To fully understand geospace we must treat the ionosphere and magnetosphere as a fully coupled system
- Ionospheric conductivity plays a key role in regulating the response of the coupled system
  - Essential role in the closure of field aligned currents and the location of energy deposition into the ionosphere and thermosphere
- Direct measurement of the ionospheric conductivity is extraordinarily difficult
  - Provides a unique opportunity for combining measurement and modeling techniques
- Ionospheric conductivity can have significant consequences on the response of the system to solar wind driving

Outline

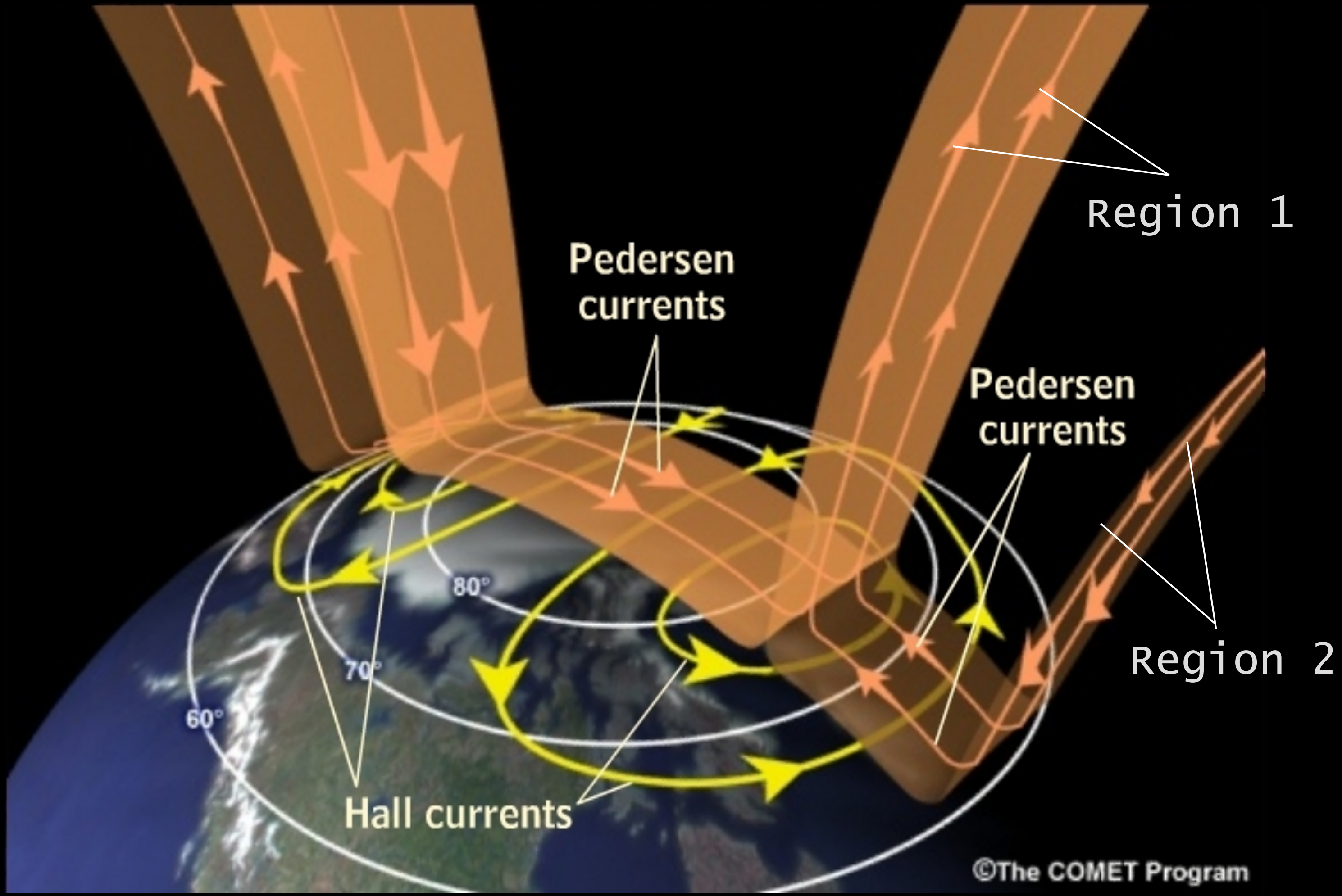
- Motivation & Background
  - System Structure
  - MI Coupling Basics
- Measurement
  - Particle Path
  - Current – Potential Path
- Modeling
  - Knight - FL
  - Advanced LFM with Ovation Prime comparison
- Impacts
  - Hemispheric Current Differences
  - Aurora and substorms
  - Magnetotail Dynamics
- Conclusions

Magnetospheric Currents



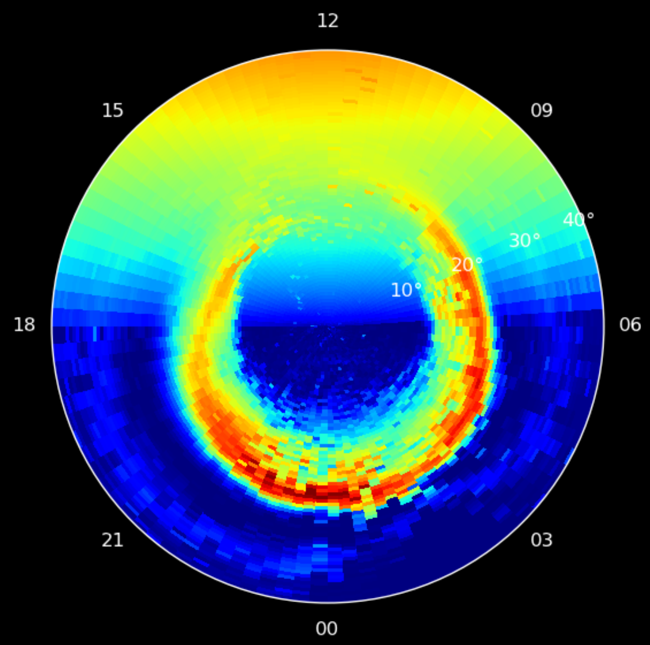
- Magnetopause current systems are created by the force balance between the Earth's dipole and the incoming solar wind

High Latitude Ionospheric Currents



- FAC from the magnetosphere close though Pedersen and Hall Currents in the ionosphere

Aurora and Conductance



- The aurora is formed by complicated process involving collisions between the energetic particles carrying the field-aligned currents and the ionosphere and leads to enhancements in conductance through out the aurora oval

MI Coupling Equations

- As described in *Kelley [1989]* The fundamental equation for MI coupling is obtain by breaking the ionospheric current into parallel and perpendicular components and requiring continuity

$$\nabla \bullet \vec{J} = \nabla_{\perp} \bullet J_{\perp} + \frac{\partial J_{\parallel}}{\partial s} = 0$$

- Assuming no current flows out the bottom of the ionosphere we get

$$J_{\parallel} = \int_{\Delta s} (\nabla_{\perp} \bullet J_{\perp}) ds$$

- Further assuming the electric field is uniform with height we get

$$J_{\parallel} = \nabla_{\perp} \bullet \left(\overleftrightarrow{\Sigma} \bullet \vec{E}_I \right)$$

- And finally using and electrostatic approximation in the MI coupling region we obtain

$$J_{\parallel} = -\nabla_{\perp} \bullet \left(\overleftrightarrow{\Sigma} \bullet \nabla_{\perp} \Phi \right)$$

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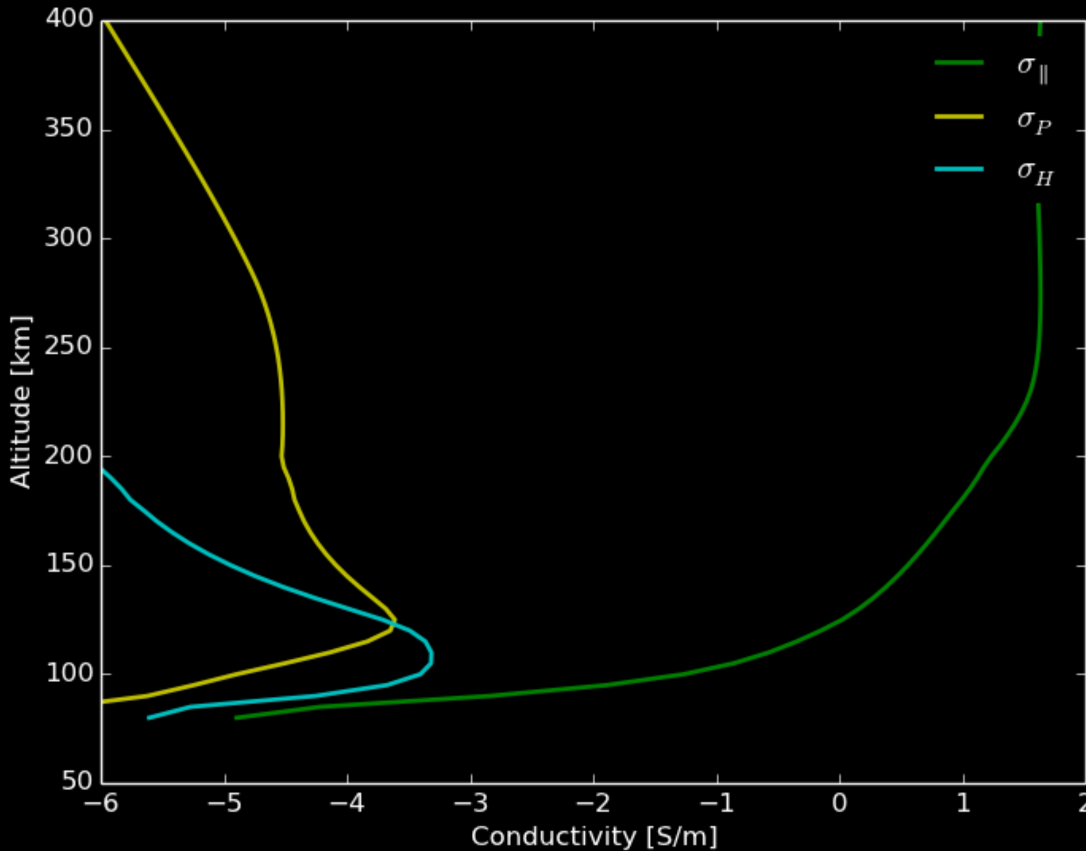
Conductivity from Particle Measurements

- Initial work in determining ionospheric conductivity came based upon understanding the height structure of ionosphere and measurements of N_e, ν, Ω



$$\sigma_\parallel = \frac{N_e e^2}{m_e(\nu_{en\parallel} + \nu_{ei\parallel})}$$

$$\sigma_P = \frac{eN_e}{B}\left(\frac{\nu_{in}\Omega_i}{\nu_{in}^2 + \Omega_i^2} + \frac{\nu_{en\perp}\Omega_e}{\nu_{en\perp}^2 + \Omega_e^2}\right)$$

$$\sigma_H = \frac{eN_e}{B}\left(\frac{\Omega_e^2}{\nu_{en\perp}^2 + \Omega_e^2} - \frac{\Omega_i^2}{\nu_{in}^2 + \Omega_i^2}\right)$$

$$\Sigma = \int \sigma \, dh$$

$$\vec{J} = \sigma_P \vec{E}_\perp + \sigma_H \hat{b} \times \vec{E}_\perp + \sigma_\parallel E_\parallel \hat{b}$$

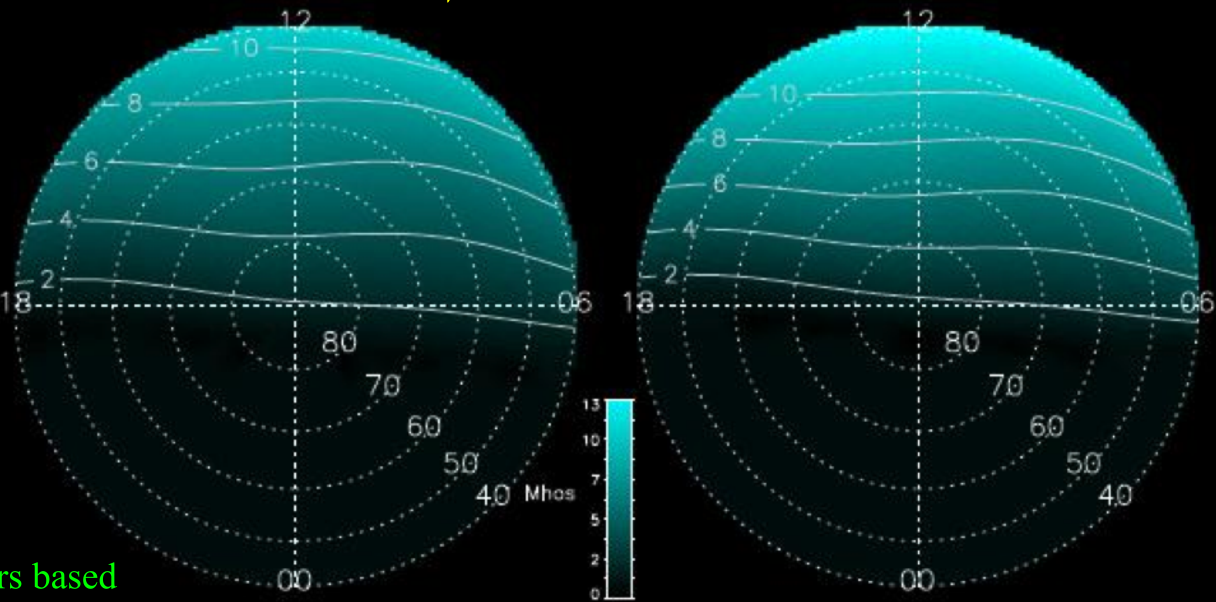
Based upon IRI data run by A. Richmond

EUV Conductance

- Combination of ISR, neutral models, and collision frequency leads to conductance models for solar contribution

$$\Sigma_p = F_{10.7}^{0.49}\left(0.34\cos\chi + 0.93\cos^{1/2}\chi\right)$$

$$\Sigma_H = F_{10.7}^{0.53}\left(0.81\cos\chi + 0.54\cos^{1/2}\chi\right)$$



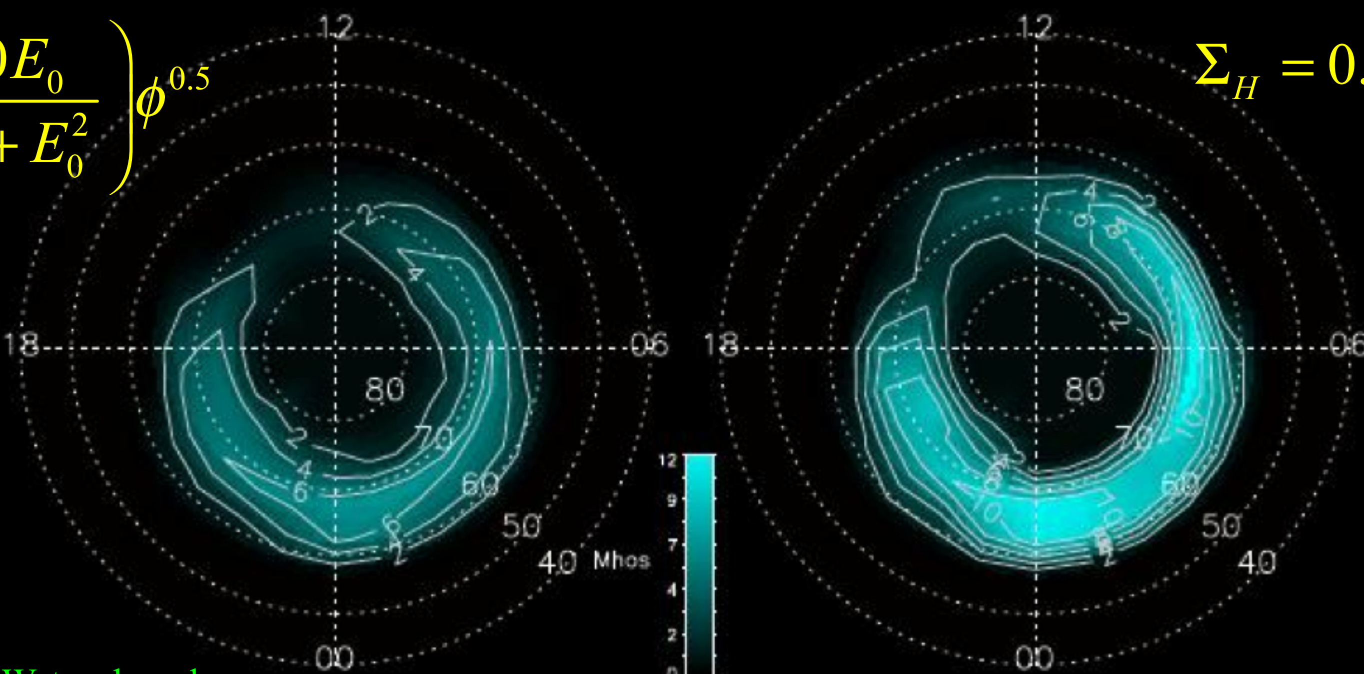
Adapted from C. Waters based upon Rasmussen et al. (1988)

Auroral Zone Conductance

- Direct calculation from satellite observations of particle flux
- Inferred from auroral imaging

$$\Sigma_P = \left(\frac{40E_0}{16 + E_0^2} \right) \phi^{0.5}$$

$$\Sigma_H = 0.45 E^{0.85} \Sigma_P$$



Adapted from C. Waters based upon Hardy et al. 1987

Conductance from Fields

- It is possible to use sophisticated spherical vector calculus tools to compute the conductance from a combination of magnetic field perturbation observations and ionospheric electric fields

$$\vec{J}_\perp = \Sigma_P \vec{E}_\perp + \Sigma_H \left(\vec{B} \times \vec{E}_\perp\right) = \begin{pmatrix} \Sigma_P & \Sigma_H \\ -\Sigma_H & \Sigma_P \end{pmatrix} \bullet \vec{E}_\perp$$

$$\Sigma_P = \frac{\vec{J}_\perp \bullet \vec{E}_\perp}{\left|\vec{E}_\perp\right|^2} \quad \Sigma_H = \frac{\hat{r} \bullet \left(\vec{J}_\perp \times \vec{E}_\perp\right)}{\left|\vec{E}_\perp\right|^2}$$

$\vec{E}_\perp$ from ion radar

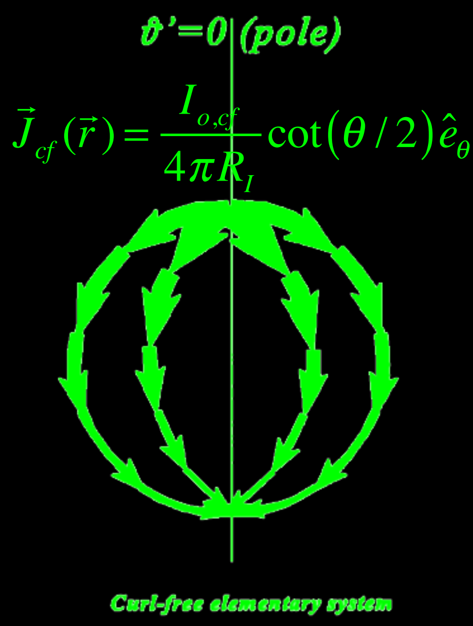
$$\vec{J}_\perp = \vec{J}_{cf} + \vec{J}_{df}$$

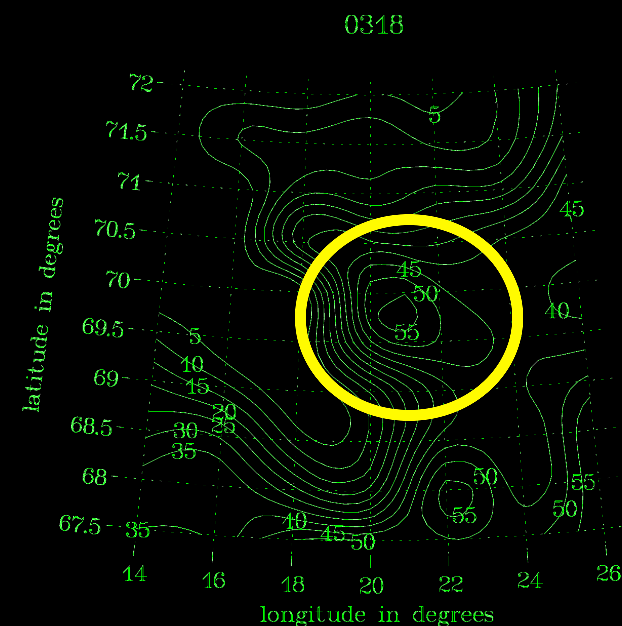
$\vec{J}_{df}$ from ground mag

$\vec{J}_{cf}$ from radial FAC

Regional Determination

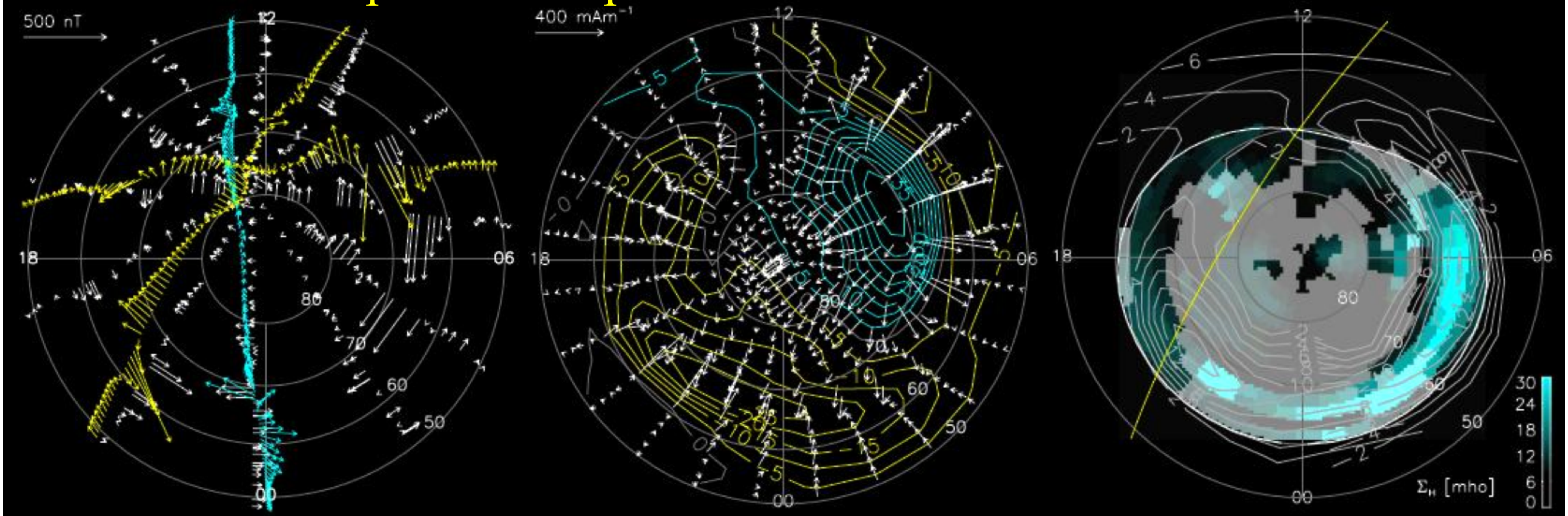
- *Amm,* 2001 used the SECS approach to combine MIRICLE and BEAR magnetometer data with STARE RADAR observations to determine
  - Upward projection of magnetometer data for determination of $\mathbf{J}_{\mathbf{cf}}$ requires assumption about Σ_H/Σ_P





Global Determination

- *Green et al., 2007* – Used Iridium, SuperDARN, Intermagnet observations to reconstruct Conductances over polar cap
  - Since Iridium provides $\mathbf{J_{cf}}$ no need to make assumption about Σ_H/Σ_P
  - Uses Spherical Cap Harmonics instead of SECS



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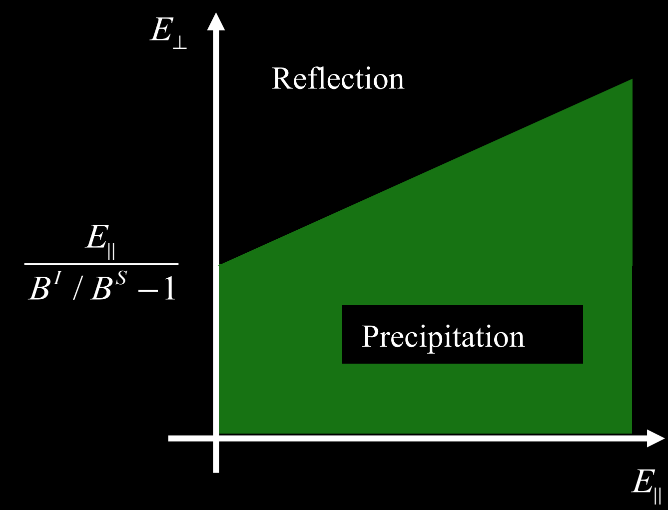
Auroral Electron Fluxes

- *Fridman and Lemaire*, 1980 developed a kinetic model for the flux downward going electrons in the auroral acceleration region
- Starting with conservation of total energy and adiabatic invariants you get

$$E^I = E^S + E_{\parallel}$$

$$E_{\parallel}^I = E_{\parallel}^S - E_{\perp}^S \left(\frac{B^I}{B^S} - 1 \right) + E_{\parallel}$$



- Integrating a isotropic distribution function over the region where precipitation occurs yields

$$F = F_o \frac{B^I}{B^S} \left[1 - \frac{e^{-xE_{\parallel}/E^S}}{1+x} \right] \text{ with } \mathrm{F_o} = N_e \left(\frac{E^S}{2\pi m_e} \right)^{\frac{1}{2}} \text{ and } x = \frac{1}{B^I / B^S - 1}$$

Energy Fluxes

- Considering the limit where the parallel potential drop is larger than the thermal energy in the source region we get the *Knight 1973* relationship between the FAC strength and the parallel potential drop

$$\varepsilon^S \ll \varepsilon_{\|} \ll \frac{\varepsilon^S}{x} \Rightarrow x \ll \frac{x\varepsilon_{\|}}{\varepsilon^S} \ll 1$$

$$\varepsilon_{\|} \approx \frac{F\varepsilon^S}{xF_o B^I / B^S} \approx \left(\frac{B^I / B^S - 1}{B^I / B^S}\right)\left(\frac{\sqrt{2\pi m_e \varepsilon^s}}{N_e e}\right) J_{\|}$$

Auroral Fluxes in the LFM

- Begin by computing the particle energy and number flux at the inner boundary of the LFM simulation domain

$$\varepsilon_o = \alpha c_s^2 \qquad\qquad \phi_\mathrm{o} = \beta\rho\varepsilon_o^{1/2}$$

  - α includes effects of calculating electron temperature from the single fluid temperature known in MHD
  - β includes effects possible effects plasma anisotropy and loss cone filling
  - The initial number flux is the $E_{||}$=0 case of the Flux equation which allows for the inclusion of diffuse aurora

- The total energy of the particles is

$$E = E^S + E_{||} = E^S + \frac{RJ_{||}\left(E^S\right)^{1/2}}{\rho}$$

  - The factor R allows for scaling the parallel potential drop based upon the sign of the current and account for the possibility of being outside the regime of the scaling

Auroral Fluxes in the LFM

- The final step is to compute the flux of precipitating electrons using the flux formula in regions of upward current or downward streaming electrons

$$\phi = \phi_o \left(8 - 7 e^{\frac{-\varepsilon_{||}}{7\varepsilon_o}} \right) \quad \forall \;\; \varepsilon_{||} > 0$$

  - Using $B^I/B^S = 8$ for a dipole magnetic field and 2 R_E gap between the source region and the ionosphere

- In regions of downward current we apply

$$\phi = \phi_o e^{\frac{\varepsilon_{||}}{\varepsilon_o}} \quad \forall \;\; \varepsilon_{||} < 0$$

  - With the additional correction that the factor R is taken to be 5 time smaller in these regions

- We also utilize the linearization the energy flux is simply the product of the energy and the number flux

Conductances from Particle Flux

- *Spiro et al*. [1982] used Atmospheric Explorer observations to determine a set of empirical relationships between the average electron energy and the electron energy flux

$$\Sigma_P = \left(\frac{20E_0}{4+E_0^2}\right)\phi^{0.5} \qquad \Sigma_H = E^{0.625}\Sigma_P$$

- *Robinson et al*. [1987] revised the relationships using Hilat data and careful consideration of Maxwellian used to determine the average energy

$$\Sigma_P = \left(\frac{40E_0}{16+E_0^2}\right)\phi^{0.5} \qquad \Sigma_H = 0.45E^{0.85}\Sigma_P$$

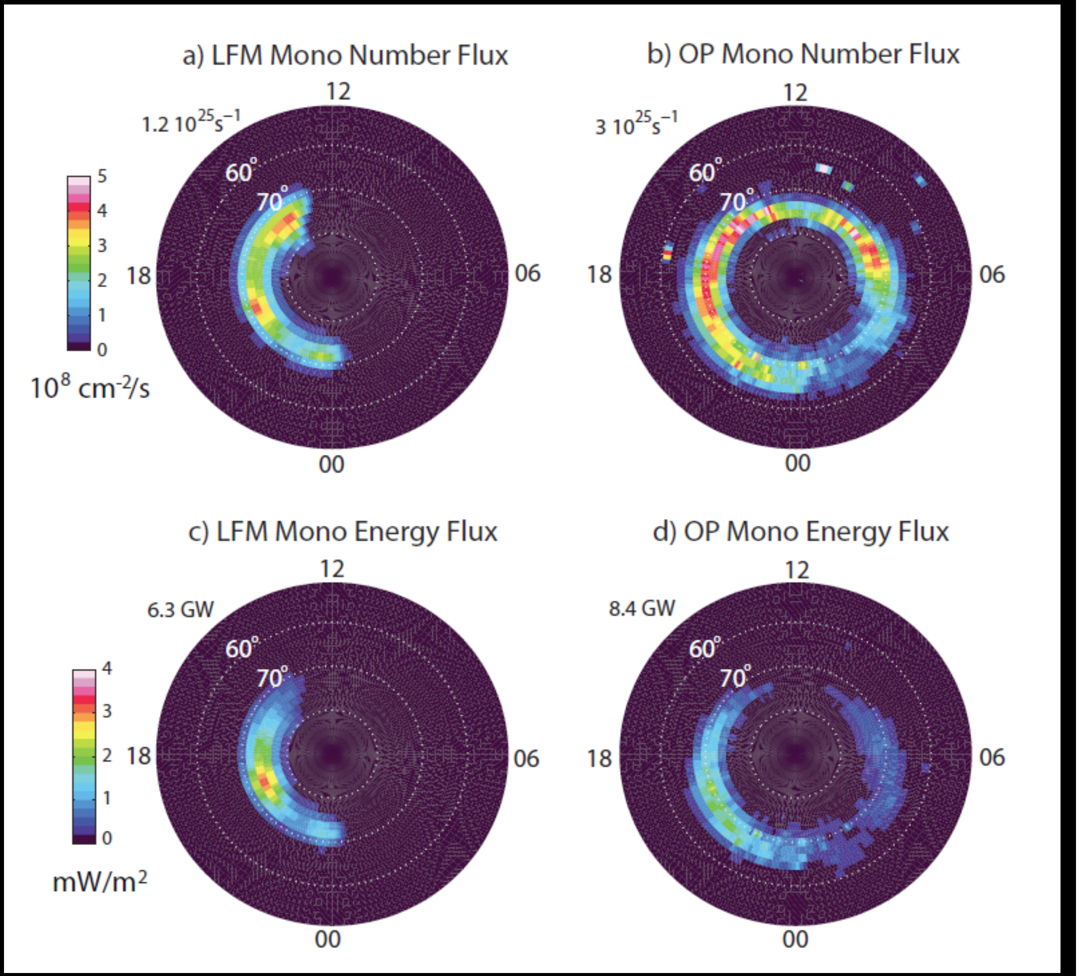
- *Hardy et al*. [1987] reports a version of the *Robinson et al*. with slight typographical error

$$\Sigma_P = \left(\frac{40E_0}{16+E_0^2}\right)\phi^{0.5} \qquad \Sigma_H = 0.45E^{0.625}\Sigma_P$$

Alternative Approach to e⁻ precip

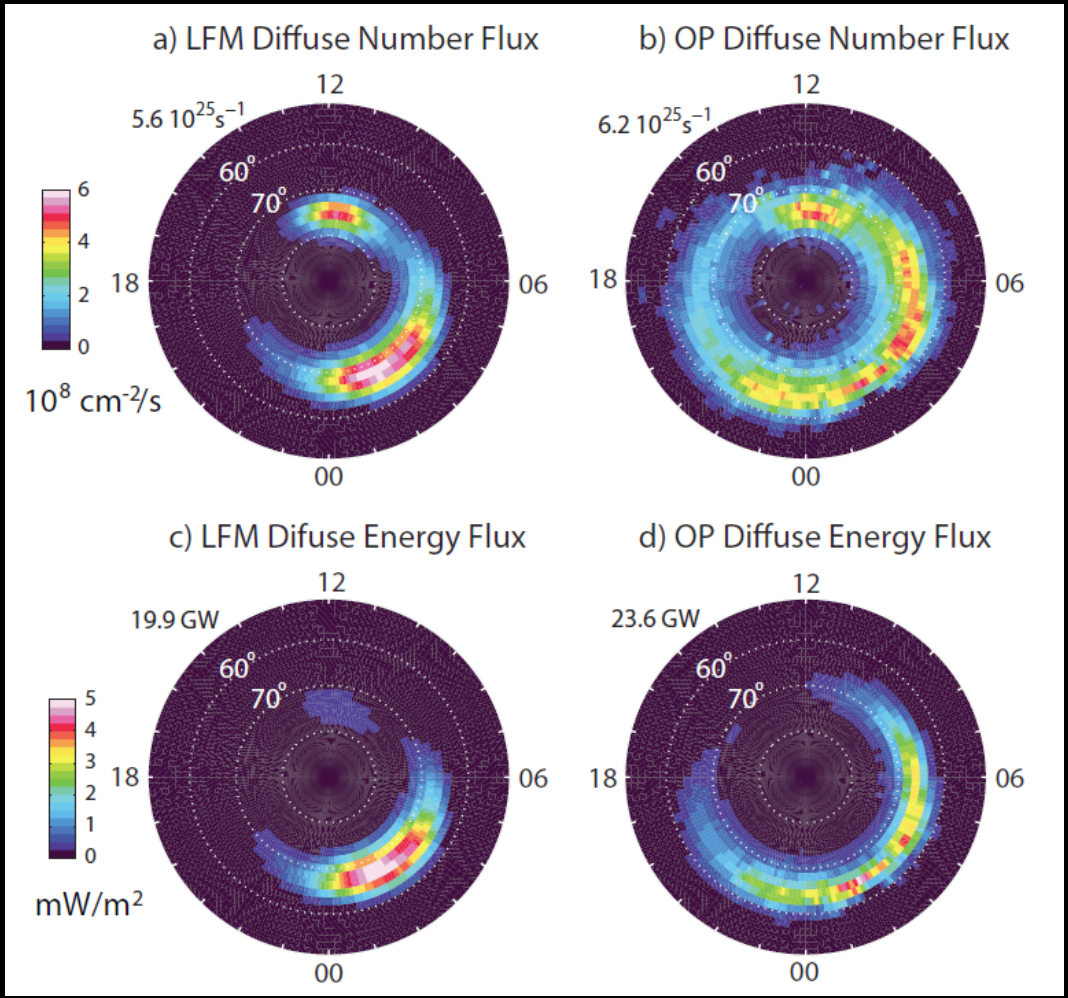
- Zhang noted the circular nature of using the Knight relationship to define the potential drop
- Alternative anomalous resistivity formulation based upon *Lotko and Shen 1991*

$$V = R' \frac{\bar{v} J_{\parallel}}{n_e} \text{ with } R' = \frac{R m_e \Delta l}{R_M e^2}$$



From Zhang with Ovation Prime from *Newell et al.* 2010

Improved Diffuse Precip



From Zhang with Ovation Prime from *Newell et al.* 2010

- Zhang also noted need for improving the diffuse precipitation model
  - Use a DPB to specify non uniform values of β over the polar cap
  - Identify the location of the cusp and set β=1 inside that region

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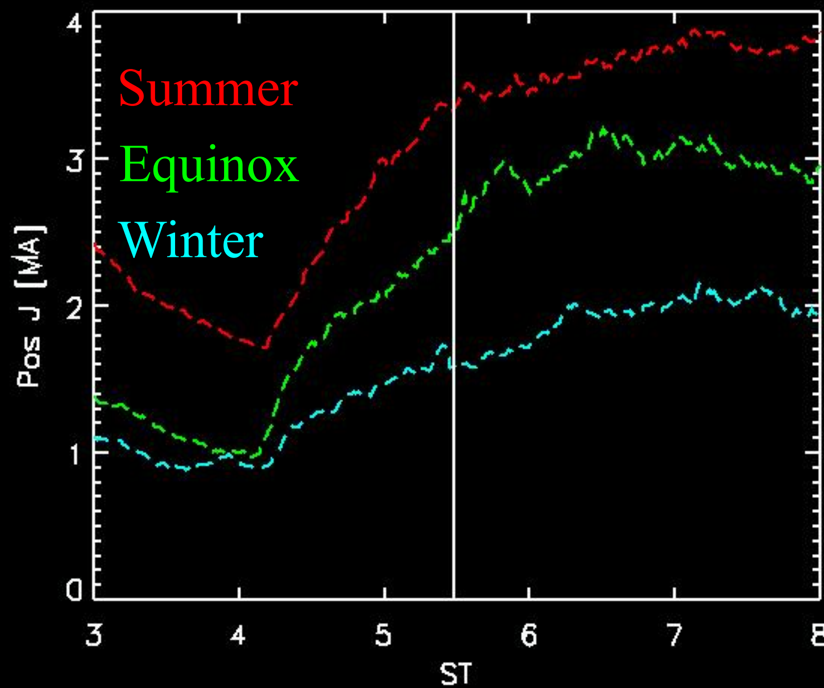
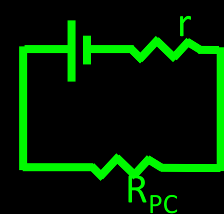
Global Field Aligned Currents



From *Wiltberger et al.* 2009

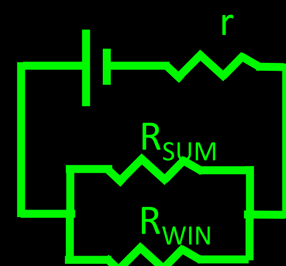
- *Papitashvili et al.* [2002] reported near ratio of 1.57 NS/SW and 1.00 NE/SE for conditions similar to those used in this study
  - We see 1.0 in equinox and approximately 1.8 for solstice

- *Fedder and Lyon*, 1987 showed that the magnetosphere has current-voltage relationship that similar to a simple circuit of a generator with internal resistance driving an external resistor as proposed by *Hill*, 1984



$$\Phi_{PC} = IR_{PC} = \Phi_M - Ir$$

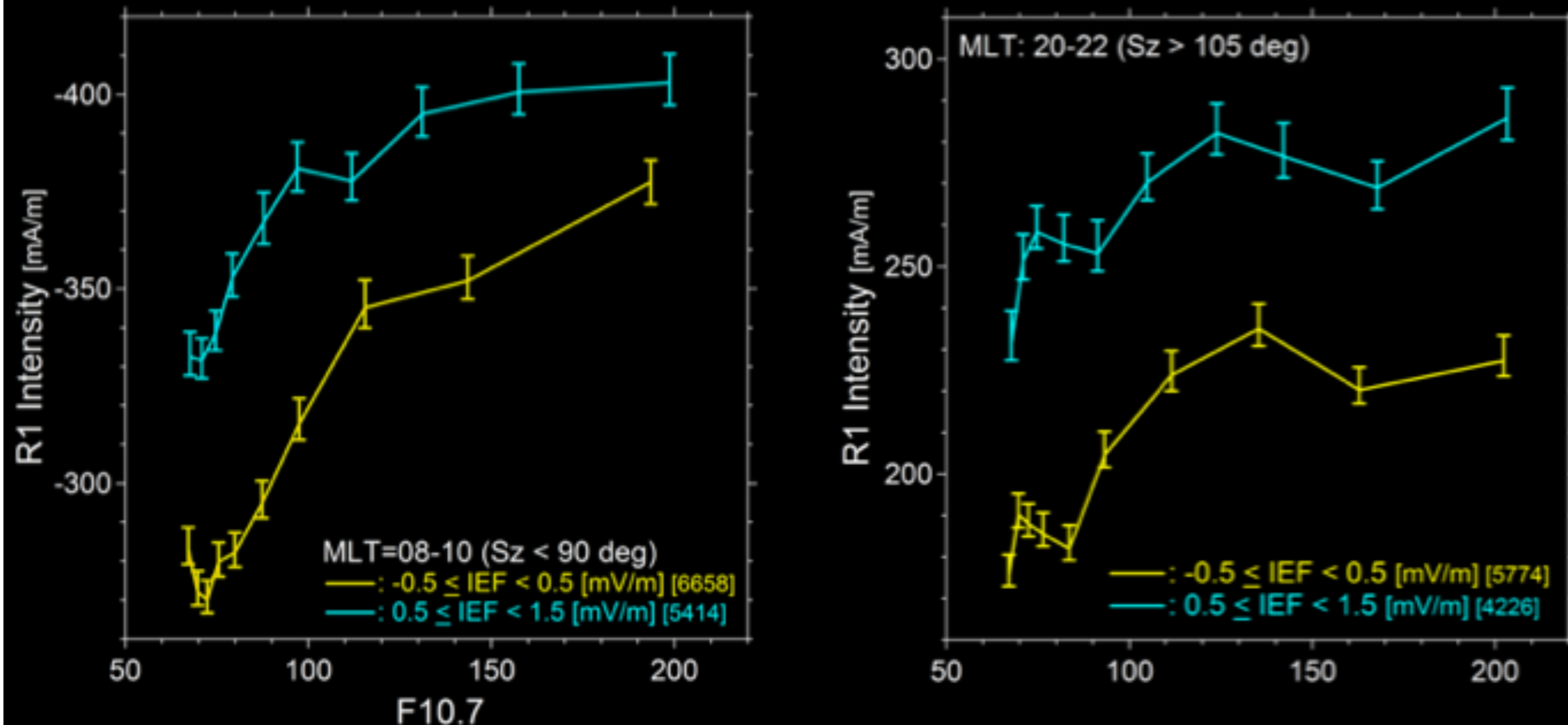
- In order to explain the ordering of the currents we need to expand this model to consider hemispheres with different conductivities



$$R_{PC} = \frac{R_{NOX}}{2}$$

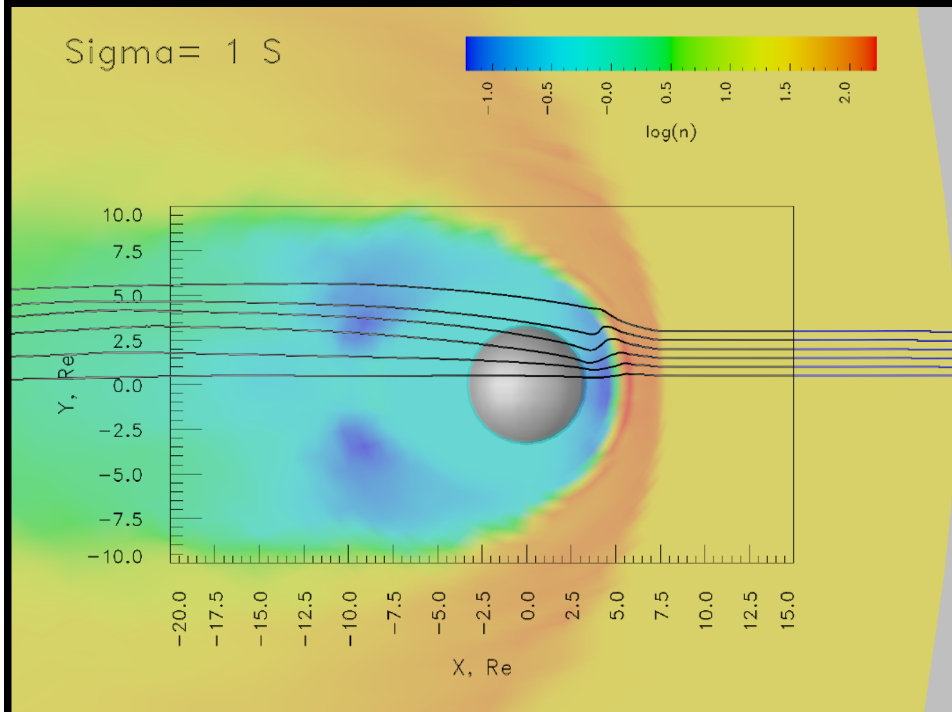
$$R_{PC} = \frac{R_{SUM} R_{WIN}}{R_{SUM} + R_{WIN}}$$

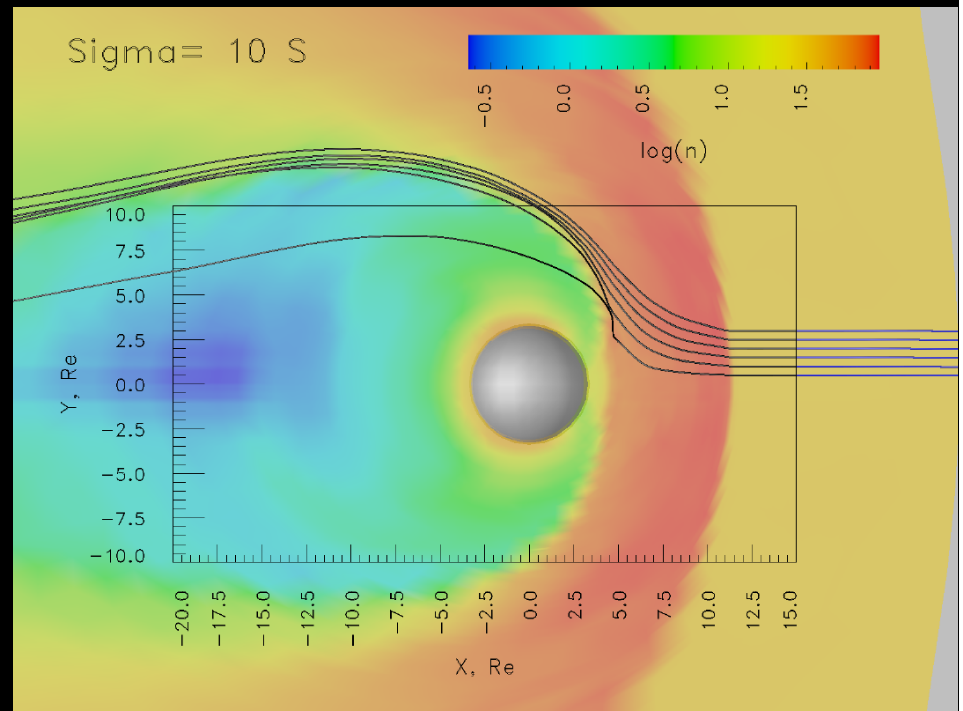
Ohtani Current Study



- *Ohtani et al.* [2014] examined the dependence of FAC currents on solar illumination
  - Found similar scaling properties regardless of F107 levels
  - Conclude that ionospheric conductance plays a key role in SW-M-I coupling

Conductance and BS and MP



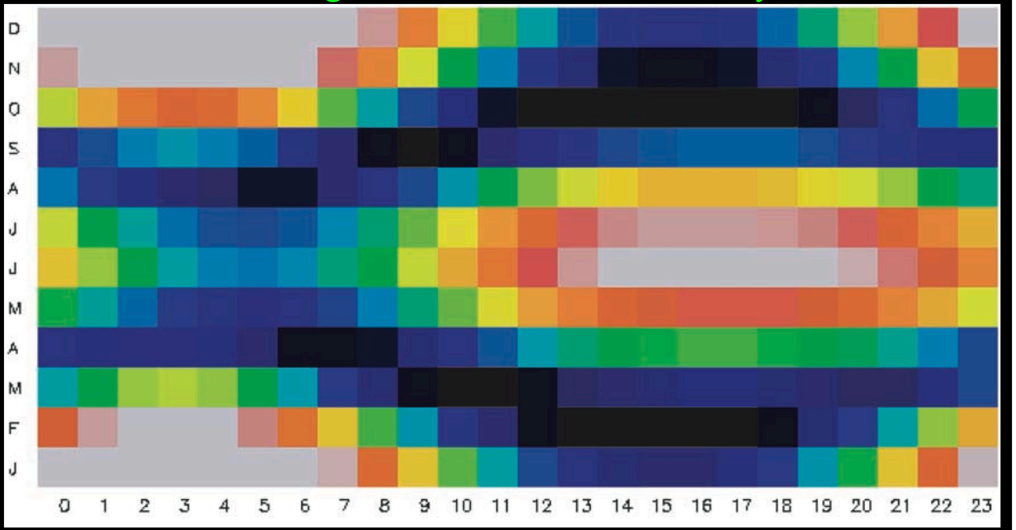


- *Merkin et al.,* 2005 used LFM simulations with fixed Pedersen conductance to examine its influence on MI coupling with the same SW conditions
  - The shape and location of the MP & BS change with conductance
    - Also has an impact on the CPCP and can play a role in polar cap saturation

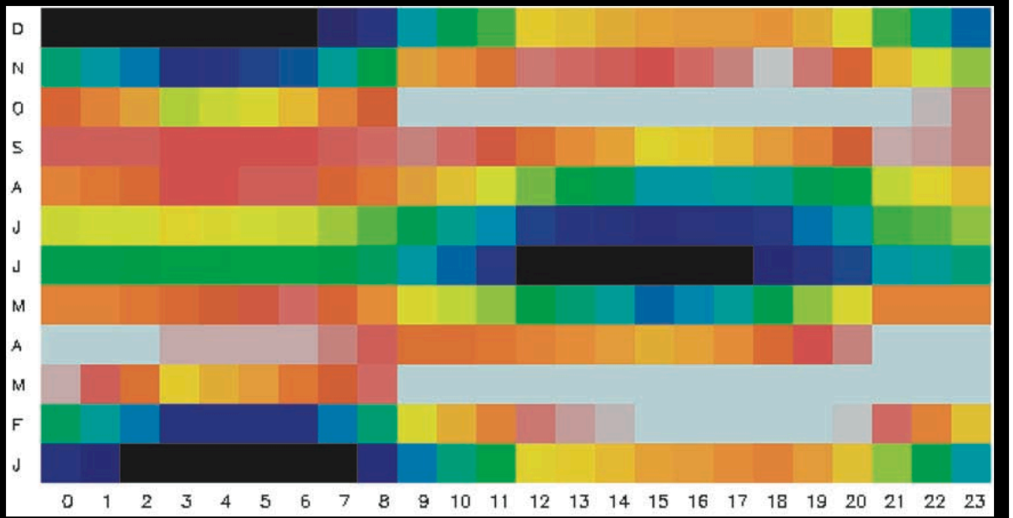
Discrete Aurora and Conductance

- *Newell et al.*, 1996 & 2002 examined DSMP data to find that discrete aurora rarely occur in regions of solar illumination or diffuse aurora
  - Presume that sufficient ionospheric conductivity exists to support MI coupling electric fields
  - Conclude that ionospheric conductivity is a "key factor" controlling discrete aurora occurrence

Average Auroral Zone Conductivity

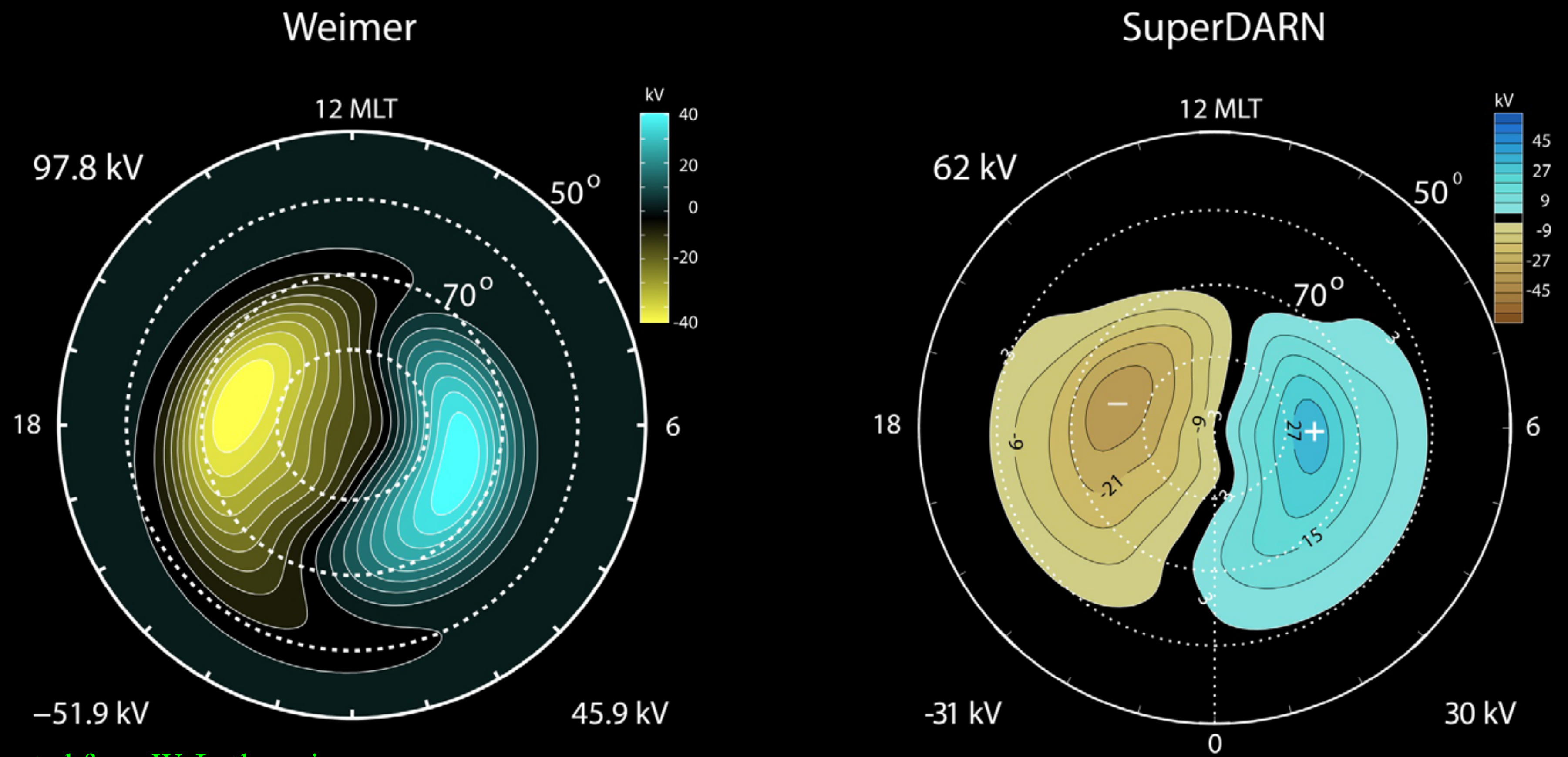


Seasonal and Diurnal Variation in Amm



Adapted from *Newell et al.* 2002

Clockwise tilt of Convection

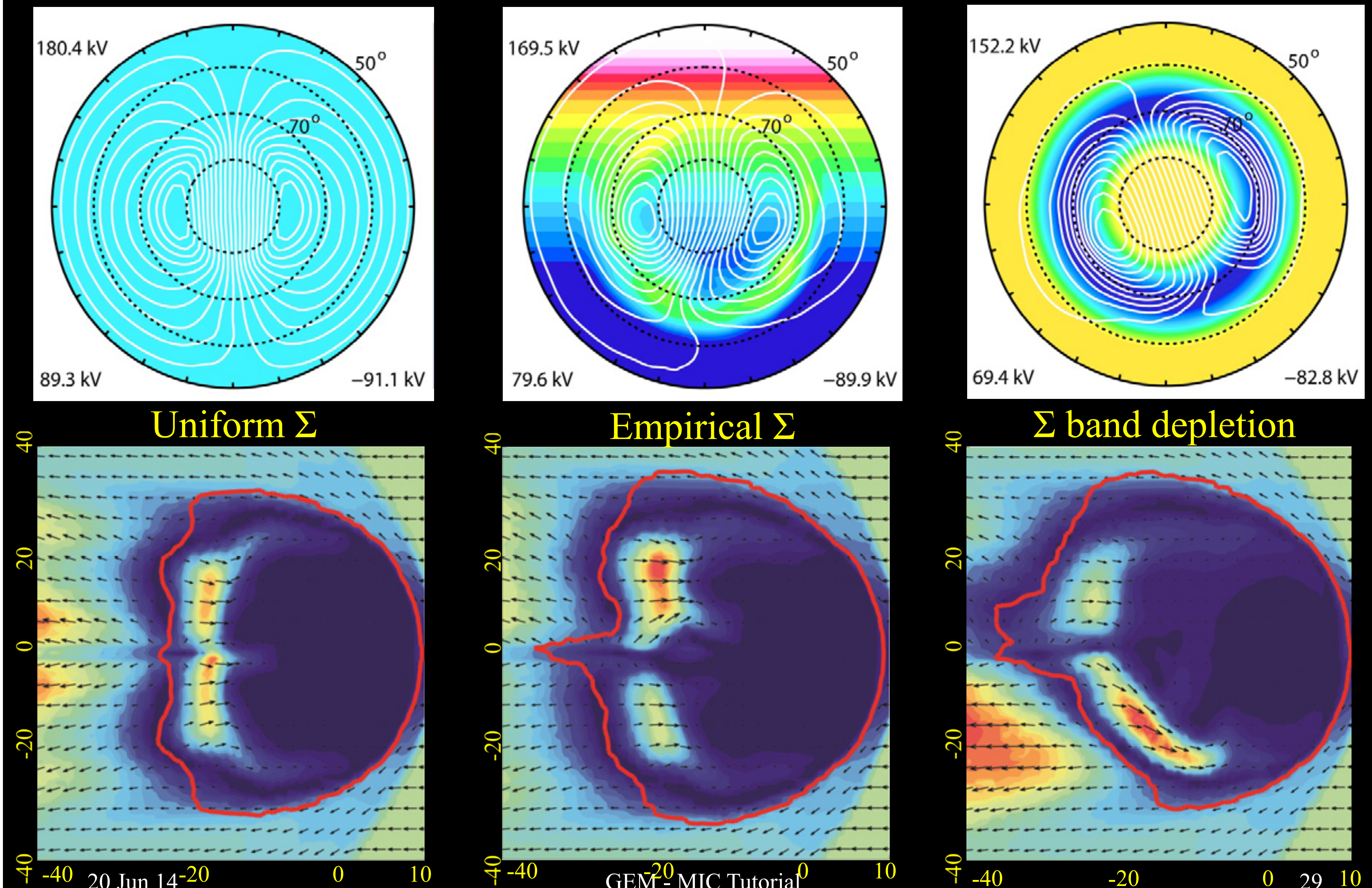


Adapted from W. Lotko using W05 and Cousins

IMF: $B_z = -5$ nT SW: $V_x = 400$ km/s, $n = 8/\text{cm}^3$

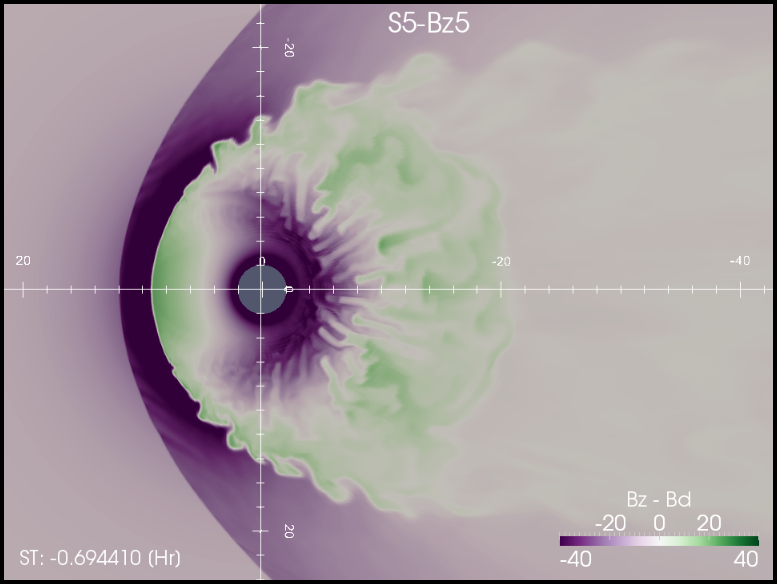
- *Yasuhara et al.*, 1983 explained this was a result of the meridional gradient in hall conductance at PC boundary

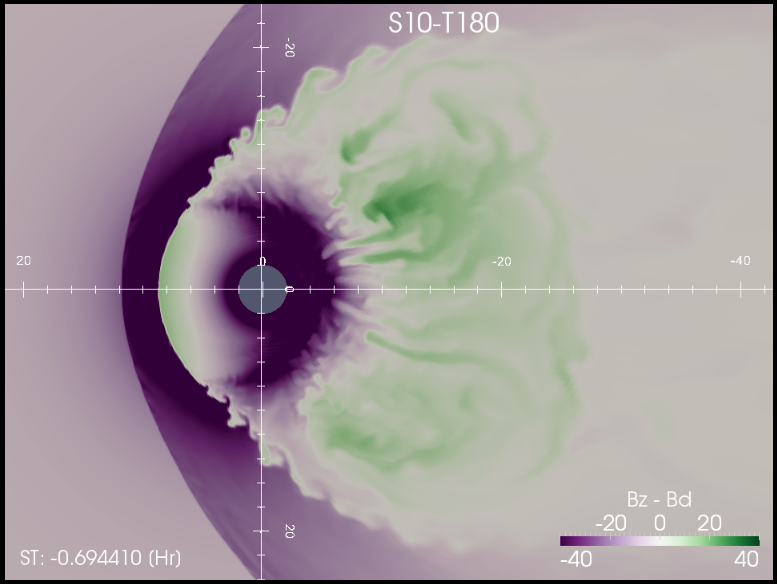
Conductance and Magnetotail Flows

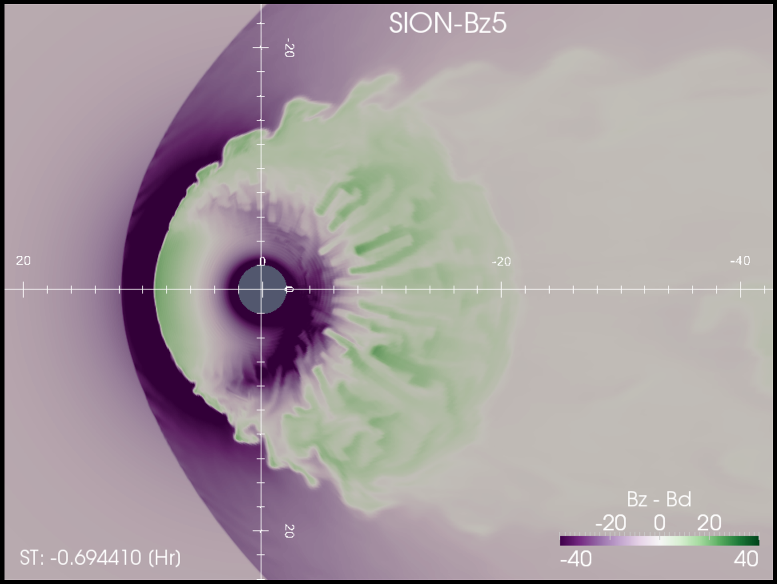


Adapted from W. Lotko

Conductance and BBFs







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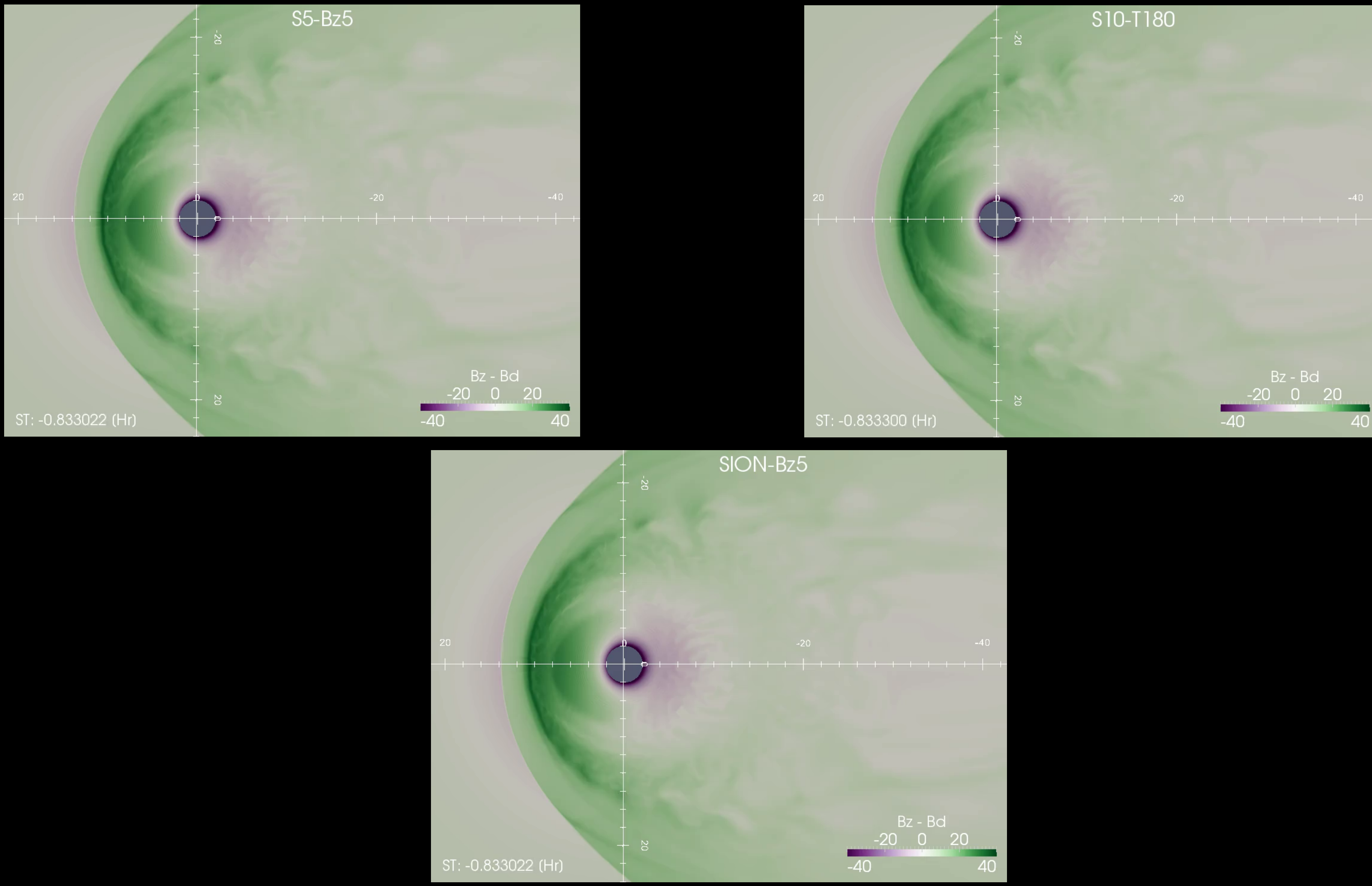

Conclusions

- Conductance plays an essential role in the coupling of the magnetosphere – ionosphere
- Understanding of the global conductance parameters is being advanced by clever combination of ground and space based magnetic field measurements combined with electric field observations
- Global models are implementing improved models of conductance as part of their development paths
- Ionospheric conductance has impacts
  - Distribution of currents and structure of bow show and magnetopause
  - Substorm levels show strong correlation with ionospheric conductance distribution
  - Models show role for conductance to control location and intensity of flows in the magnetotail

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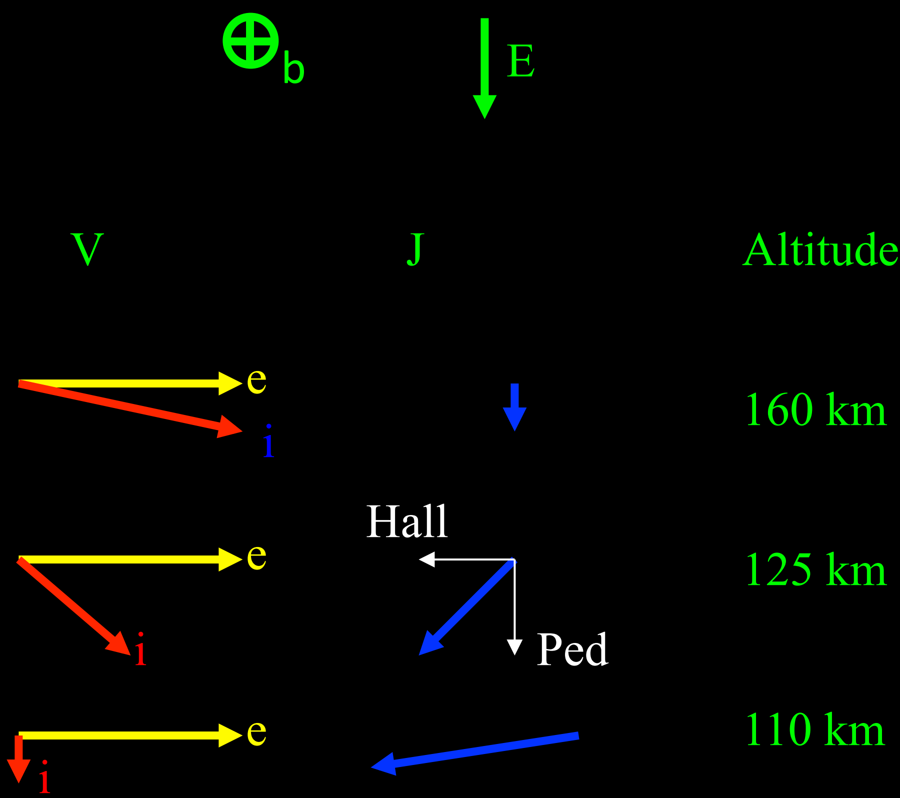
Extra slides

Comments on Conductance

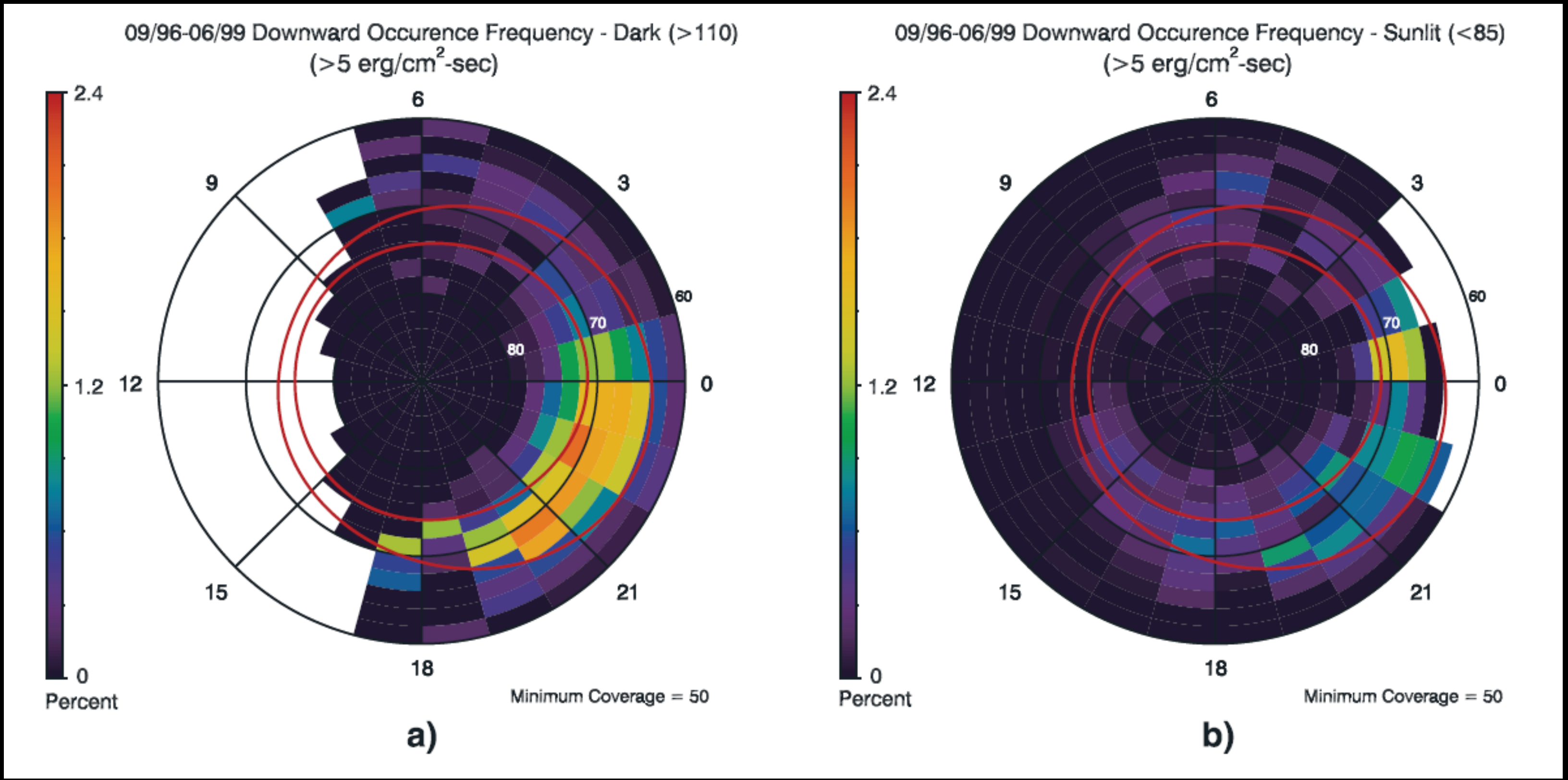
- In the direction parallel to B the electron velocity dominates over the ion velocity and conductivity in the parallel direction is quite large resulting $E_{||} \sim 0$ for scales larger than 1 km
- At high altitudes both the ions and electrons move with the ExB drift velocity due to fact the collision freq are much smaller than the gyro freq
- The electrons retain the ExB drift for the entire portion of the conducting ionosphere because the gyro freq remains larger than the collision freq
- The ratio of the ion gyro to collision freqs changes dramatically over the height of the ionosphere

$$\vec{J} = \sigma_P E'_\perp + \sigma_H \vec{b} \times E'_\perp + \sigma_{||} E'_{||} \vec{b}$$



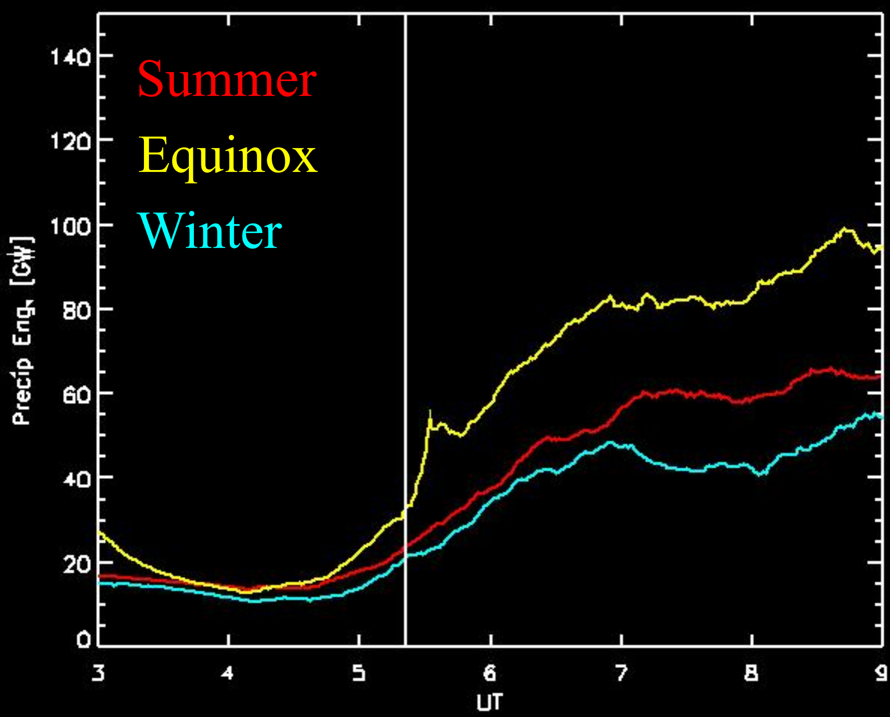
After Richmond and Thayer, 2000

Seasonal Dependence of Auroral Occurrence



- *Cattell et al.* [2006] used FAST observations to examine the relationship between solar illumination and downward energy flux
  - Results are quite similar to those reported by Newell et al. with DMSP observations
  - They are argue the difference is due to change in the scale height of the potential drop caused by the increased heating during solar illumination
  - An important additional point is the significant reduction in precipitation energy in the beams seen in the sunlit hemisphere

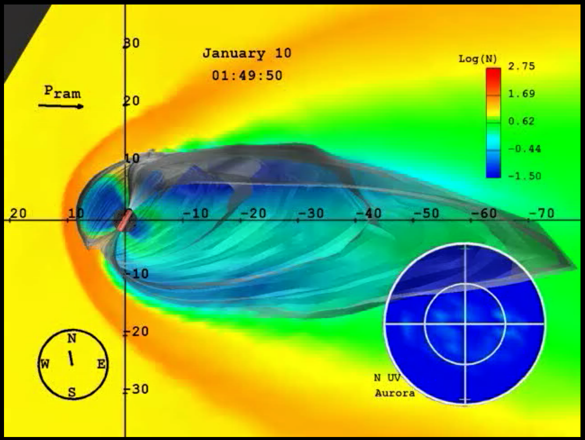
Substorm Behavior



- The total energy flux is computed by integrating the energy precipitating electrons over the entire hemisphere
  - Equinox case shows a clear spike at the substorm onset time seen in the FAC and the simulated AL
  - No clear indication of abrupt increase flux present in either Winter or Summer cases
  - More flux is clearly flowing into Equinox
  - Interestingly Summer case has slightly more flux then Winter case

LFM Magnetospheric Model

- Uses the ideal MHD equations to model the interaction between the solar wind, magnetosphere, and ionosphere
  - Computational domain
    - 30 $R_E < x <$ -300 R_E & ±100R_E for YZ
    - Inner radius at 2 R_E altitude
  - Calculates
    - full MHD state vector everywhere within computational domain
  - Requires
    - Solar wind MHD state vector along outer boundary
    - Empirical model for determining energy flux of precipitating electrons
    - Cross polar cap potential pattern in high latitude region which is used to determine boundary condition on flow



LFM Ionospheric Simulation

- 2D Electrostatic Model
  - Conservation of current
    - $\nabla \bullet \left(\Sigma_P + \Sigma_H \right) \nabla \Phi = J_{\|} \sin(\eta)$
  - $J_{\|}$ determined at magnetospheric BC
- Conductivity Models
  - Solar EUV ionization
    - Creates day/night and winter/summer asymmetries
  - Auroral Precipitation
    - Empirical determination of energetic electron precipitation
- Electric field used for flow at magnetosphere
  - $\vec{V} = -\dfrac{\vec{E} \times \vec{B}}{B^2}$