Magnetosphere-Ionosphere-Thermosphere Coupling During Storms and Substorms

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Why (or when do we need to) worry about the complications of SW-M-I-T coupling?

- M, I and T are especially interactive for strong SW driving
- Model predictions don’t do well w/o coupling
- Utility depends on the fidelity of prediction: Space weather
- “Understanding” is demonstrated by prediction
- The coupled M-I-T system is equisitely complex and interesting

What might you learn from this tutorial?

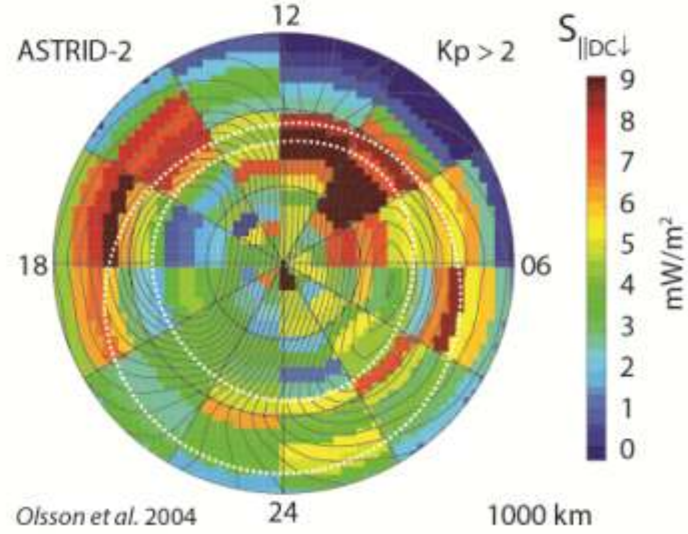
(or be reassured you that what you once thought was true is still true)

- Coupling agents
- Pathways (coupled) and feedback
  - Electromagnetic
  - Material
- Insights into M-I-T coupling
- Coupling during storms

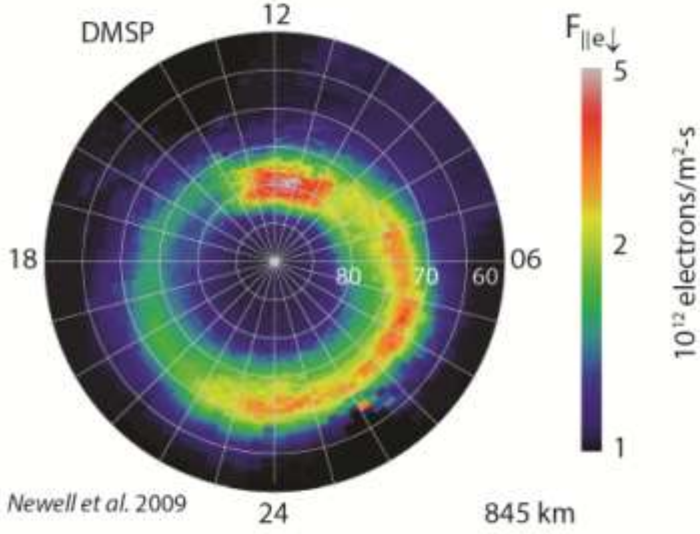
  (with data-model comparisons)

Agents of M-I-T Coupling

DOWNWARD DC POYNTING FLUX

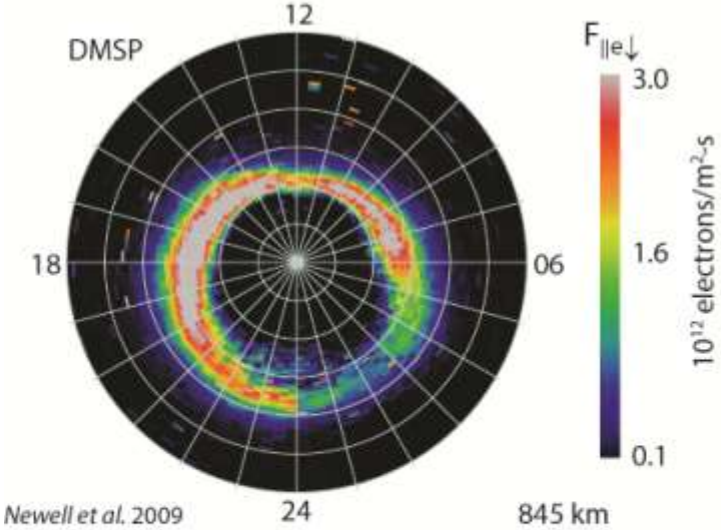


DIFFUSE ELECTRON FLUX



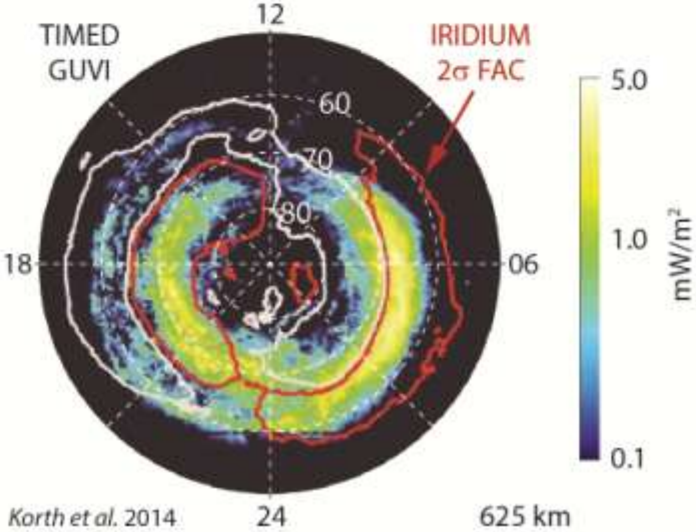
Winter, high driving

MONOENERGETIC ELECTRON FLUX



Winter, high driving

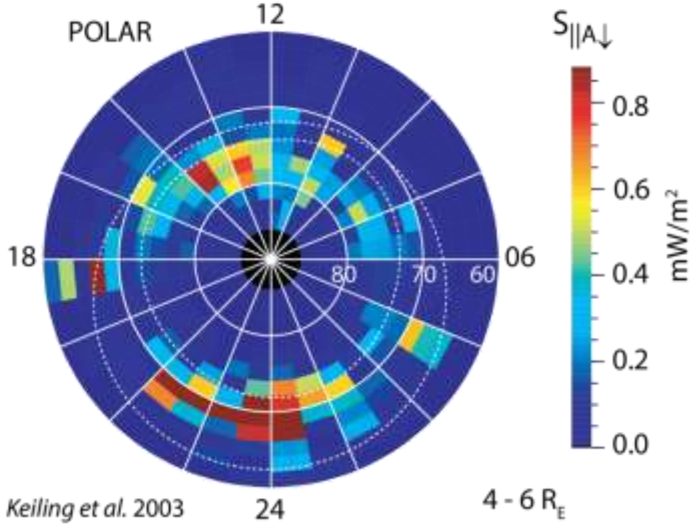
ELECTRON ENERGY FLUX



$135^\circ < \theta_{IMF} < 225^\circ$

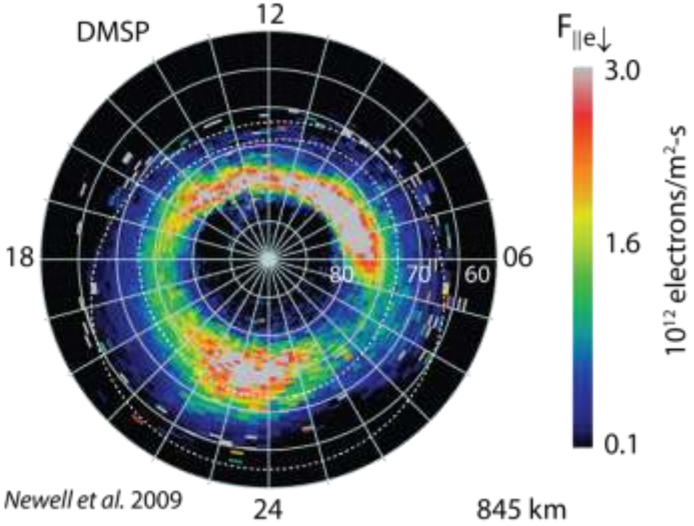
Agents of M-I-T Coupling

DOWNWARD ALFVÉNIC POYNTING FLUX



Keiling et al. 2003

BROADBAND ELECTRON FLUX

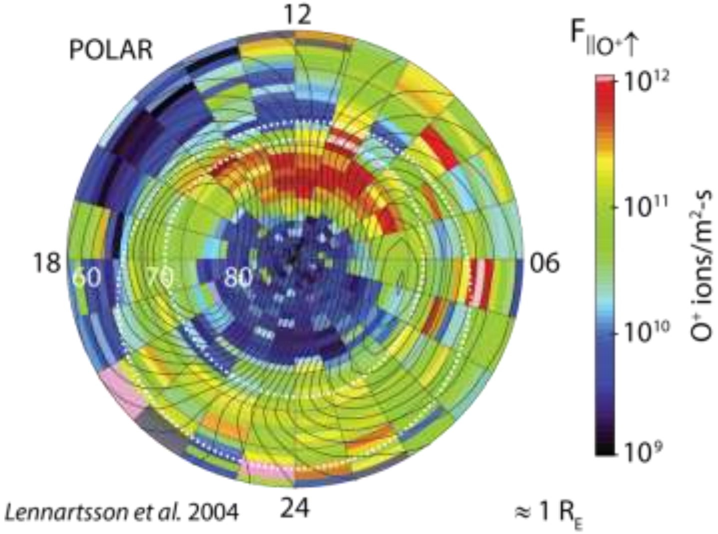


Newell et al. 2009

Winter, high driving

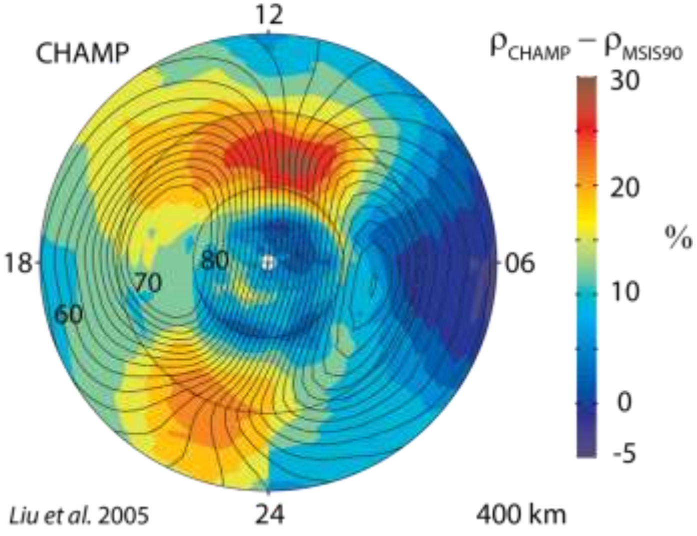
Conductance?

O⁺ OUTFLOW (0.015 to 33 keV)



Lennartsson et al. 2004

Δ THERMOSPHERE MASS DENSITY



Liu et al. 2005

Pathways of M-I-T Interaction

1. Electromagnetic

Ionospheric Ohm's law, electrostatic condition, current continuity $\Rightarrow$

Fejer 1953

Current source

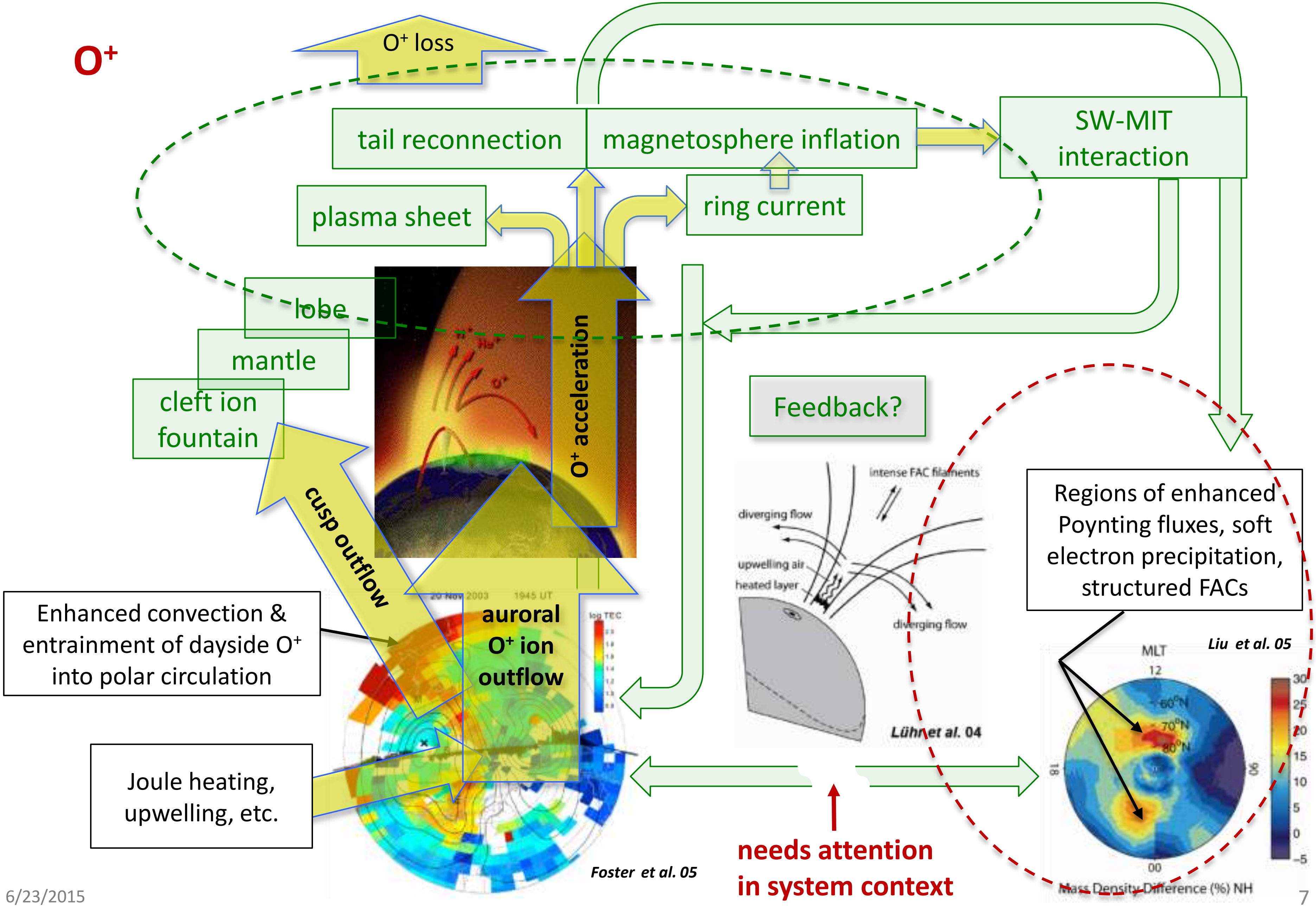
$$j_{\parallel i}\cos\delta = \nabla\cdot\overleftrightarrow{\Sigma}\cdot\nabla\Phi_{i}$$

Find Φ_i

Spatial distribution of $\overleftrightarrow{\Sigma}$ determines Φ_i for given $j_{||i}$ and vice-versa

2. Material transport

Global M-I-T Interactions (active periods)



Enhanced convection & entrainment of dayside O^+ into polar circulation

Joule heating, upwelling, etc.

Foster et al. 05

Lühr et al. 04

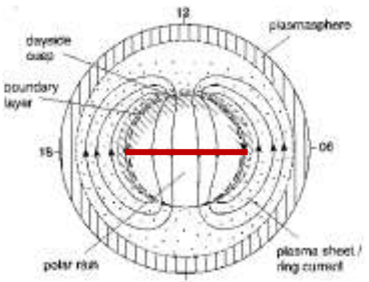
Regions of enhanced Poynting fluxes, soft electron precipitation, structured FACs

Liu et al. 05

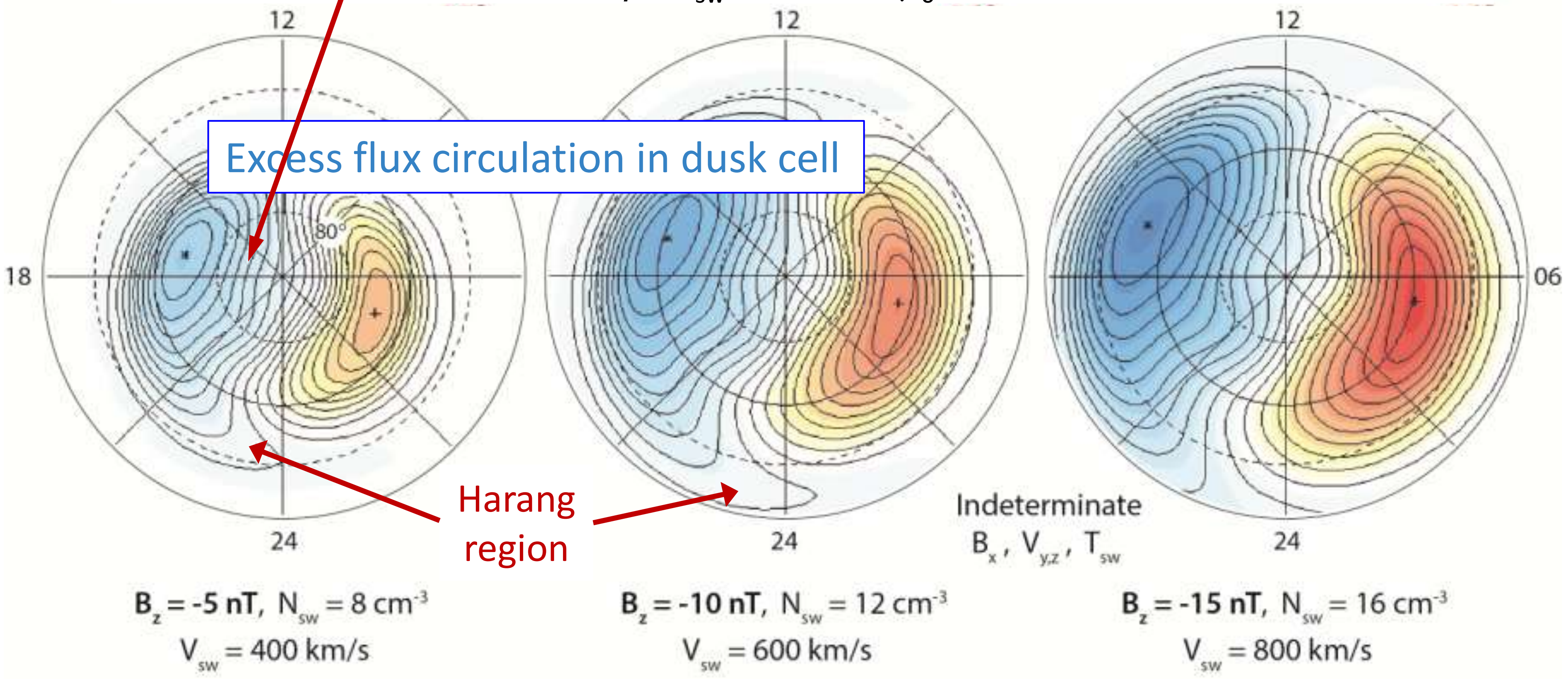
needs attention in system context

Empirical convection: Increasing strength of SW driving

CW rotation of the convection pattern when viewed from above NP



SMagnetopause location: $\rho v^2|_{sw} = 4B(r)^2/2\mu_0$ (Better: *Shue et al.,* 1998)



Excess flux circulation in dusk cell

Harang region

Indeterminate B_x, $V_{y,z}$, T_{sw}

$B_z = -5$ nT, $N_{sw} = 8$ cm^{-3}
$V_{sw} = 400$ km/s

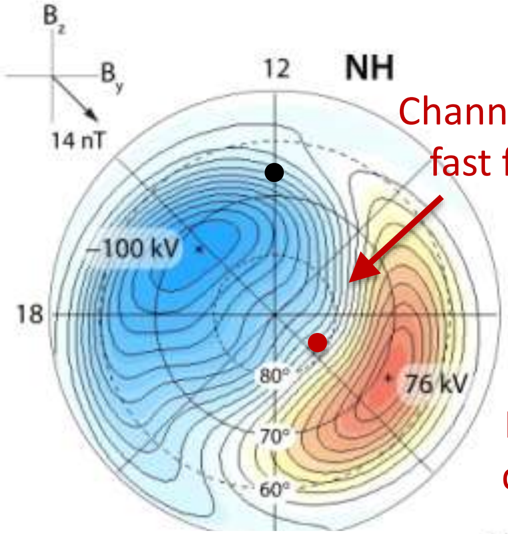
$B_z = -10$ nT, $N_{sw} = 12$ cm^{-3}
$V_{sw} = 600$ km/s

$B_z = -15$ nT, $N_{sw} = 16$ cm^{-3}
$V_{sw} = 800$ km/s

Weimer-2005 model

Empirical convection: Effect of IMF B_y

Weimer model

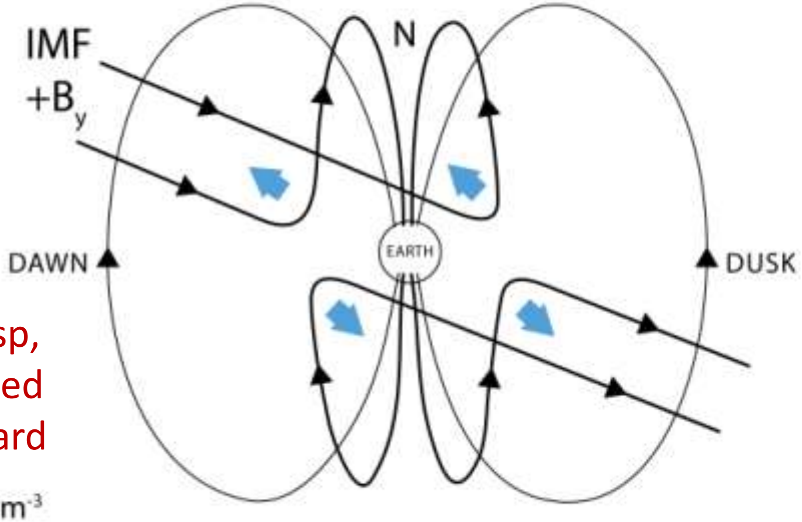


Channelized fast flow

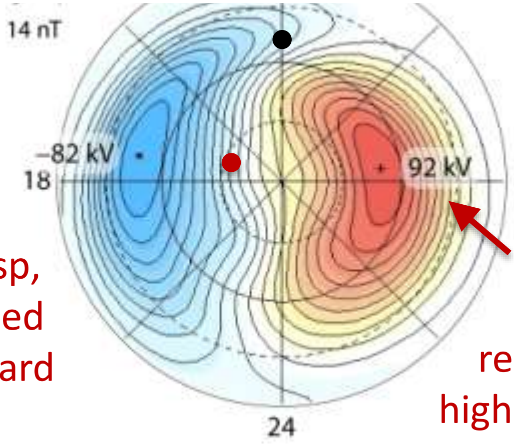
NH cusp, PC pulled duskward

$N_{sw} = 20\ cm^{-3}$

$V_{sw} = 800\ km/s$

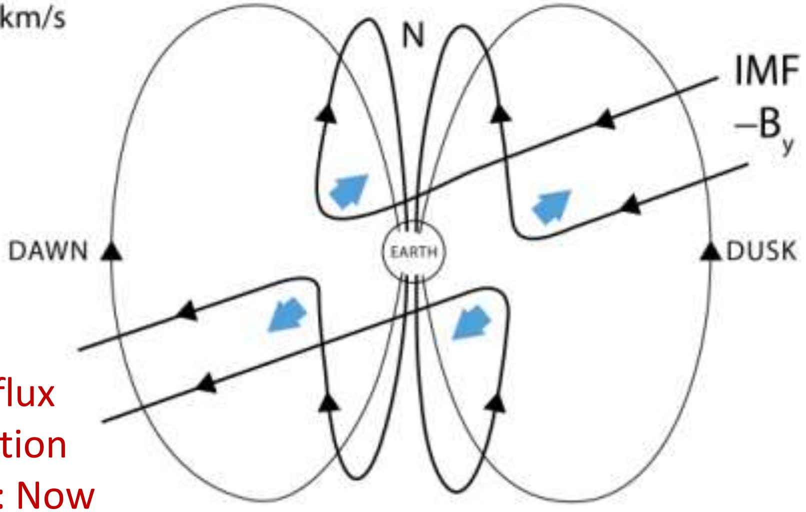


No mirror symmetry with change in sign of B_y (*Heppner* 1972)



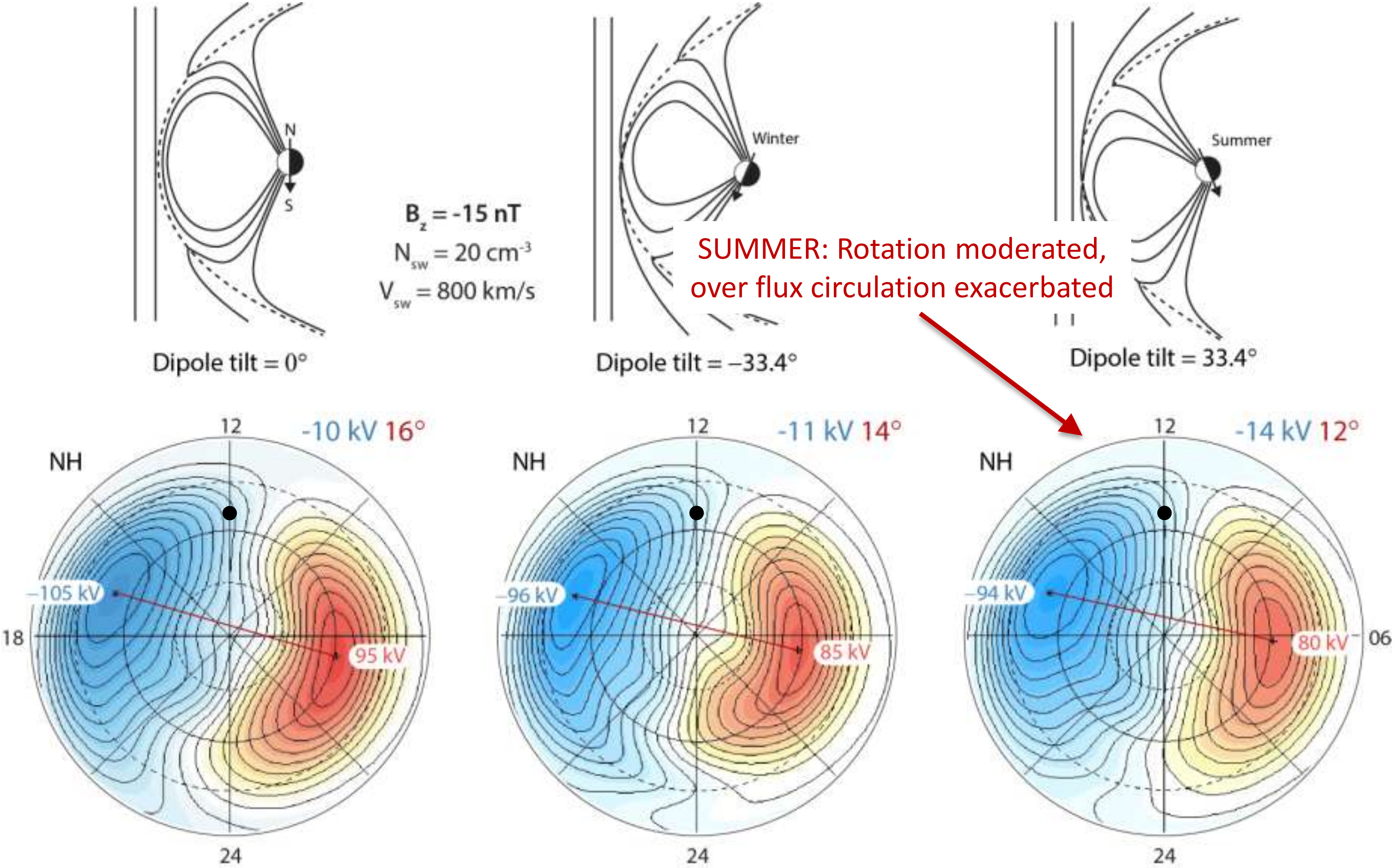
NH cusp, PC pulled dawnward

Over flux circulation reverses: Now higher in dawn cell



Effect of season/dipole tilt

Weimer model



SUMMER: Rotation moderated, over flux circulation exacerbated

Weimer-2005 model

Effect of EUV Hall conductance gradient

BATSRUS global simulation

Atkinson and Hutchison 1978

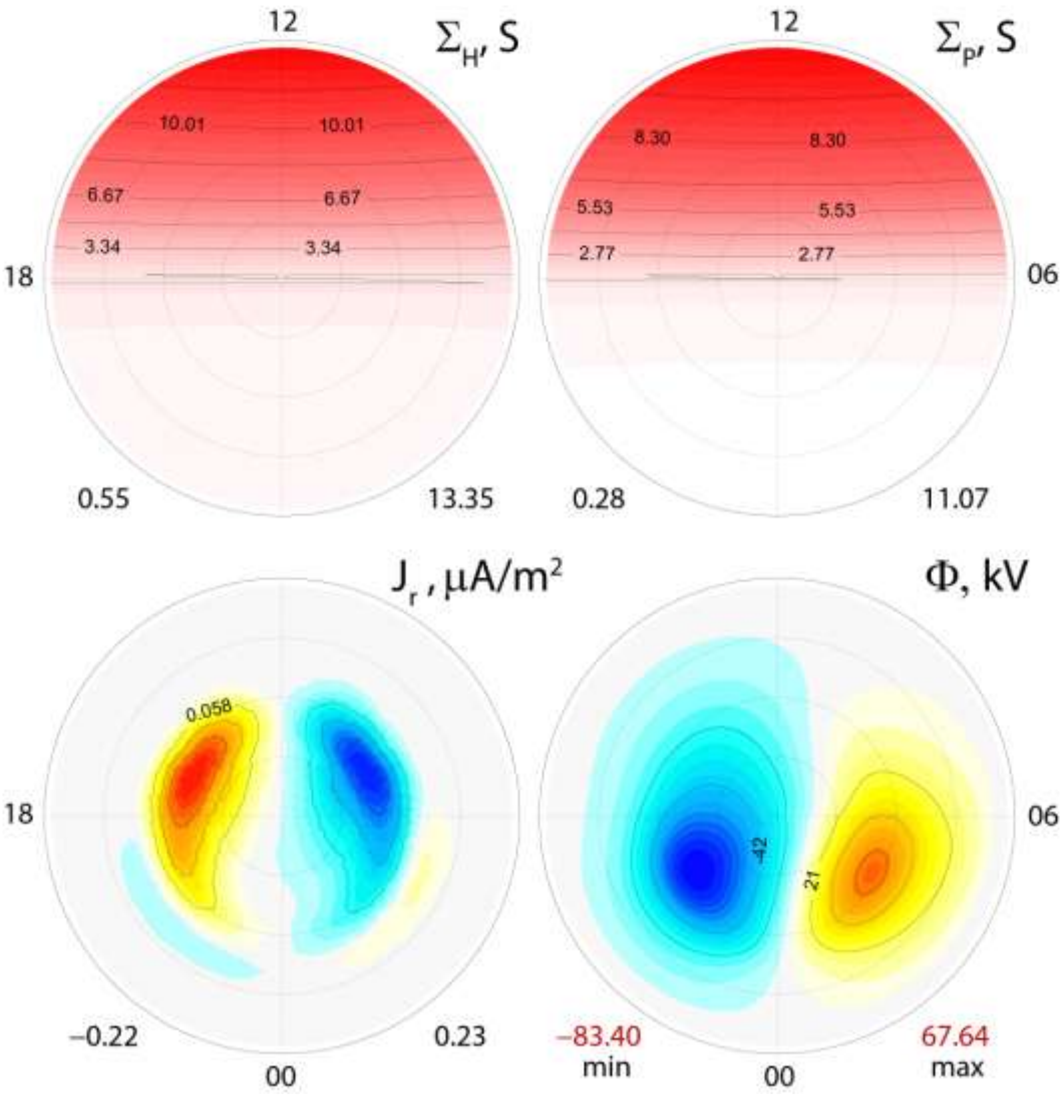
Ridley et al. 2004

- CW rotation
- More flux circulates in dusk cell

CONCLUSION

Ionosphere polarizes so as to maintain

$$\nabla\cdot\vec{\mathbf{J}}_{\mathrm{H}} = \hat{\mathbf{b}}\times\vec{\mathbf{E}}\cdot\nabla\Sigma_{\mathrm{H}} \approx 0$$

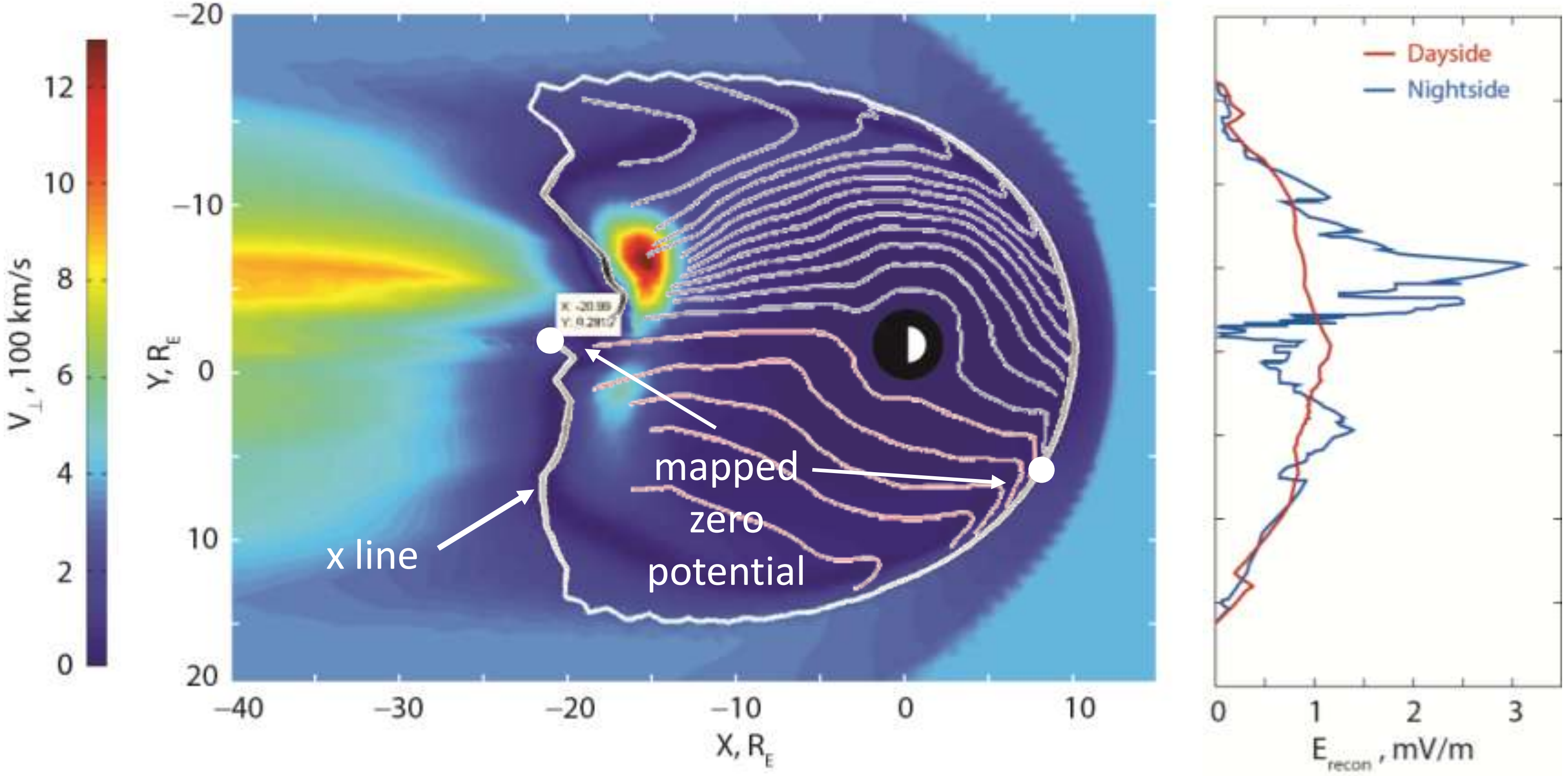


Effect of EUV Hall conductance gradient

LFM global simulation

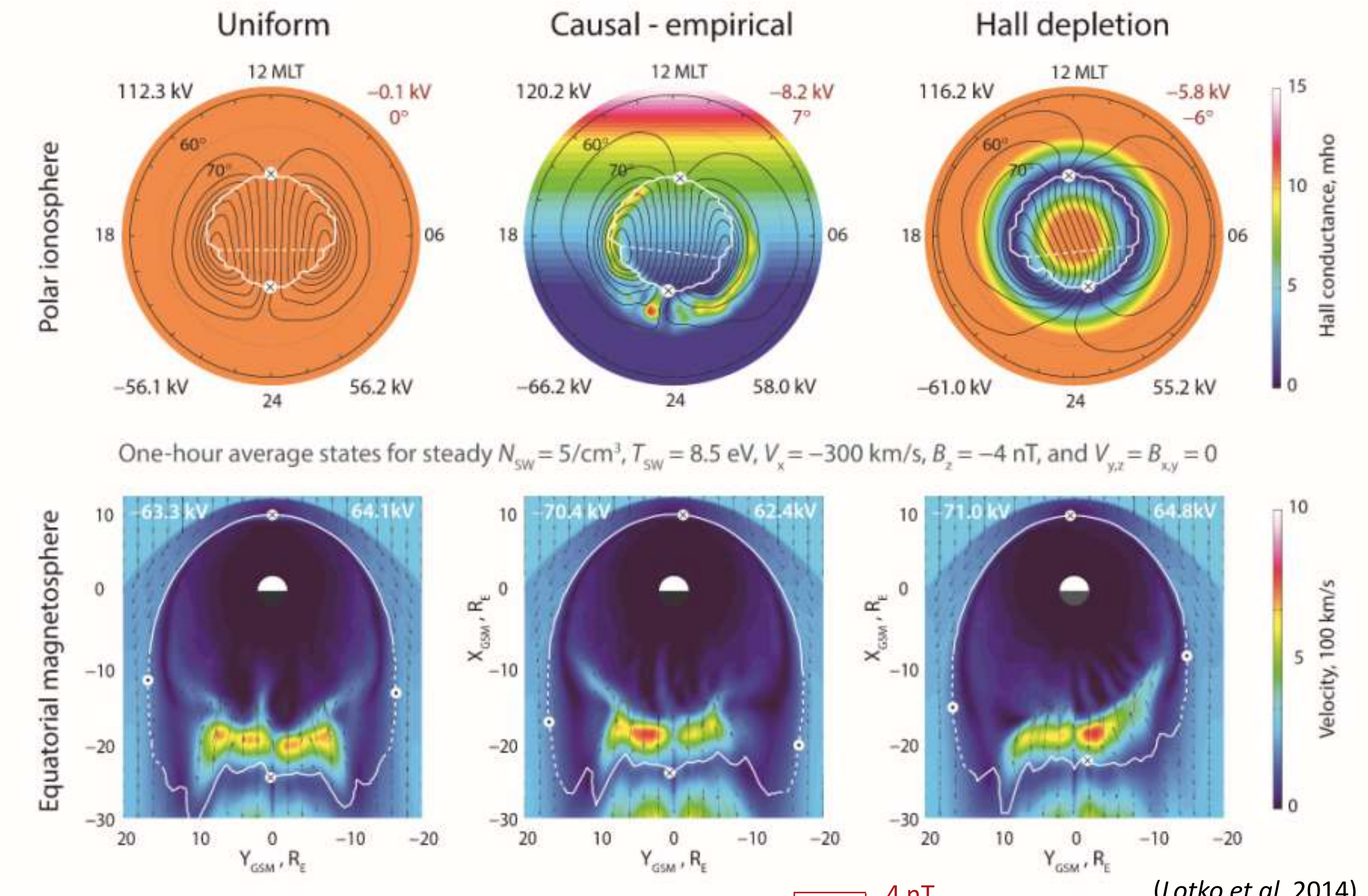
Perpendicular Velocity in Equatorial Plane

Reconnection Rate Along the X-line



1-HOUR AVERAGE STATES

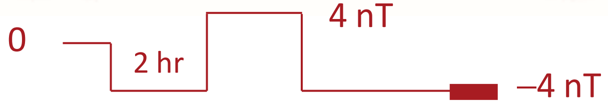
Effect of combined EUV and auroral Hall conductance gradient LFM global simulation



One-hour average states for steady $N_{SW} = 5/\text{cm}^3$, $T_{SW} = 8.5$ eV, $V_x = -300$ km/s, $B_z = -4$ nT, and $V_{y,z} = B_{x,y} = 0$

(*Lotko et al.* 2014)

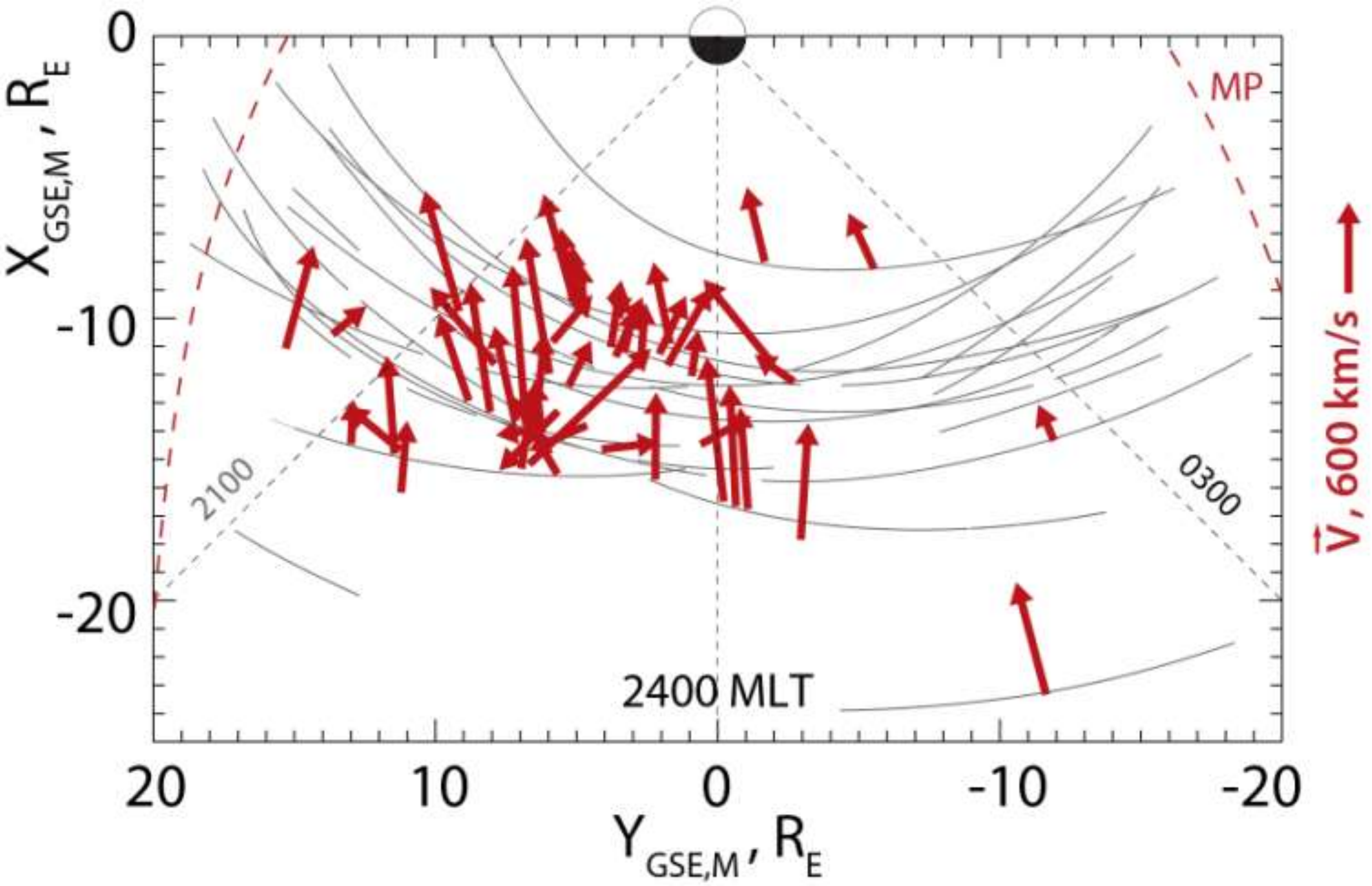
1-HOUR AVERAGE STATES



Pre/Post-Midnight Asymmetry in Plasmasheet Fast Flows, Mass and Flux Transport

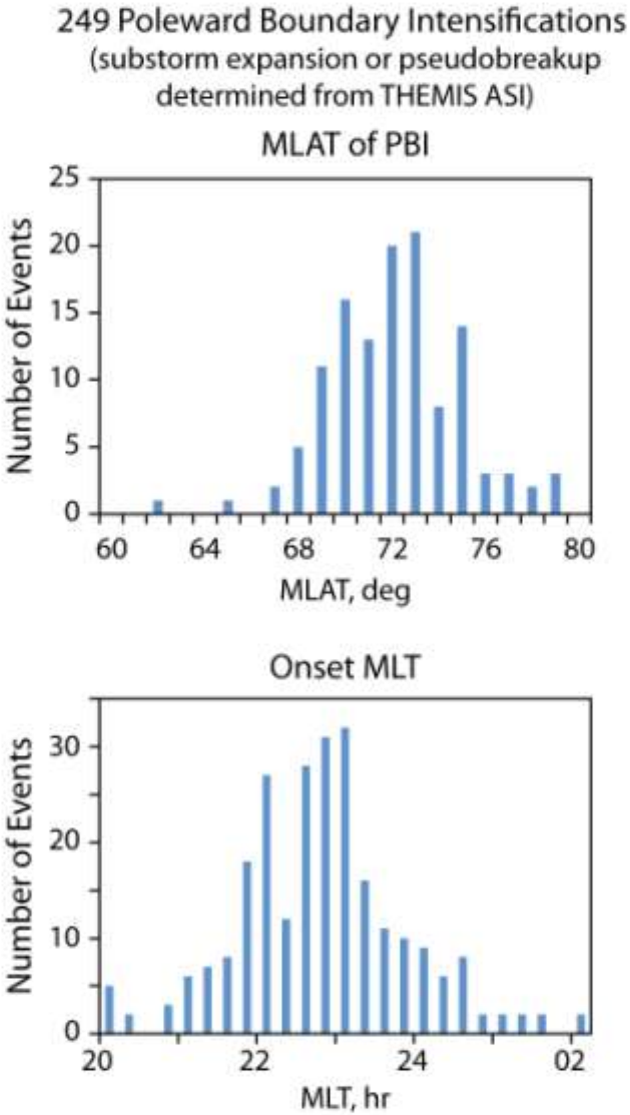
WIND, 17 Perigee Passes, 1995-97

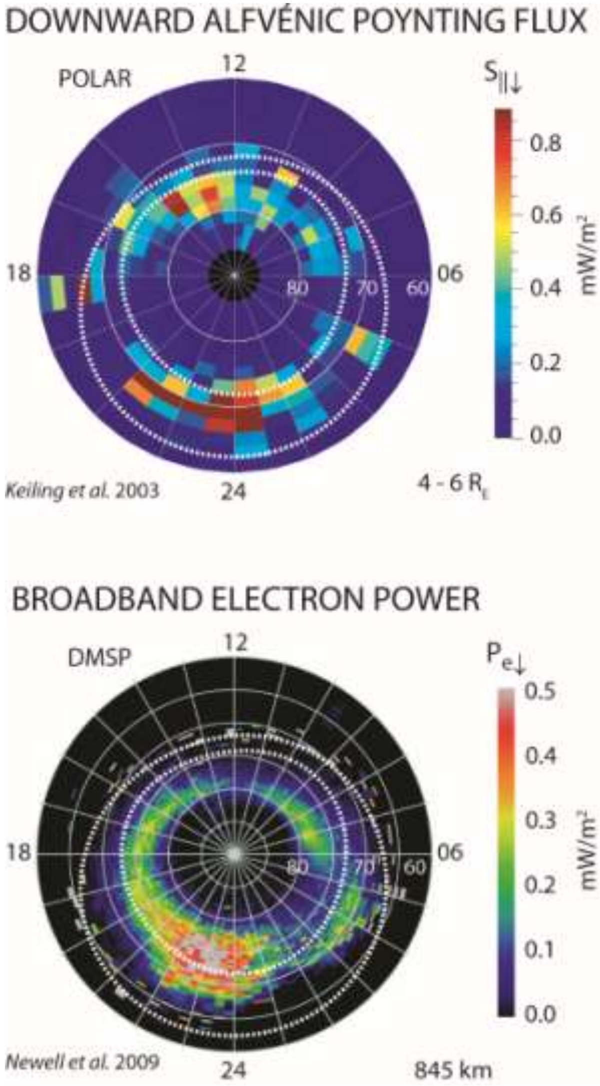
Raj et al. 2002



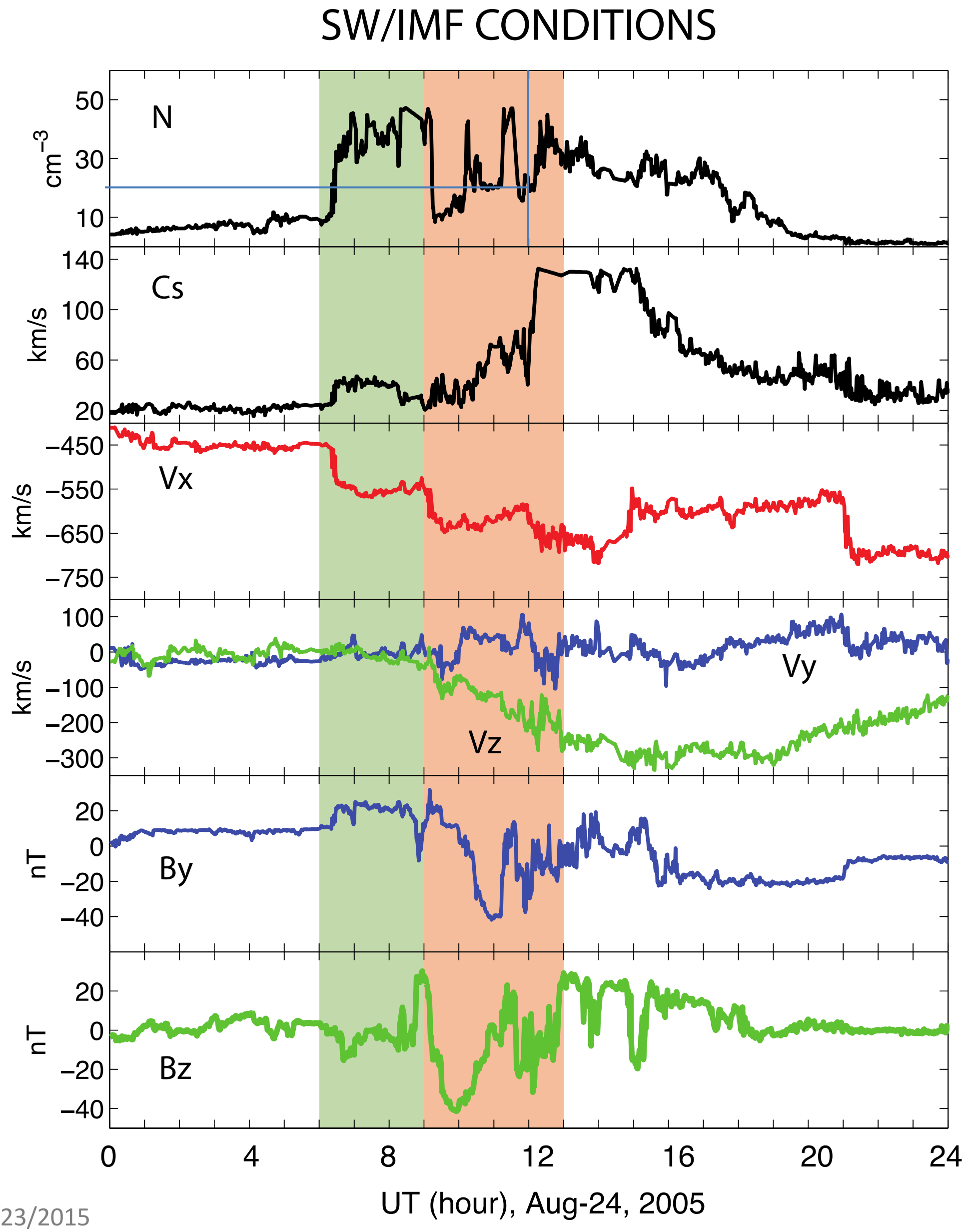
Events selected for $\vec{V} > 250$ km/s and $\beta > 0.5$ (neutral sheet)

Asymmetries in poleward boundary intensifications and Alfvénic aurora





Nishimura et al 2010



24 Aug 2005 CME Storm

Initial phase: 06:00 – 09:00 UT

B_z ≈small B_y ~ 20 nT

Kp ~ 3-6

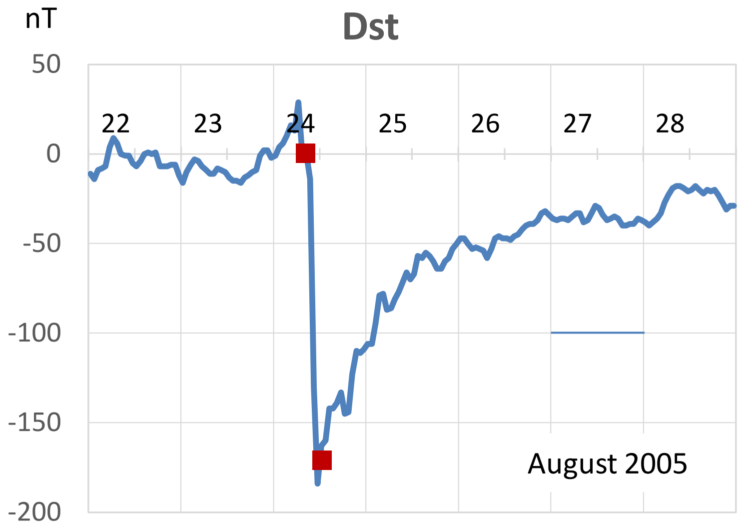
The B_y-dominant time period has been studied by *Crowley et al*. [2010] using TIME-GCM.

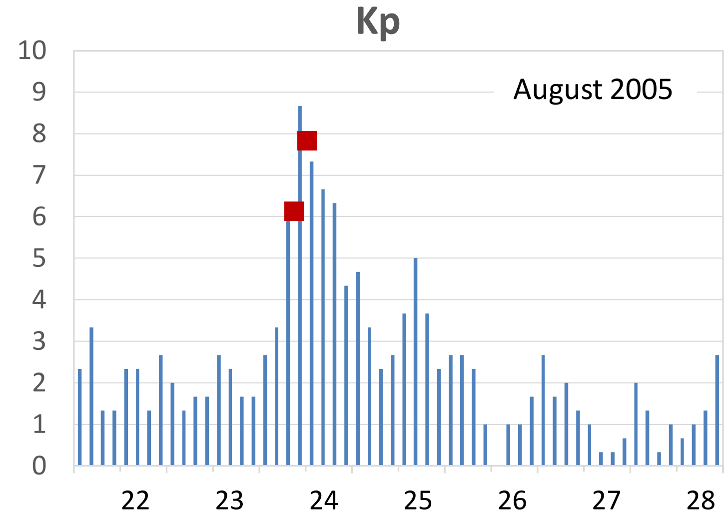
→ Results show Joule heating is important in enhancing the *F*-region neutral density.

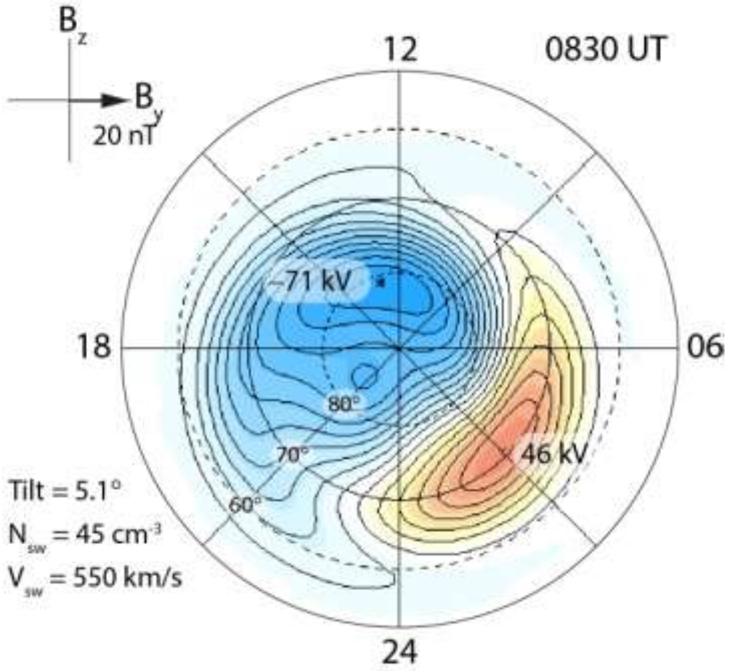
Main phase: 09:00 – 16:00

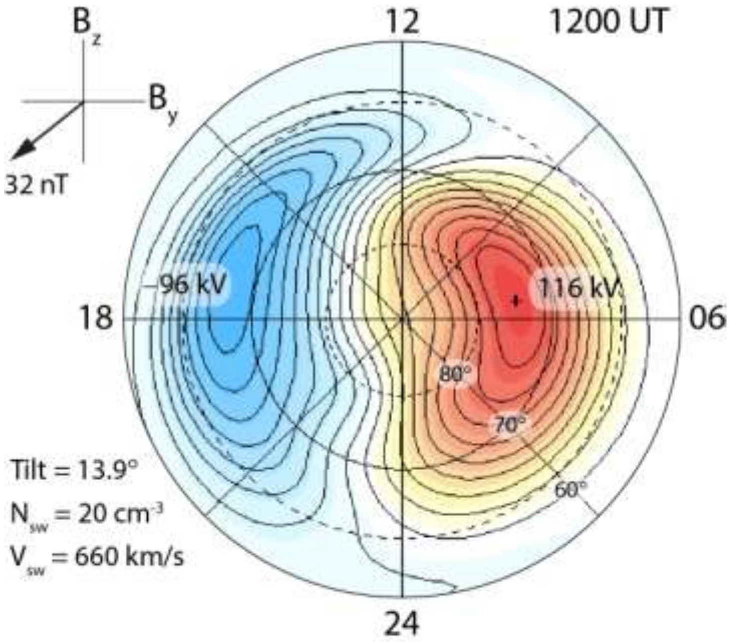
$B_z \rightarrow -40$ nT $B_y \rightarrow -40$ nT

Kp ≈ 9, Dst = -184 nT at 1200 UT



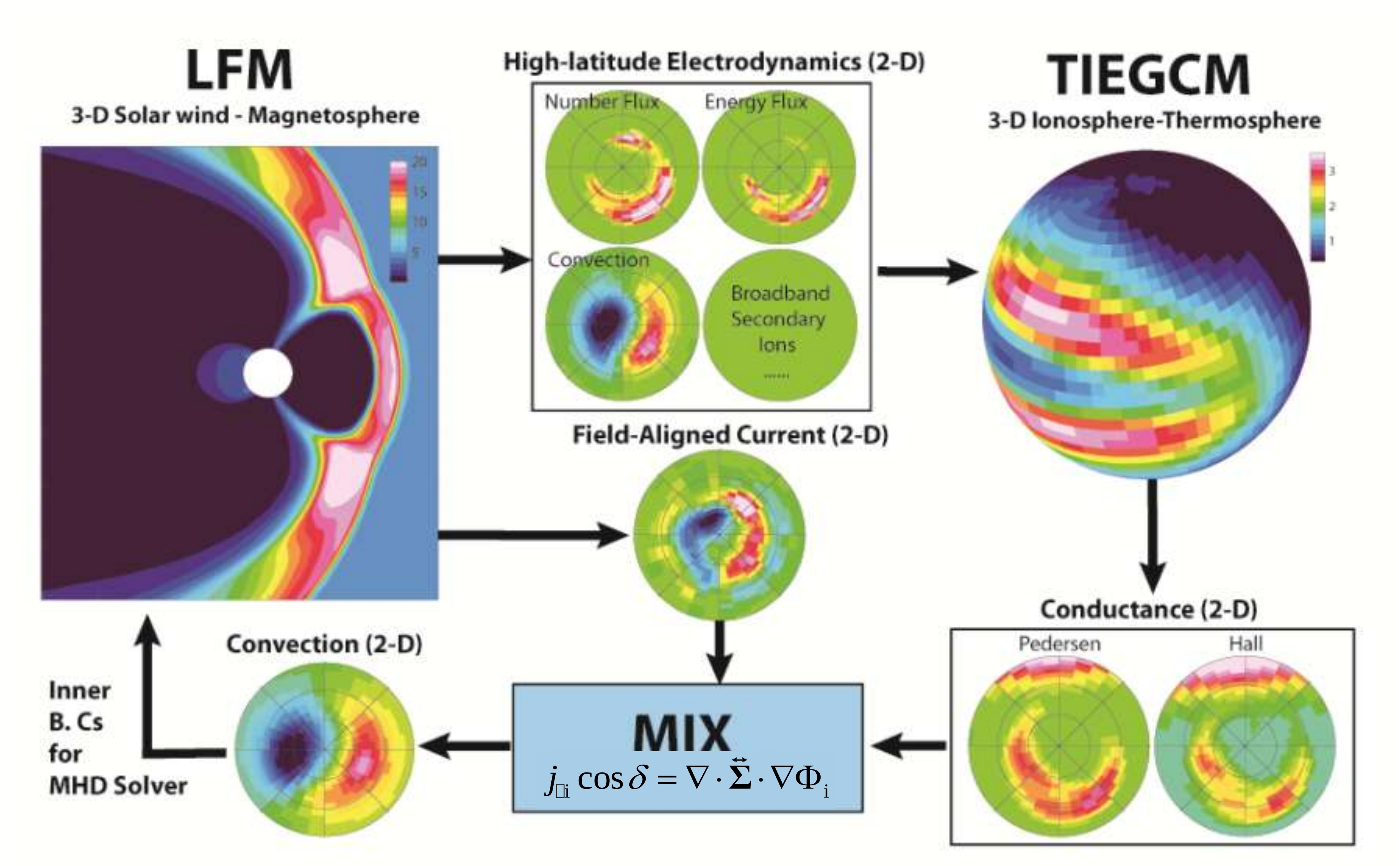






Weimer disclaimer: Model works best for $|B_y|$ and $|B_z| < 15$ nT.

Coupled M-I-T (CMIT) model



LFM

3-D Solar wind - Magnetosphere

High-latitude Electrodynamics (2-D)

Number Flux

Energy Flux

Convection

Broadband
Secondary
Ions
......

TIEGCM

3-D Ionosphere-Thermosphere

Field-Aligned Current (2-D)

Conductance (2-D)

Pedersen

Hall

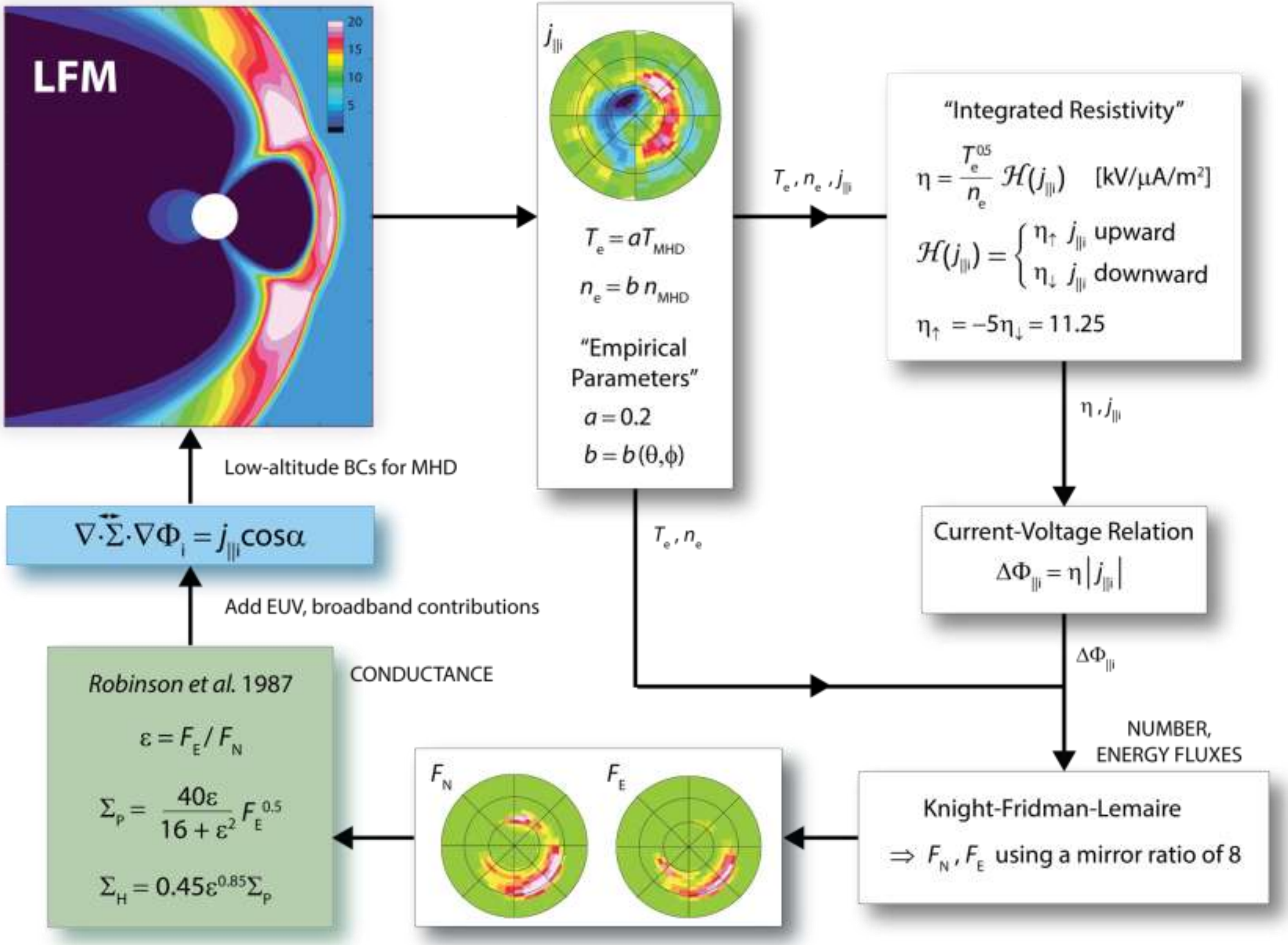
MIX

$$j_{\parallel i}\cos\delta = \nabla\cdot\overleftrightarrow{\Sigma}\cdot\nabla\Phi_{i}$$

Convection (2-D)

**Inner
B. Cs
for
MHD Solver**

Monoenergetic and Diffuse Electron Precipitation Algorithm



$$T_e = aT_{MHD}$$

$$n_e = b\, n_{MHD}$$

"Empirical Parameters"

$$a = 0.2$$

$$b = b(\theta,\phi)$$

"Integrated Resistivity"

$$\eta = \frac{T_e^{0.5}}{n_e}\,\mathcal{H}(j_{\|i}) \quad [\mathrm{kV/\mu A/m^2}]$$

$$\mathcal{H}(j_{\|i}) = \begin{cases} \eta_\uparrow & j_{\|i} \text{ upward} \\ \eta_\downarrow & j_{\|i} \text{ downward} \end{cases}$$

$$\eta_\uparrow = -5\eta_\downarrow = 11.25$$

Current-Voltage Relation

$$\Delta\Phi_{\|i} = \eta\,|j_{\|i}|$$

NUMBER, ENERGY FLUXES

Knight-Fridman-Lemaire

$\Rightarrow F_N, F_E$ using a mirror ratio of 8

Robinson et al. 1987

$$\varepsilon = F_E / F_N$$

$$\Sigma_P = \frac{40\varepsilon}{16+\varepsilon^2} F_E^{0.5}$$

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

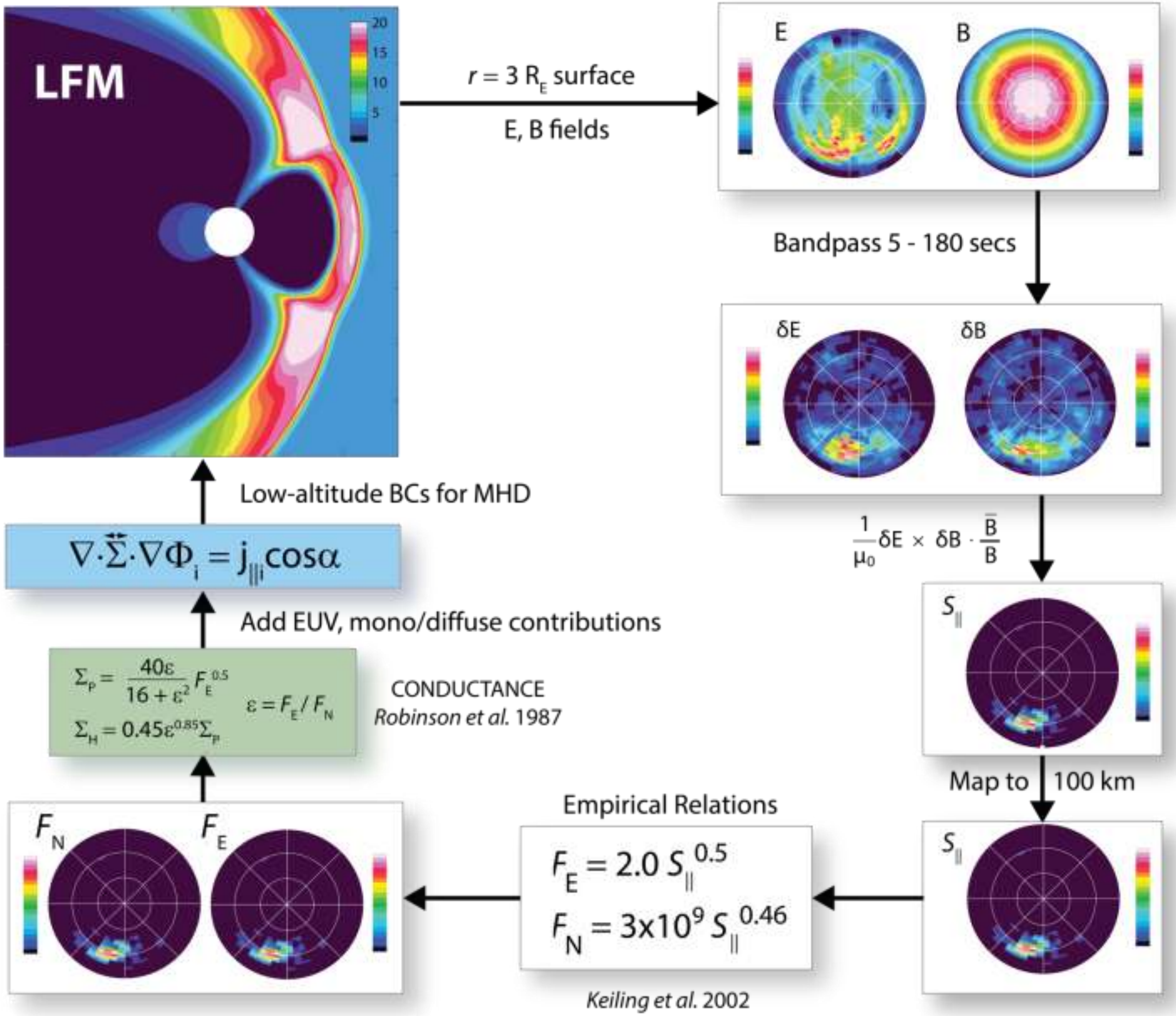
CONDUCTANCE

Add EUV, broadband contributions

$$\nabla\cdot\overleftrightarrow{\Sigma}\cdot\nabla\Phi_i = j_{\|i}\cos\alpha$$

Low-altitude BCs for MHD

Broadband Electron Precipitation Algorithm



$r = 3\ R_E$ surface

E, B fields

Bandpass 5 - 180 secs

$\frac{1}{\mu_0}\delta E \times \delta B \cdot \frac{\bar{B}}{B}$

Map to 100 km

Empirical Relations

$$F_E = 2.0\ S_{\parallel}^{0.5}$$

$$F_N = 3\text{x}10^9\ S_{\parallel}^{0.46}$$

Keiling et al. 2002
Strangeway, 2010

$$\Sigma_P = \frac{40\varepsilon}{16+\varepsilon^2} F_E^{0.5} \qquad \varepsilon = F_E / F_N$$

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

CONDUCTANCE
Robinson et al. 1987

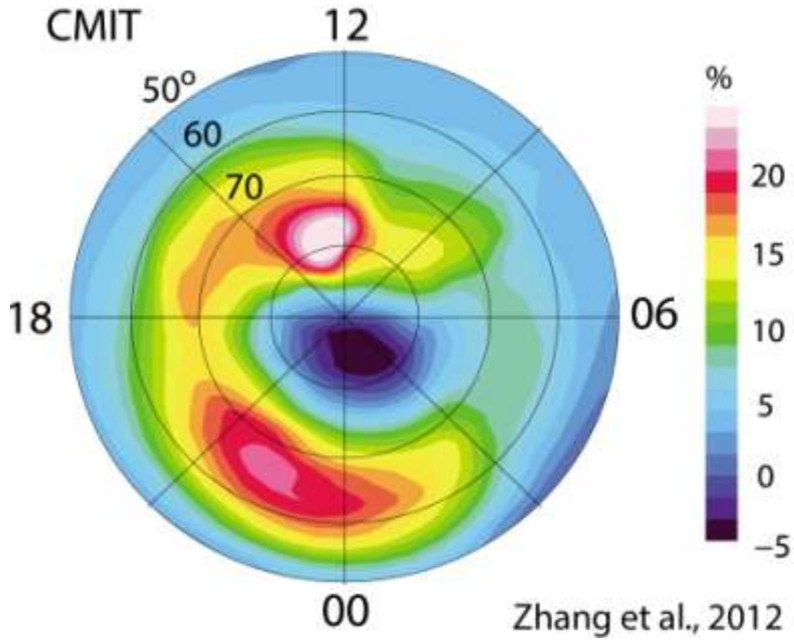
Add EUV, mono/diffuse contributions

$$\nabla \cdot \overleftrightarrow{\Sigma} \cdot \nabla \Phi_i = j_{\|i} \cos\alpha$$

Low-altitude BCs for MHD

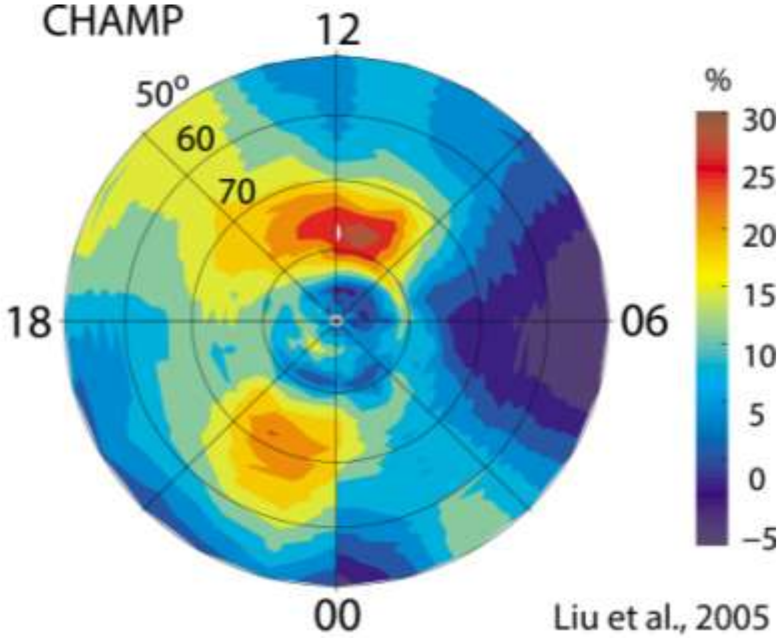
***Zhang et al.* 2012**

Change in Thermospheric Density due to Soft Electron Precipitation



Zhang et al., 2012

Difference between CMIT simulations w/ and w/o soft electron precipitation (BBE, cusp)



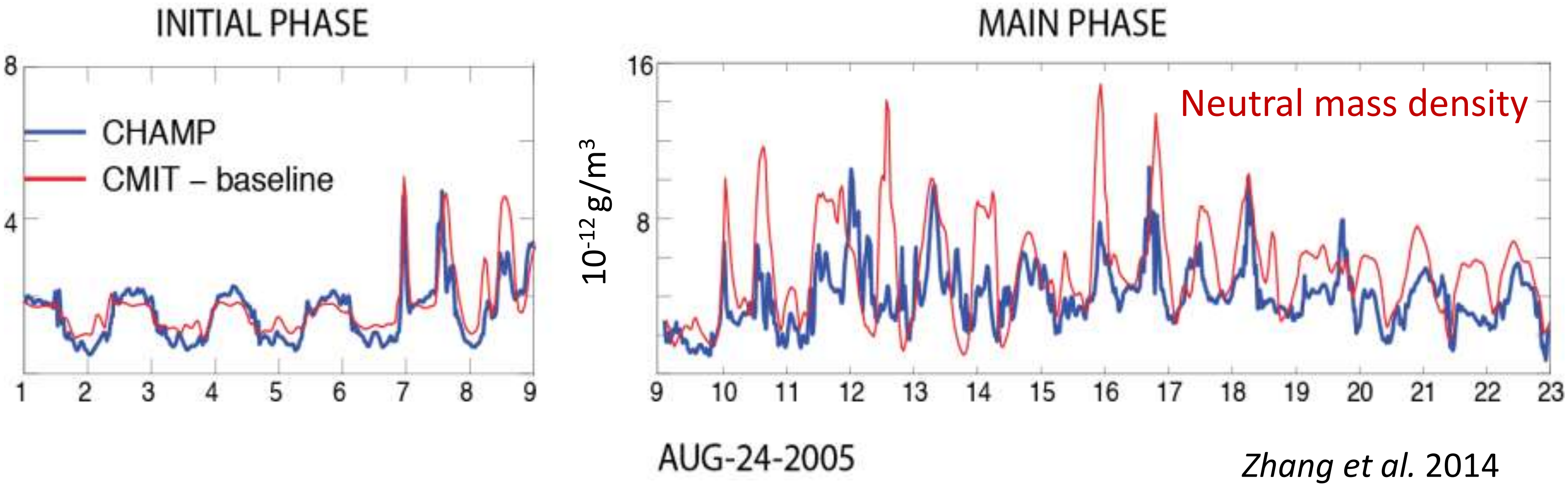
Liu et al., 2005

Difference between CHAMP accelerometer measurements and MSIS90 model results

Comparisons at 400 km altitude. CHAMP data are averages for 2002 for intervals of Kp = 0 – 2.

CMIT results are a 1-hour averages for V_{sw} = 400 km/s, n_{sw} = 5 cm^{-3}, IMF B_z = – 5 nT, $F_{10.7}$ = 150.

“Standard” CMIT simulation for the storm

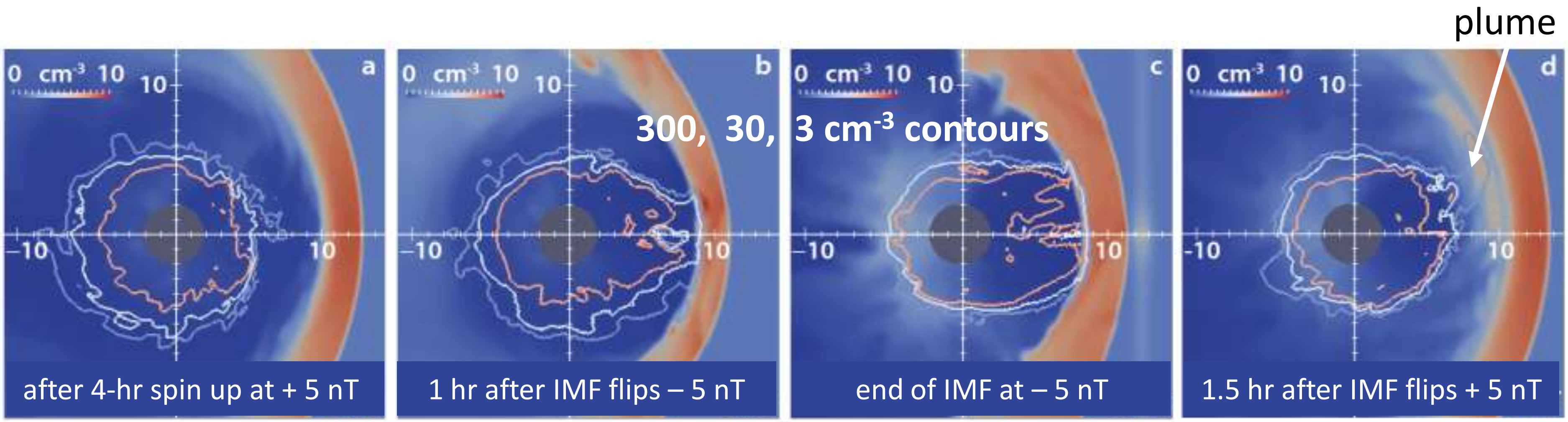


Zhang et al. 2014

- CMIT tracks CHAMP reasonably well for weak driving (0600 – 0900 UT)
- CMIT overestimates (≈ x2) the CHAMP mass density during the main phase (0900 – 1600 UT)
- ***Question:*** What’s missing in the model during the main-phase simulation? Plasmaspheric effects? Ionospheric outflows? …?

Effects of plasmaspheric plumes on dayside reconnection

- Plasma of plasmaspheric origin is observed in the dayside reconnection region [*Borovsky and Denton*, 2006; *Walsh et al*. 2014]
- To what extent does the plasmasphere influence dayside reconnection?



plume

300, 30, 3 cm^{-3} contours

after 4-hr spin up at + 5 nT

1 hr after IMF flips – 5 nT

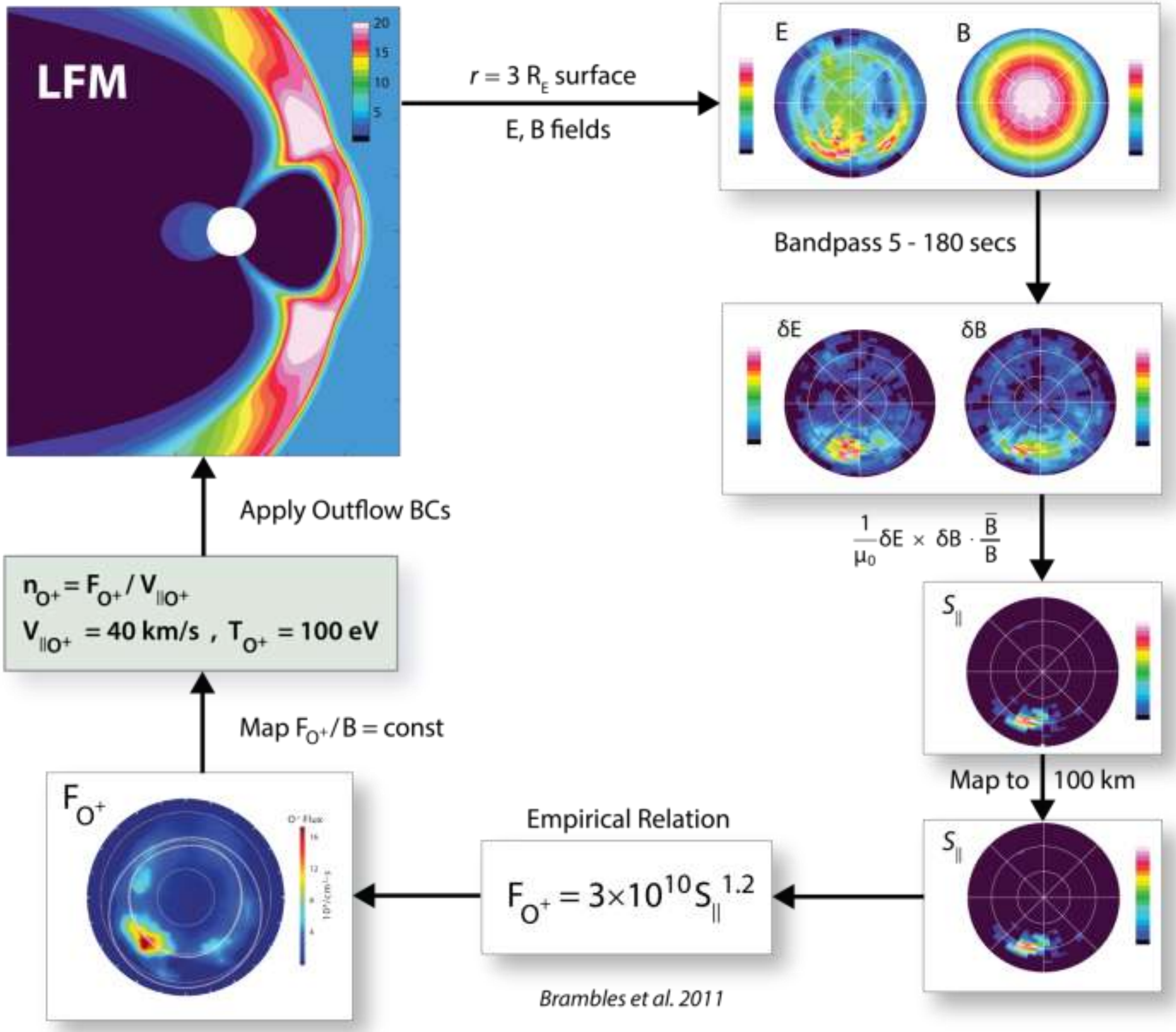
end of IMF at – 5 nT

1.5 hr after IMF flips + 5 nT

- The dayside reconnection rate is smaller in a multi-fluid global magnetosphere simulation when plasmaspheric H^+ is included.

Does plasmaspheric H^+ influence the stormtime *F*-region neutral density?

O^+ Outflow Algorithm



$r = 3\ R_E$ surface

E, B fields

Bandpass 5 - 180 secs

$$\frac{1}{\mu_0}\delta E \times \delta B \cdot \frac{\bar{B}}{B}$$

Map to 100 km

Empirical Relation

$$F_{O^+} = 3\times10^{10} S_{\parallel}^{1.2}$$

Brambles et al. 2011

Map $F_{O^+}/B = \text{const}$

$n_{O^+} = F_{O^+} / V_{\parallel O^+}$

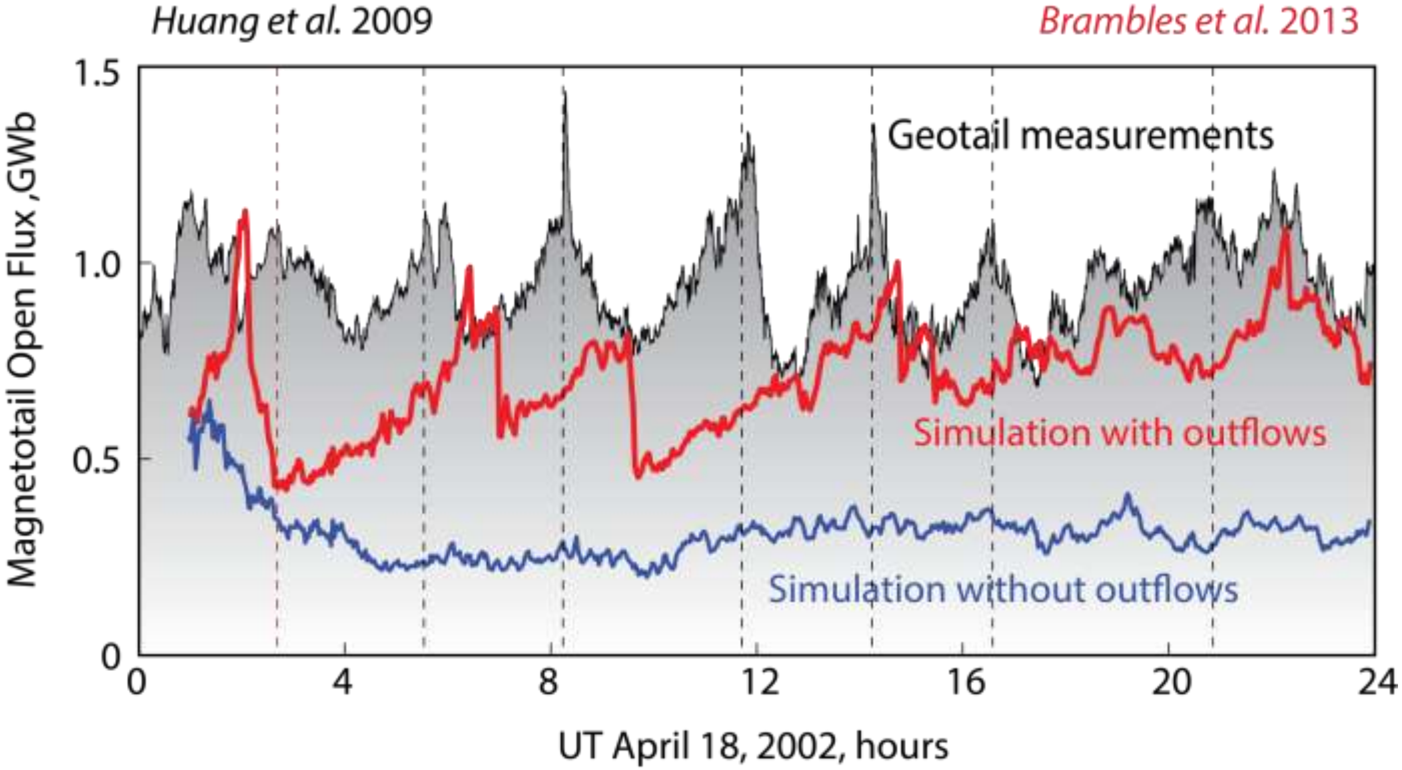
$V_{\parallel O^+} = 40$ km/s , $T_{O^+} = 100$ eV

Apply Outflow BCs

***Brambles et al.* 2011**

Effects of ionospheric O^+ outflow on stormtime substorms

Observations and modeling studies show that outflows of ionospheric O^+ are important in stormtime solar wind-magnetosphere-ionosphere coupling, especially during CME-driven storms exhibiting "sawtooth oscillations."



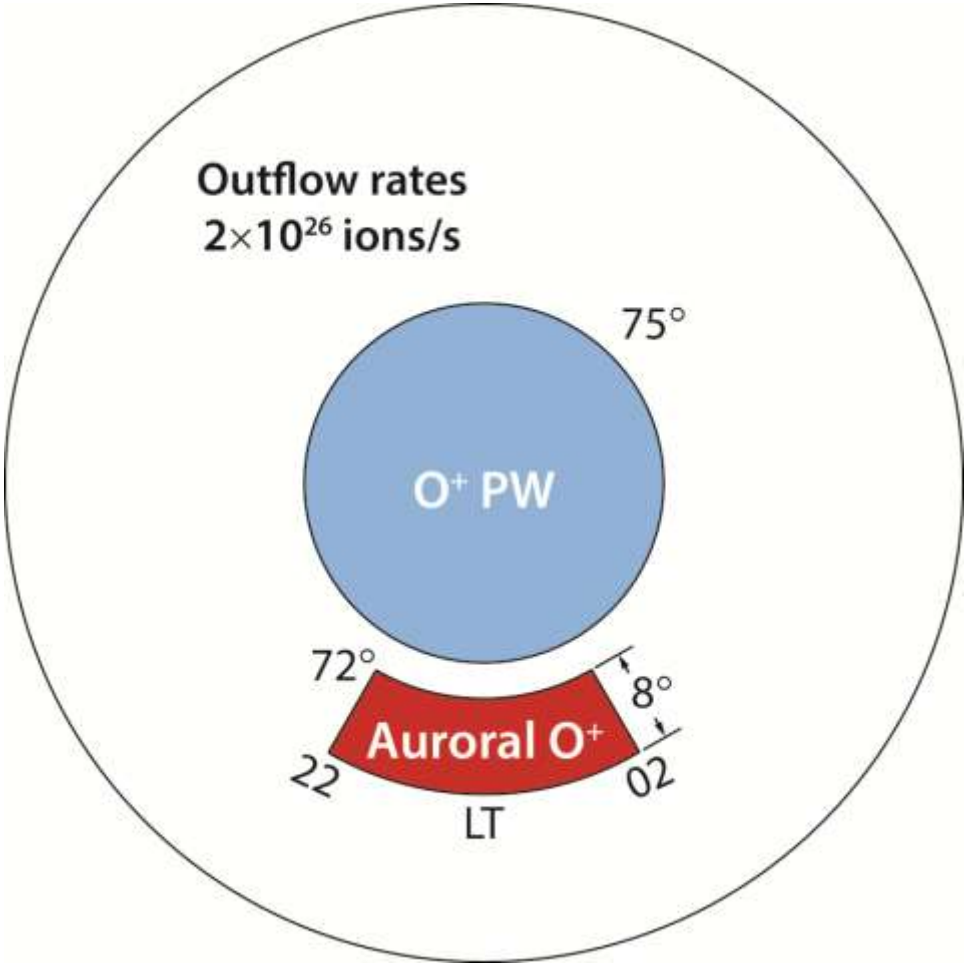
Note: Simulated onsets (with outflow) occur but are delayed ≈ 1.5 hr relative to observed onsets.

Do O^+ outflows influence the stormtime *F*-region neutral density?

Controlled Simulation Experiments

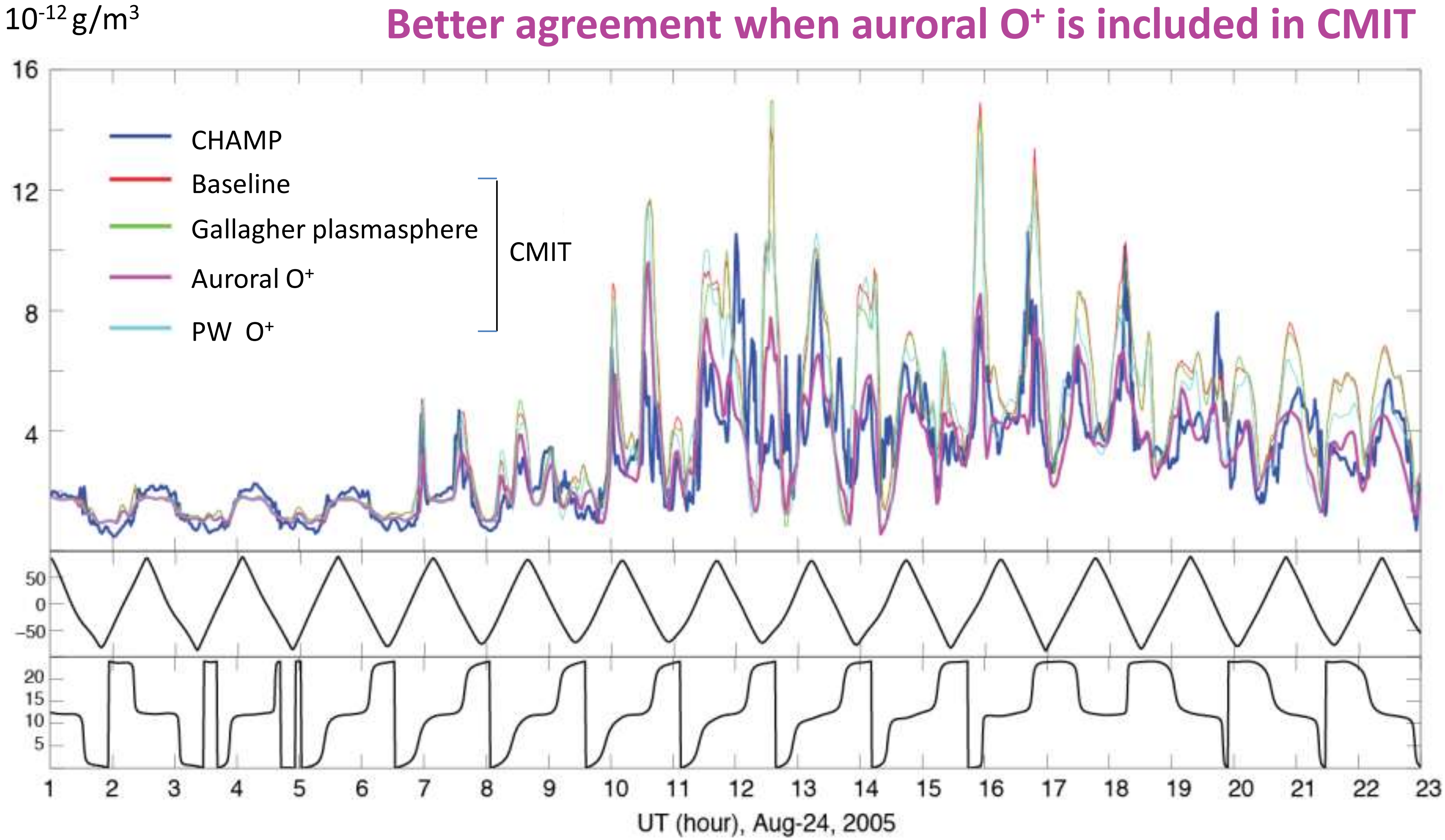
CMIT with:

- *Gallagher et al*. [1988] statistical H^+ plasmasphere initialized at 0:00 UT 24 Aug 2005 but not sustained.
- Two types of O^+ outflow
- Fixed outflow flux: No causal regulation



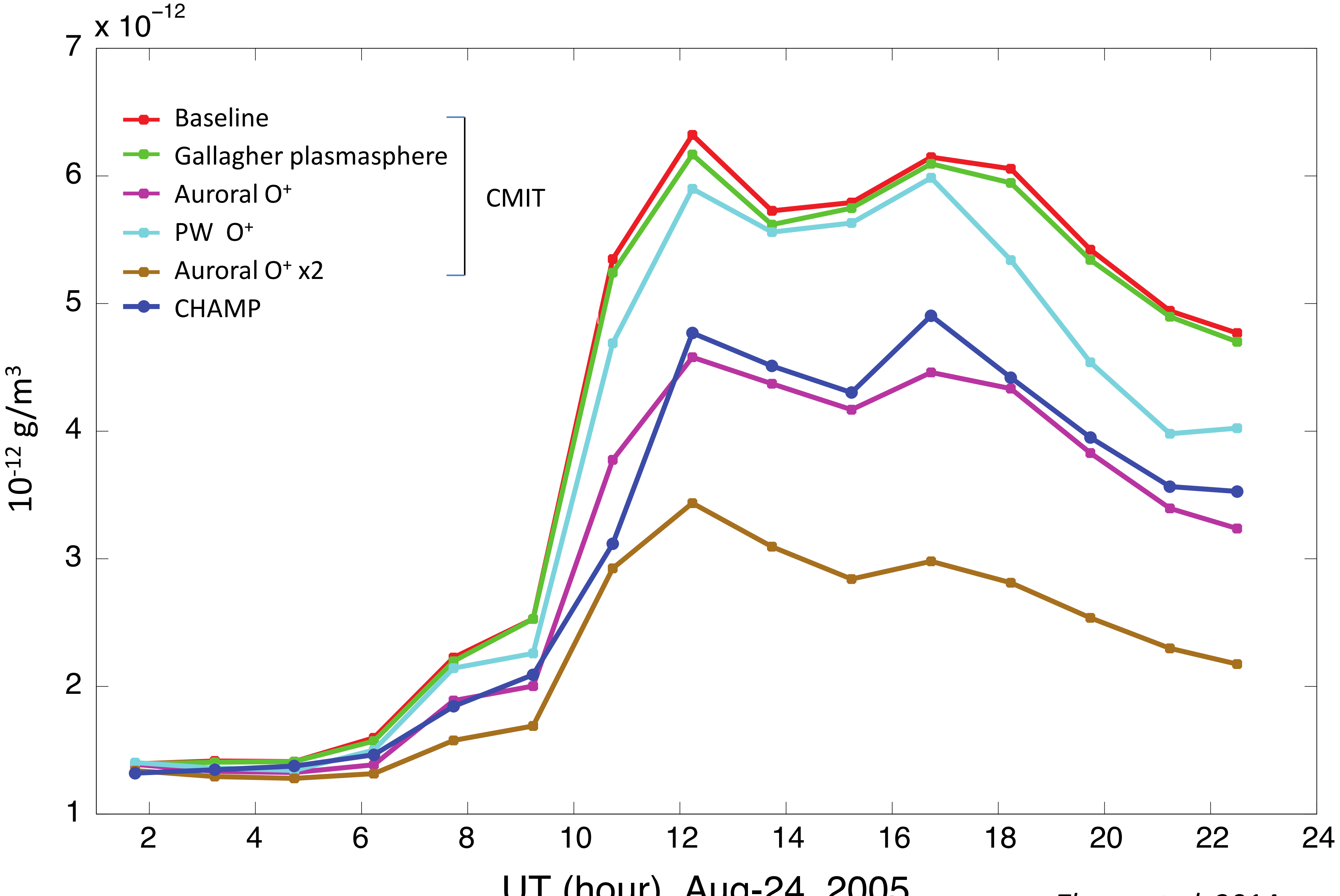
Simulated *F*-region Neutral Density Compared to CHAMP

Better agreement when auroral O^+ is included in CMIT



Zhang et al. 2014

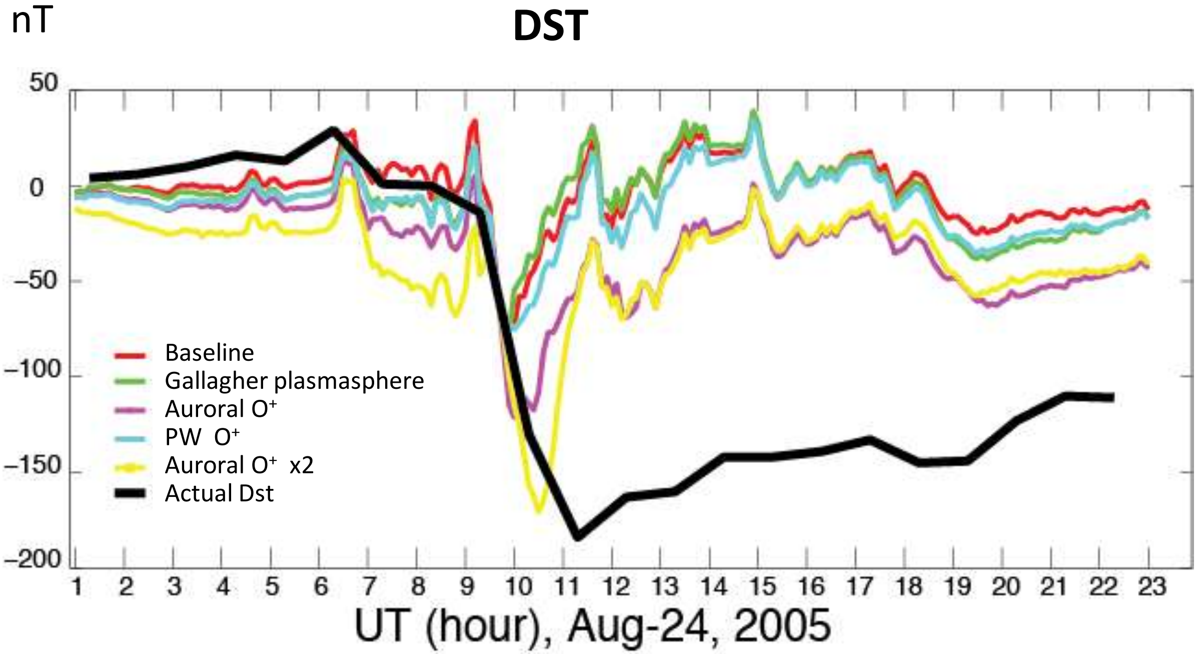
Orbit-Averaged Neutral Density Compared to CHAMP

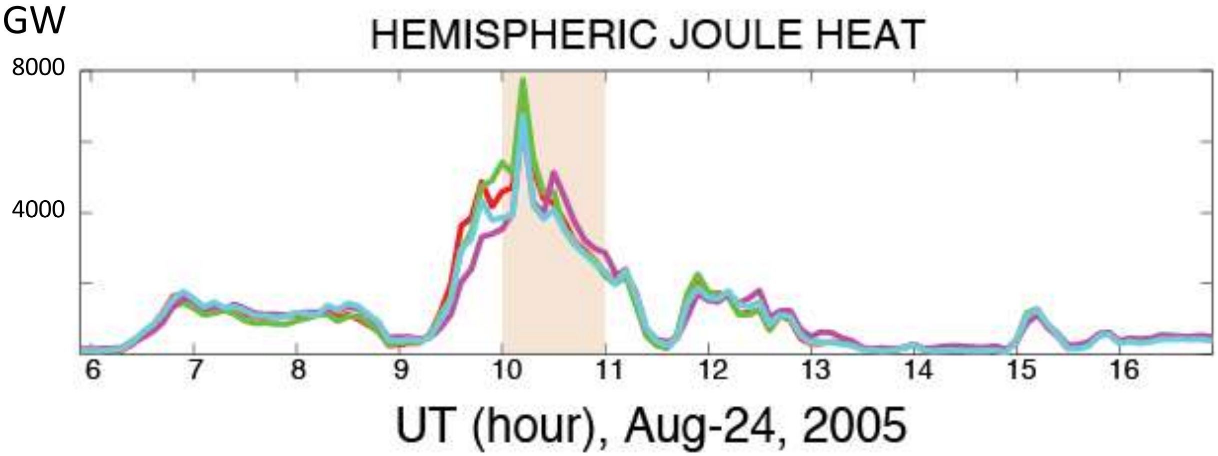


Zhang et al. 2014

Effects of O$^+$ on M-I Coupling

- **Plasmaspheric H$^+$:** Little effect on CPCP, field-aligned current
- **Polar wind O$^+$:** Reduces CPCP
- **Auroral O$^+$ outflow:** Reduces CPCP, increases ring current intensity (but not enough and not sustained in these simulations)
- Hemispheric power is similar in all four runs between 10-11 UT but with different polar cap distributions.

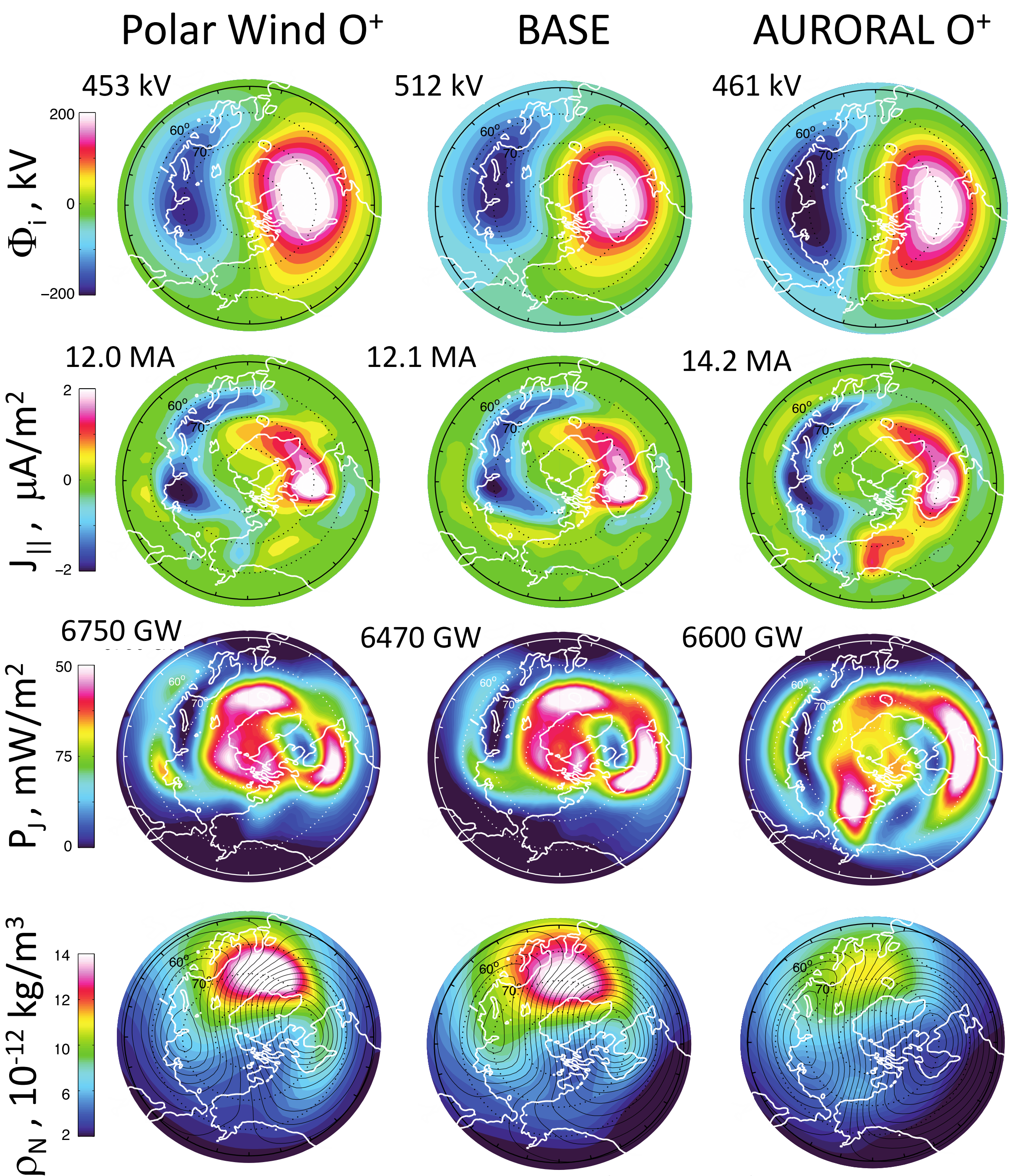




Zhang et al. 2014

Effects cont'd

- CPCP is smaller when O^+ outflow is included in the simulation
- Region-2 currents are larger when auroral O^+ outflow is included $\Rightarrow$ higher integrated current
- Less Joule heating in polar cap with more R1-R2 current closure
- Neutral temperature and density at 400 km altitude are lower when auroral O^+ outflow is included



Zhang et al. 2014

Key Points: Auroral precipitation

- Increases meridional gradient in *E*-region conductivity
  - Ionosphere polarizes at the gradient
  - Exacerbates dawn-dusk asymmetry in

    ionospheric convection

    plasmasheet fast flows

Why does the M-I system maintain nearly divergence-free Hall currents?

Key Points: Soft electron precipitation

- Produced by direct-entry (cusp) and conversion of Alfvén wave power to field-aligned electrons (cusp and nightside convection throat)
- Enhances conductivity in the bottomside *F*-region
- Joule heating is enhanced there $\Rightarrow$ neutral mass density is elevated at CHAMP altitude (but it increases too much)

Key Points: O^+ ionospheric outflows

- Lowers reconnection rate (dayside and nightside
  - Lower CPCP
  - Slower convection
  - Less Joule heating, esp. in polar cap
- Auroral outflows have greatest impact

Do ionospheric outflows directly affect the neutral gas and vice-versa?