Magnetosphere-Ionosphere Coupling

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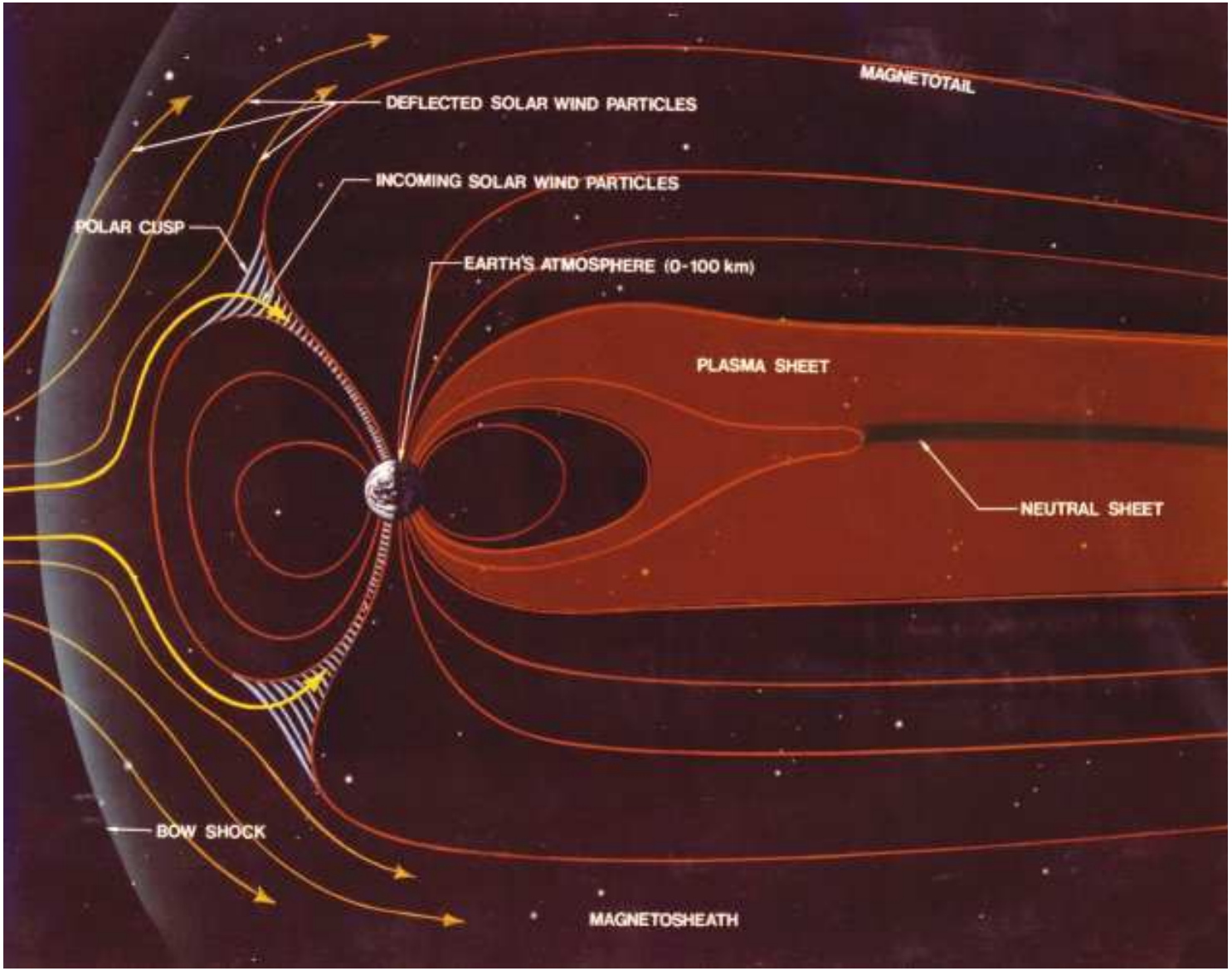
Some Types of MI Coupling

1. Particle Precipitation
2. Electrodynamical Coupling
3. Ion Outflow

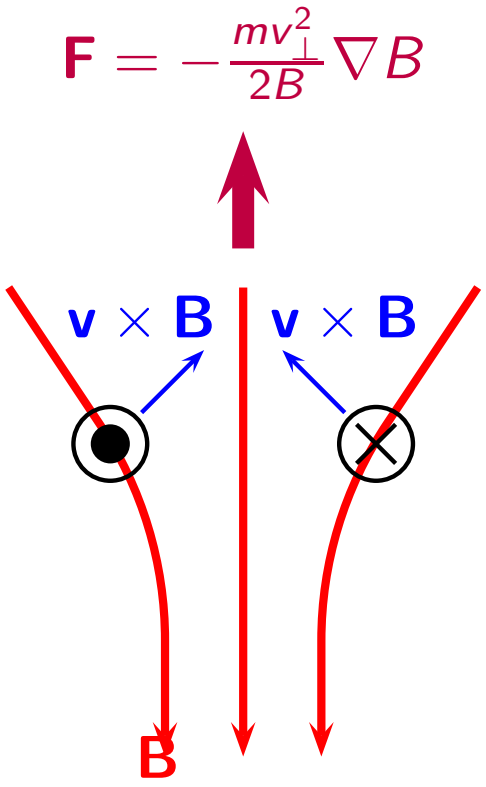
Aurora (Poker Flat April 10, 2018)

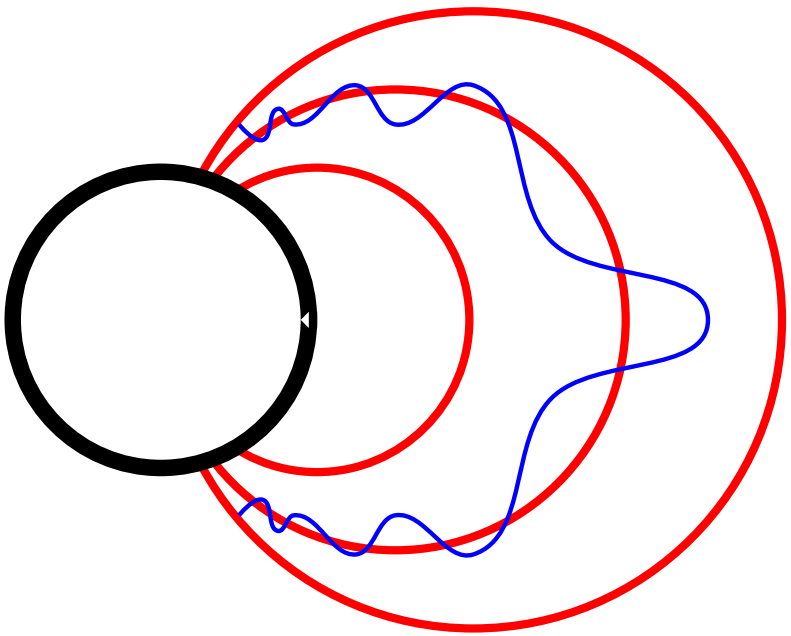
Video courtesy of Jason Ahrns and Don Hampton, U. Alaska Fairbanks.
https://www.youtube.com/watch?v=yopO7wrnqaw

Solar Wind Only Has Direct Access via the Cusp



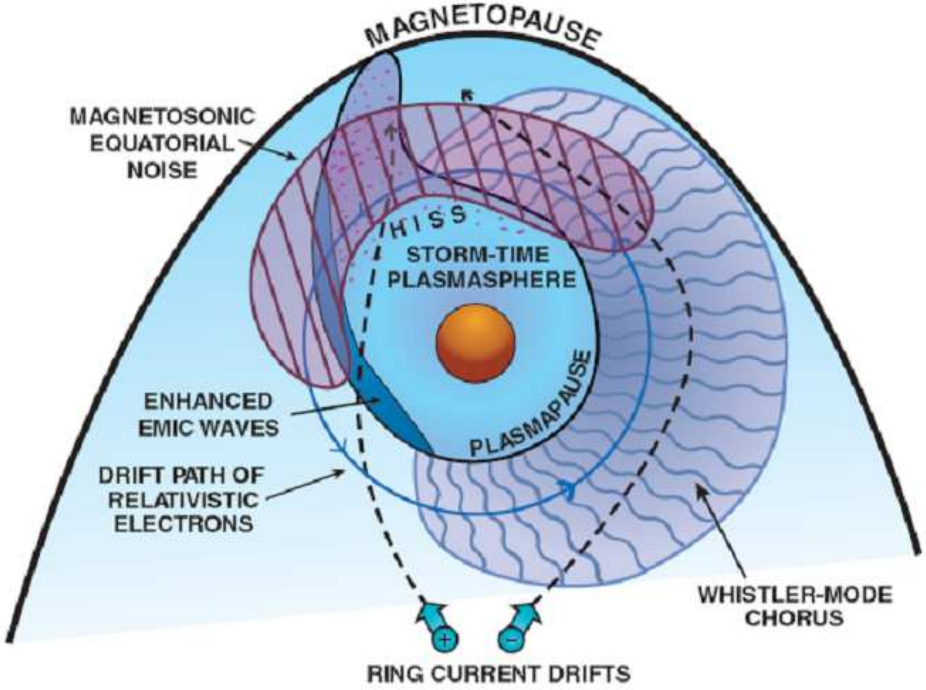
Magnetic Mirror Force and Bounce Motion

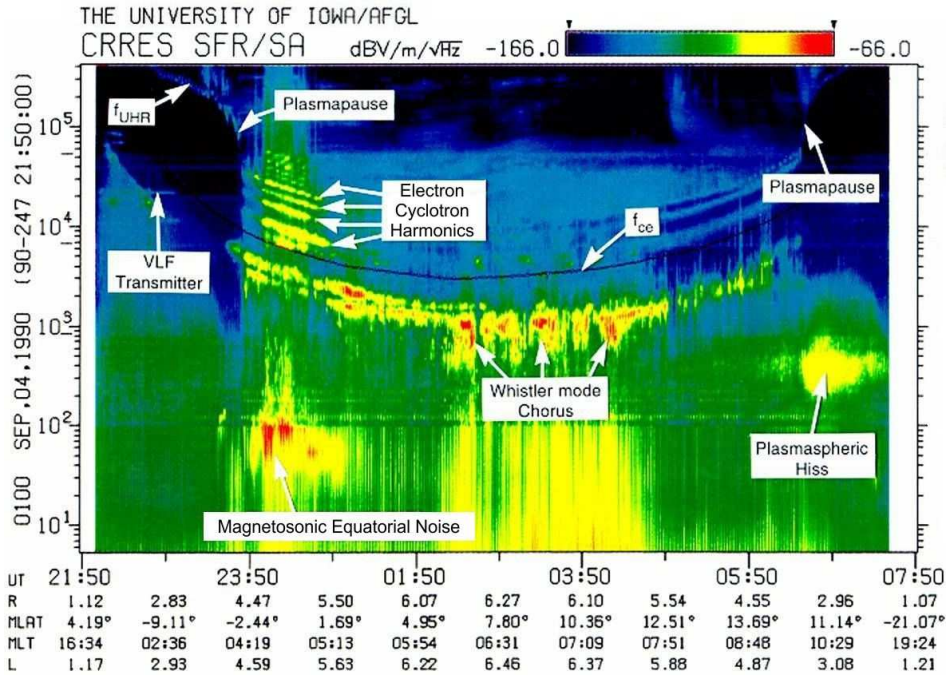




1st adiabatic invariant $\mu = \frac{\frac{1}{2}mv_\perp^2}{B}$ is a constant of motion

Breaking the Adiabatic Invariants: Wave Environment

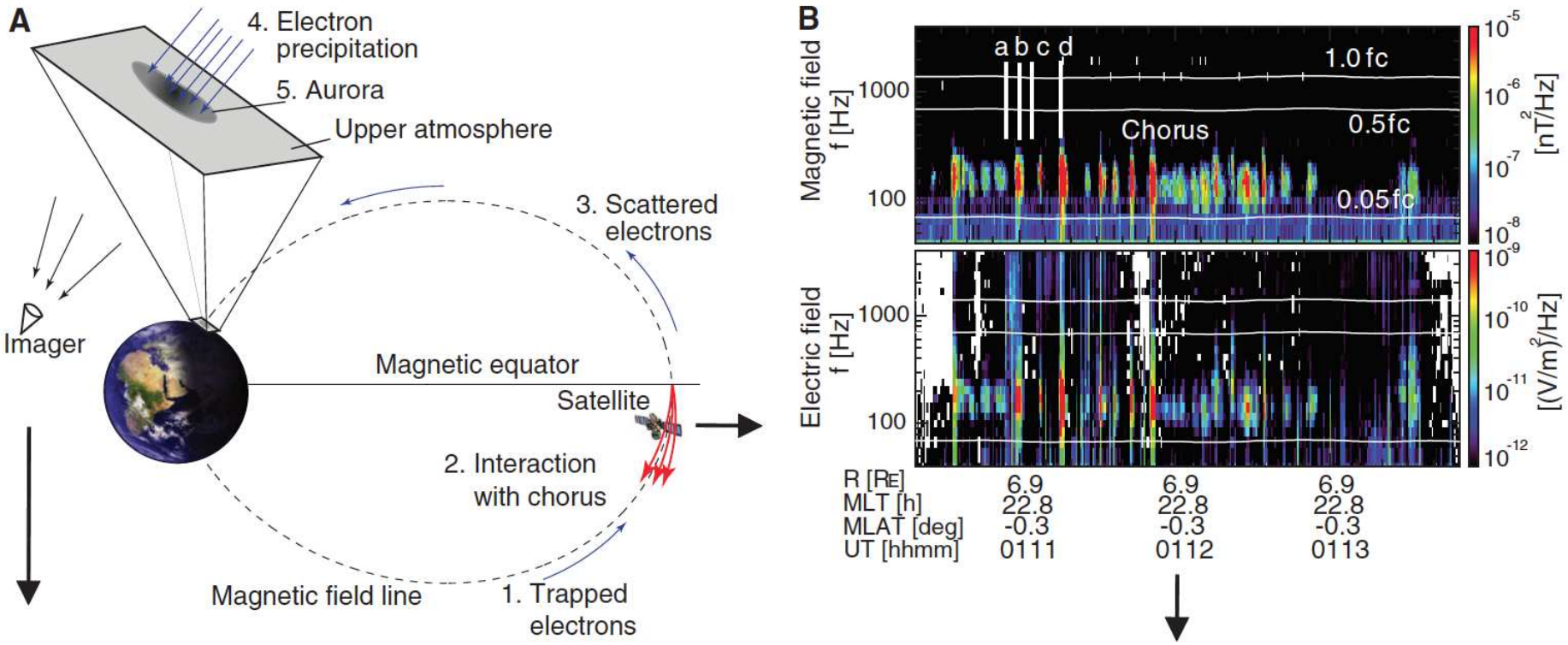




Thorne et al. [2010, *Nature*] argue that the diffuse aurora is primarily driven by whistler mode chorus.

Images courtesy the U. of Iowa EMFISIS Team

Chorus and Pulsating Aurora



Nishimura et al. [2010, *Science*] showed that bursts of chorus waves are correlated with pulsating aurora.

Upwards Field-Aligned Currents and Discrete Aurora

How can field lines carry upwards FAC?

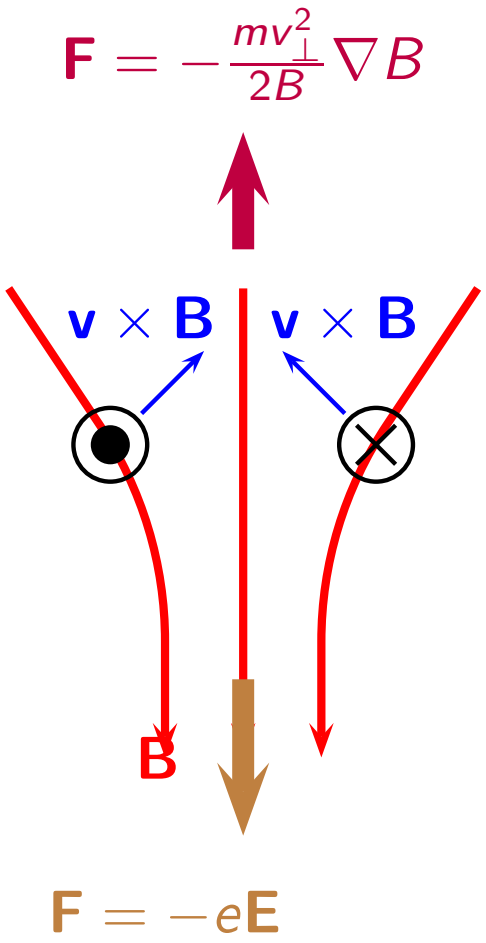
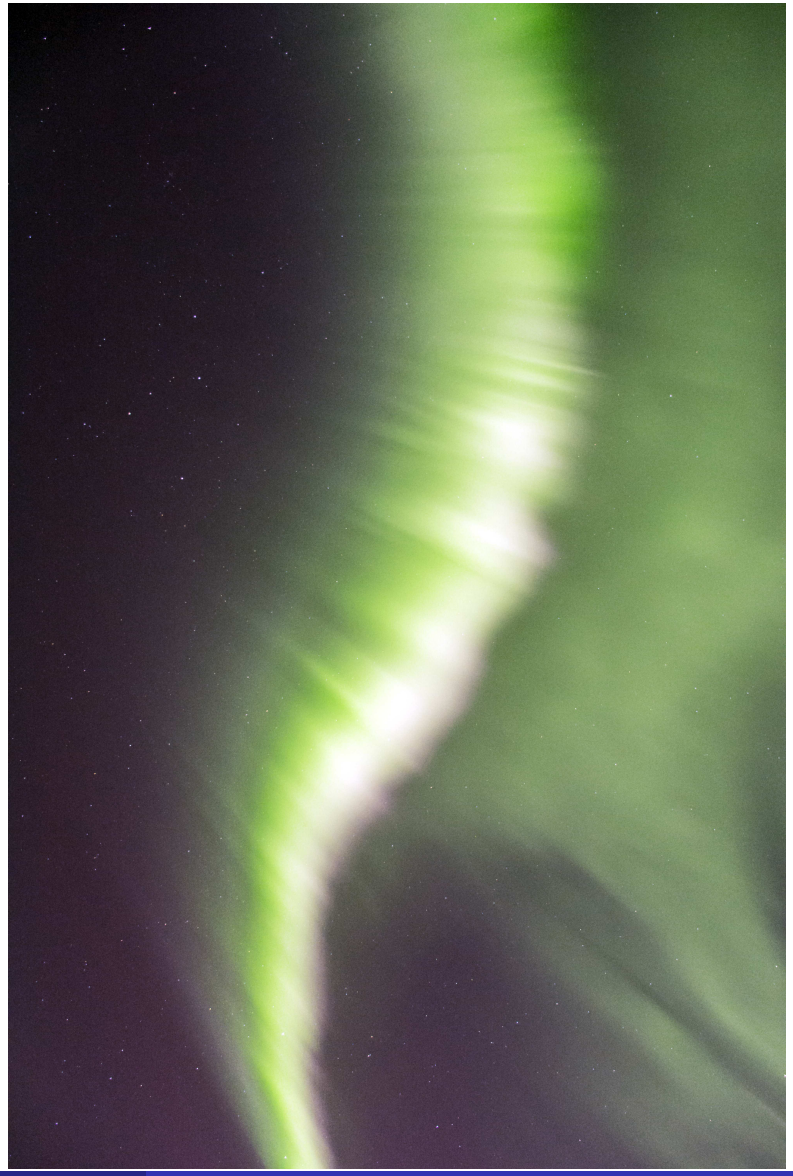


Photo Credit: Ashton Reimer

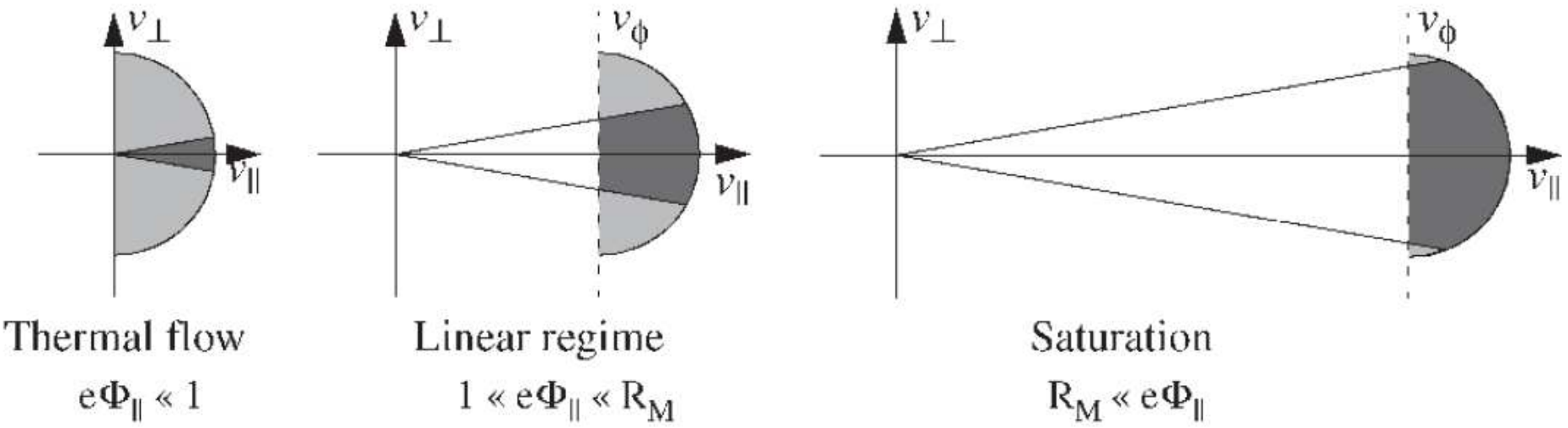


Parallel Electric Fields

Knight relation determines the parallel electric potential drop needed.

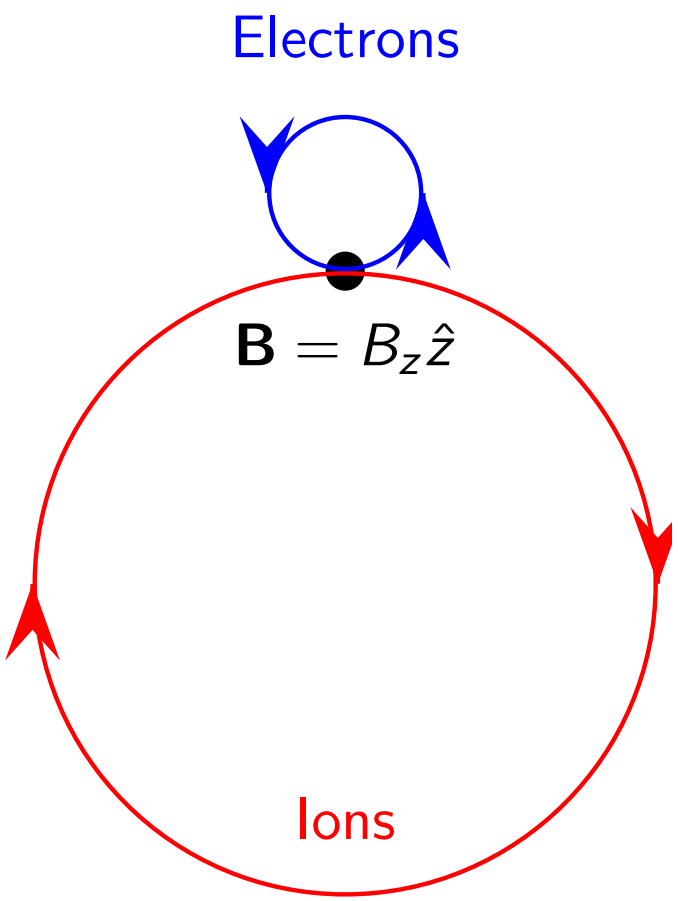
$$J_{\parallel} = J_{\text{thermal}} \left[R_M - (R_M - 1) \exp\left\{ -\frac{e\Phi_{\parallel}}{k_B T_e (R_M - 1)} \right\} \right]$$

$$R_M \equiv \frac{B_{\text{ionosphere}}}{B_{\text{top}}}$$

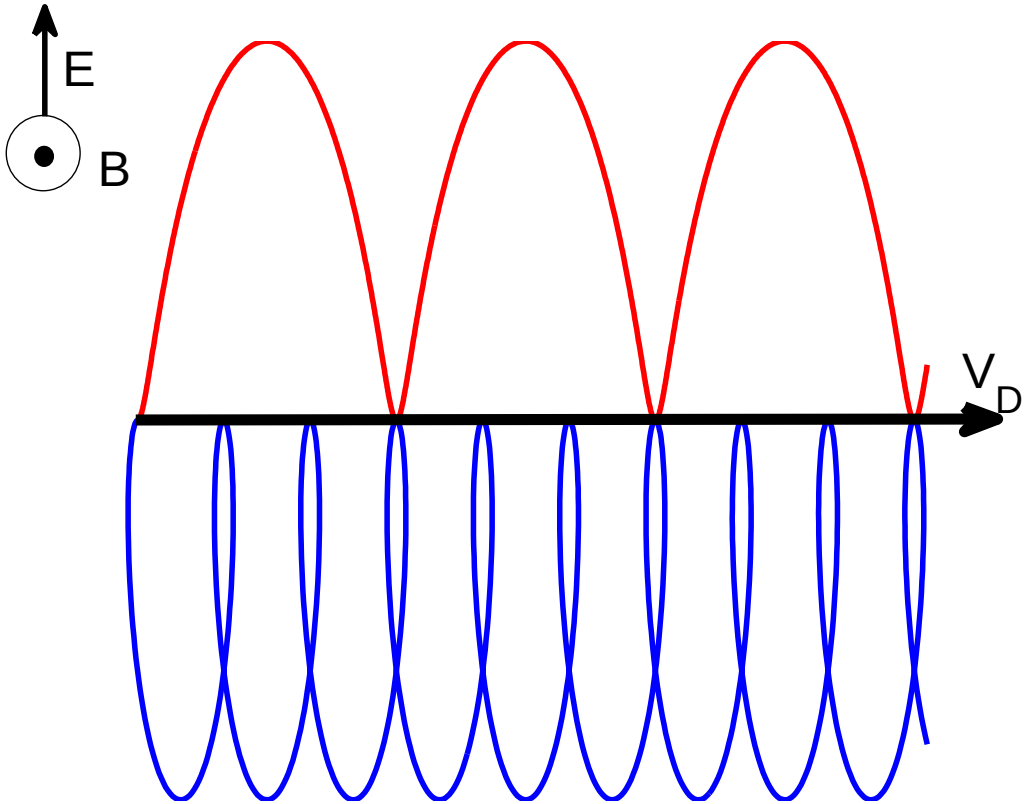


Particle Motion in Fields

Uniform **B** Field



Crossed Uniform **E** and **B**



$$v_D = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

Note $\mathbf{E} + \frac{\mathbf{E}\times\mathbf{B}}{B^2} \times \mathbf{B} = 0$ as long as $\mathbf{E}\cdot\mathbf{B} = 0$

Effects of Collisions: Ohm's Law for the Ionosphere

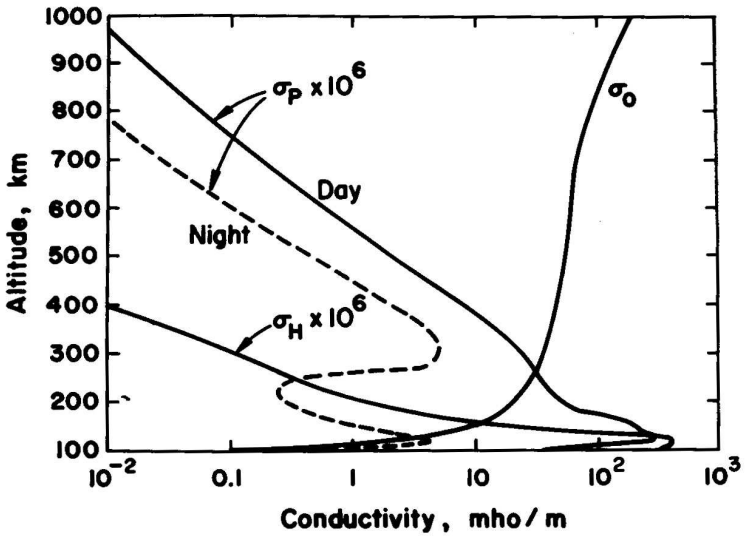
Steady-state momentum equation for each species (zero neutral wind case):

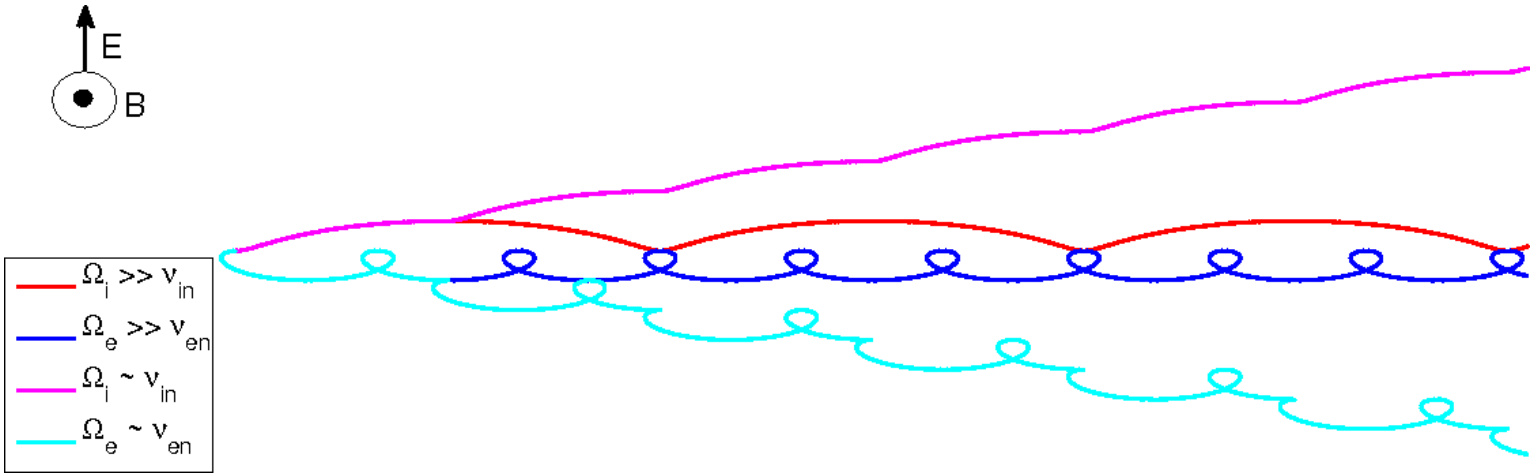
$$0 = n_\alpha q_\alpha \left(\mathbf{E} + \mathbf{u}_\alpha \times \mathbf{B}\right) - \nu_{\alpha n} m_\alpha n_\alpha \mathbf{u}_\alpha$$

Resulting Ohm's Law:

$$\mathbf{J} = \sum_\alpha n_\alpha q_\alpha \mathbf{u}_\alpha \longrightarrow \mathbf{J} = \begin{pmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix} \cdot \mathbf{E}$$

Conductivity Profiles





Closure of Field Aligned Currents in a Slab Ionosphere

Low Frequency Limit of Ampere-Maxwell Law:

$$\frac{1}{\mu_0}\nabla \times \mathbf{B} = \mathbf{J} + \epsilon_0 \cancel{\frac{\partial \mathbf{E}}{\partial t}} \Longrightarrow \nabla \cdot \mathbf{J} = 0$$

3D potential equation with magnetospheric currents:

$$\nabla \cdot [\mathbf{J}_{\mathrm{iono}} + \mathbf{J}_{\mathrm{mag}}] = 0 \Longrightarrow \nabla \cdot \sigma \cdot \nabla \Phi = \nabla \cdot \mathbf{J}_{\mathrm{mag}}$$

Integrate over altitude, assume equipotential field lines:

$$\nabla_\perp \cdot \Sigma \cdot \nabla_\perp \Phi = \int \nabla \cdot \mathbf{J}_{\mathrm{mag}}\, dz$$

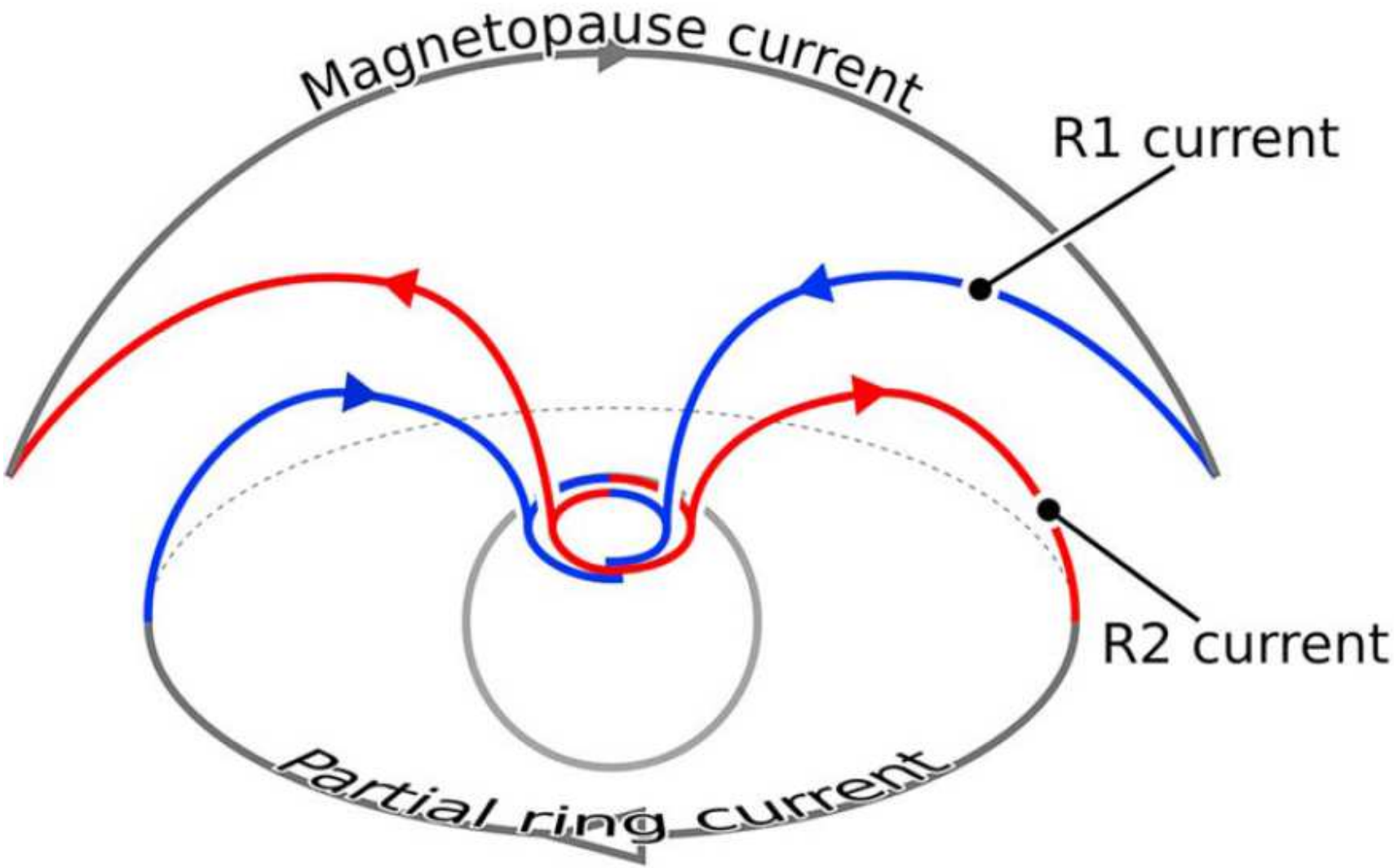
$\mathbf{J}_\perp$ goes to 0 above ionosphere, thus:

$$\int \nabla \cdot \mathbf{J}_{\mathrm{mag}}\, dz = J_\parallel$$

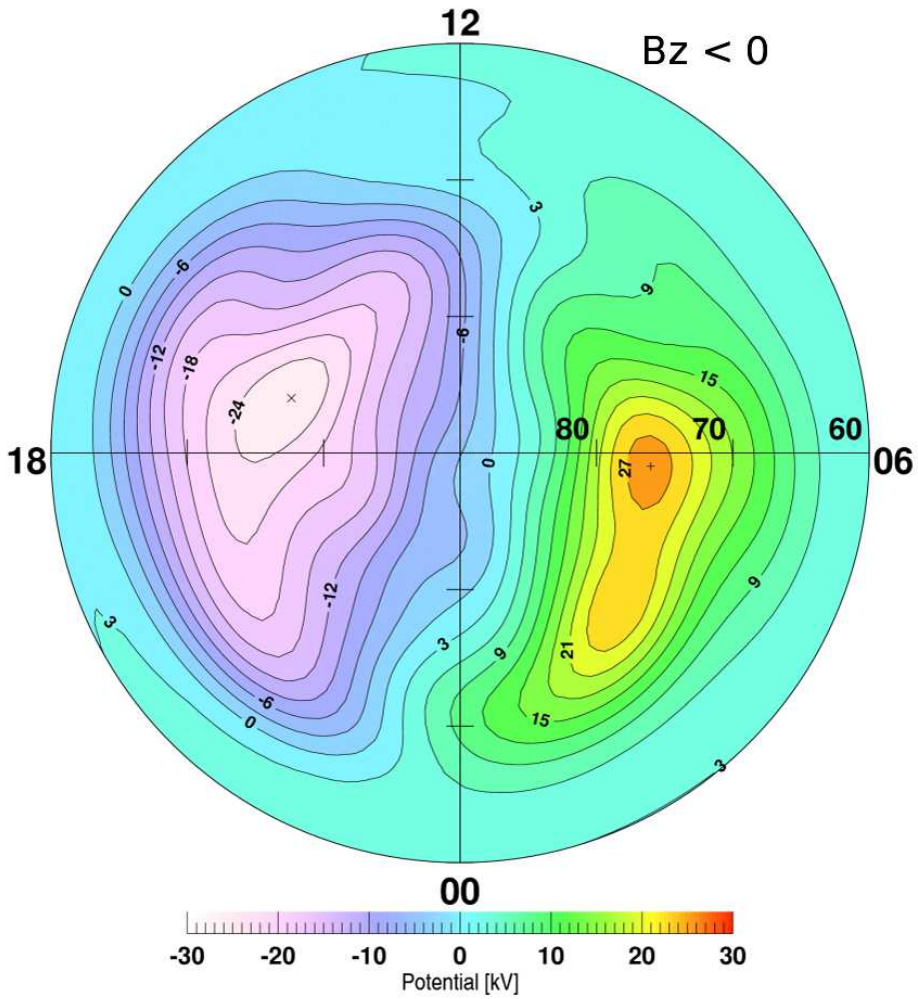
2D slab ionosphere potential equation:

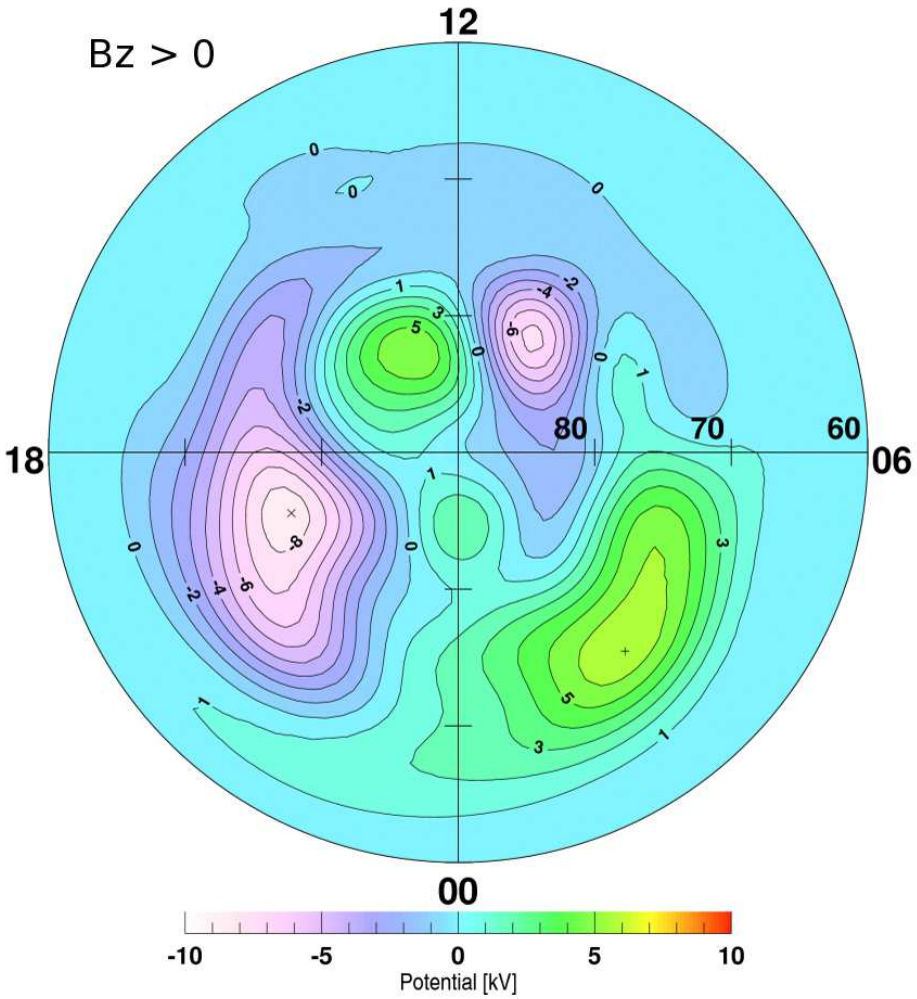
$$\nabla_\perp \cdot \Sigma \cdot \nabla_\perp \Phi = J_\parallel$$

Region 1 and Region 2 Current Systems



High Latitude Convection Patterns

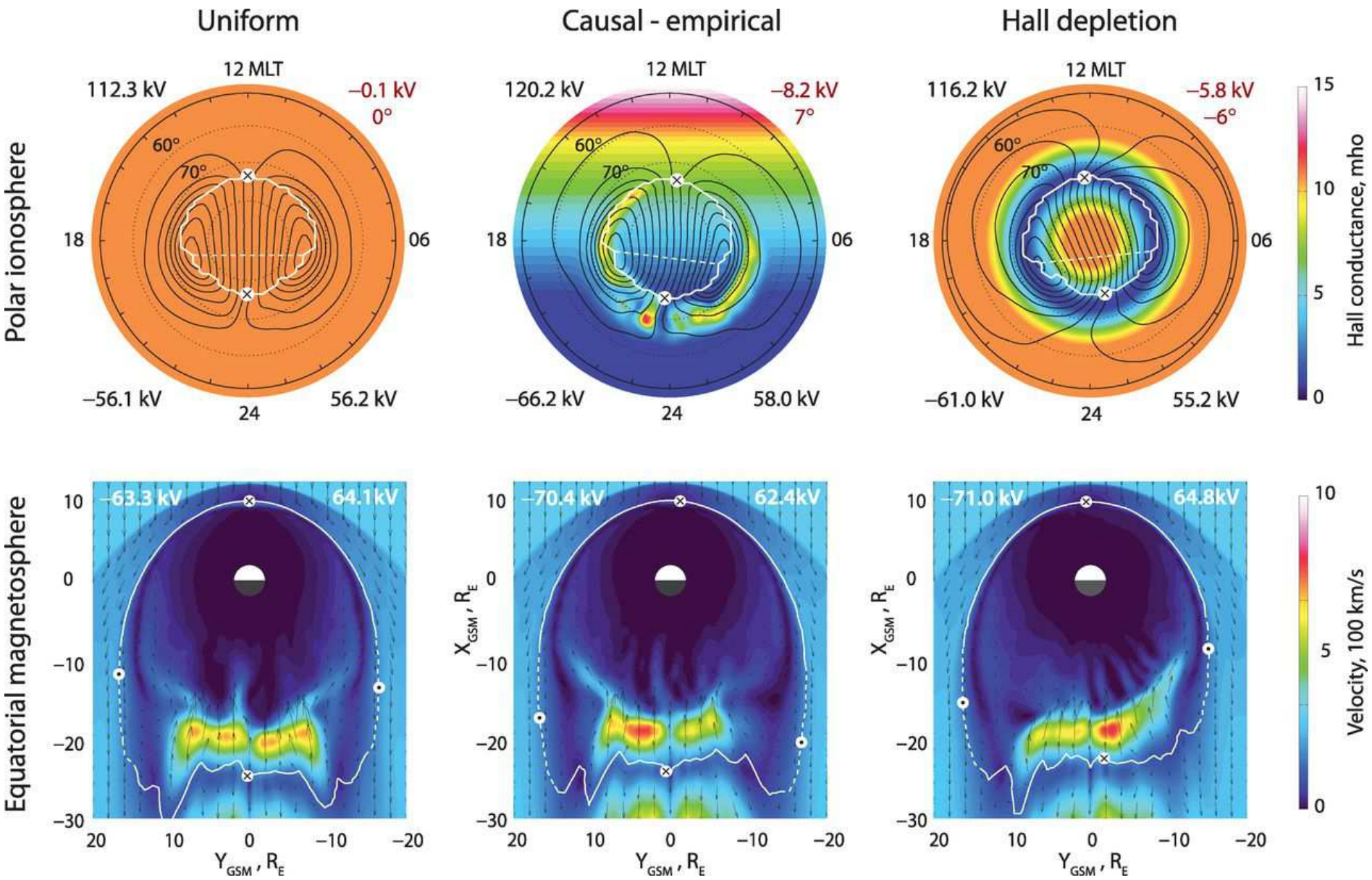




Interplay Between $J_{\|}$, Precipitation, $\mathbf{\Sigma}$, and Φ

Quad-res LFM-RCM, St. Patrick's Day Storm 2015, courtesy of M. Wiltberger

Conductivity Effects on Magnetosphere (Lotko et al., 2014)



Mechanical vs. Electrical Points of View

Electrical View

- Input is FAC, $J_{\|}$
- Responses is electric fields, $\mathbf{E}$
- Dissipation related to conductance, Σ
- Heating is Joule heating:

$$\mathbf{J} \cdot \mathbf{E}' = \left(\sigma \cdot \mathbf{E}'\right) \cdot \mathbf{E}' = \sigma_P \left|\mathbf{E} + \mathbf{u}_n \times \mathbf{B}\right|^2$$

Mechanical View

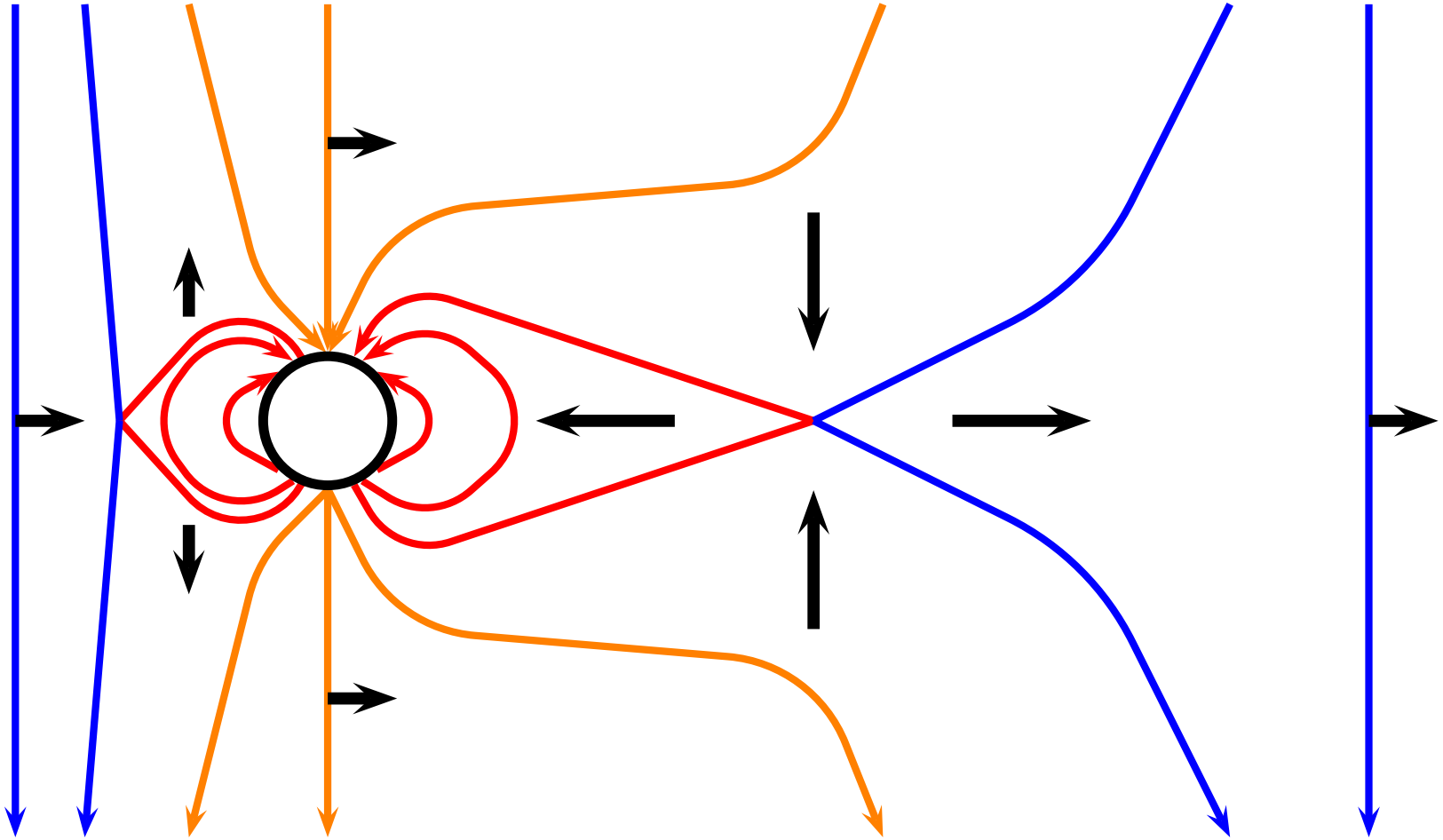
- Input is magnetic stress, $\frac{1}{\mu_0}\left(\nabla \times \mathbf{B}\right) \times \mathbf{B}$
- Responses is plasma drift, $\mathbf{u}_i$
- Dissipation related to friction, $\nu_{in}\left(\mathbf{u}_i - \mathbf{u}_n\right)$
- Heating is frictional heating:

$$Q_J = n_i m_i \nu_{in} \left|\mathbf{u}_i - \mathbf{u}_n\right|^2$$

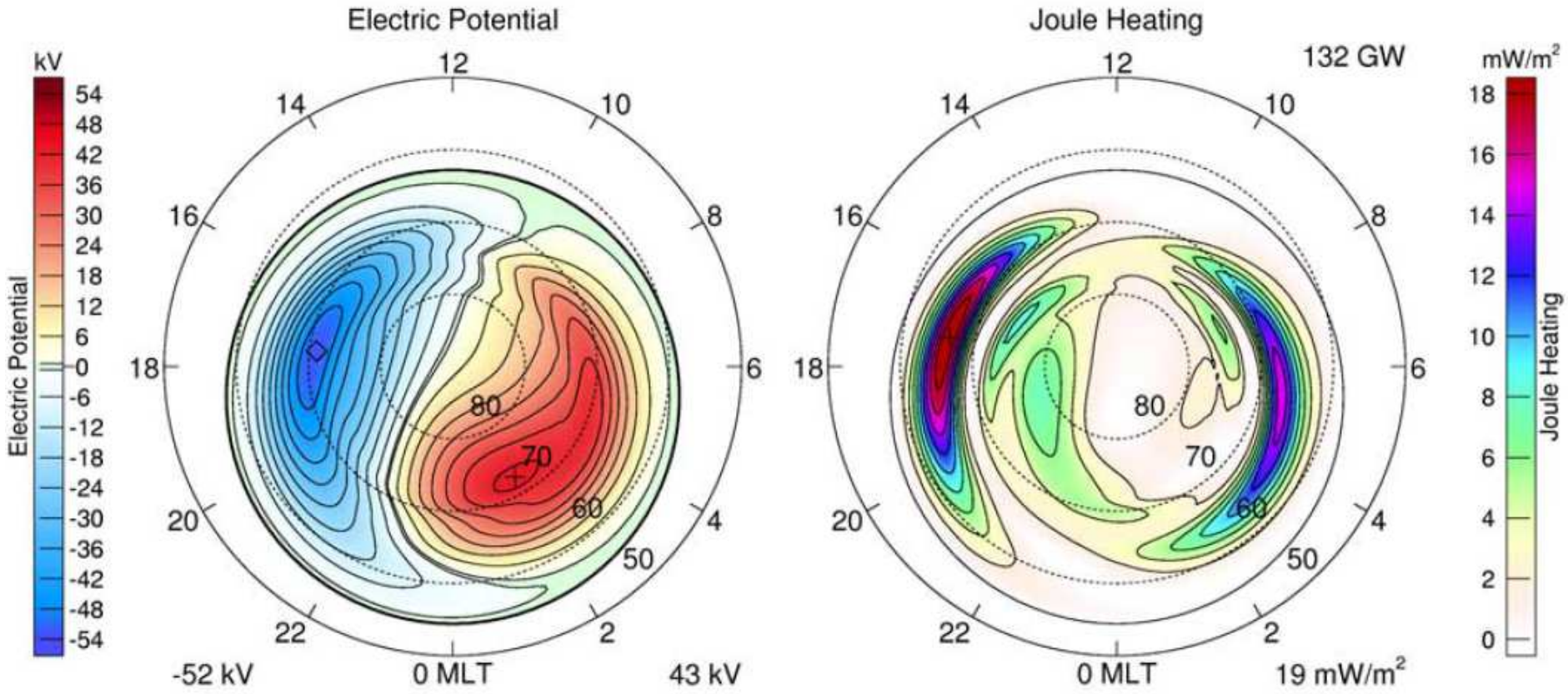
Appendix A of Thayer and Semeter, 2004, JASTP proves:

$$\sigma_P \left|\mathbf{E} + \mathbf{u}_n \times \mathbf{B}\right|^2 = n_i m_i \nu_{in} \left|\mathbf{u}_i - \mathbf{u}_n\right|^2$$

Convection During B_z South (Dungey Cycle)

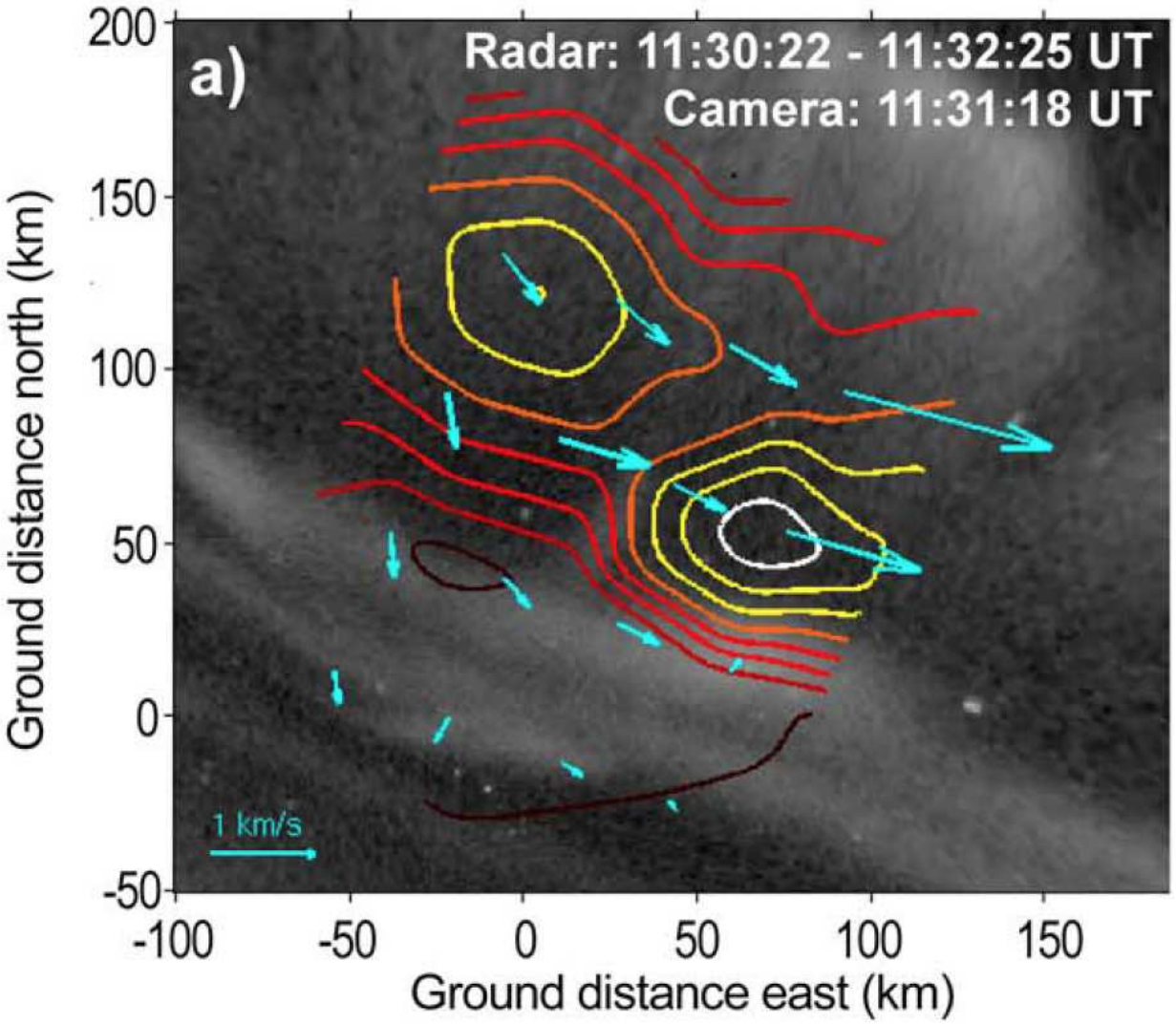


Large Scale Joule Heating

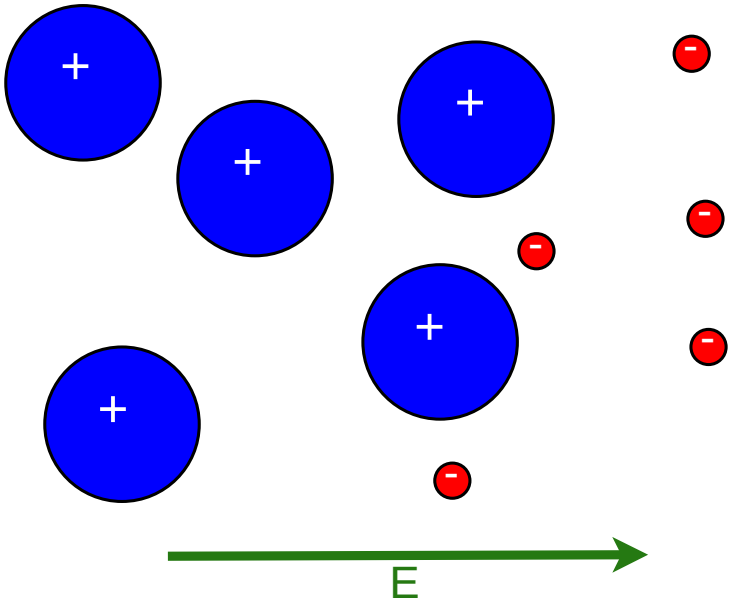


Weimer, 2005.

Arc-Scale Joule Heating (Semeter et al. 2010)



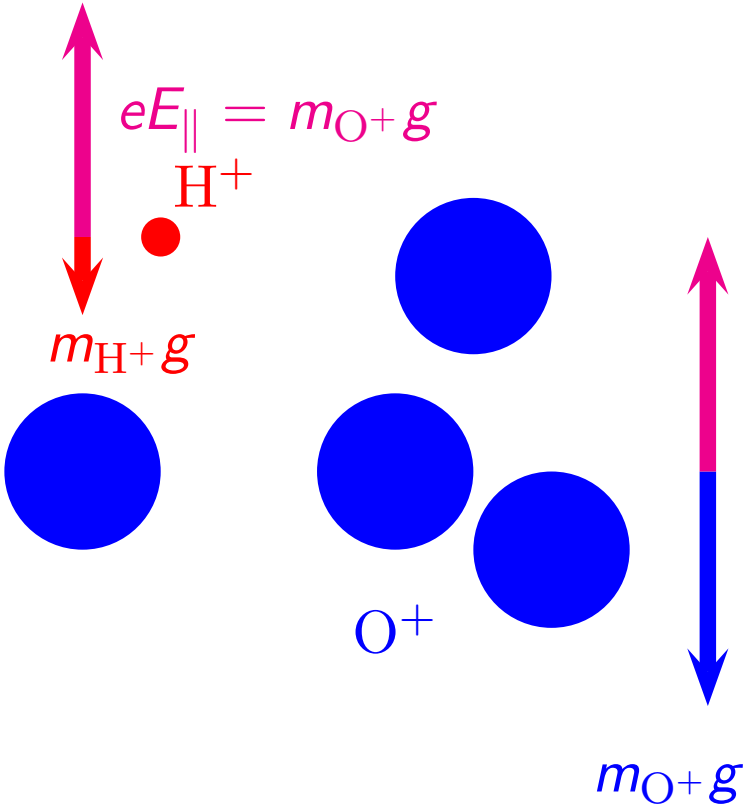
Ambipolar Electric Fields

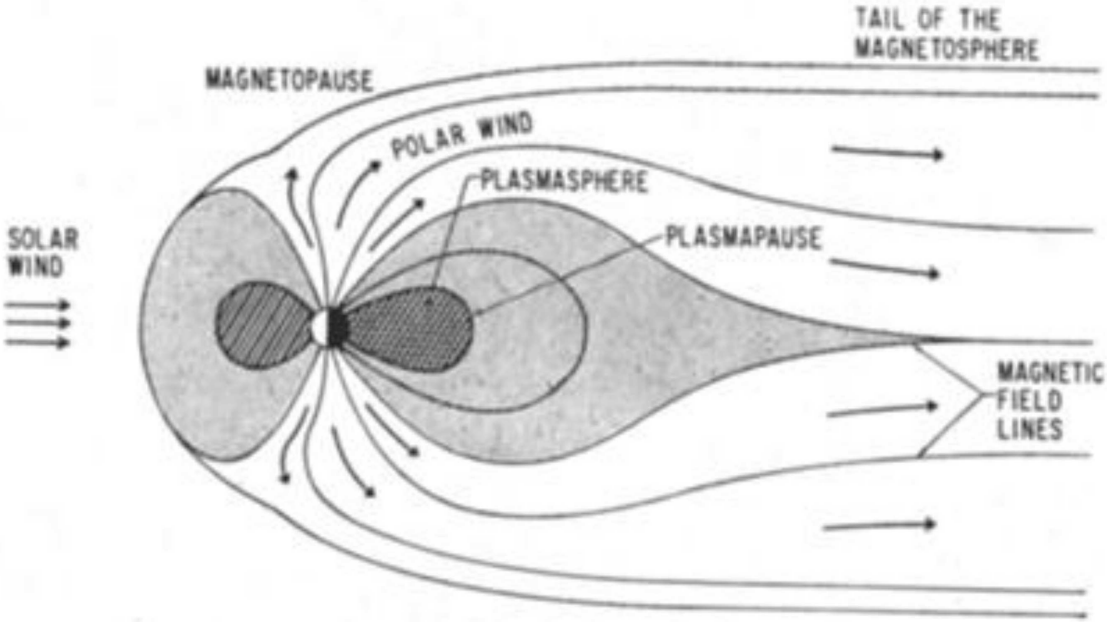


$$\mathbf{E} + \mathbf{u} \times \mathbf{B} - \frac{1}{en}\mathbf{J} \times \mathbf{B} = -\frac{1}{en}\nabla p_e$$

$$E_{\parallel} = -\frac{1}{en}\nabla_{\parallel} p_e$$

Classical Polar Wind

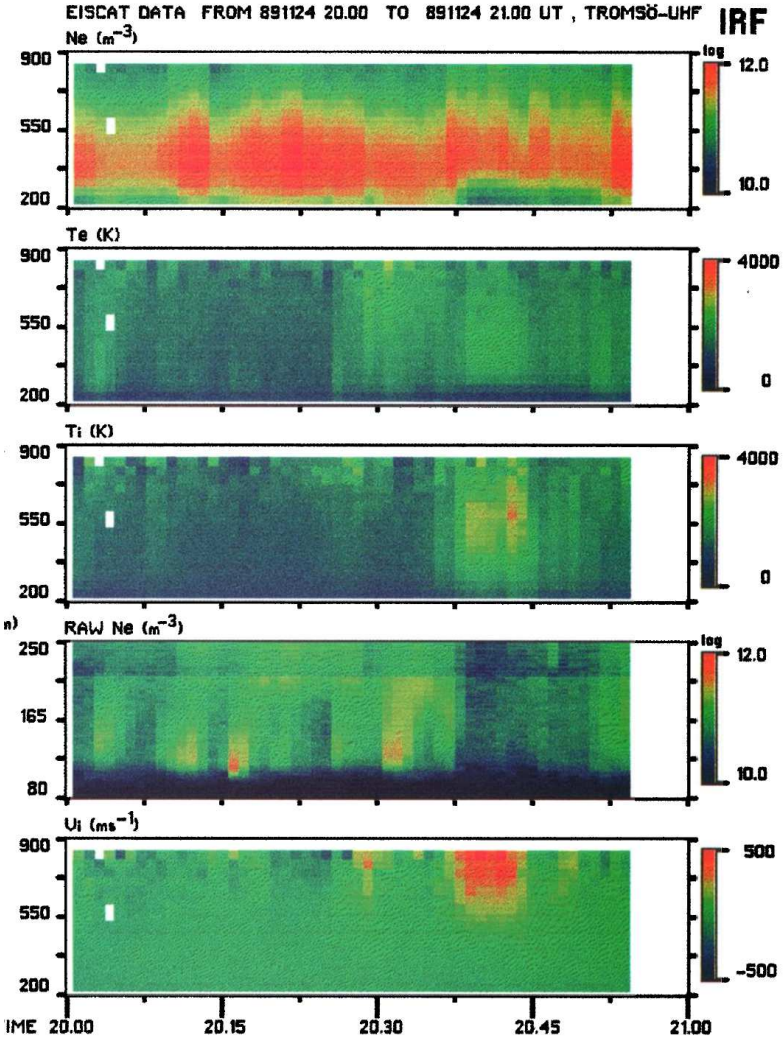




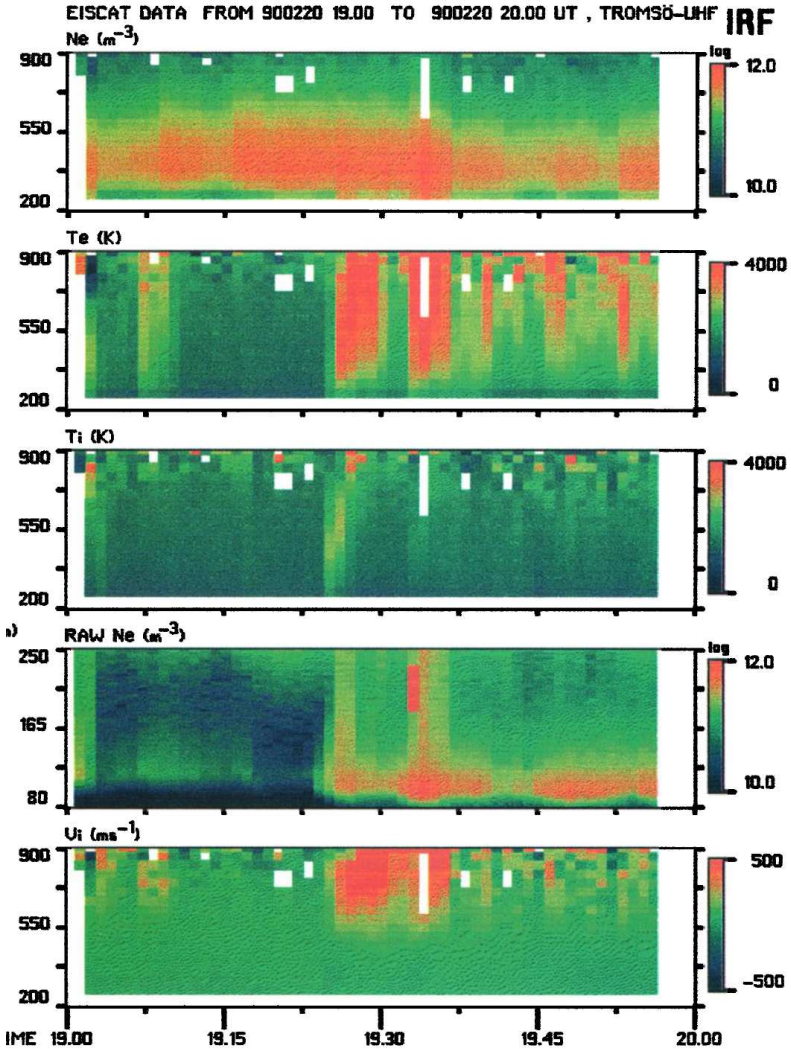
- In steady state ambipolar field balances gravity for major ion species (O^+)
- Light minor ions (H^+ and He^+) feel same field

Drivers of Ion Upflow (Wahlund et al. 1992)

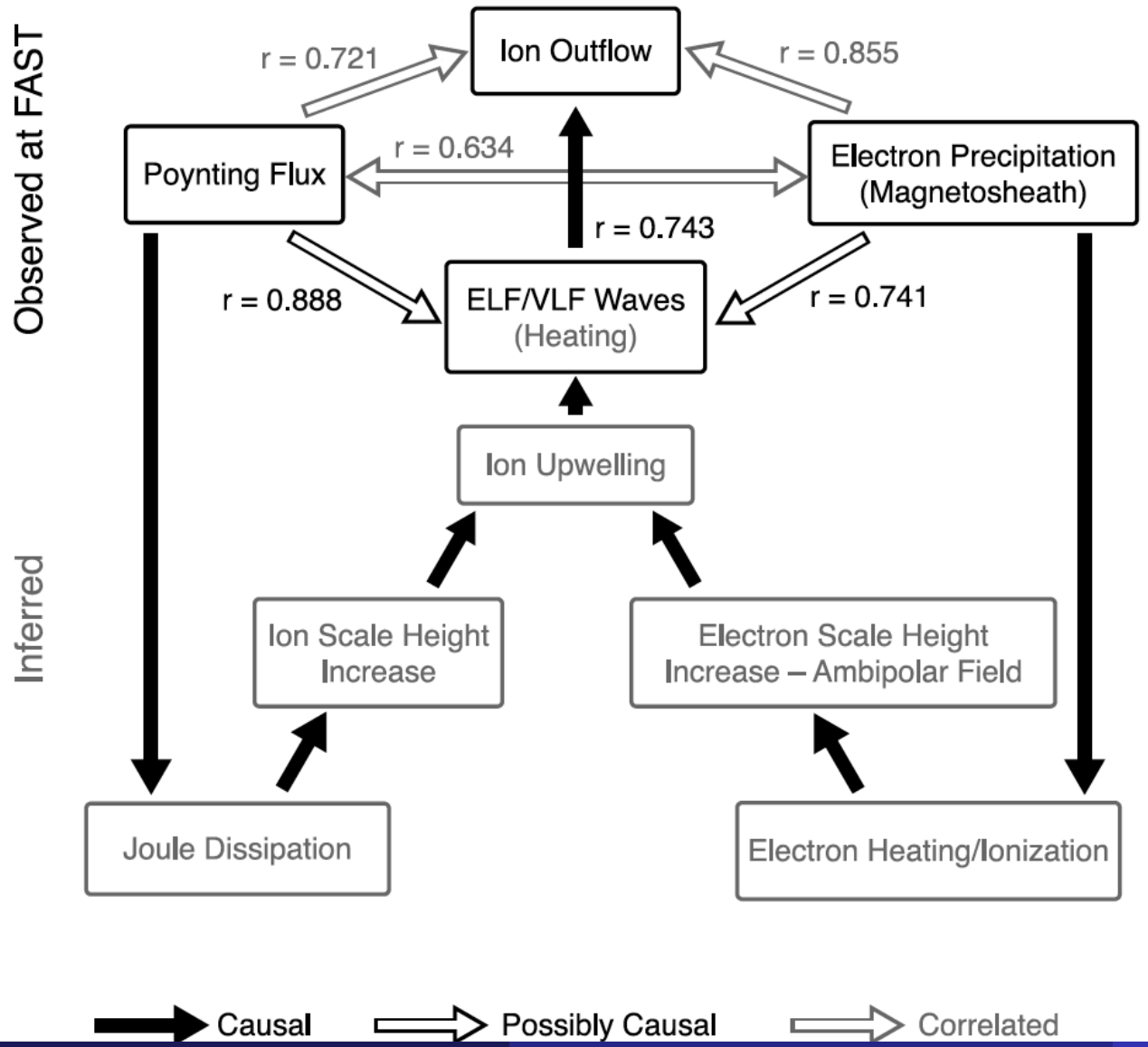
Type I (Enhanced T_i)



Type II (Enhanced T_e)

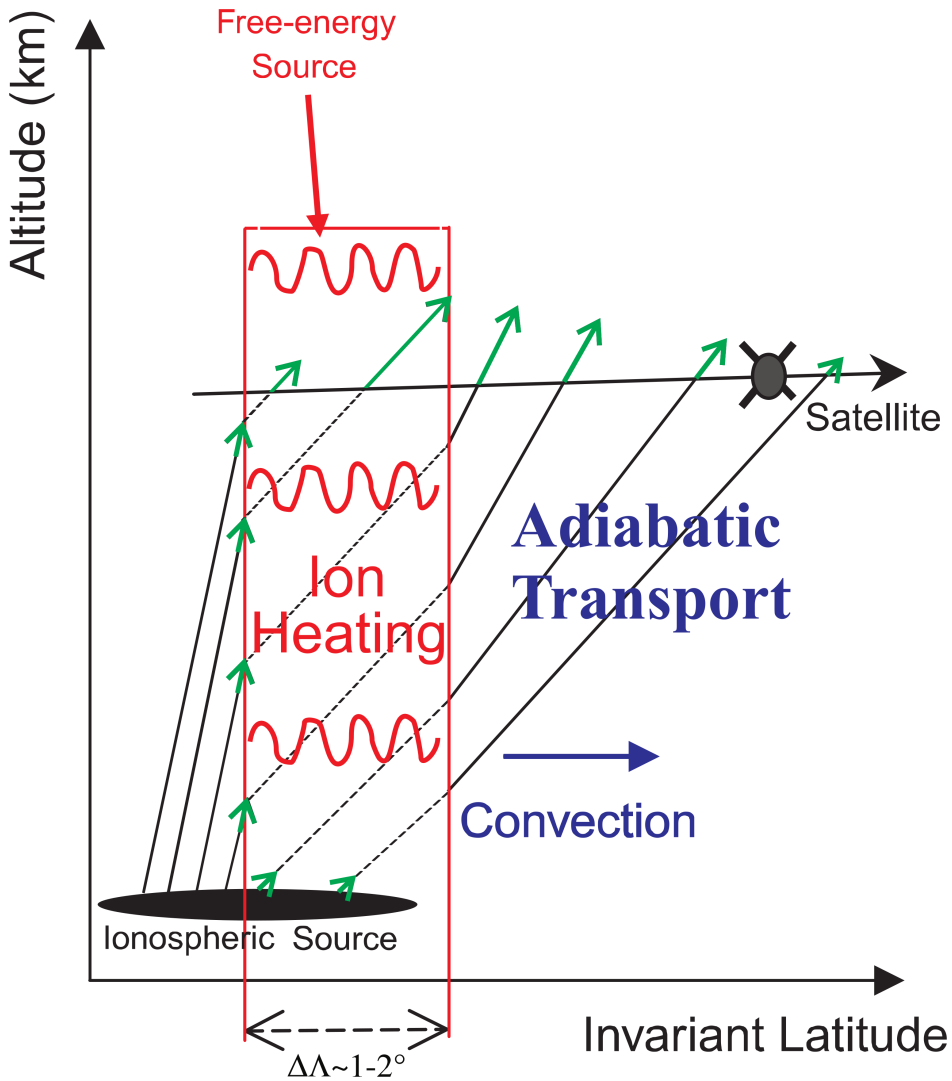


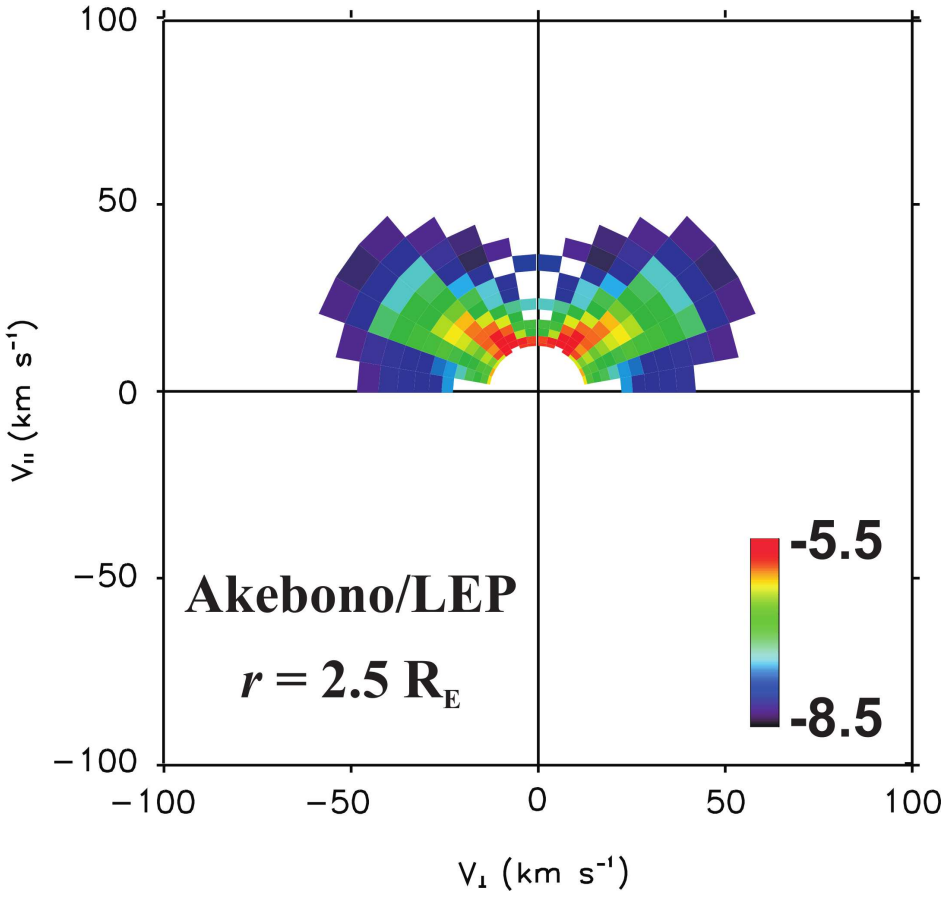
Ion Outflow as a Multistep Process



Strangeway et al. (2005)

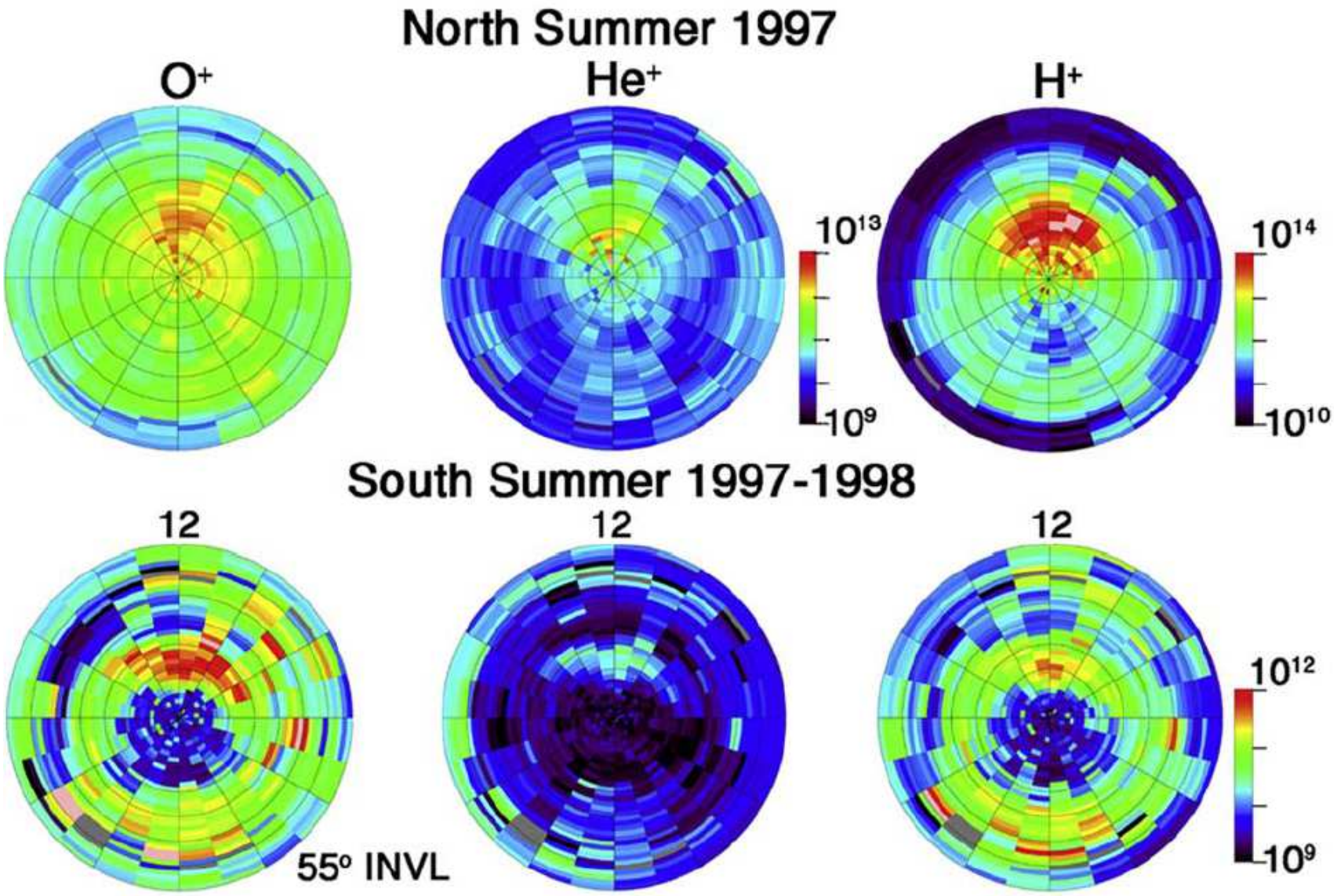
Upflow to Outflow Conversion



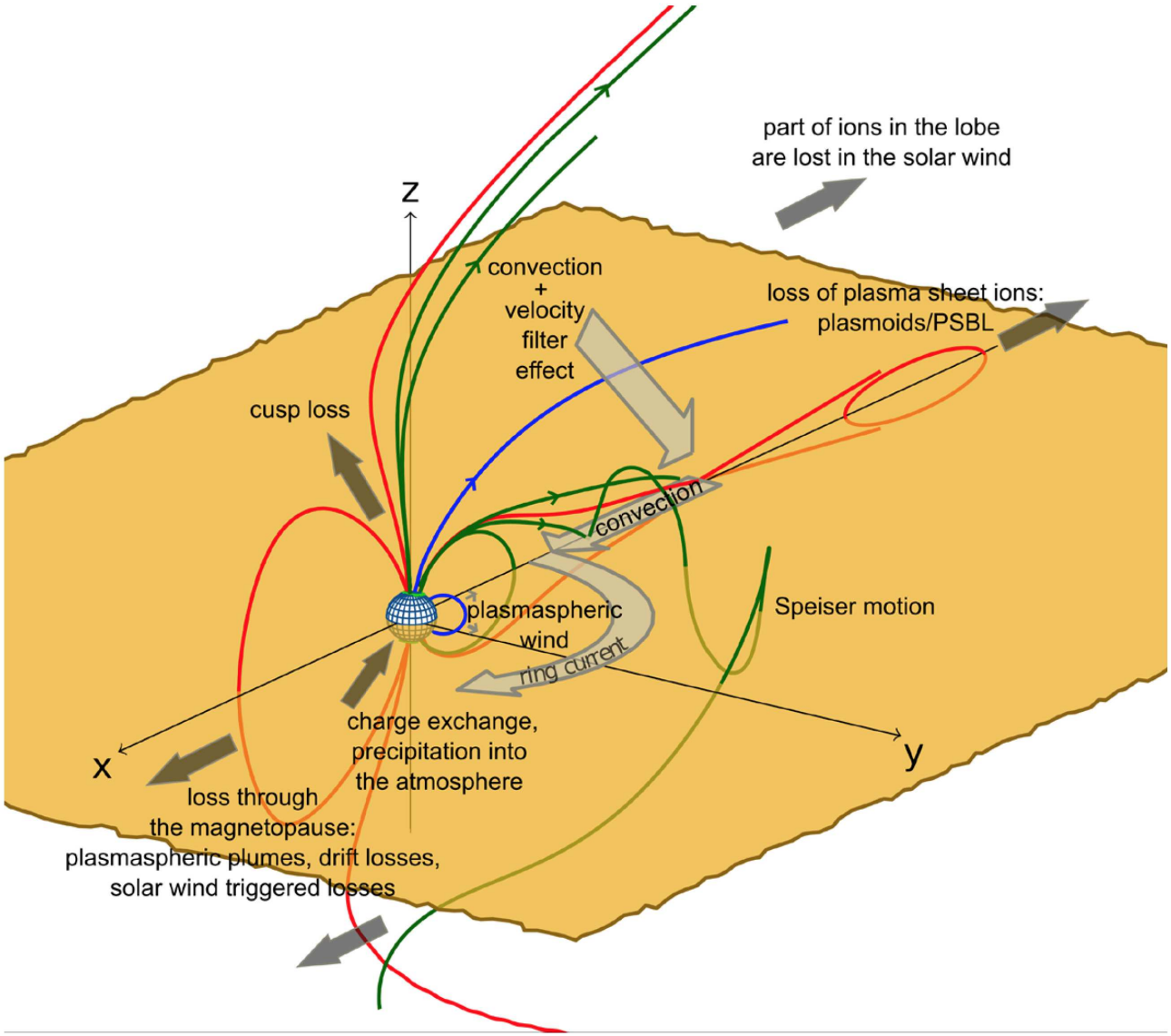


Bouhram et al. [2004]

Global Distribution of Outflow (Lennartsson et al. [2004])



Ion Transport and Energization in the Magnetosphere



Kronberg et al. [2014, Space Sci. Rev.]

Open Research Areas

Individual processes

- Formation of $E_{\|}$
- Processes controlling waves in the inner magnetosphere
- Mechanisms energizing ion outflow

System dynamics

- Feedback loops
- Emergent behavior
- Formation of characteristic modes of response (substorms, sawtooth oscillations, steady-magnetospheric convection)
- Preconditioning and hysteresis