Electromagnetic Energy Input to the Atmosphere

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Summary

- What is Poynting flux?
- Where does it come from?
- Where does the energy go?
- Why should we care?
- What are the major scientific challenges?
- What do we hope to achieve?

What is Poynting flux?

In examining the role of the ionosphere-thermosphere system in the energy exchange with the magnetosphere at high latitudes, we need to recognize that the net current and electric field are the result of all processes occurring along the field line, including both ionospheric and magnetospheric influences. Separating these two contributions in terms of currents and electric field is not feasible- measuring the winds, conductivities, and electric fields simultaneously over a range of spatial scales to evaluate the ionospheric influences at high latitudes is extremely challenging. This has led to the concept of applying Poynting's theorem to the high-latitude ionosphere.

Richmond and Thayer, 2000

What is Poynting flux?

Poynting's theorem (derived from Maxwell's equations):

$$\frac{\partial}{\partial t}\left(\frac{B^2 + E^2/c^2}{2\mu_0}\right) + \nabla \cdot \left(\frac{\mathbf{E} \times \mathbf{B}}{\mu_0}\right) + \mathbf{J} \cdot \mathbf{E} = 0$$

EM energy density   Poynting vector   Joule dissipation

E – Electric field
B – Magnetic field
J – current density
c – speed of light
μ_0 – Permeability of free space

What is Poynting flux?

In the ionospheric case, we can substitute:

$$\mathbf{B} = -\nabla V_0 + \delta\mathbf{B}$$

Where: V_0 – scalar magnetic potential ("main" geomagnetic field)

Φ – electric potential

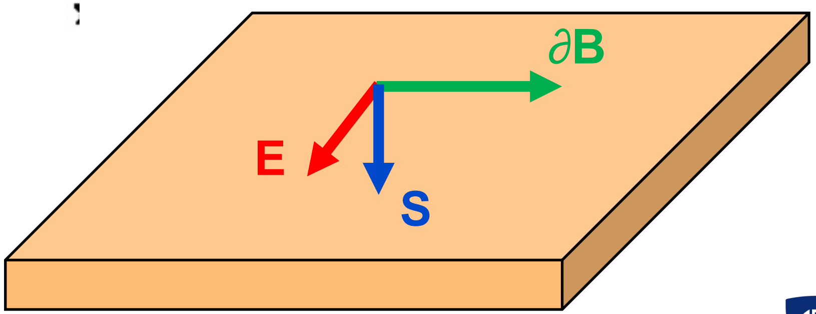
And note that the main field term vanishes:

$$\nabla \cdot (\nabla\Phi \times \nabla V_0)$$

Then, Poynting's vector **S** can be expressed:

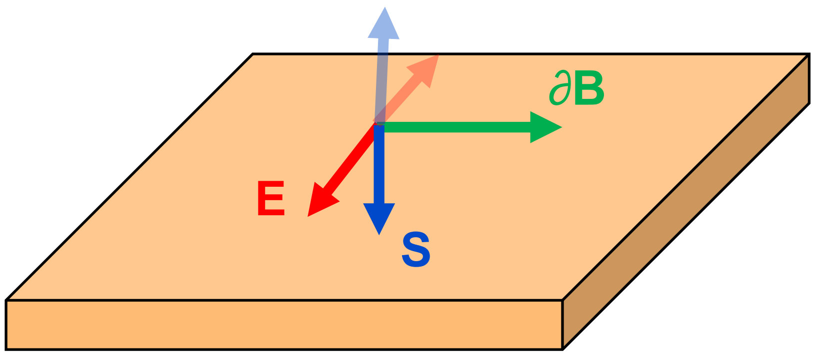
$$\mathbf{S} = \frac{\mathbf{E} \times \delta\mathbf{B}}{\mu_0},$$

S represents the directional electromagnetic energy flux through a volume

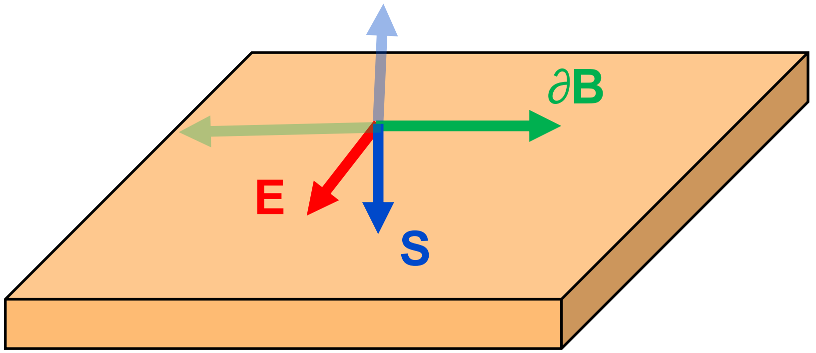


Effects of measurement error on Poynting flux

E and ∂B measurement sign errors can lead to erroneous upward Poynting flux. Data inconsistency (e.g. different measurement locations) can lead to large errors.



E with wrong sign

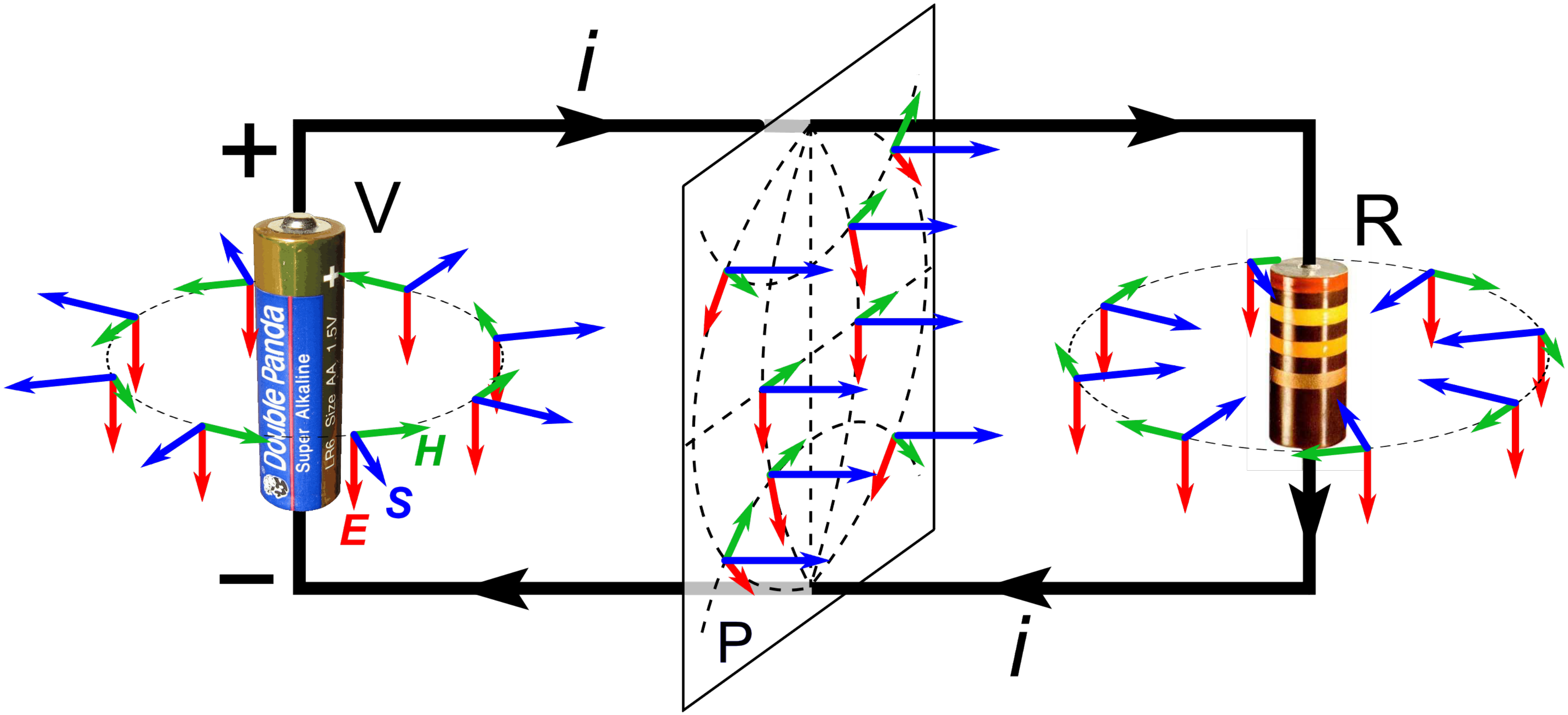


∂B with wrong sign

Note: **S** can genuinely point upward in cases of strong neutral wind driving (e.g. thermospheric "flywheel" effect)

What is Poynting flux?

In a circuit, the electromagnetic energy flows from the source to the load between the currents



What is Poynting flux?

In the quasi-DC treatment (periods > ~10 mins), the time-dependent term is very small in the ionosphere, so the Poynting flux approximately balances the Joule dissipation:

$$S_{||}^{\text{LEO}} \approx \pm \int_{90\text{km}}^{200\text{km}} \mathbf{J} \cdot \mathbf{E} dz$$

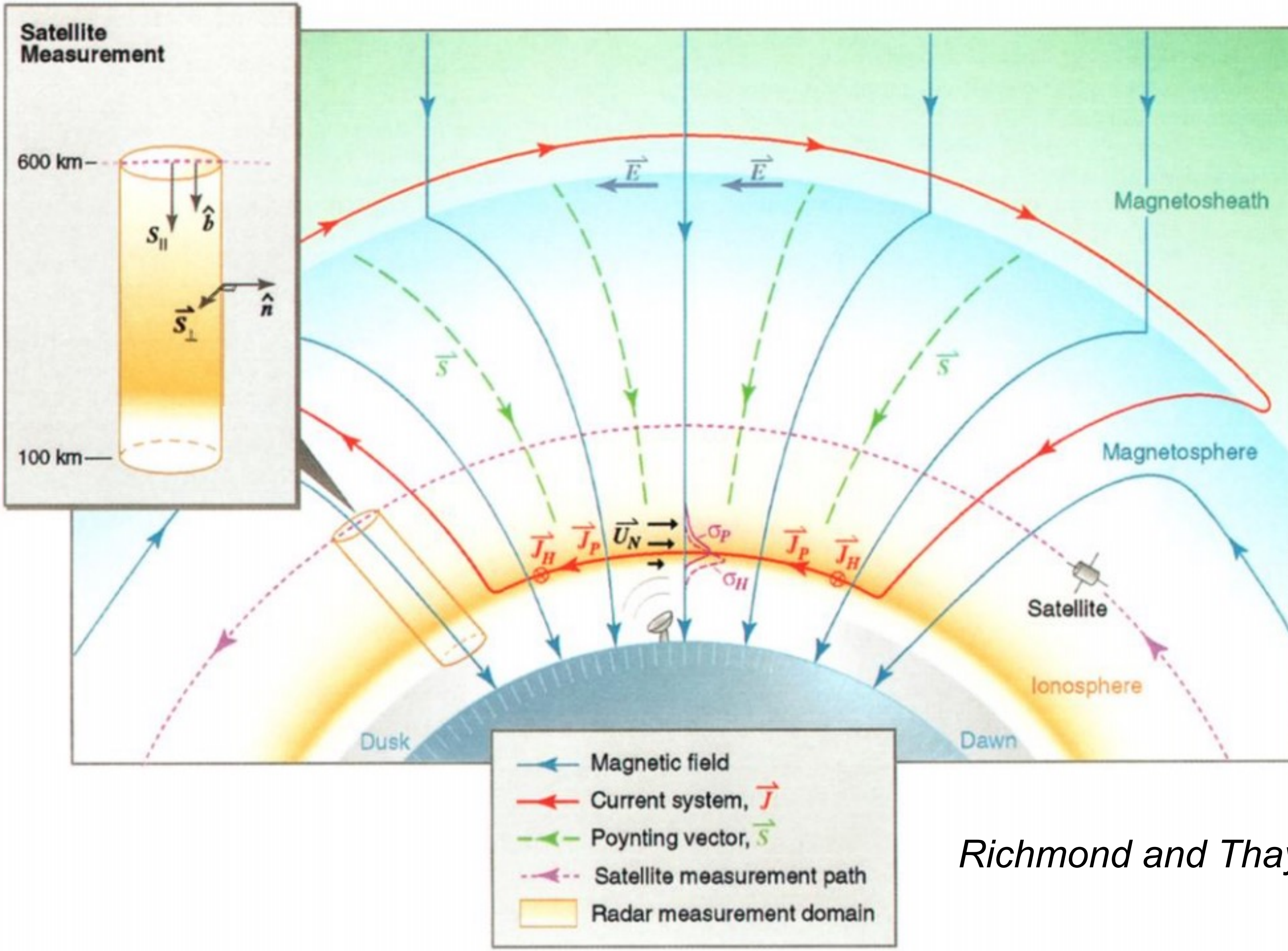
Notes:

#1 **S** is almost constant from ~600 km up to the acceleration region (>1500km), so the exact spacecraft altitude is not important.

#2 EM energy tends to be dissipated through the ionosphere, though it can also flow out horizontally

#3 The **wave (AC) term is not small** – can be 30% or more *Verkhoglyadova et al*. (2018)

What is Poynting flux?



Richmond and Thayer, 2000

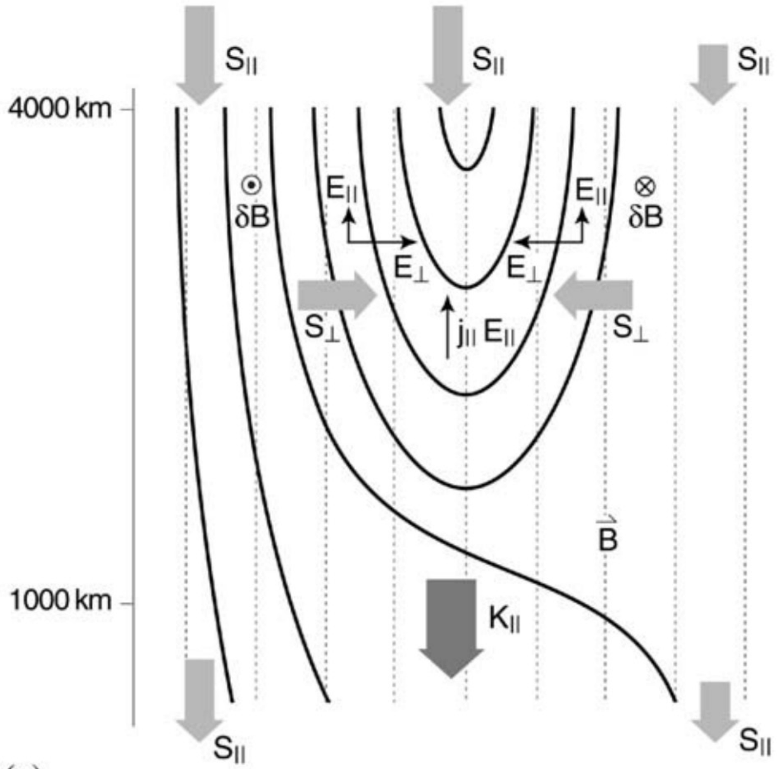
Where does it come from?

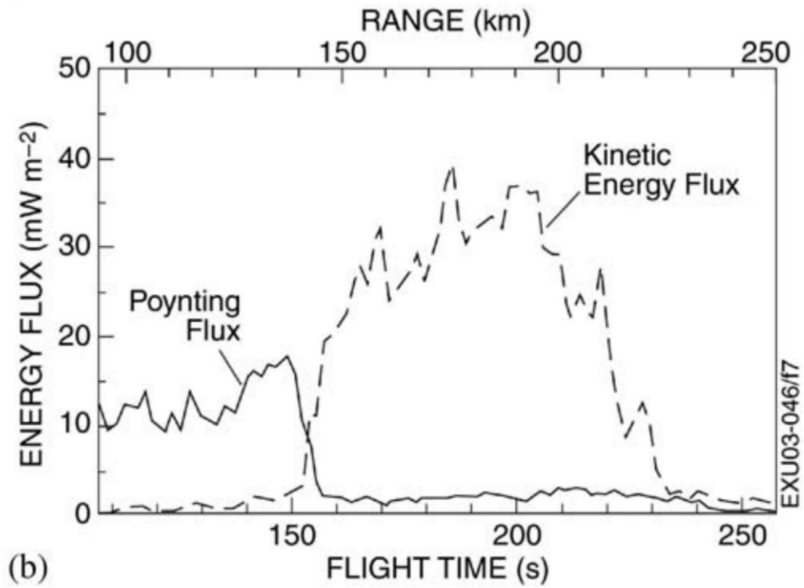
Poynting flux in the magnetosphere originates in solar wind driving.

In “perfect M-I coupling” FACs carry all EM energy to the ionosphere.

When FACs saturate, particle accelerations occur so that EM energy is converted to kinetic energy (Knight, 1973).

DC flux believed to map, while Alfvénic flux converges in auroral region





Thayer and Semeter (2004) and Evans et al. (1977) show links between **S** and KE

Where does the energy go?

To understand the dissipation of EM energy in the atmosphere, remember Ohm's Law applies to the reference frame of the material. In case of nonzero neutral winds **U** in Earth frame, apply a transformation:

$$\mathbf{E}' = \mathbf{E} + \mathbf{U} \times \mathbf{B}$$

Then substitute in:

$$\mathbf{J} \cdot \mathbf{E} = \boxed{\mathbf{J} \cdot \mathbf{E}'} + \boxed{\mathbf{U} \cdot \mathbf{J} \times \mathbf{B}}$$

Thermospheric heating

Wind acceleration

Where does the energy go?

Partitioning

EM energy => Joule heating + Mechanical energy

$$q_{EM}(z) = q_J(z) + q_m(z)$$

$q_J(z) = \sigma_P(z)\,[\mathbf{E} + \mathbf{U} \times \mathbf{B}]^2$

$q_m(z) = \mathbf{u}(z) \bullet (\mathbf{j}(z) \times \mathbf{B})$

$\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, so $q_J \propto (\mathbf{U} - \mathbf{V})^2$

q_m is not necessarily positive

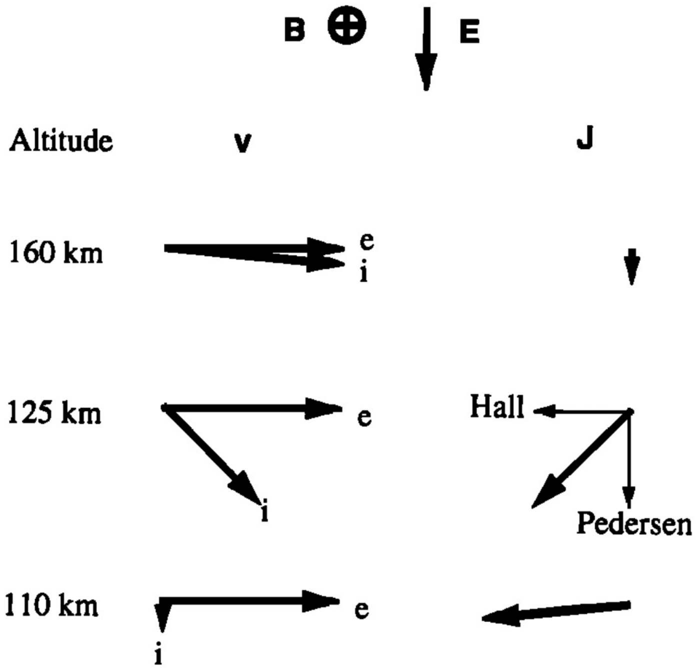
Joule "frictional" heating proportional to the difference in ion and neutral velocities

Where does the energy go?

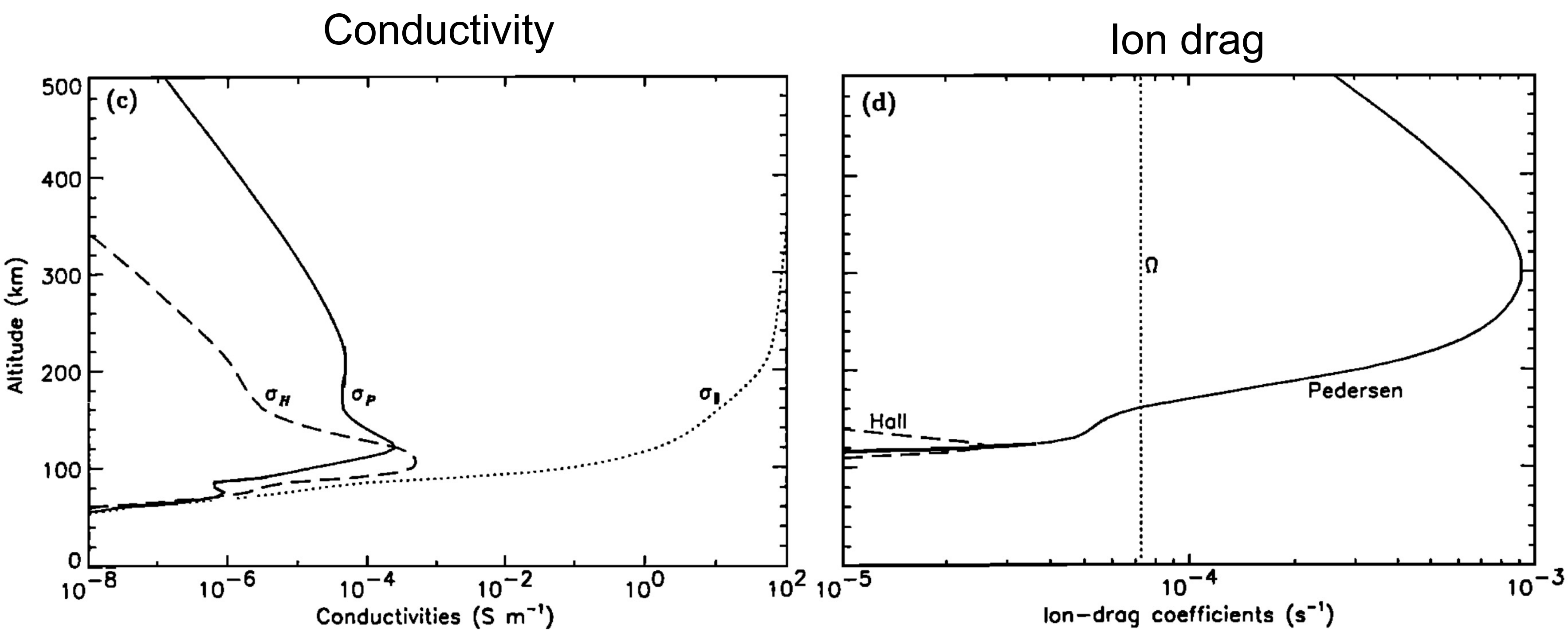
The altitudinal variation of the currents is controlled by variations of the Hall and Pedersen conductivities, σ. Unit magnetic field vector is **b**.

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

The resulting ion and electron velocities and current directions vary with altitude



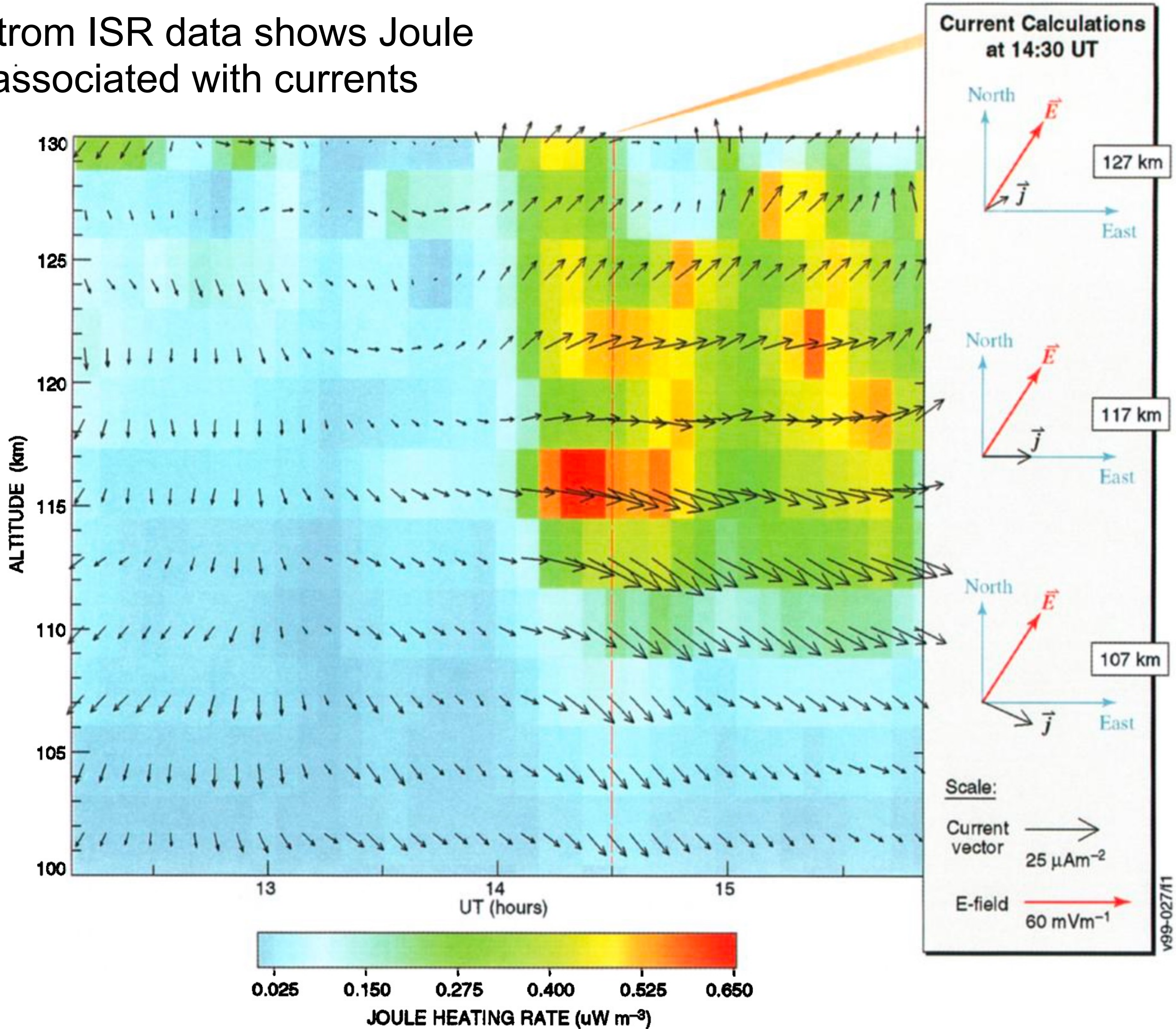
Where does the energy go?



Hall and Pedersen conductivity-altitude profiles explain why most heating occurs between ~90-200 km, whereas ion drag is most effective higher, around 300 km

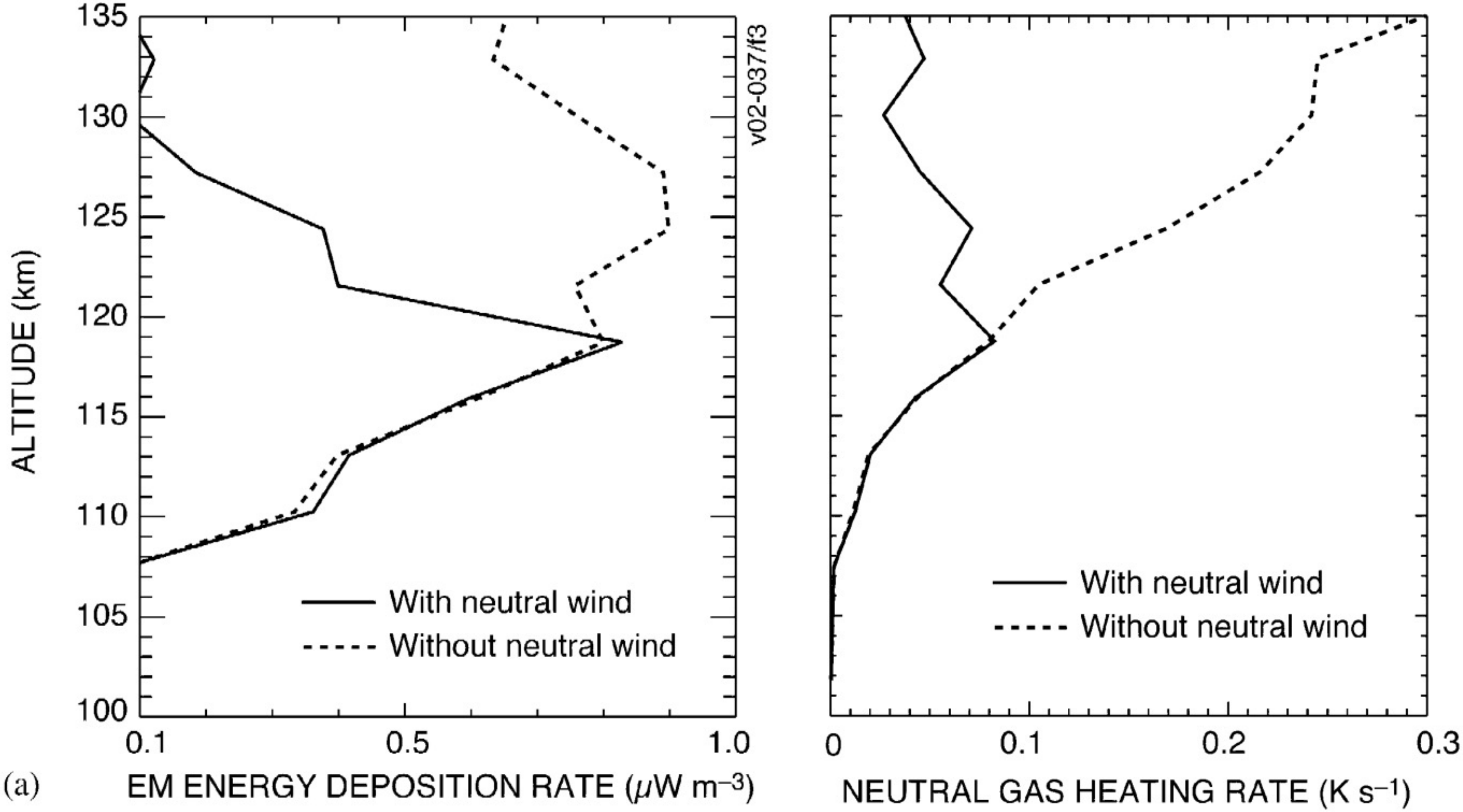
Where does the energy go?

Sondrestrom ISR data shows Joule heating associated with currents



Where does the energy go?

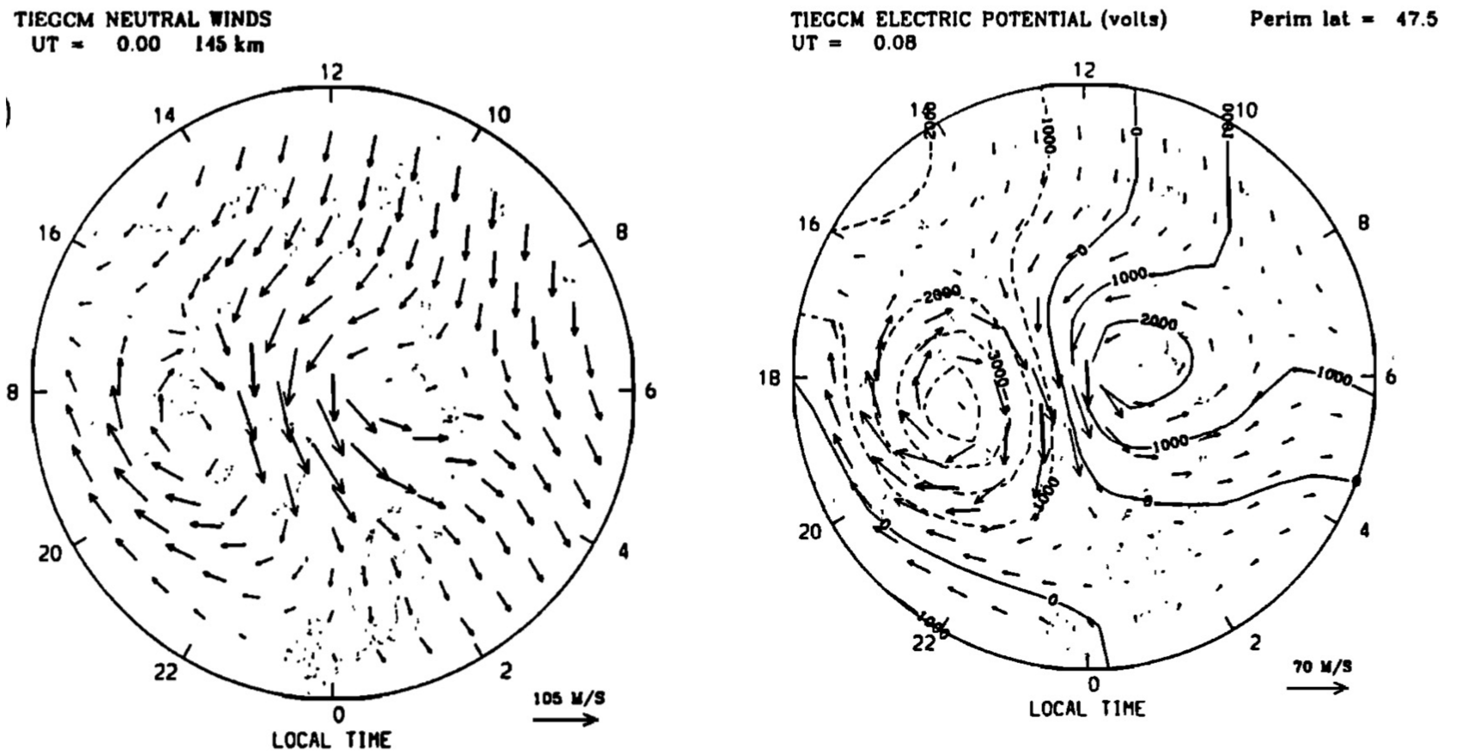
Thayer and Semeter (2005) show the importance of the neutral winds in controlling energy deposition and heating:



Where does the energy go?

Modeling indicates neutral winds drive upgoing Poynting flux that has important effects on the magnetosphere (Ridley et al., 2003).

The “flywheel” effect occurs when the thermosphere stores energy from **E**x**B** convective driving, then sends the energy back via dynamo action.



Thermospheric winds and the electric potential generated by them. From Richmond (1995)

Why should we care?

Poynting flux represents probably the **largest unknown energy input to the upper atmosphere and ionosphere**

Ionosphere-Thermosphere energy inputs:

Solar flux ~1000GW globally

S ~30-180 GW hemispheric (Knipp et al., 2011; DMSP)

K.E. ~10-35 GW hemispheric (Newell et al., 2011; DMSP)

During storms:

S >350 GW hemispheric (Cosgrove et al., 2013; FAST)

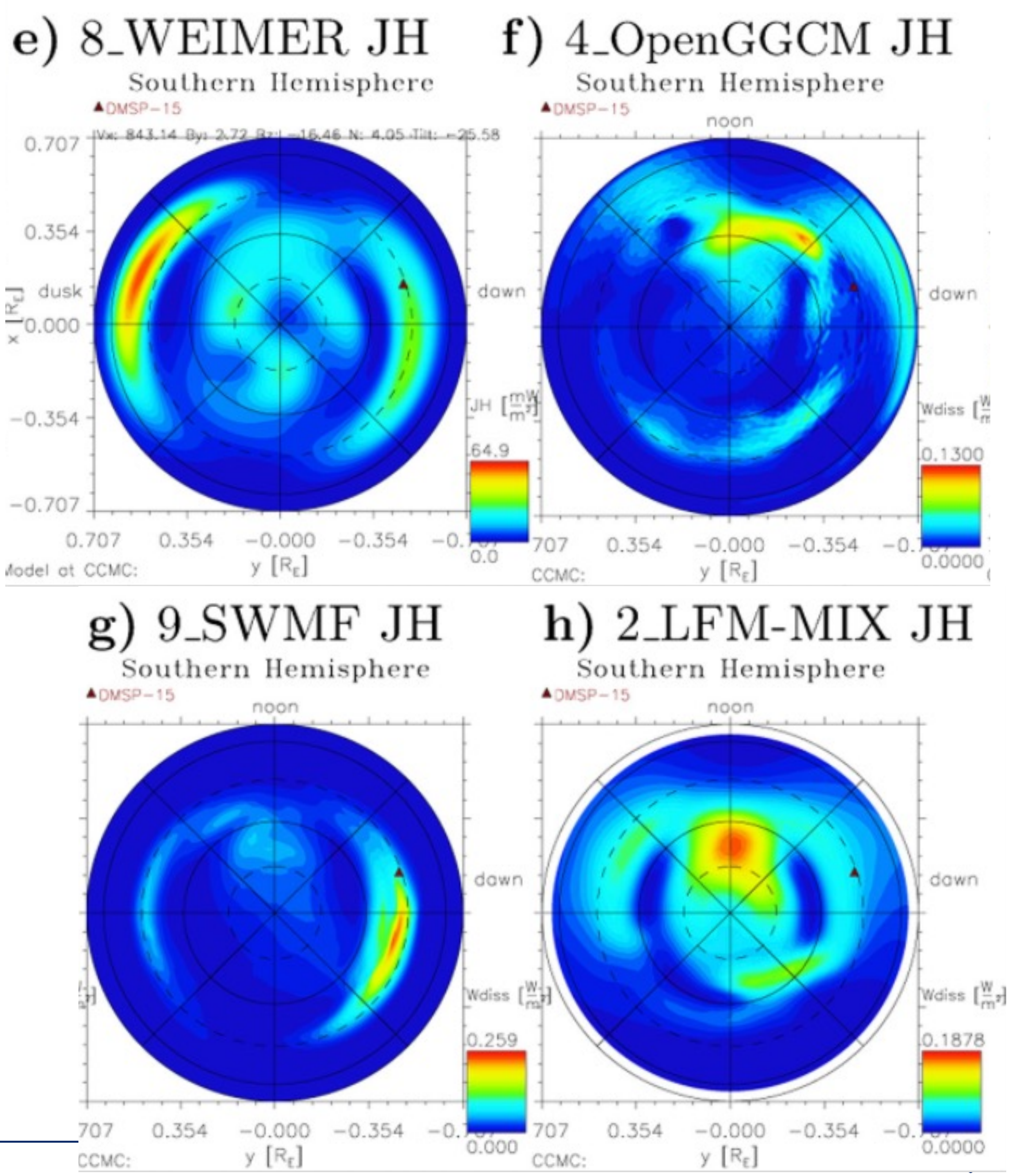
K.E. ~300 GW hemispheric (Zhang & Paxton; 2008, SSUSI/GUVI)

Unlike solar flux, Poynting flux is poorly observed and highly structured, both spatially and temporally.

Why should we care?

Models show huge discrepancies in Joule Heating rates.

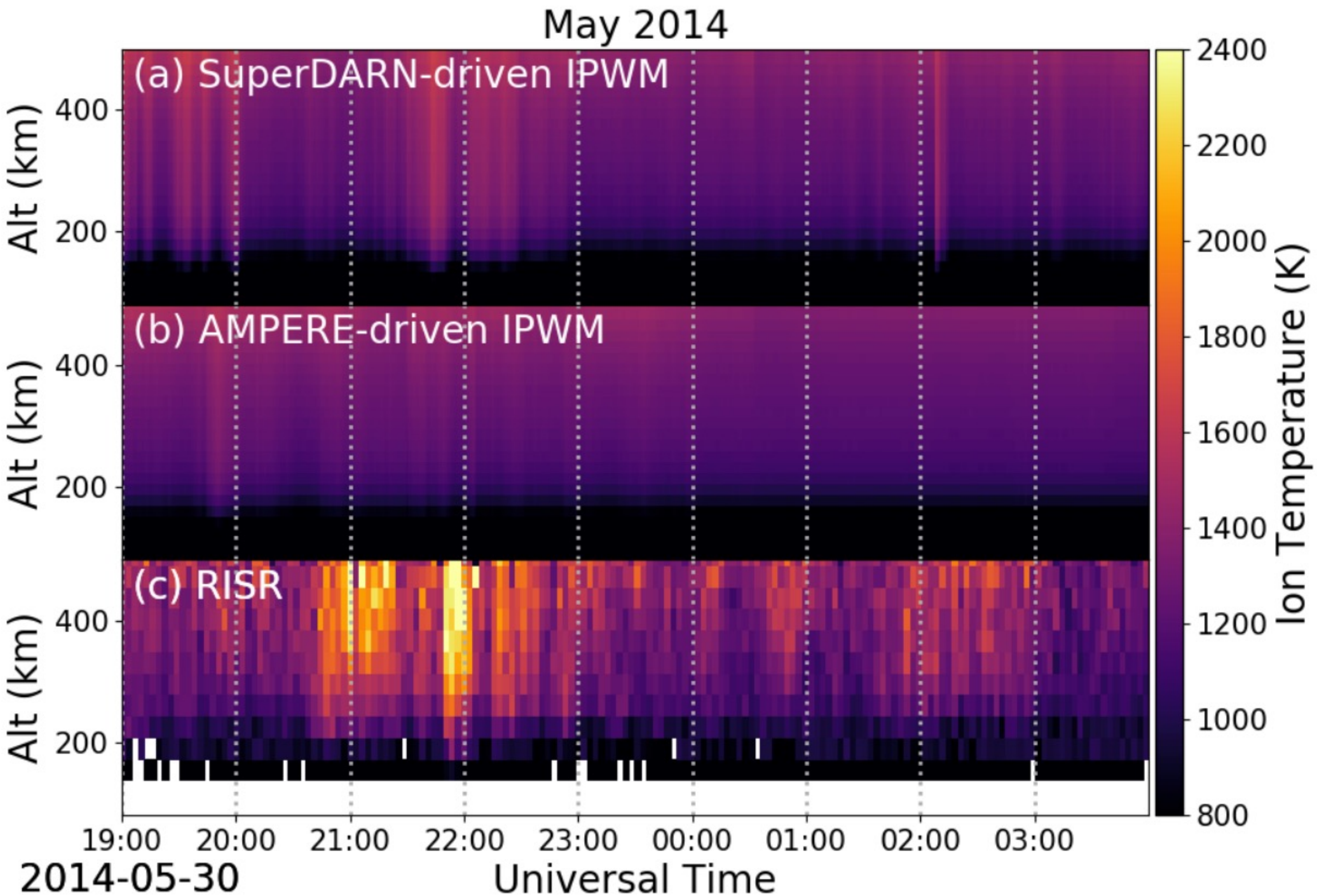
Empirical and physics-based models show totally different magnitudes and spatial structures



23:45 UT, 14 Dec 2006, South Hem. From GEM-CEDAR Challenge (Rastätter et al., 2016). Note different color scales are used.

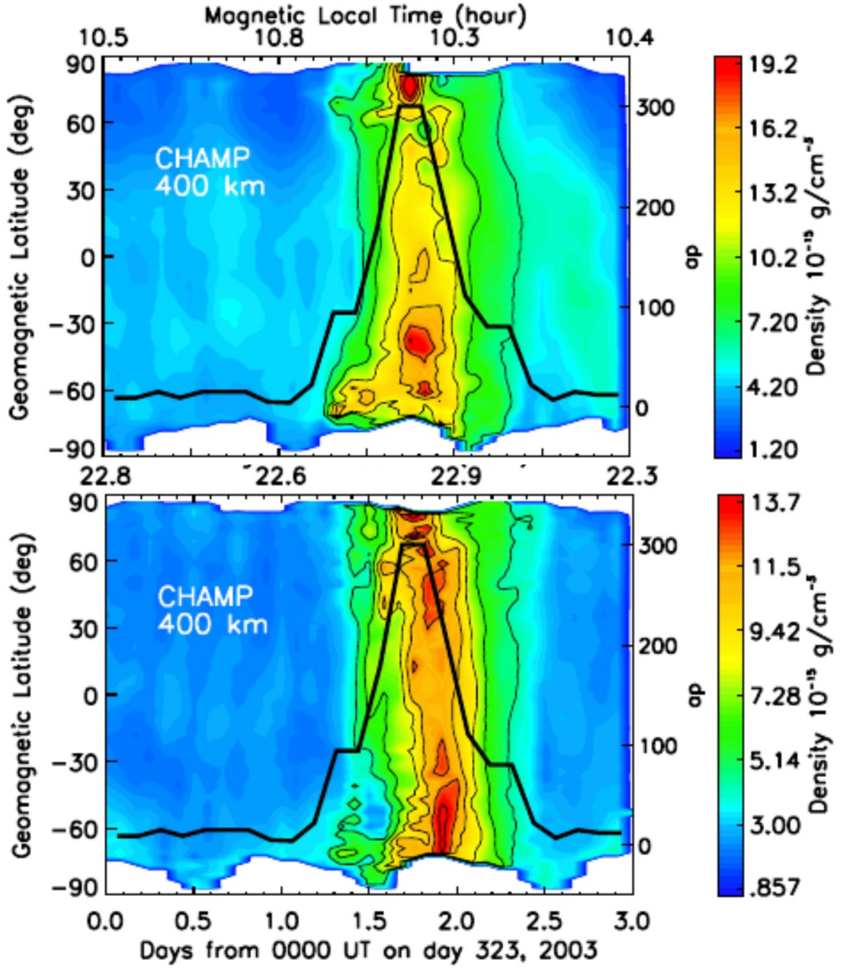
Why should we care?

Data and models show huge 1000K disagreement in Joule heating rates, indicating important small-scale processes (Lamarche et al., 2021)

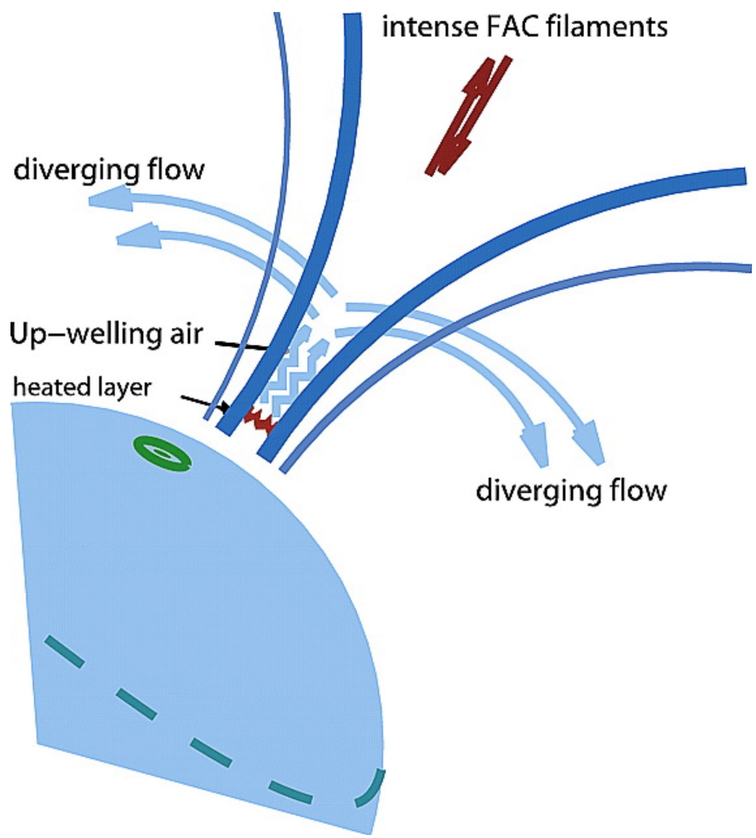


Why should we care?

Joule Heating in the cusps may drive up to 800% neutral density enhancements, affecting satellite drag



Bruinsma et al (2006) show storm density enhancements near noon/midnight



Proposed cusp heating mechanism from Lühr et al. (2004).

Summary

- To determine Poynting flux, measure **E** and ∂**B** carefully
- $\mathbf{S}_{||}$ has important DC and AC (wave) components
- Other terms are needed to understand where the energy goes (neutral winds, conductivities etc.)
- Downward $\mathbf{S}_{||}$ energy is closely linked to kinetic energy (auroral precipitation). Partition occurs in the acceleration region (~1500 – 4000 km)
- Occasionally see upward $\mathbf{S}_{||}$, indicating net flow of E.M. energy from Ionosphere/Thermosphere to Magnetosphere

Grand Challenge sessions Thursday and Friday

- **Please participate in the sessions from 10-12 MDT.**
- **There will be talks and Decadal White Paper discussions**
- **Last year's session is up on YouTube and contains great talks:**
  search "CEDAR Grand Challenge: Poynting Flux"
- **Preliminary running order:**

Thursday (all times MDT)	Speaker	Title
10:00	Ridley	Energy deposition from a fluid's perspective
10:20	Pakhotin	Northern preference for terrestrial electromagnetic energy input from space wea
10:40	Weimer	Using HASDM neutral densities to validate thermosphere density predictions b
11:00	Pena	Ionospheric heating due to auroral precipitation: sensor measurements and mo
11:10	Verkhoglyadova	Role of Alfven waves in electromagnetic energy input to Earth's atmosphere
11:20	Rodriguez-Zuluaga	Equatorial Spread F-related Poynting flux seen at LEO altitudes
11:40	Decadal white paper discussion	
Friday (all times MDT)		
10:00	Deng	Poynting Flux in the Dayside Polar Cap Boundary Regions From DMSP Mea
10:20	Zhang	Alfvénic Heating and Thermospheric Upwelling in the Cusp
10:40	Billett	Statistical Poynting flux patterns from SuperDARN and AMPERE: Is Poyntir
11:00	Zesta	Plans for Poynting flux measurement on the upcoming GDC mission
11:20	Knipp	Nine satellite years of DMSP Poynting flux—Insight and Even More Questions
11:30	Decadal white paper discussion	