JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

GC Report: Electromagnetic Energy Input to Earth's Atmosphere (Poynting Flux)

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Outline

What is Poynting Flux?

Why should we care?

Theoretical limitations

What we don’t know, and next steps

What is Poynting flux?

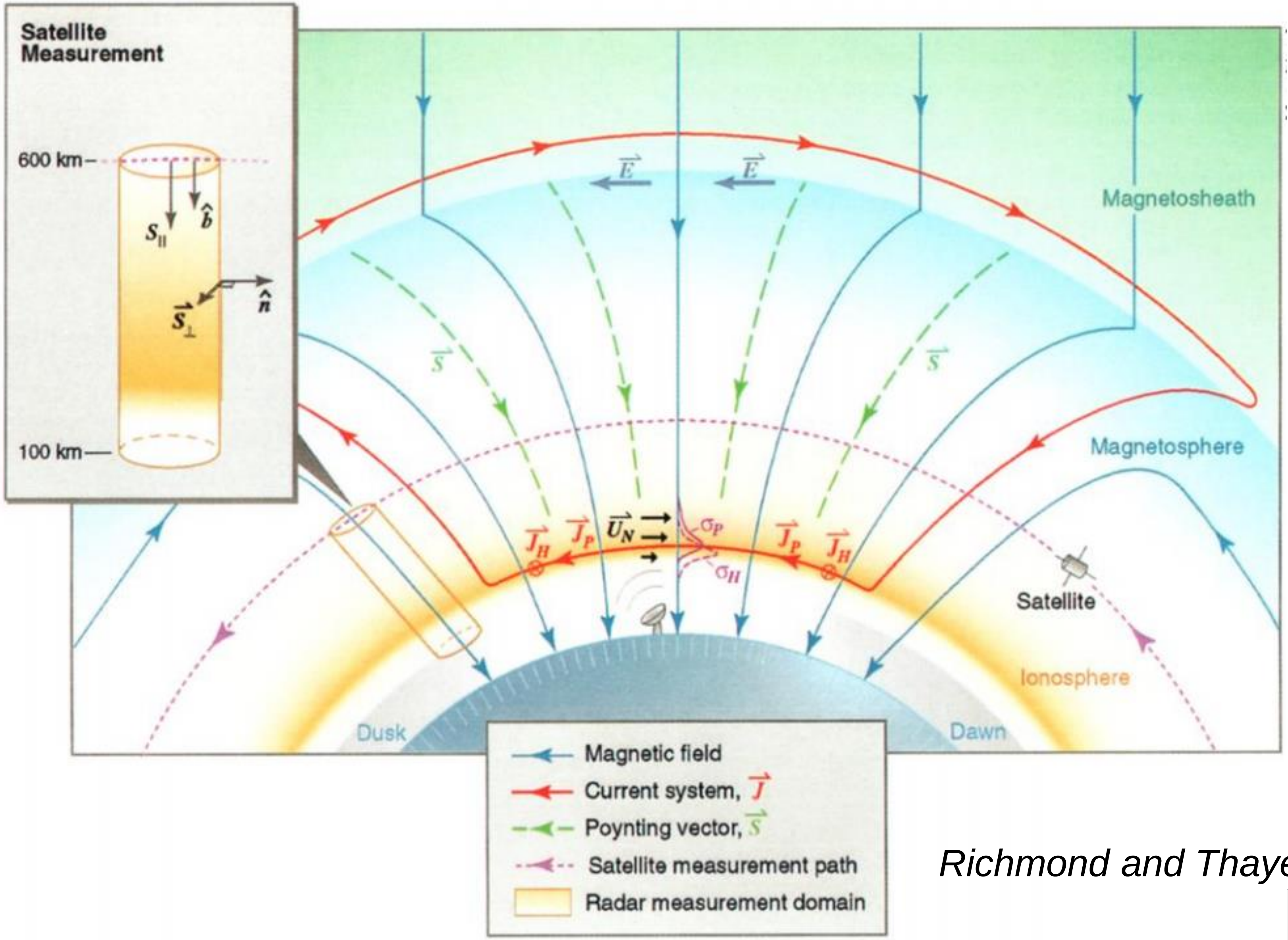
Poynting's theorem (derived from Maxwell's equations):

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

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?



Richmond and Thayer, 2000

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:

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

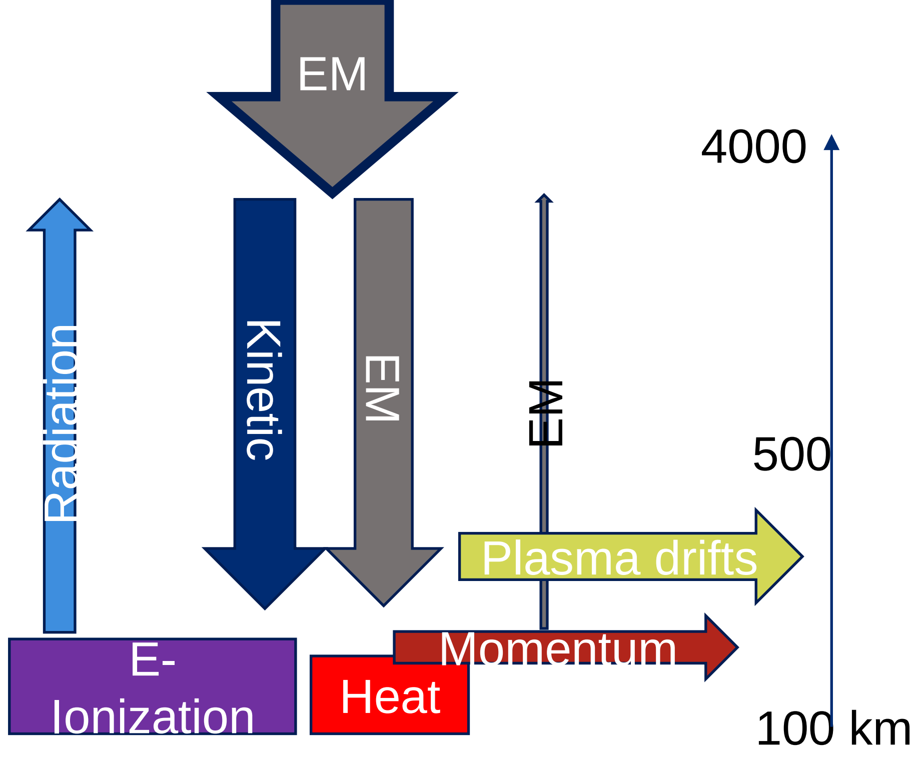
Notes:

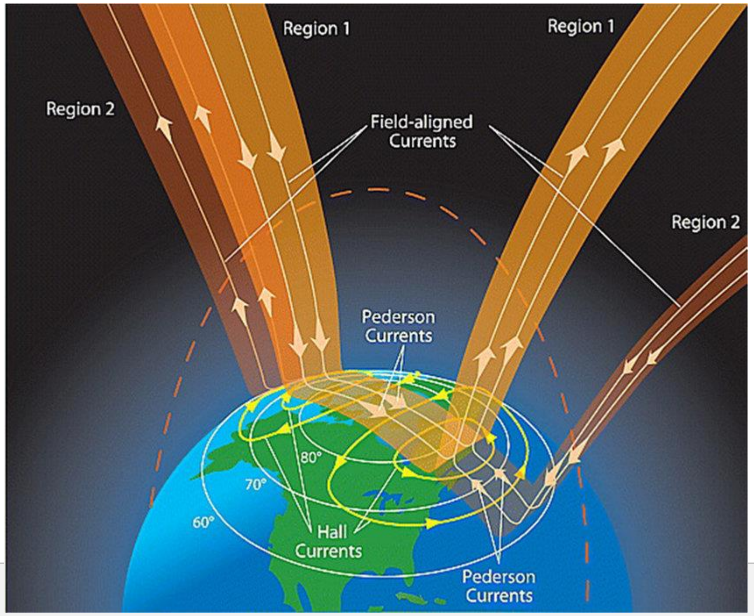
#1 **S** is almost constant from ~600 km up to the acceleration region (>1500km), so the exact spacecraft altitude is not important.

#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?





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., 2009; DMSP)

During storms:

S **>350 GW** hemispheric (Cosgrove et al., 2014; FAST)

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

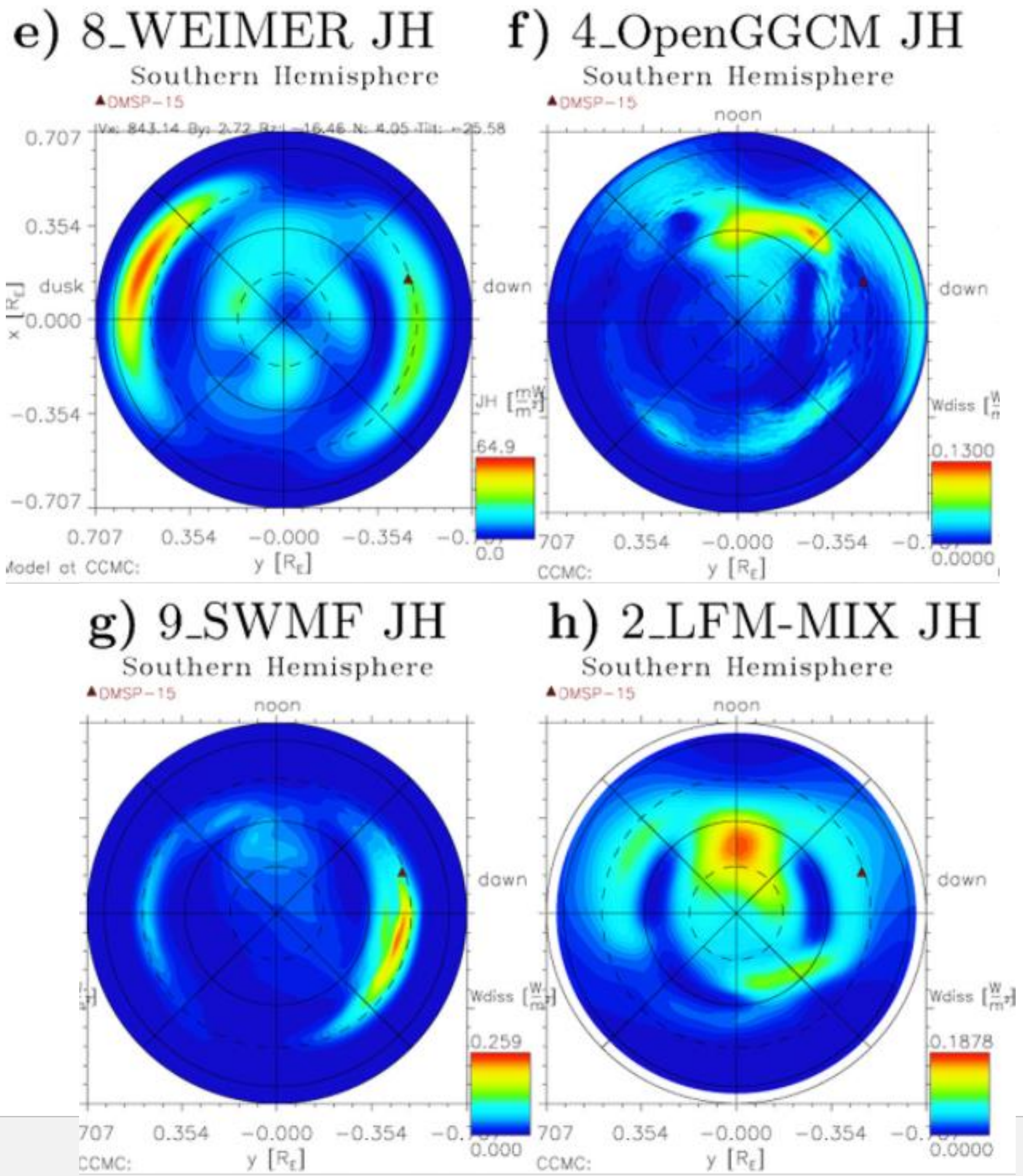
Unlike solar flux, Poynting flux is poorly observed and highly structured, both spatially and temporally.

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.**

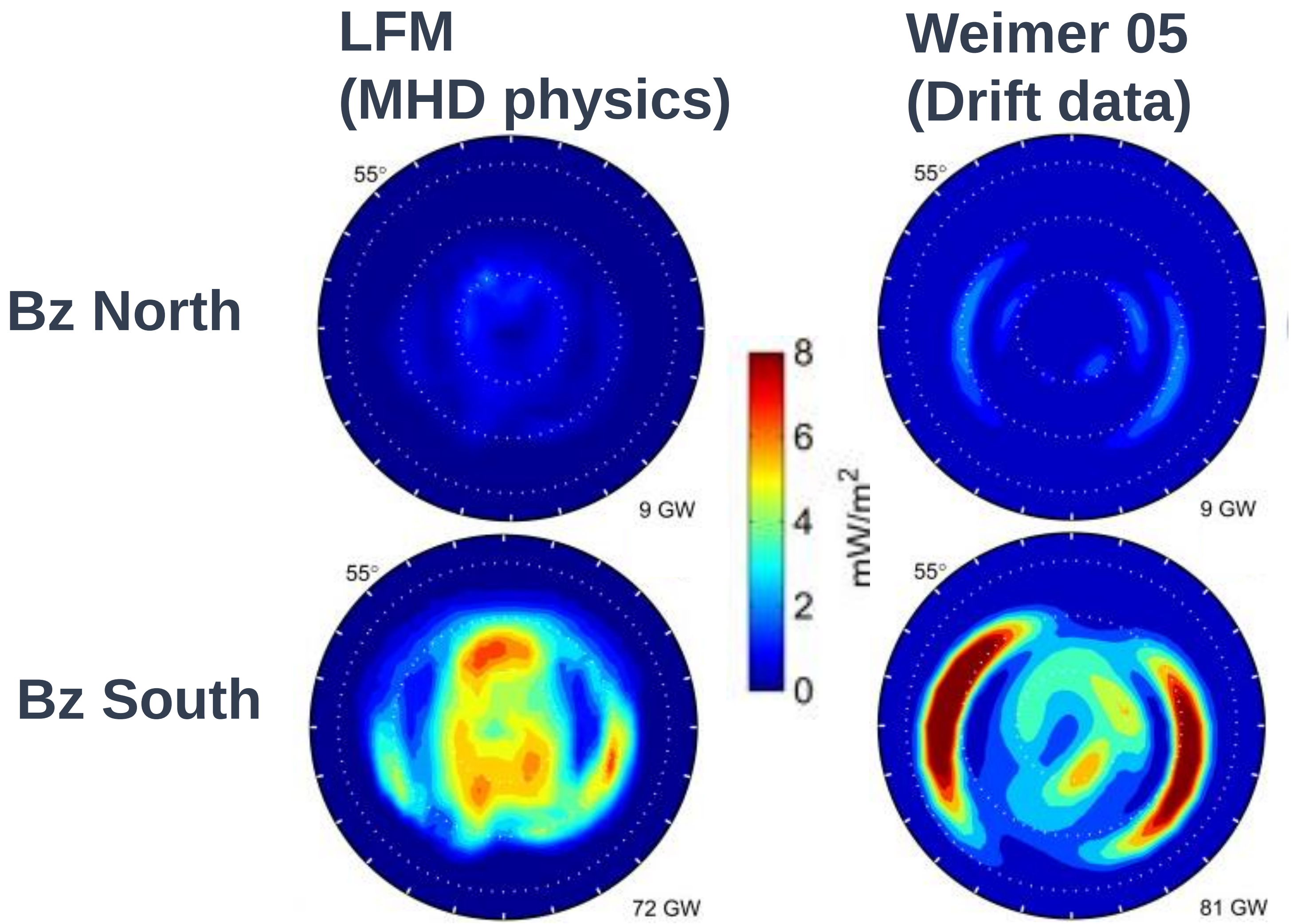


(more inconsistencies)

#1 Models and data show huge increases in energy flux during southward IMF

#2 Location and magnitude of energy flux varies greatly between models

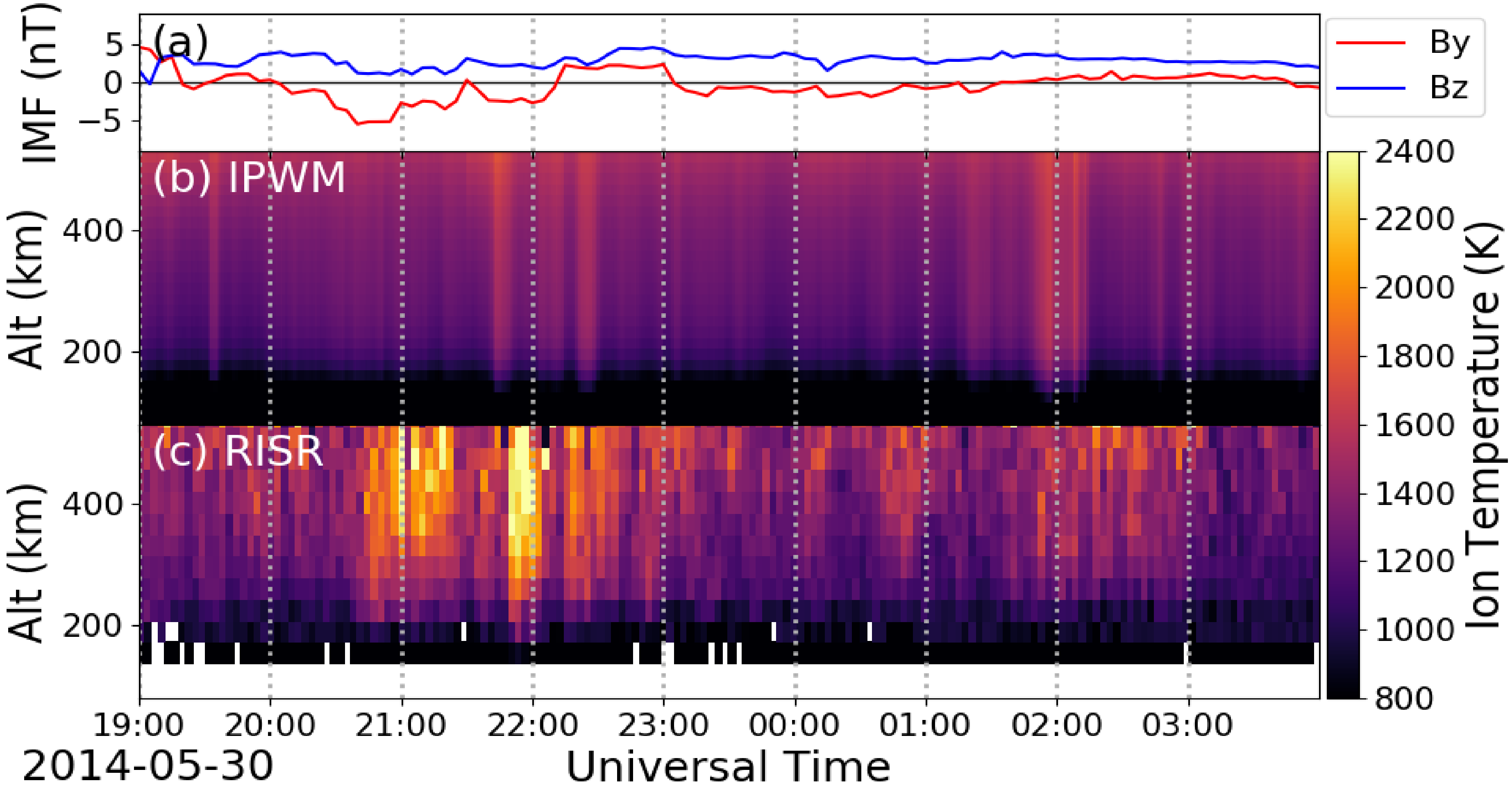
#3 AC ("wave") flux is not accounted for in either of these models



Zhang et al. (2011)

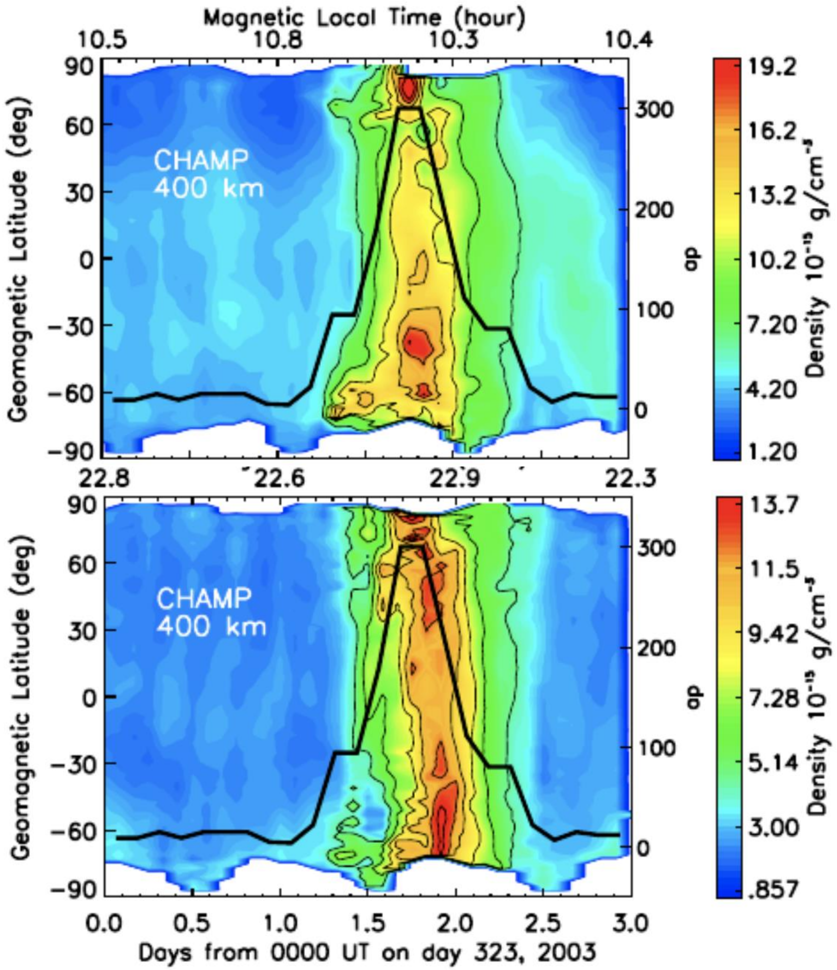
Why should we care?

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

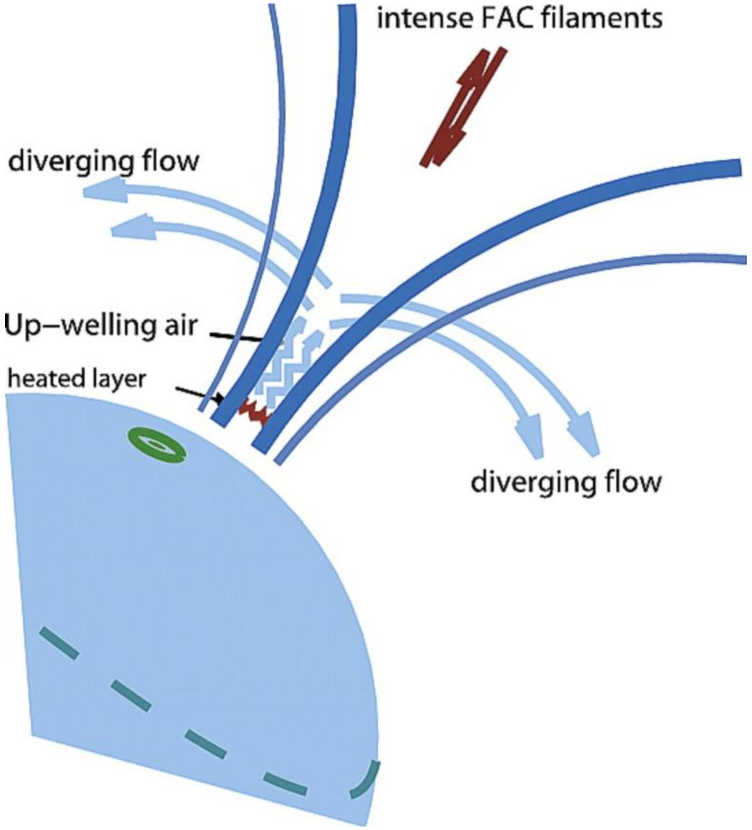


Why should we care?

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

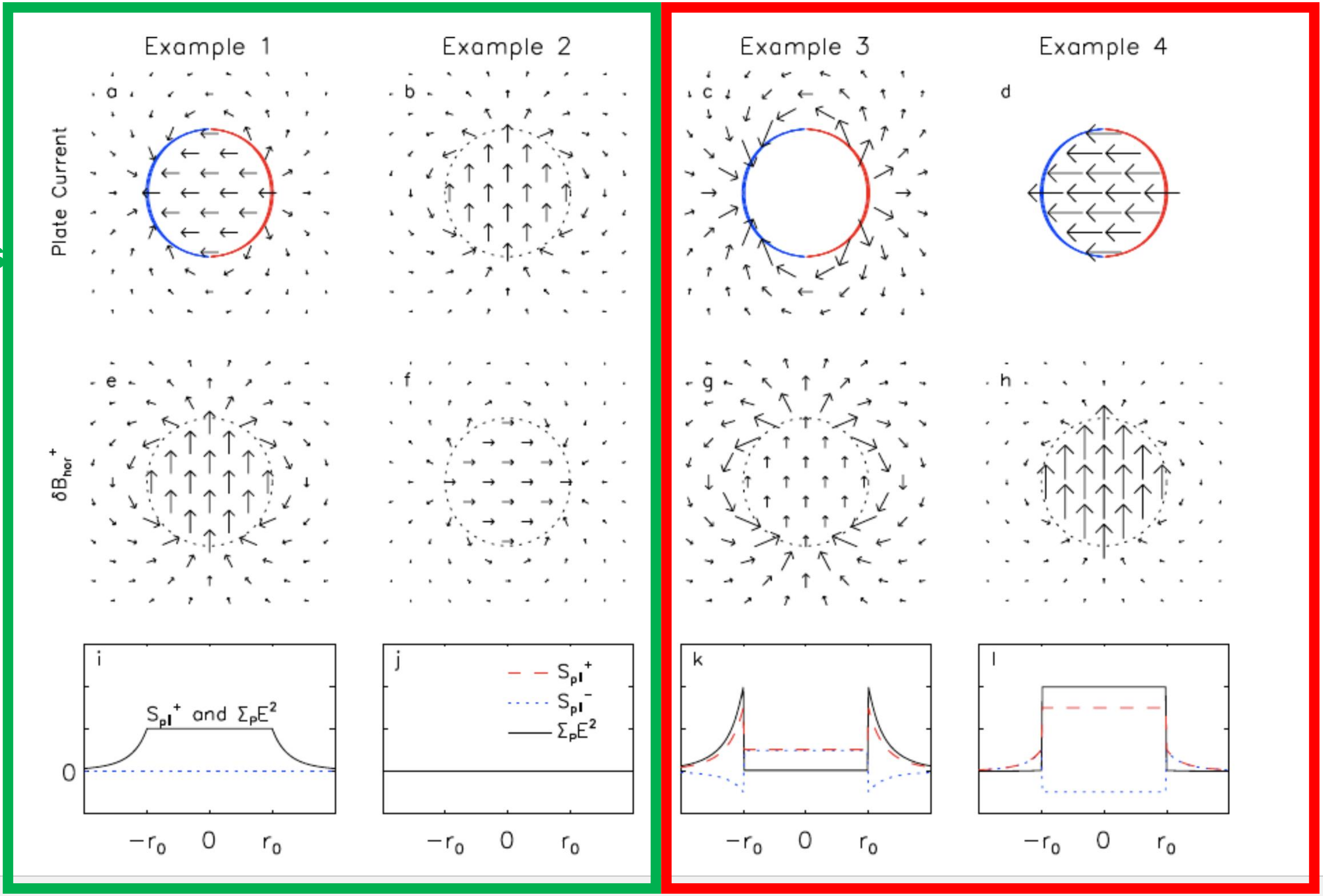


Proposed cusp heating mechanism from Lühr et al. (2004).

Theoretical limitations to interpretation of S Richmond (2010)

Matches typical assumptions

S_{above} = J.E
S_{below} = 0



Does not match typical assumptions

S_{above} = J.E
S_{below} not 0

What we don't know

How much EM energy is coming in (and going out)?

What is the conductance ("normal" + anomalous terms) that regulates the EM energy input?

How do sub-auroral plasma variations influence the high-latitude ionospheric system?

What are the dominant mechanisms responsible for the formation of plasma irregularities?

Next steps

- Move from climatology to global observation
- Test predictions using upcoming mission data (GDC, Dione, petitSat)
- Advance Mag-ITM models to/beyond order-of-magnitude agreement with data

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