Magnetosphere-Ionosphere-Thermosphere Coupling: Energy Dissipation Processes During Superstorms

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Outline

- Storms and Superstorms
- April 6, 2000 Storm
  - Case study illustrates Fukushima's Theorem and why we need satellite measurements of field-aligned currents (FACs)
- Poynting's Theorem shows how to succeed

Magnetic Storms

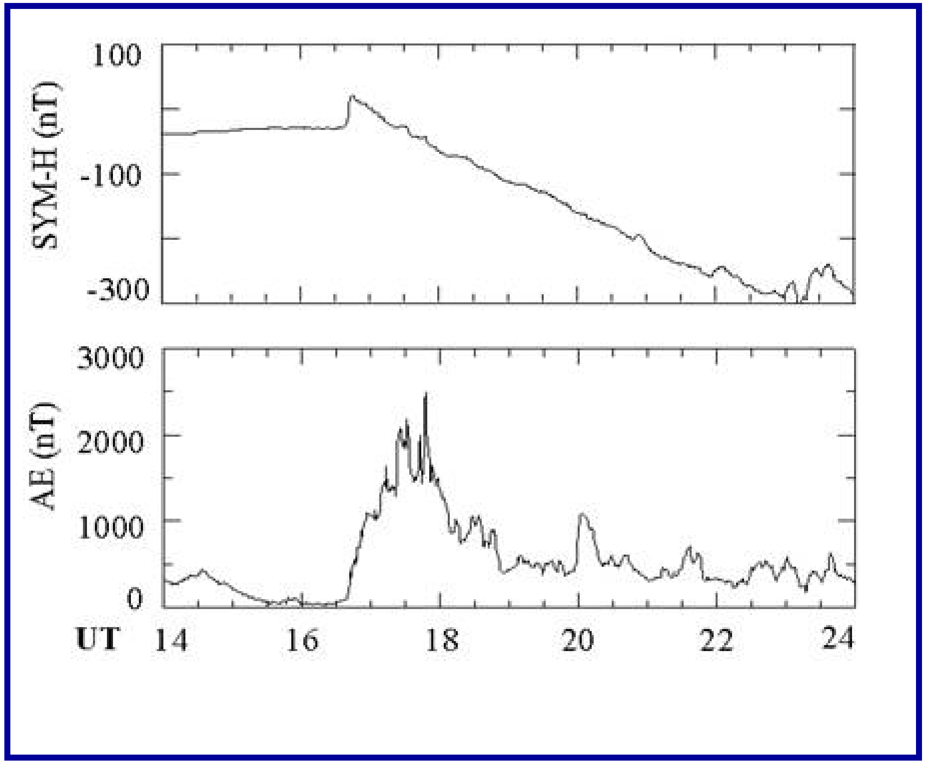
- Increase in cross-polar cap potential
- Characterized by increase in ring current leading to decrease in Dst or Sym-H
- Boundary of auroral zone moves to lower latitudes
- Increase in auroral activity (AE index)
- Increase in strength of Region 1 field-aligned FACs
- Precipitating electrons have energies > 1 keV
- FACs close via Hall currents in E region (100 km)
- Development of Region 2 Facs (shielding currents)

Magnetic Superstorms

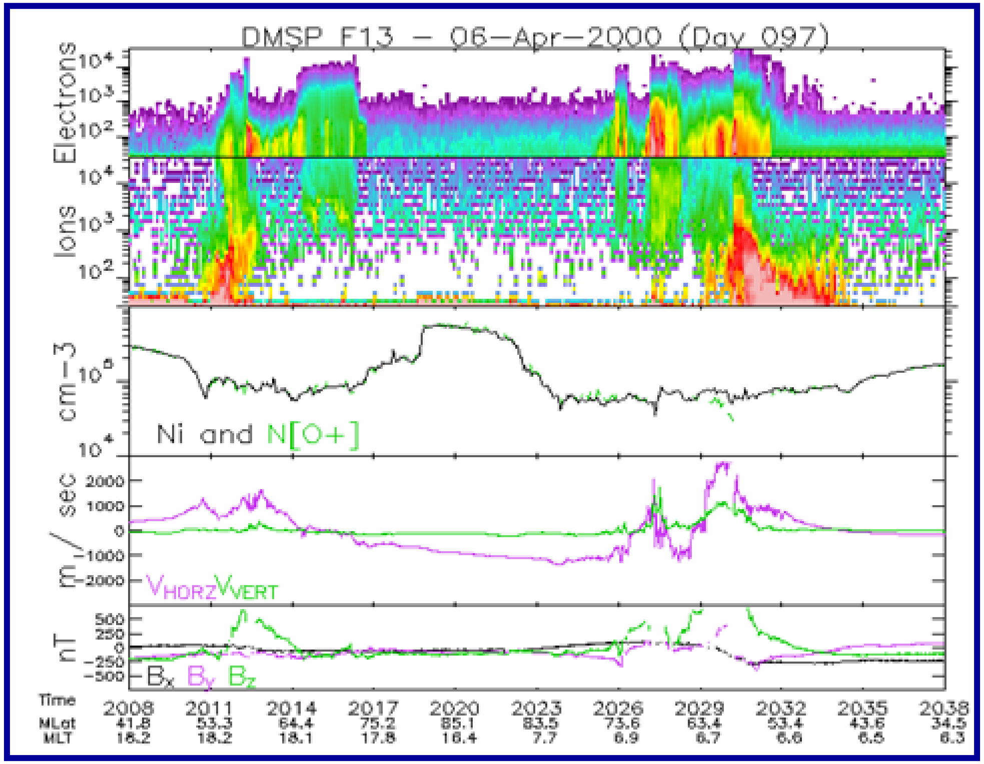
- **Large increase in cross-polar cap potential**
- **Dst or Sym-H < -200 nT**
- **Boundary of auroral zone moves to mid-latitudes, often below 60°**
- **Transient intense FACs, often correlated with increases in AE index**
- **Currents carried by *high* fluxes of *low*-energy electrons – no requirement for electron acceleration**
- **Precipitating low-energy electrons deposit energy in F layer, no Hall current is generated – *no ground signature*!**

April 6, 2000 Magnetic Storm

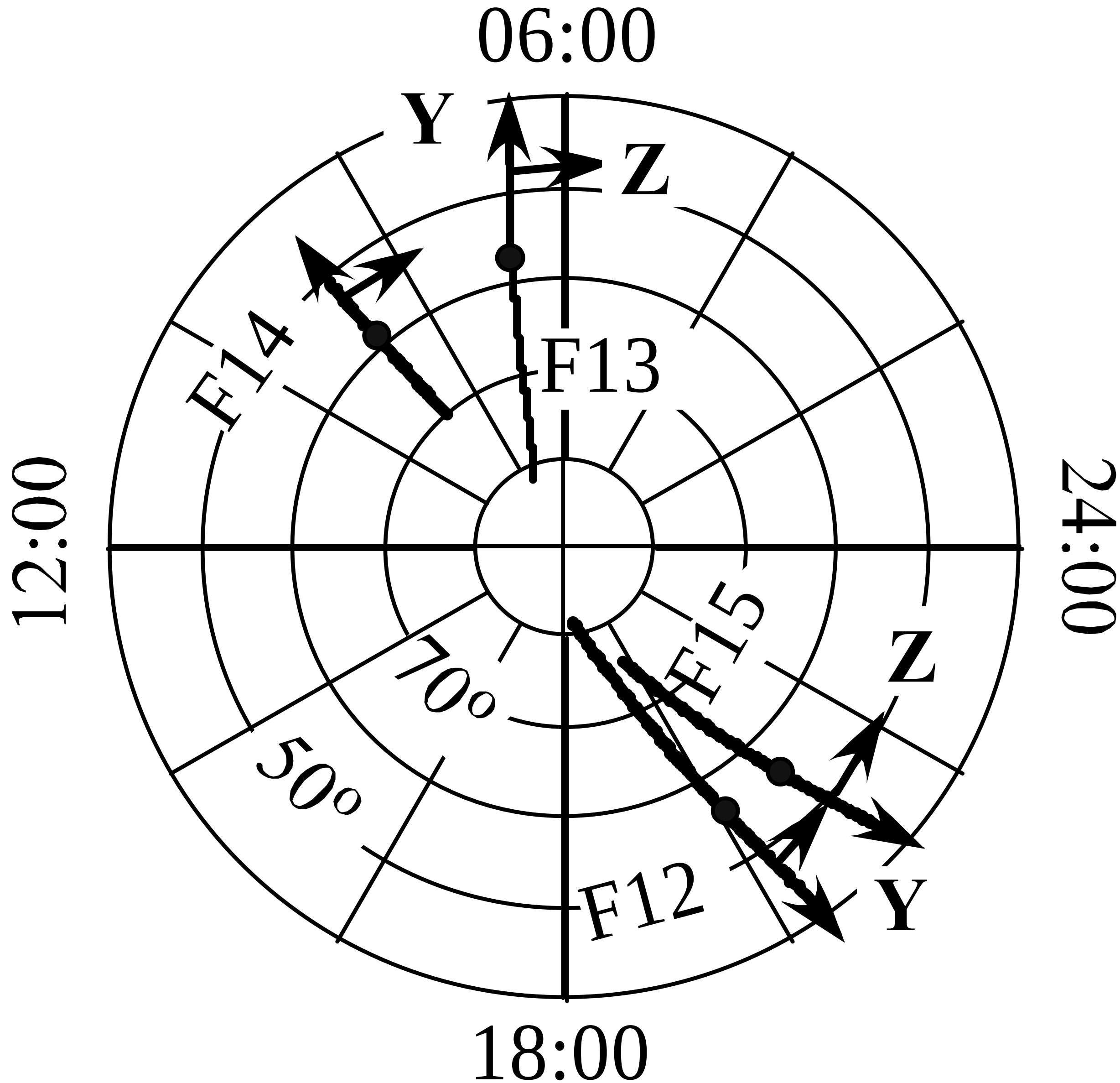
Geomagnetic Indices (10-hr period)



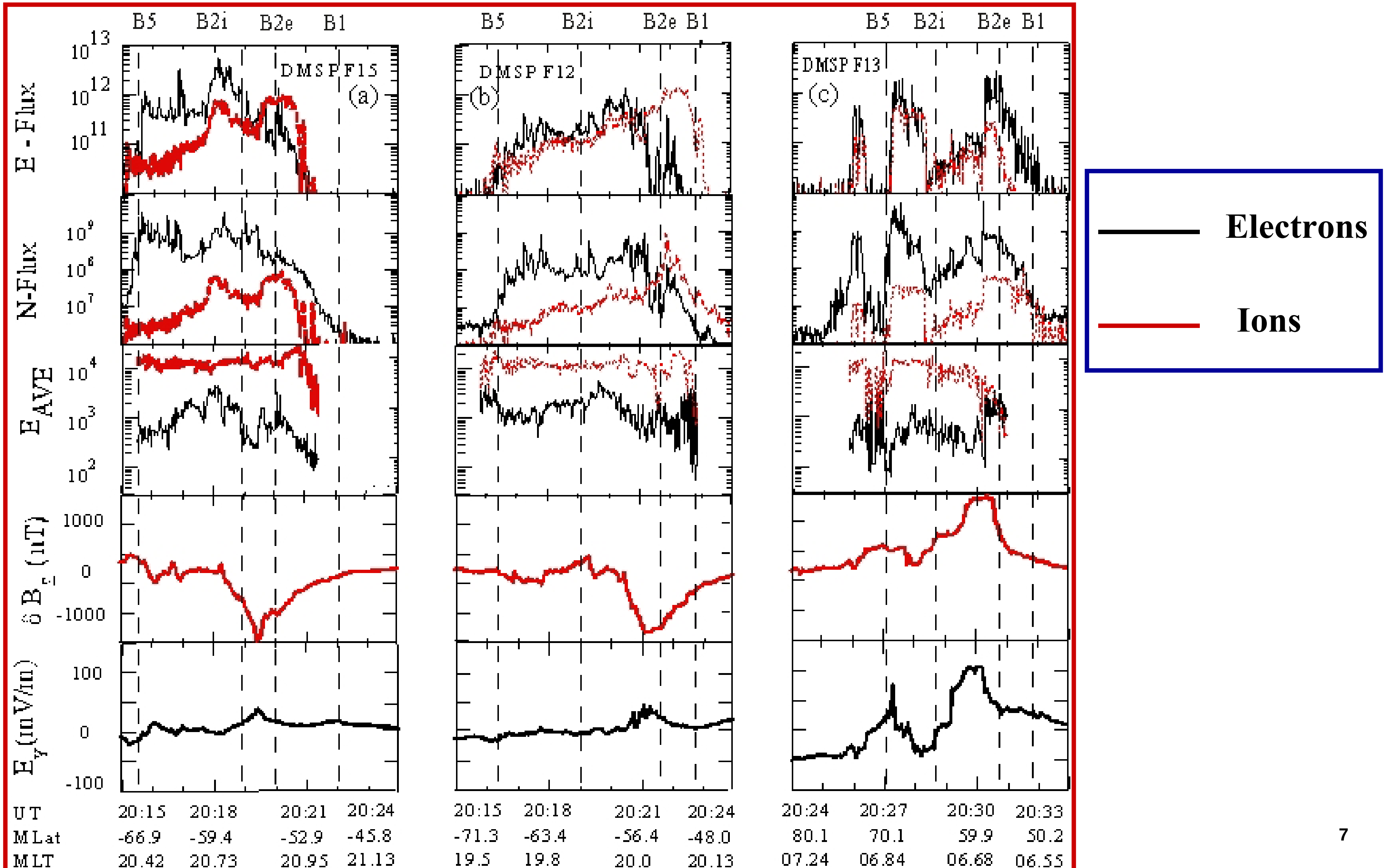
DMSP F13 Measurements (electrons, ions, plasma density, drift and magnetic perturbation)



April 6 - DMSP Satellite Locations

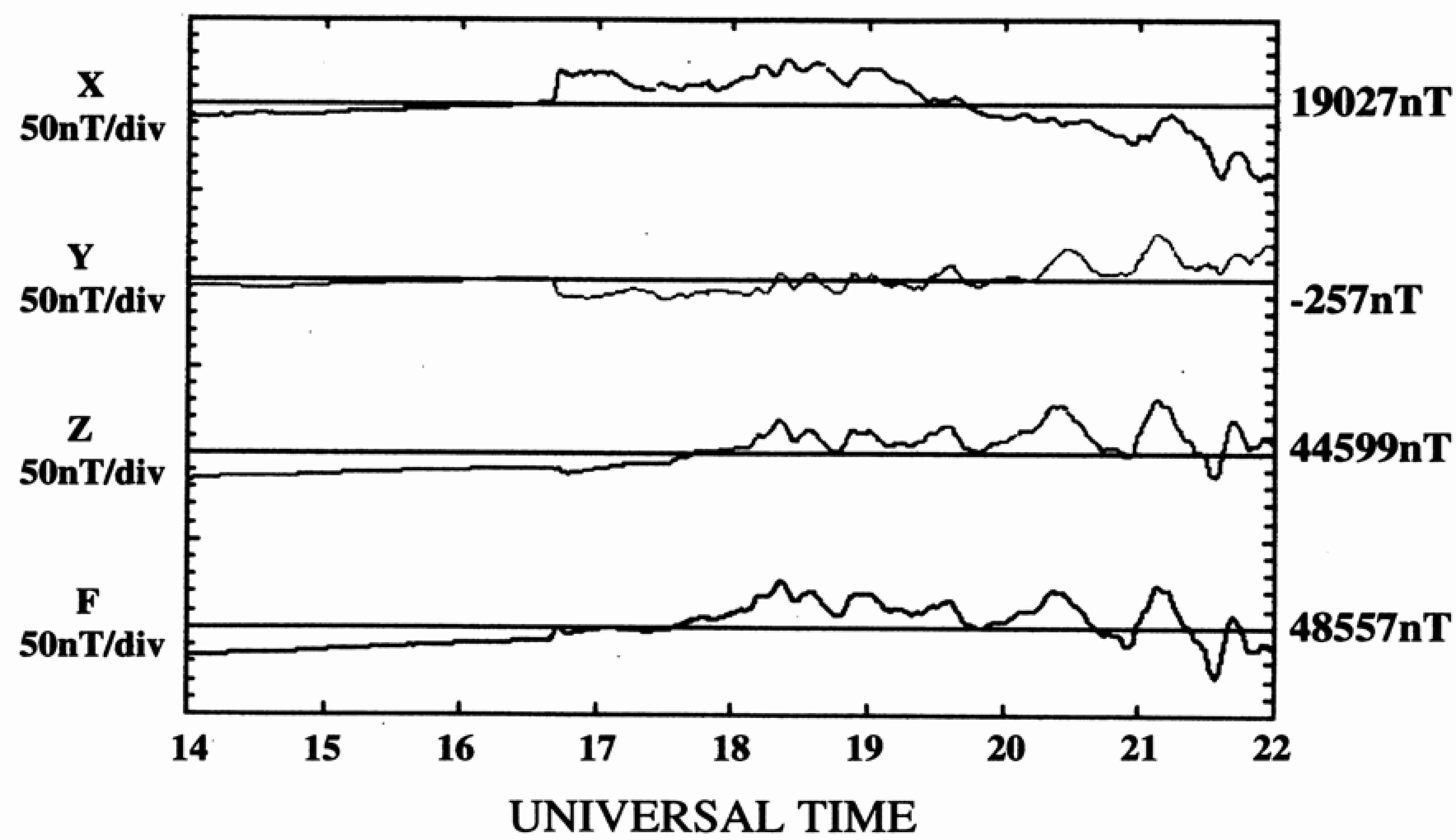


Synopsis of DMSP Measurements (F15, F12 and F13)



Magnetic Storm: 06 April 00

Valentia Magnetogram (footprint of satellite)



Why are there no commensurate ground signatures?

DMSP Observations
Magnetic Superstorms

- **Electron energy $\leq$ 500 eV**
- **High electron number fluxes – parallel acceleration not required**
- **These current-carrying electrons deposit their energy in the F-layer, closing by Pedersen currents**
- **There is *no Hall current*!**
- **From the ground, there is *no* signature of the intense FACs in the ionosphere**

Superstorms and FACs - Ohm's Law

$$j_{||} = (1/\mu_0)(\nabla \times \delta\mathbf{B})_{||} \qquad (1)$$

$$\partial j_{||} / \partial s = - \nabla_{\perp} \bullet \mathbf{j}_{\perp} \qquad (2)$$

$$\mathbf{j}_{\perp} = (\sigma_P \mathbf{E} - \sigma_H (\mathbf{E} \times \mathbf{b})) \qquad (3)$$

where σ_P is the Pedersen conductivity, and σ_H is the Hall conductivity. b is a unit vector directed along the Earth's magnetic field.

Integrating (2) along the magnetic field from the satellite to the bottom of the ionosphere gives

$$j_{||} = \nabla_{\perp} \bullet \mathbf{I}_{\perp} = \nabla_{\perp} \bullet (\Sigma_P \mathbf{E} - \Sigma_H (\mathbf{E} \times \mathbf{b})) \qquad (4)$$

For DMSP crossing the current sheet at normal incidence, $\nabla_{\perp} \rightarrow \partial_y$

$$j_{||} = (1/\mu_0)(\partial_y \delta B_z) \qquad (5)$$

Superstorms and FACs

Integrating (5) along the satellite track (Y direction) gives

$$J_{||} = (1/\mu_0)(\Delta\delta B_z) \qquad (6)$$

where Δ represents the end points of the applied integration.

$J_{||} = 1$ A/m corresponds to $\Delta\delta B_z$ of 1256 nT.

$$j_{||} = \partial_y(\Sigma_P E_y - \Sigma_H E_z) \qquad (7)$$

E_z is the electric field tangent to the sheet direction and is constant.

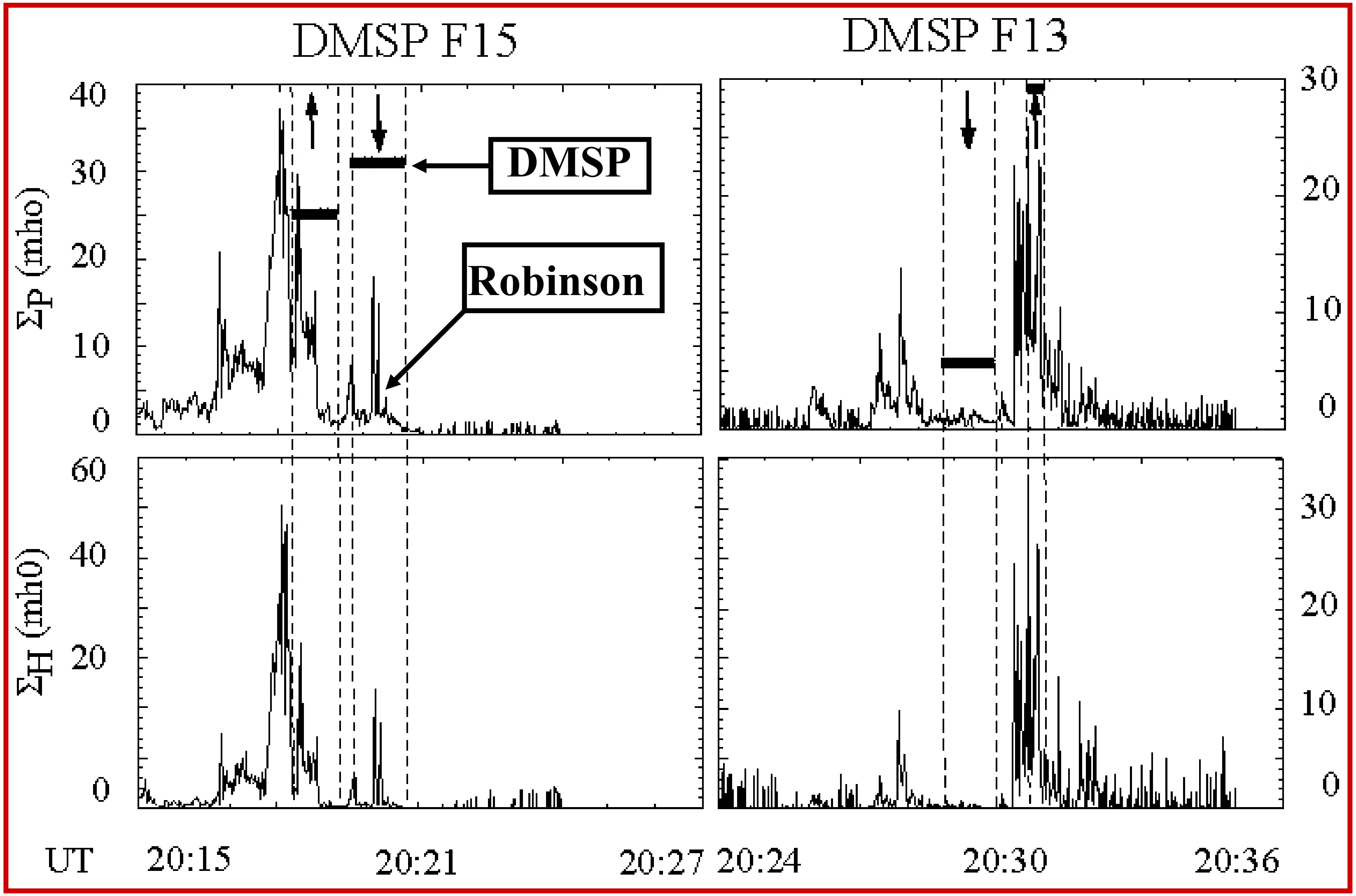
Combining (7) and (5) gives

$$\partial_y(\delta B_z - \mu_0(\Sigma_P E_y - \Sigma_H E_z)) = 0 \qquad (8)$$

If conductance gradients are weak, we can write

$$\Sigma_P \approx (1/\mu_0)(\Delta\,\delta B_z / \Delta E_y) \qquad (9)$$

Superstorms and FACs
Observed and Predicted Conductances



Magnetometer: Ground vs Satellite

- **During April 6, 2000 superstorm, intense FACs detected at 840 km had incommensurate ground signatures – demonstration of Fukushima's theorem.**

- **AMIE (Assimilative Mapping of Ionospheric Electrodynamics) model that inverts ground magnetometer measurements to specify electrodynamics of ionosphere can seriously underestimate currents, potentials, conductances and Poynting flux.**

Transmission-Line Approach

- **DMSP satellites fly well above the ionospheric current layer. Here sensors detect superposed incident (i) and reflected (r) fields of ULF Alfvén waves carrying**

  $E_Y = E_Y^i + E_Y^r = E_Y^i(1+R)$, $\delta B_Z = \delta B_Z^i + \delta B_Z^r = \delta B_Z^i(1-R)$

  where $R = E_Y^r / E_Y^i$

- **To maintain current continuity:** $R = (\Sigma_{AR} - \Sigma_P) / (\Sigma_{AR} + \Sigma_P)$, **where**

  $\Sigma_A = 1/\mu_0 V_{AR}$ **and** V_{AR} **= Alfvén speed in reflection layer.**

  For propagating Alfvén waves:

  $E_Y^i / \delta B_Z^i = V_{AS} = - E_Y^r / \delta B_Z^r$

  $E_Y^i = E_Y / (1+R)$ **and** $\delta B_Z^i = \delta B_Z / (1-R)$

  V_{AS}**, the Alfvén speed at the satellite can be calculated from DMSP measurements of magnetic fields and plasma densities.**

  Thus, $E_y^i = E_Y / (1+R)$ **and** $\delta B_Z^i = \delta B_Z / (1-R)$.

  With measured E_Y **and** δB_Z**, calculate R and** Σ_P / Σ_{AR}.

Poynting Theorem Considerations

$$\nabla \bullet \mathbf{S} + \frac{\partial W}{\partial t} + \mathbf{j} \bullet \mathbf{E} = 0$$

$$W = \frac{1}{\mu_0}\delta B^2 + \varepsilon_o E^2$$

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

Joule heat term

- **Consider the Poynting vector from measured δB_Z and E_Y.**

$$S_{\|m} = \left(\frac{\delta B_{Zm} \times E_{Ym}}{\mu_0} \right) = \left(\frac{\delta B_Z^i (1-R) \times E_Y^i (1+R)}{\mu_0} \right)$$

$$S_{\|m} = S_\|^i (1 - R^2) = S_\|^i - S_\|^r$$

- **$S_\|$ is the net Poynting flux and thus the total rate of EM energy deposition into the ionosphere-thermosphere.**

Energy Dissipation – 6 April 2000

Consider large FAC seen at 20:31 UT by F13. Net Poynting flux can be estimated from E_Y and B_Z measured between 55.5° and 61.7° MLat.

$$S_{||}\,(\mathrm{W/m^2}) = (1/\mu_0)(E \times \delta B)_{||}$$

Maximum net Poynting flux: => ~ .11 W/m²

Integrate across FAC structure: => ~ 42 kW/m

For each 15° longitude => ~ 42 GW.

For 6 hr extension in LT in 2 hemispheres: => ~ 500 GW*

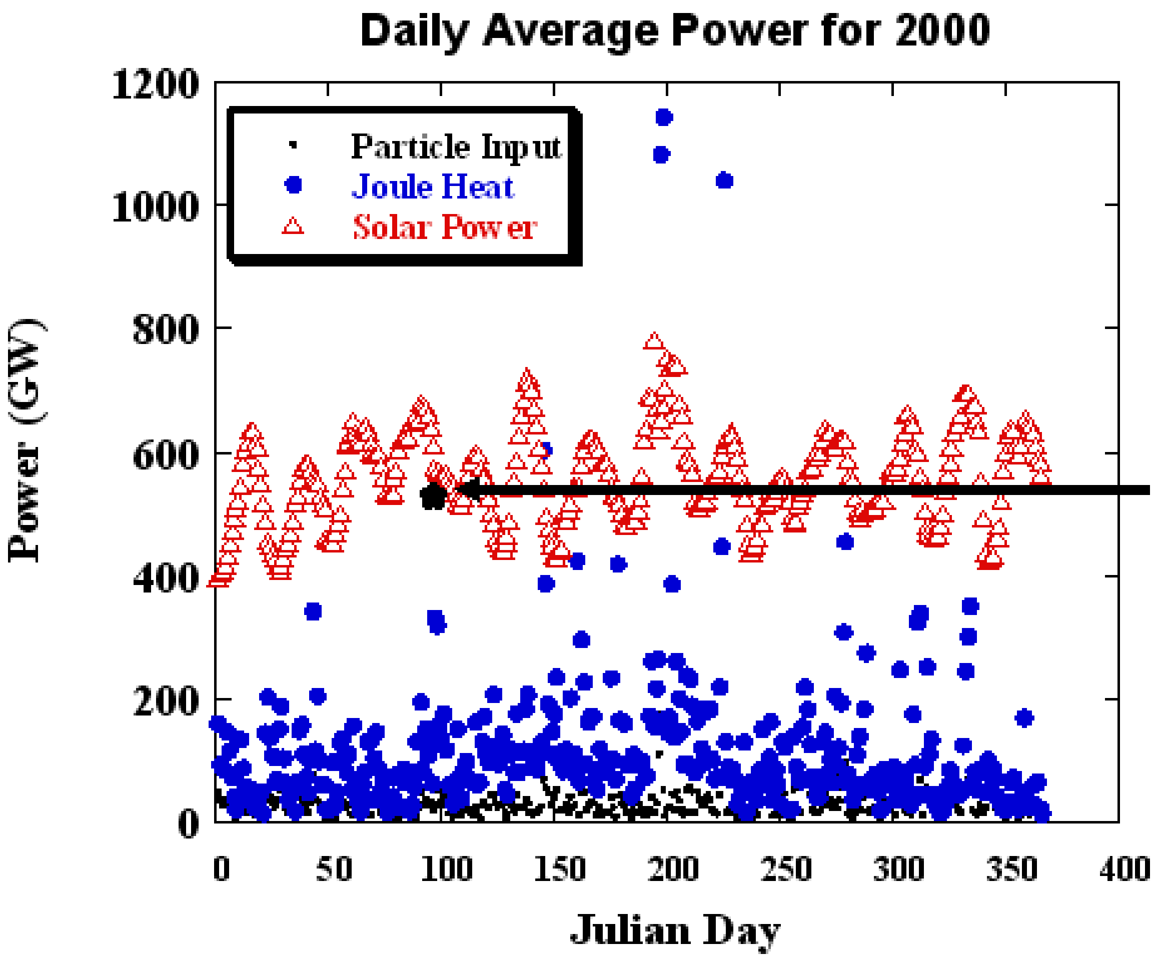
* About total solar EUV input to dayside ionosphere

Energy deposited in a 20 minute episode: => ~ 600 TJ**

** About 5% of total energy in ring current

Ring current => mid-latitude ionosphere

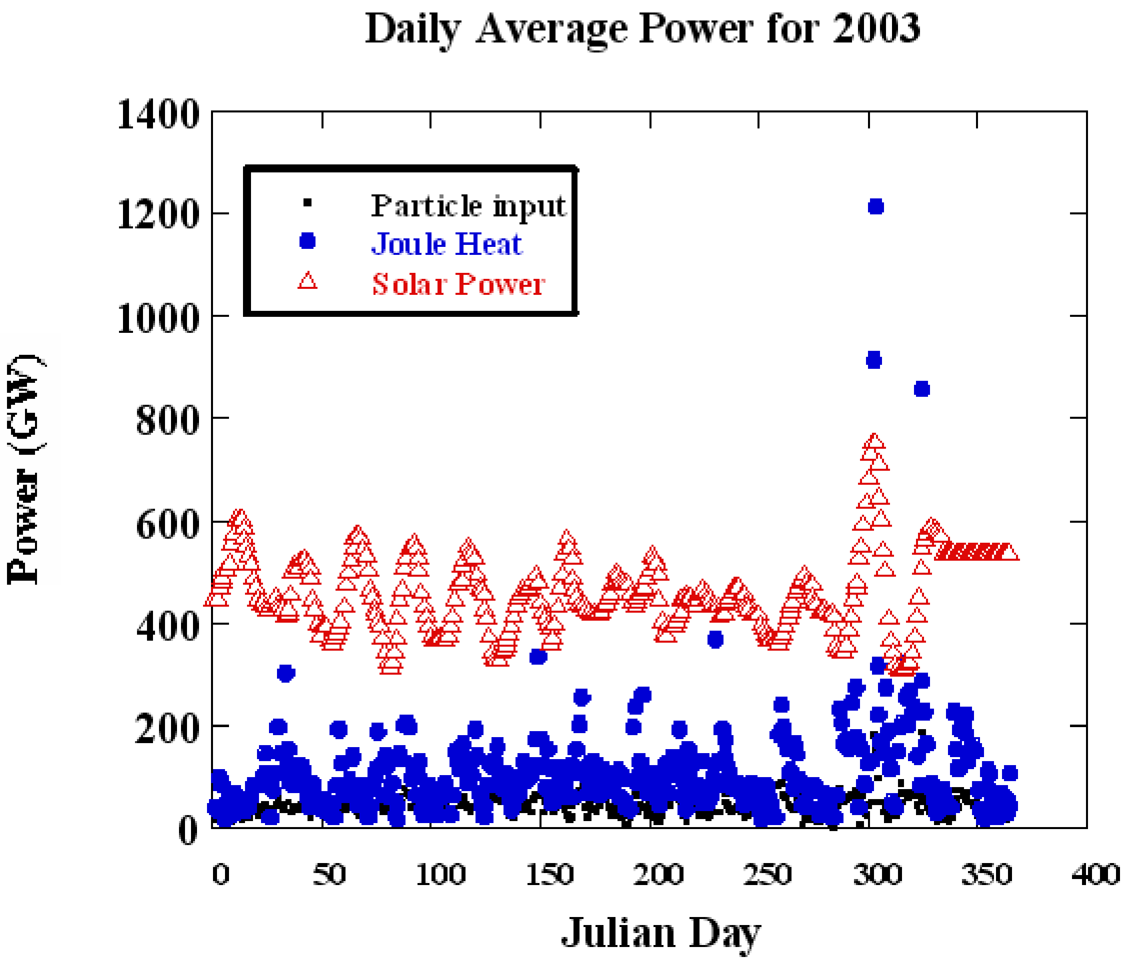
Model and Observed Values of Power 2000



Estimated Poynting flux based on DMSP measurements approximately 500 GW (both hemispheres, 6 hours of local time)

Figure courtesy of D. Knipp

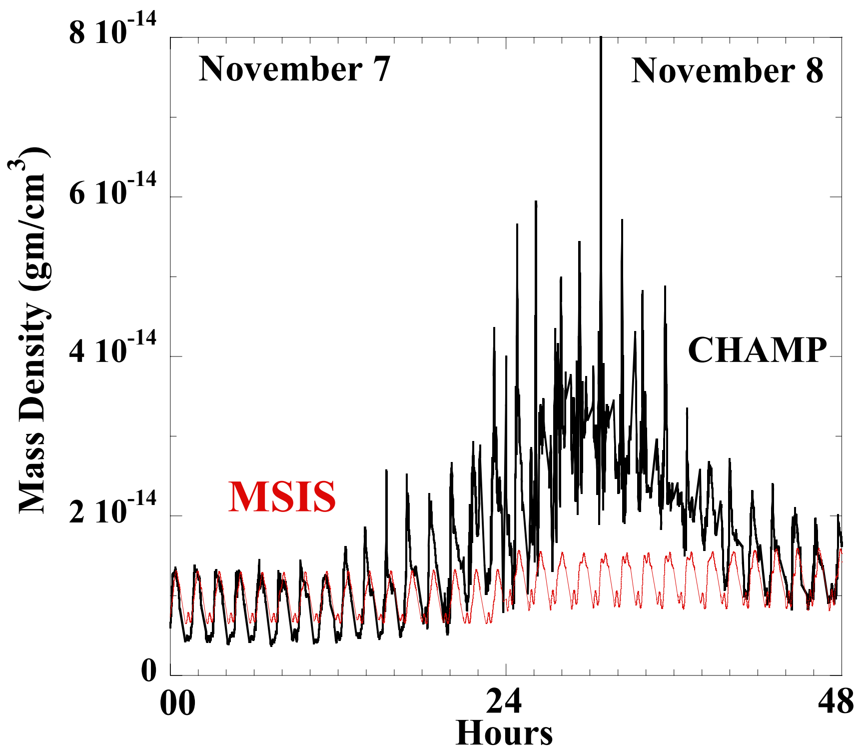
Model and Observed Values of Power 2003



Estimated Poynting flux input using DMSP observations ~ (2.65 – 3) x 10^3 GW for superstorm on 29 – 31 October 2003 (days 302 – 304)

Figure courtesy of D. Knipp

Consequences for M-I-T Modeling



Change in ionospheric mass density during superstorm of 7-9 November 2004: Comparison between observations (black) and model (red)

Consequences for M-I-T Modeling

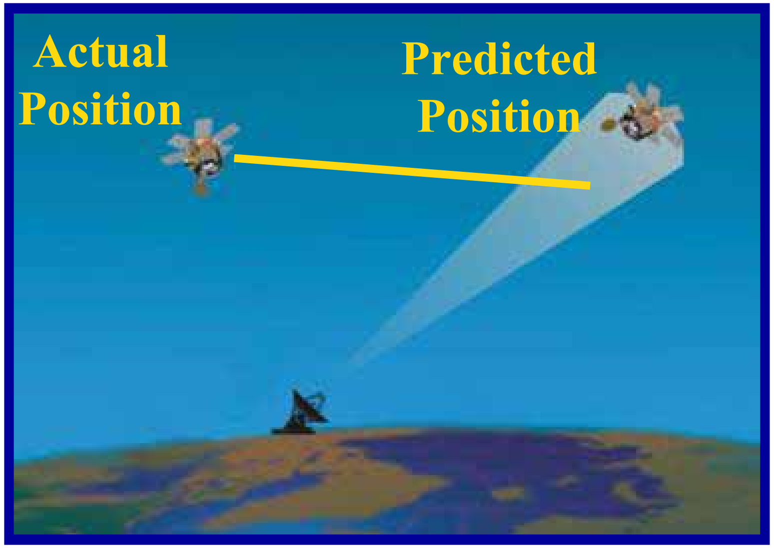
Electromagnetic Energy Flow

Interplanetary Medium → Magnetosphere → Ionosphere/Thermosphere

Poynting vector measure of electromagnetic energy transfer

Impact during Superstorms:

- Changed scale heights and wind patterns
- Degraded space-object-tracking
  - 3000 space catalog objects lost during March 1989 storm



Hundreds of TeraJoules per hour deposited in I/T, undetected from the ground

M-I-T Coupling Summary

•On 6 April 2000, four DMSP satellites crossed > 1A/m current sheets spread across 9 hours in local time and centered at Magnetic Lat < 60°

•No commensurate magnetic perturbations seen on the ground

• AMIE blind to energy inputs – underestimates currents, Poynting flux, conductances

• Poynting theorem shows that DMSP measures net rate of EM energy input to ionosphere

• 500 GW of power equivalent to 600 TJ of stealth energy deposited at mid-latitude over 20 minutes during storm

• Even higher levels of energy dissipated in ionosphere during Halloween superstorm

M-I-T Coupling References (1)

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