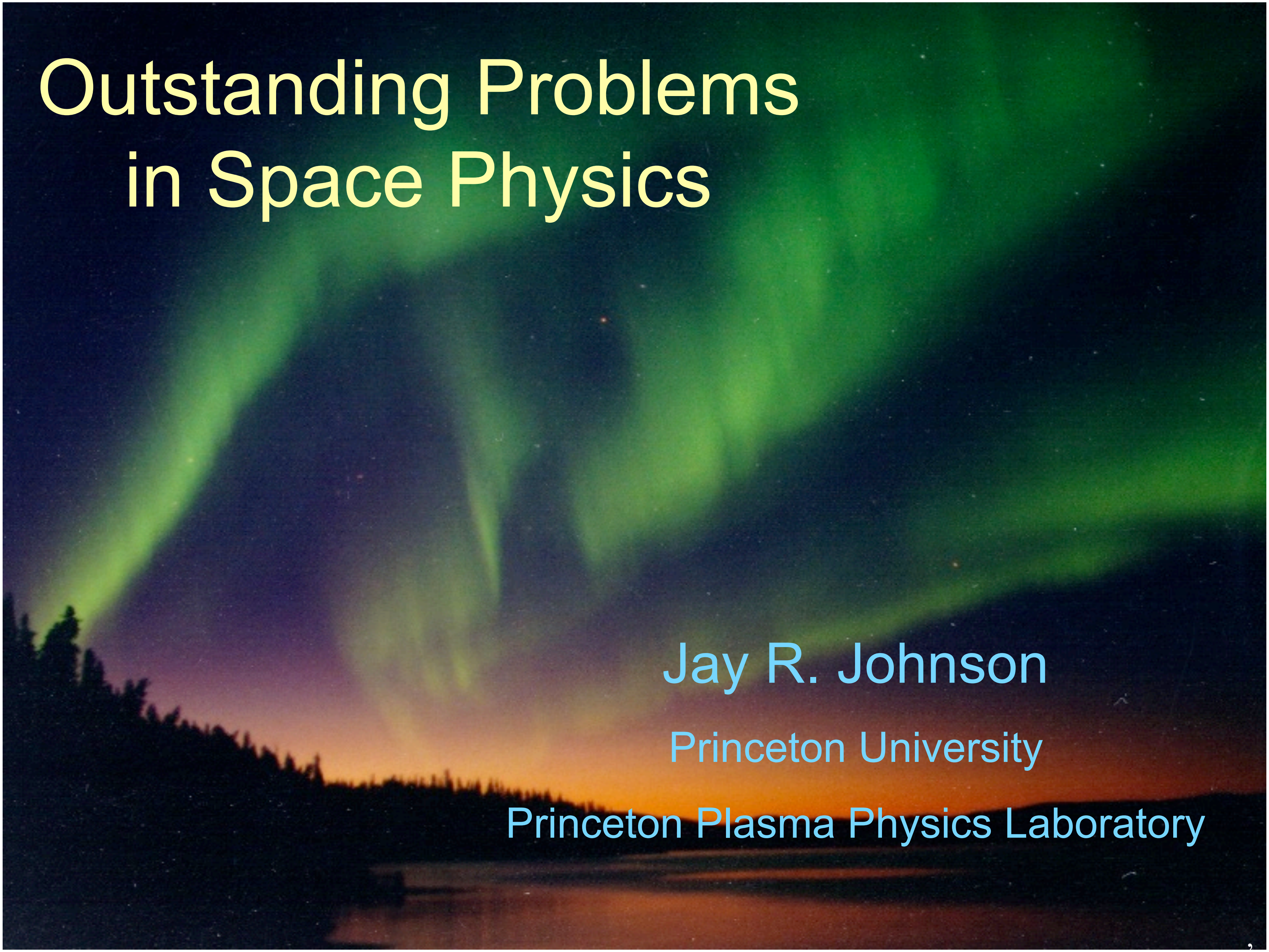
Outstanding Problems in Space Physics



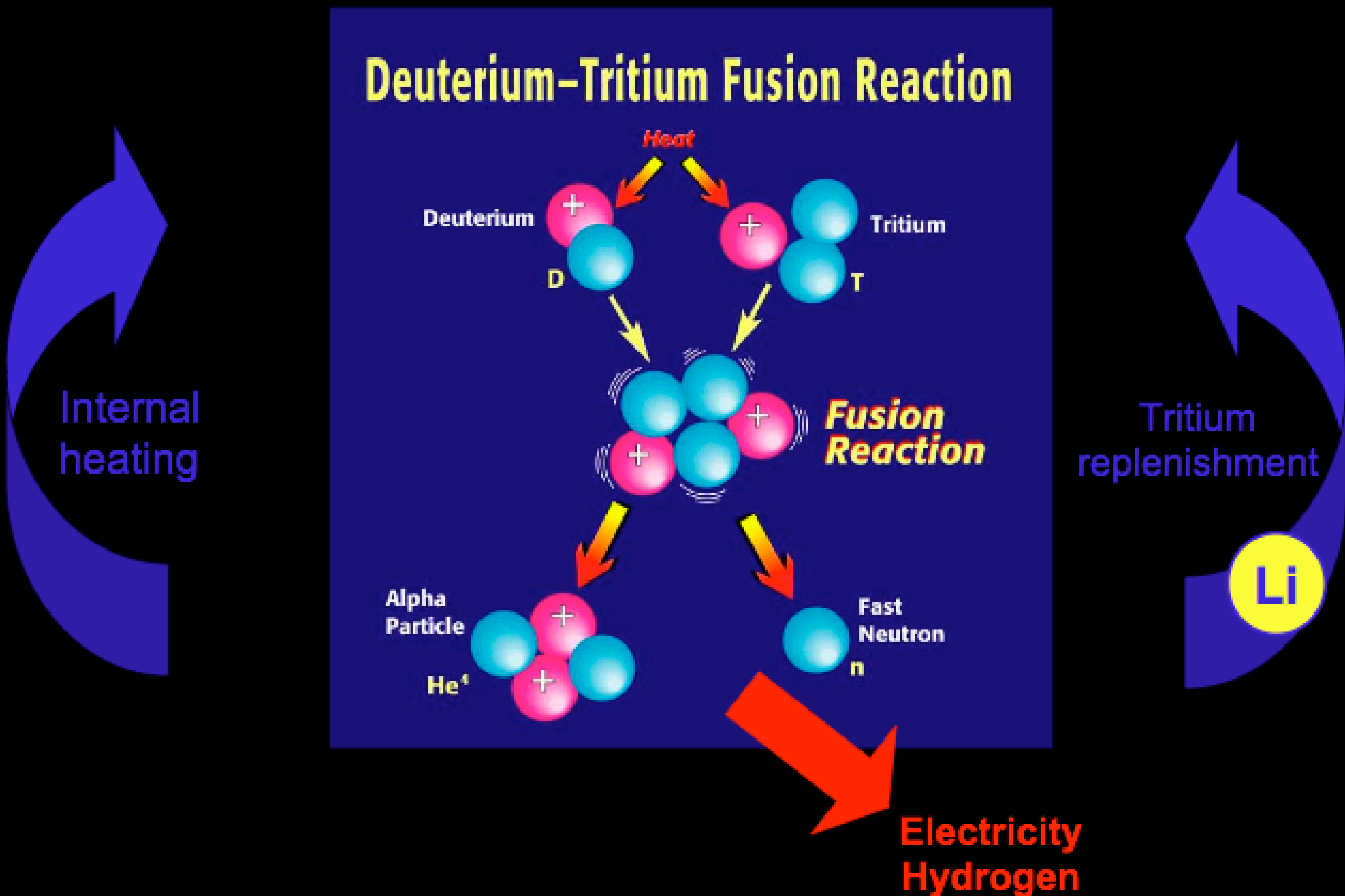
Jay R. Johnson

Princeton University

Princeton Plasma Physics Laboratory

PPPL

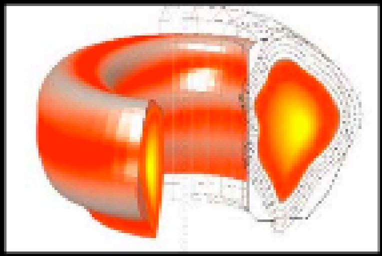
Fusion is an Attractive Long-term Form of Nuclear Energy



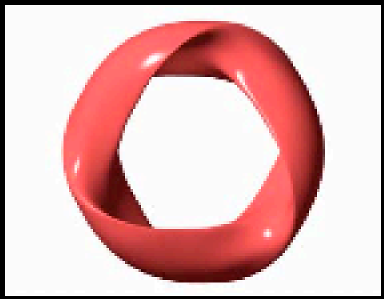
Fusion Science: Challenges and Advances

- **Energy Gain**
  - Internal heating by fusion must largely sustain the high plasma temperature against turbulent heat loss, giving high gain:
    fusion heat produced / input power provided
  - Theory and experiment support the projection that ITER will exceed energy gain of 10, and NIF / LMJ will exceed energy gain of unity.

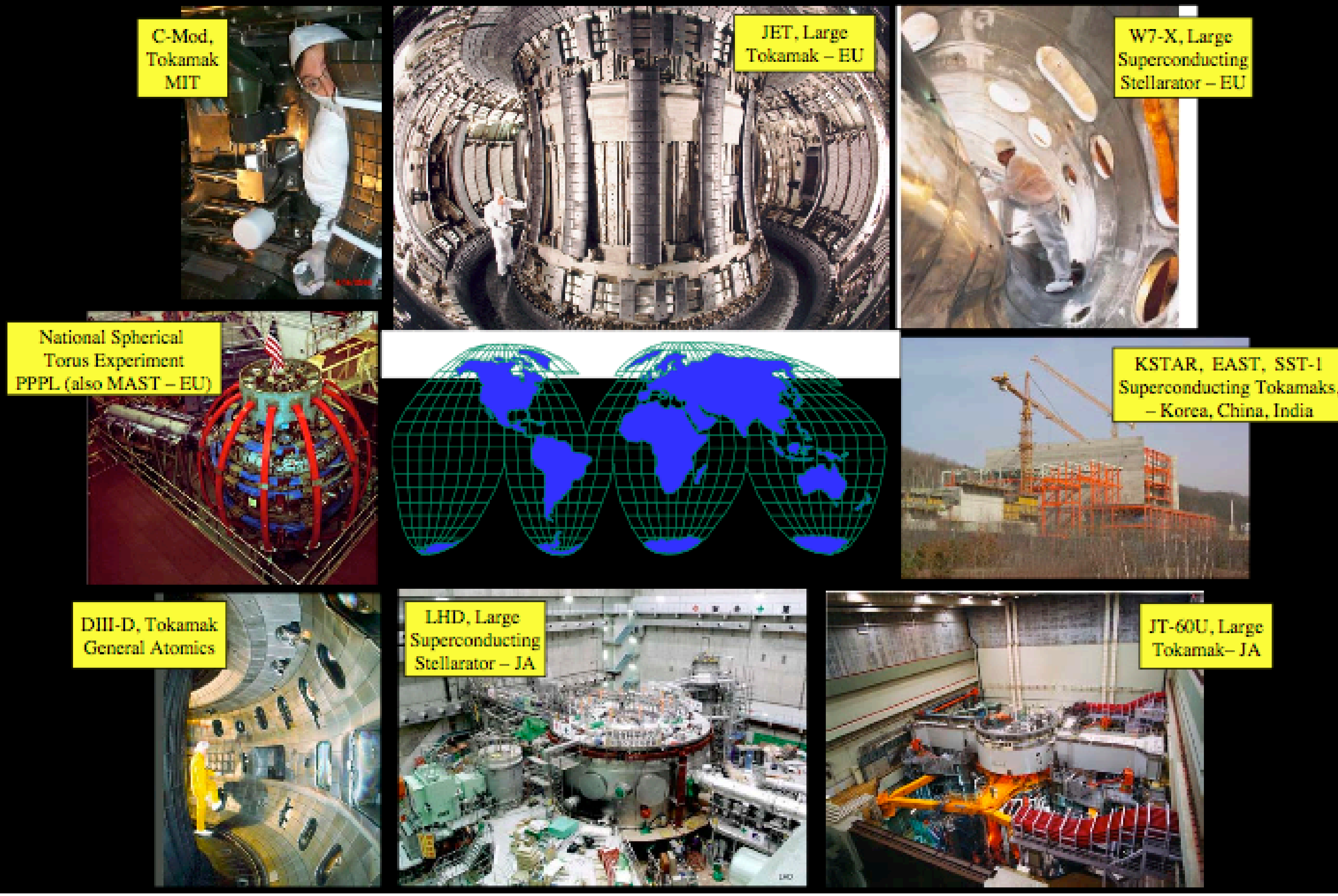
- **Power level**
  - Fusion power must be maximized for given cost.
  - Plasma shaping and active field control allow higher plasma pressure / magnetic field, so higher power level. Fast ignition in IFE promises relaxed driver requirements. Strong Japanese interest.



- **Sustainment**
  - Fusion output must be sustained steadily, with low recirculating power.
  - Self-sustaining plasma currents have been discovered, and compact configurations have been invented that do not require external drive. Substantial progress in rep-rated IFE drivers.



Magnetic Fusion Research is a Worldwide Activity: Optimizing the Configuration for Fusion



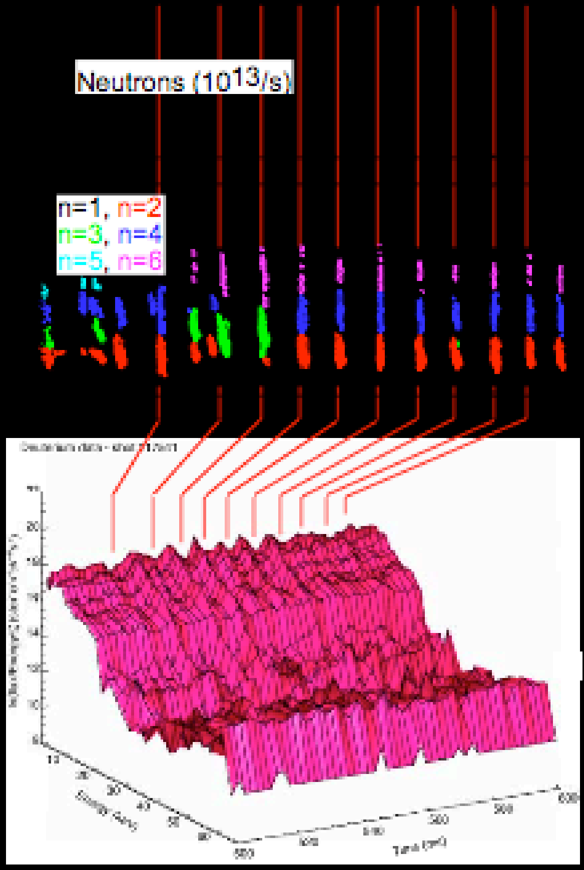
ITER will Test Magnetic Fusion Science at Power Plant Scale

- **Energy Gain:** Extend the study of turbulent heat loss to much larger plasmas, providing a strong test of how turbulent structure sizes vary with system size.

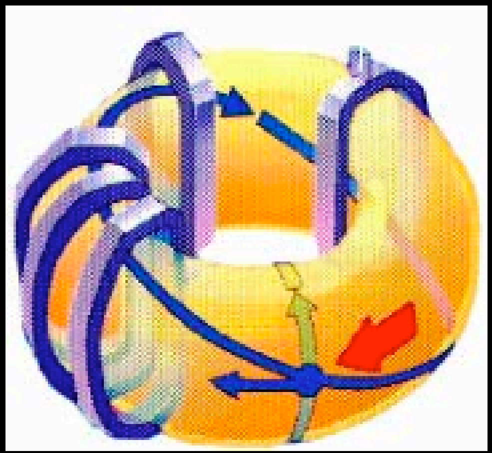
- **Power level:** Extend the understanding of pressure limits to much larger size plasmas, where particle trajectories are smaller compared with the plasma.

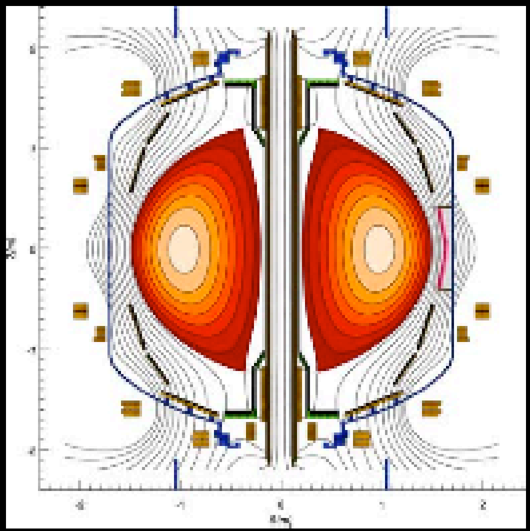
- **Sustainment:** Study – for the first time – self-sustained internal plasma heating by helium fusion products. Study external sustainment of plasma electrical currents at high temperature.

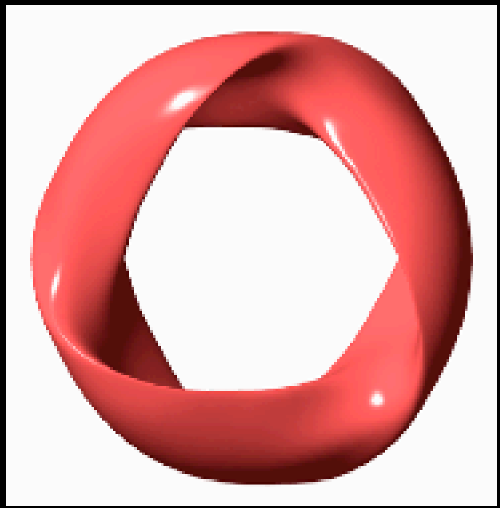
These results can be extrapolated via advanced computing to related magnetic configurations.



Research is Needed in Parallel with ITER to Make Fusion Practical







Advanced Tokamak
Active instability control and driven continuous operation.

Spherical Torus
High fusion power at given size and magnetic field.

Compact Stellarator
Passive stability and efficient continuous operation.

Practical fusion requires high power and efficient continuous operation. Improved neutron-interactive and superconducting materials are important enabling technologies for fusion.


Outstanding Problems
in Space Physics

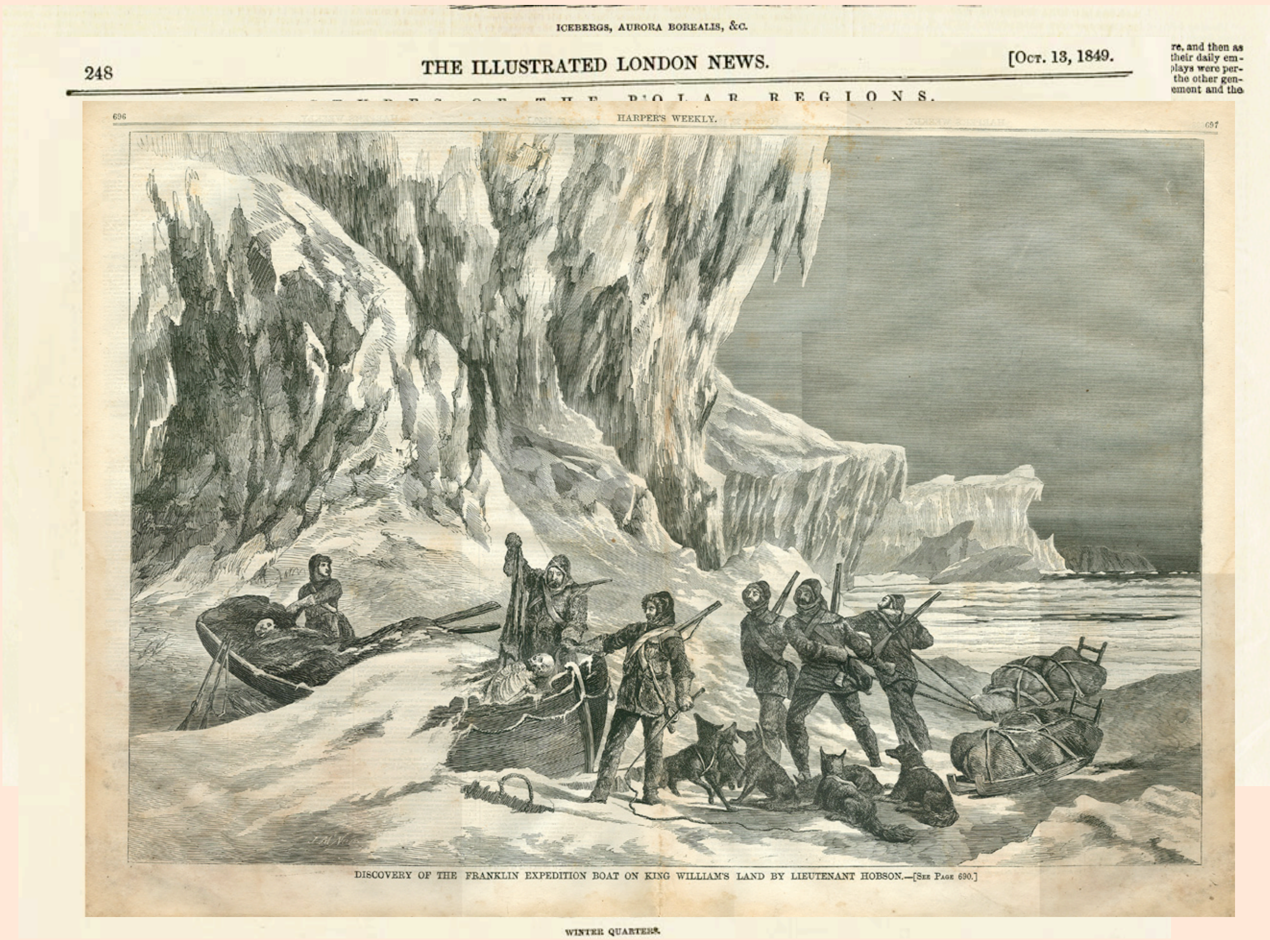
The Age of Wonder

Aurora in Antiquity

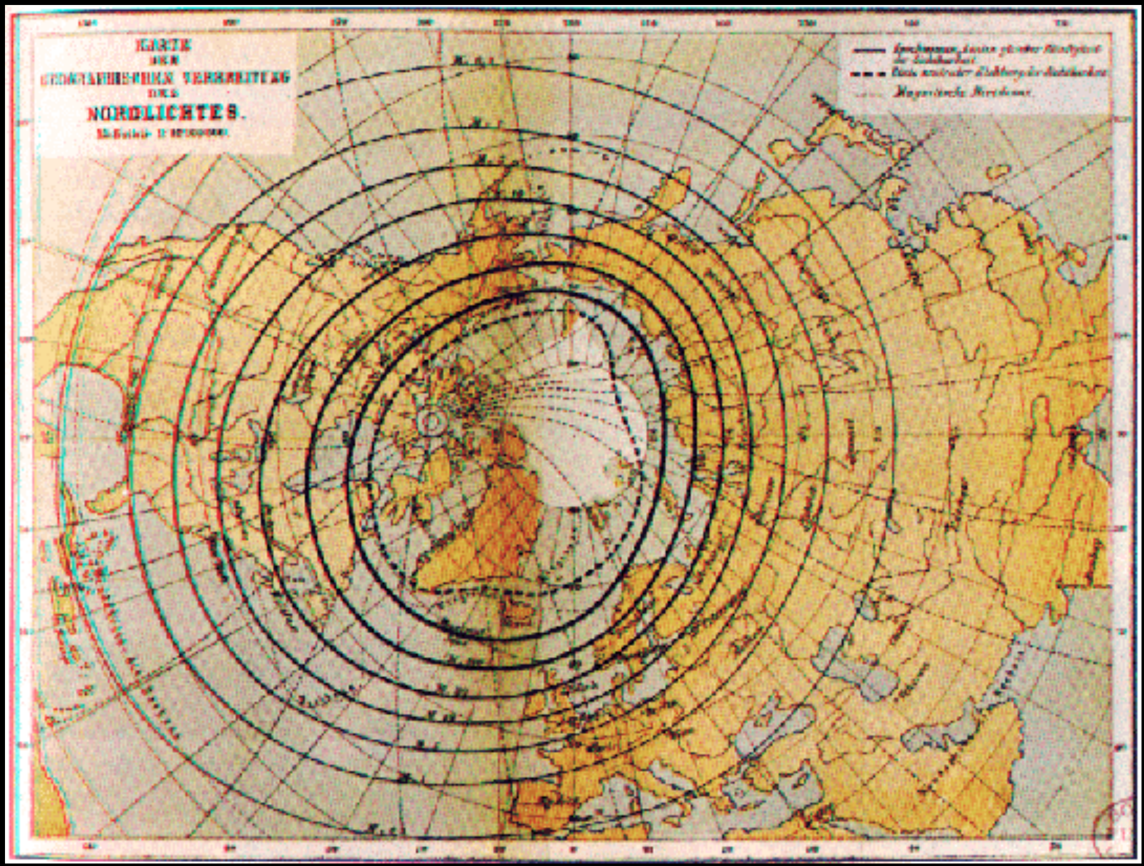
- Fires
- Bad Omen (Julius Ceasar, Attila ...)
- Dancing Animals or Dragons
- Swords of Heaven
- Red Spear Shafts
- Cracks in the Sky

The Age of Discovery

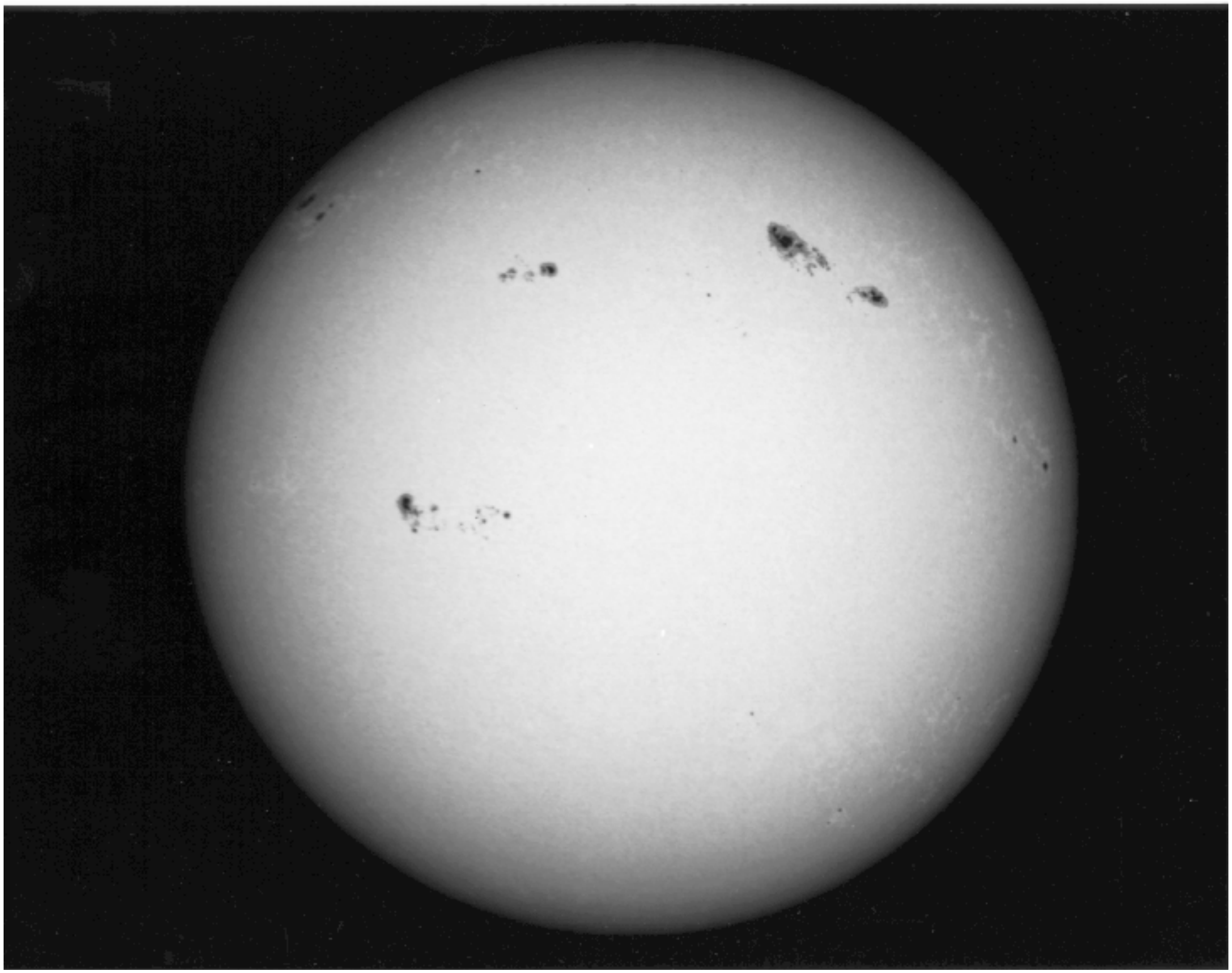
The Franklin Expedition,1845



Herman Fritz Evaluates Auroral Frequency

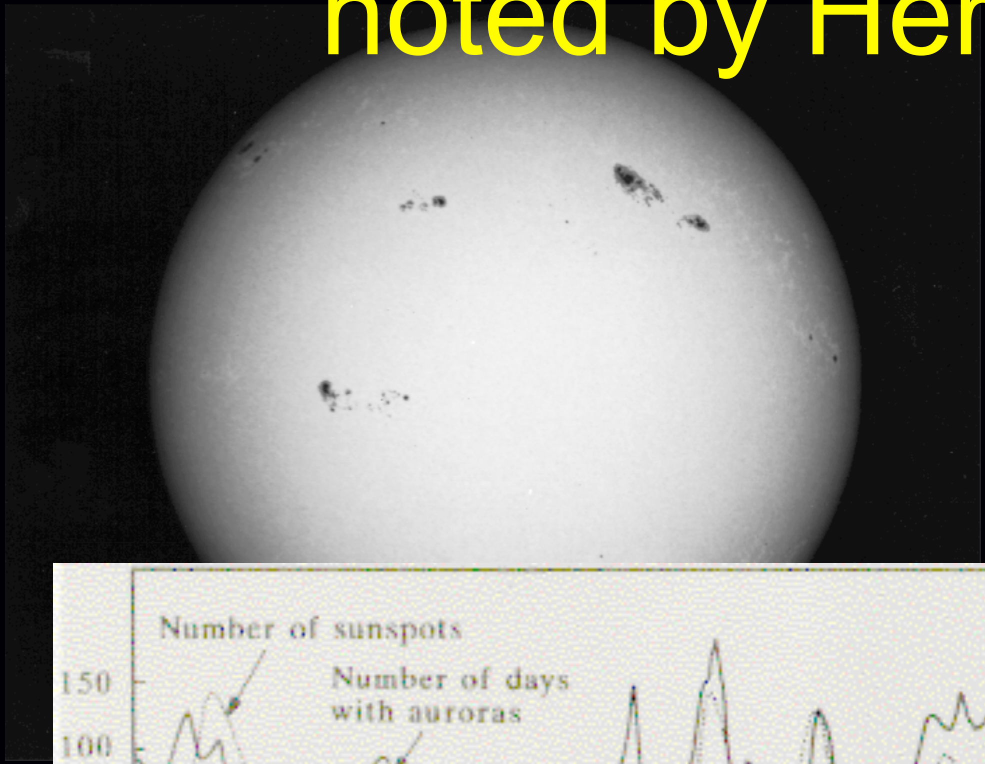


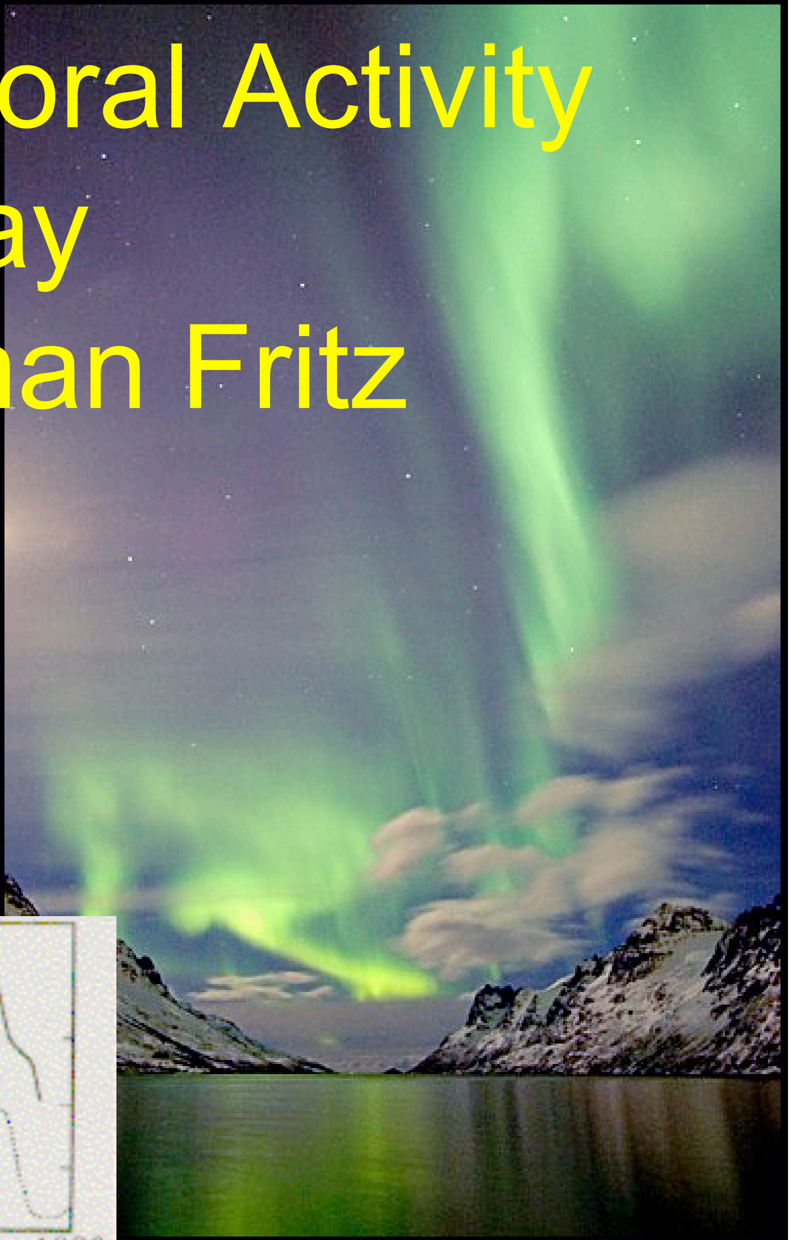
Richard Carrington, 1859

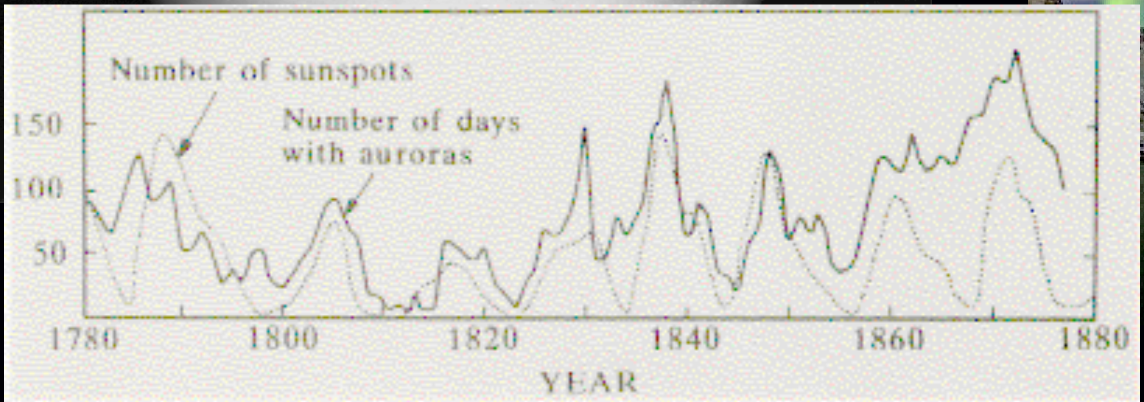


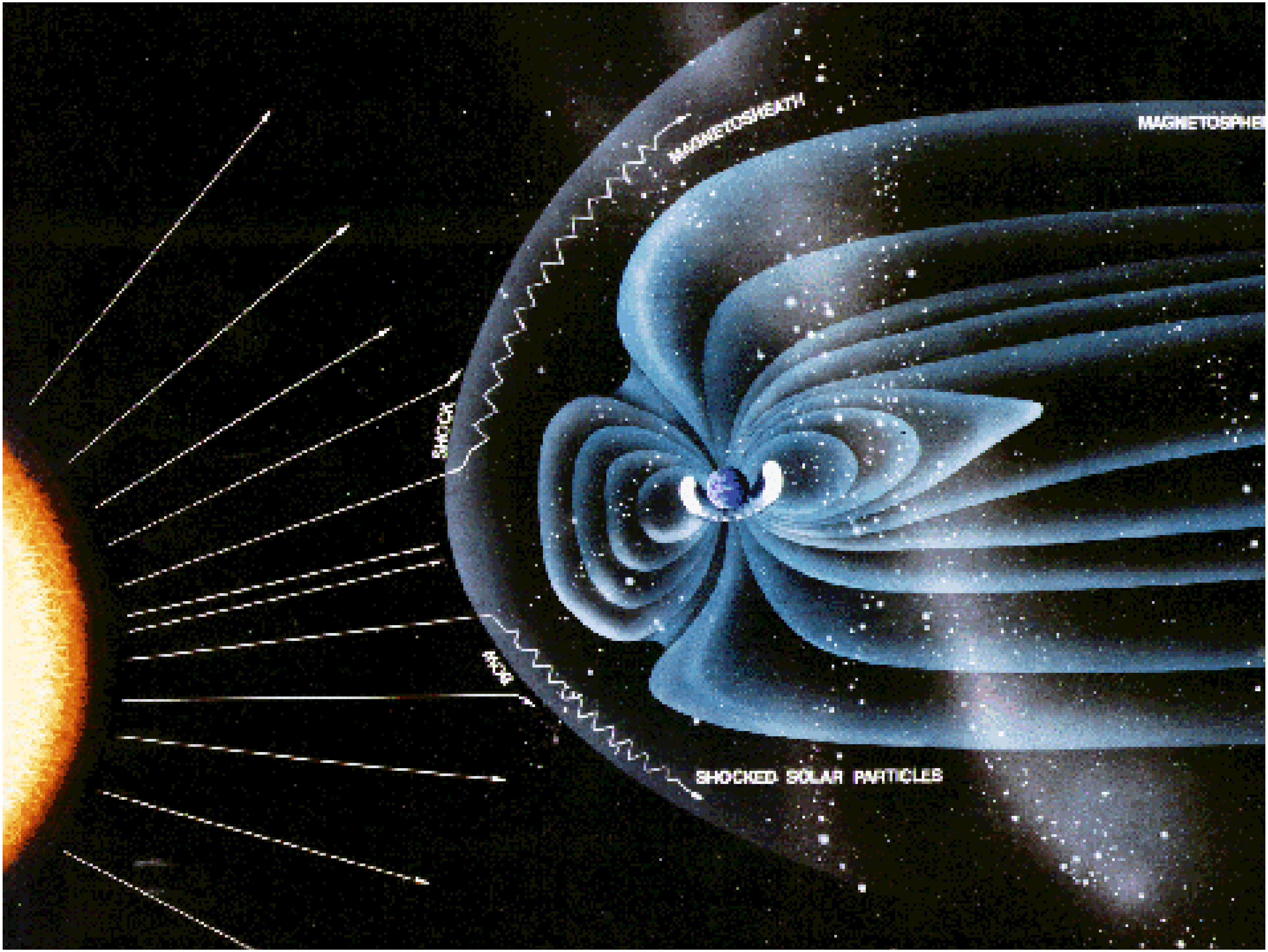
18 hours later …

Association Between Sunspots and Auroral Activity in Norway noted by Herman Fritz








MAGNETOSHEATH
MAGNETOSPHE
SHOCK
BOW
SHOCKED SOLAR PARTICLES

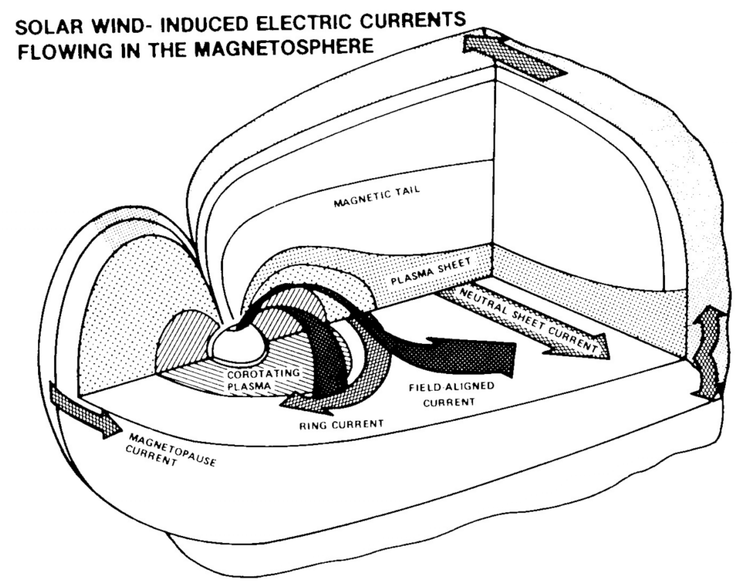
Two Important Issues

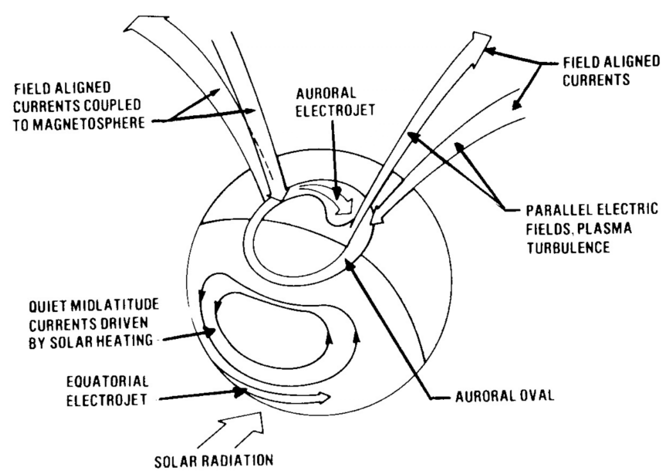
- Morphology
- Dynamics (cause-effect)

Morphology

- Magnetic field
- Current systems
- Plasma populations
- Auroral regions

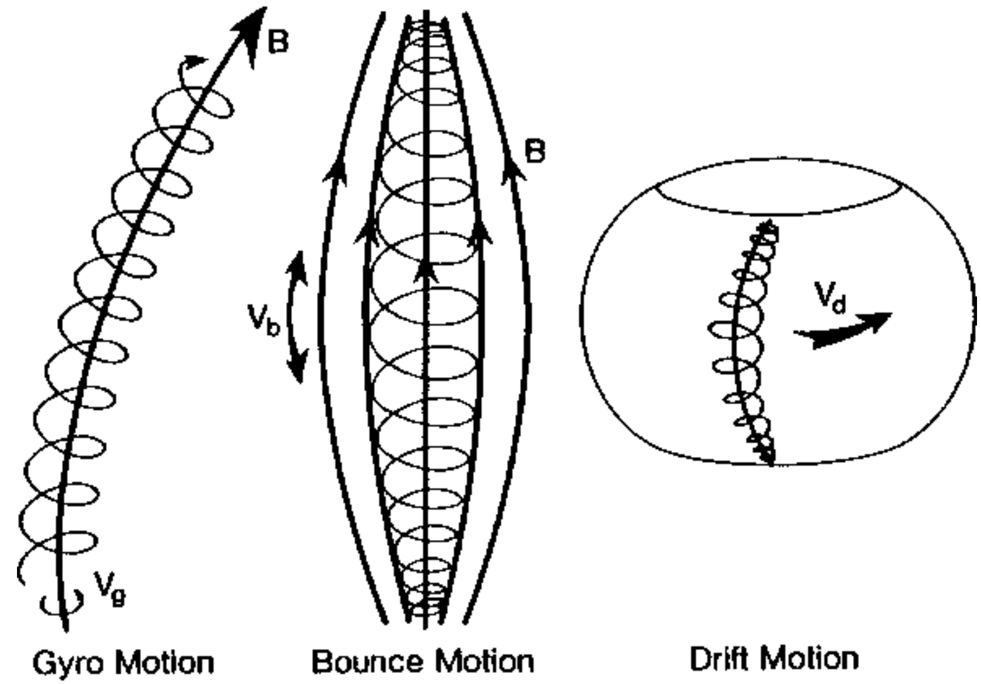
Magnetospheric Currents





- Boundary Current
- Ring Current
- Tail Current
- Birkeland Current
- Ionospheric Current

Adiabatic Invariants



$$\tau_c = (0.66s)\left(\frac{100\text{nT}}{B}\right)\left(\frac{m}{m_p}\right)$$

$$\tau_B \sim (5\min)\left(\frac{l_b}{10R_E}\right)\left(\frac{m}{m_p}\right)^{1/2}\left(\frac{1\text{keV}}{W_{\parallel}}\right)$$

$$\tau_D = (56\text{hr})\left(\frac{r}{5R_E}\right)^2\left(\frac{B}{100\text{nT}}\right)\left(\frac{1\text{keV}}{W}\right)$$

Ring Current

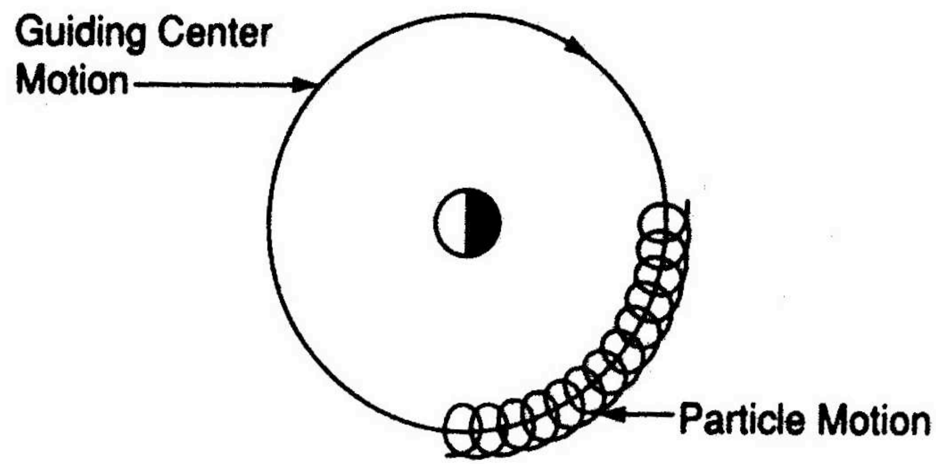
- Energy

$$W(\mu, J, \mathbf{x})$$

- Curvature/Gradient Drift/Current

$$V_{GCD} = \frac{B \times \nabla W}{qB^2}$$

- Magnetization Current
- Change in Magnetic Field $\frac{\Delta B}{B_0} \sim -\frac{2}{3}\frac{W_{particles}}{W_{mag}}$



During Storms

$$\Delta B = 100nT \Rightarrow W_{part} \sim 10^{15} J$$

Ring Current

- Energy

$$W(\mu, J, \mathbf{x})$$

- Curvature/Gradient Drift/Current

$$V_{GCD} = \frac{B \times \nabla W}{qB^2}$$

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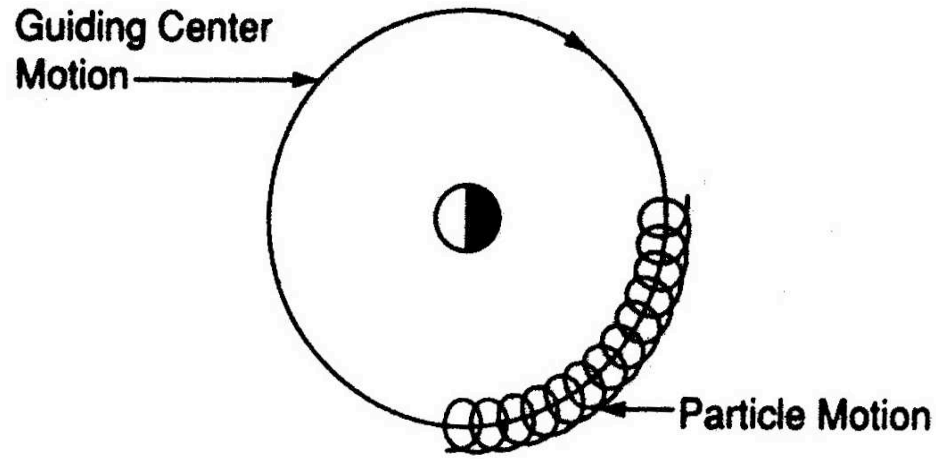
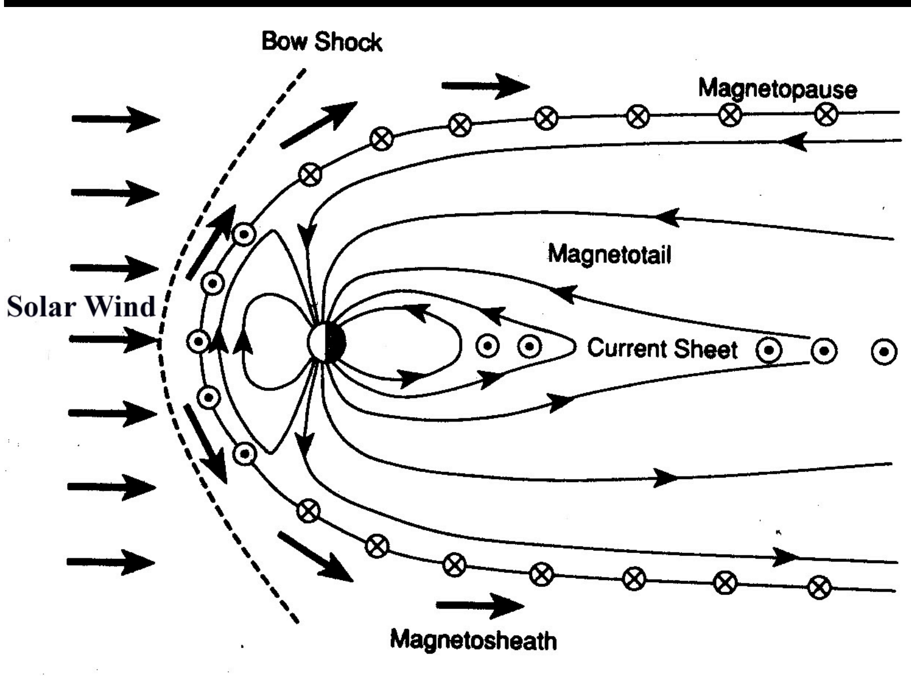


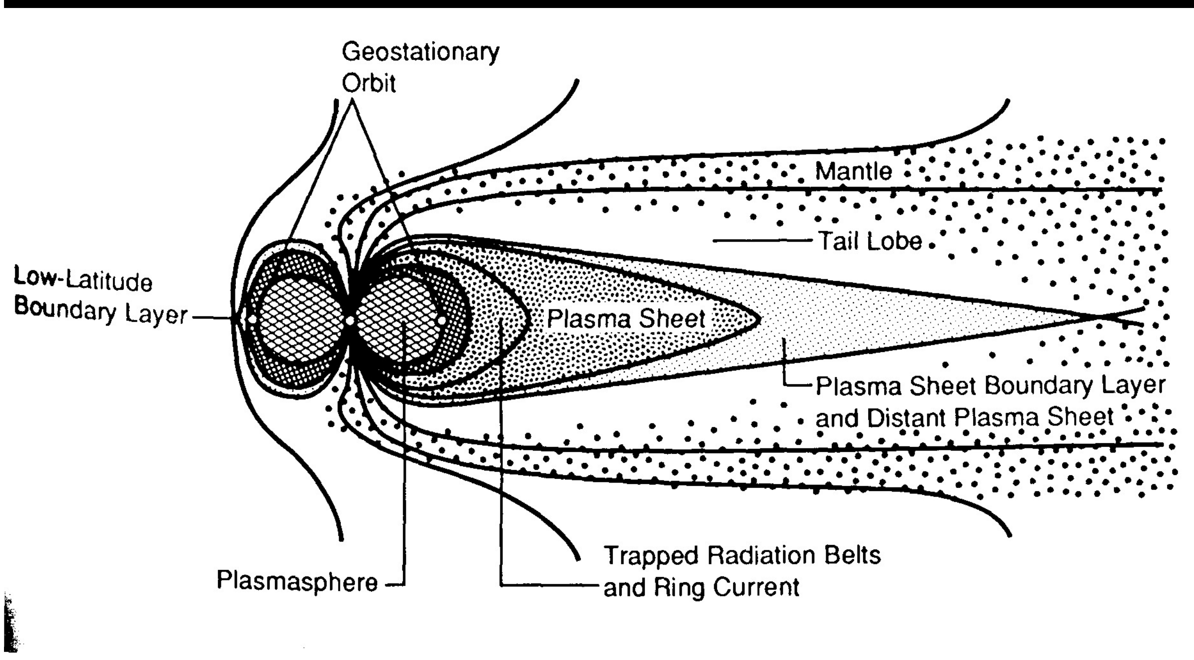
100 Early Atomic Bombs!

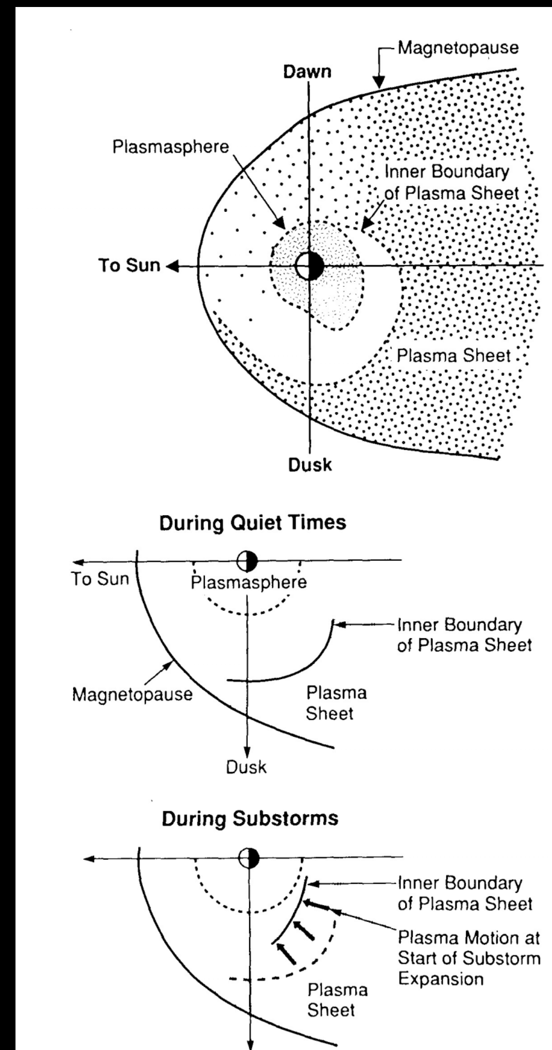
Cross Tail Current



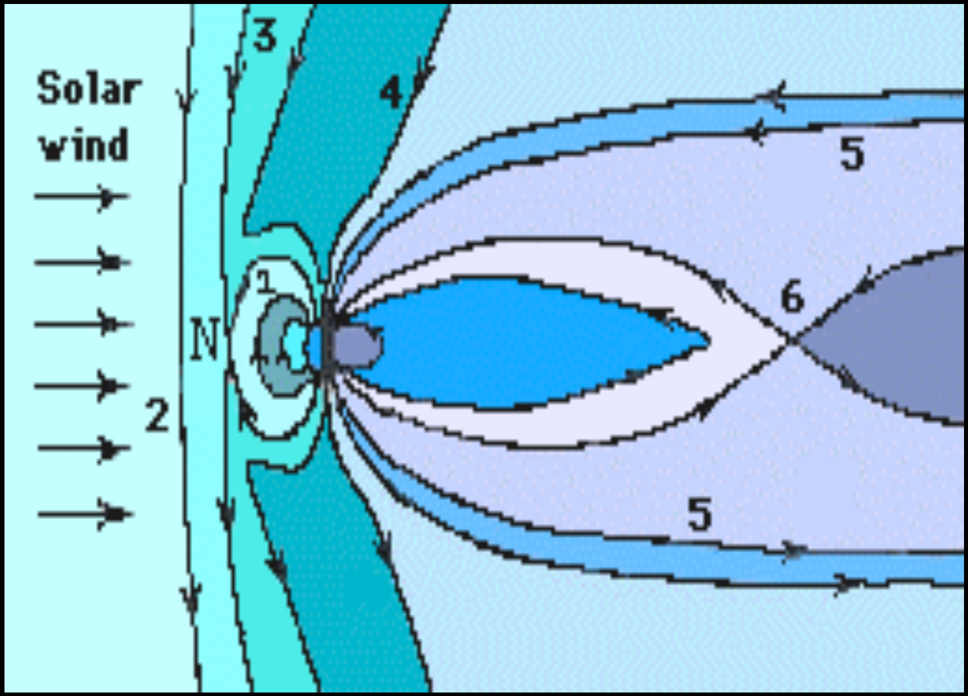
- Tail Serves as a Reservoir of Energy
- Magnetic Pressure >> Particle Pressure in Lobes
- Particle Pressure in Plasma Sheet >> Magnetic Pressure
- 10^6 A/5R_E in Tail
- Flux Added to Tail Increases Lobe Pressure and Intensifies Current in Current Sheet

Magnetospheric Plasma Populations



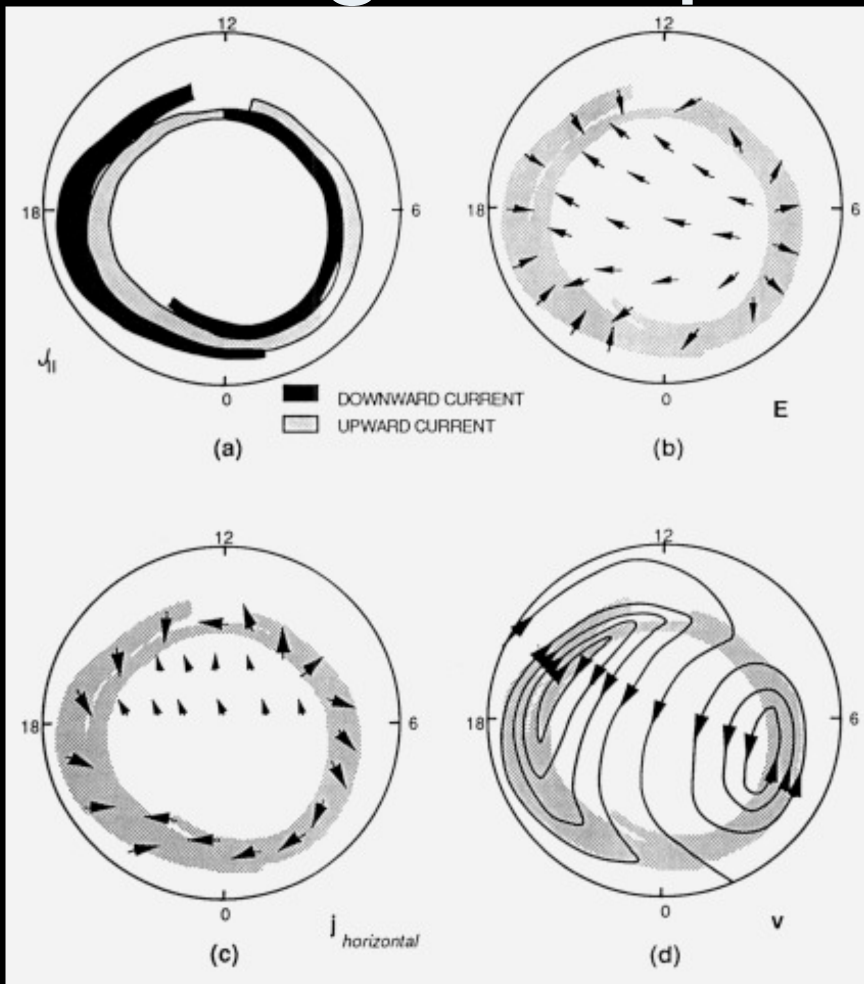


Convection Model



- Ionospheric Flows Map to Magnetospheric Convection
- Dungey (1961) Reconnection
- Antisunward Flow in Polar Cap
- Return Flow at Lower Latitudes
- Electric Field (VxB)

Electric Fields and Magnetospheric Convection



- Birkeland Current
- Electric Field
- Ionospheric Current
- Plasma Velocity
- Potential Drop = Transport of Mag Flux

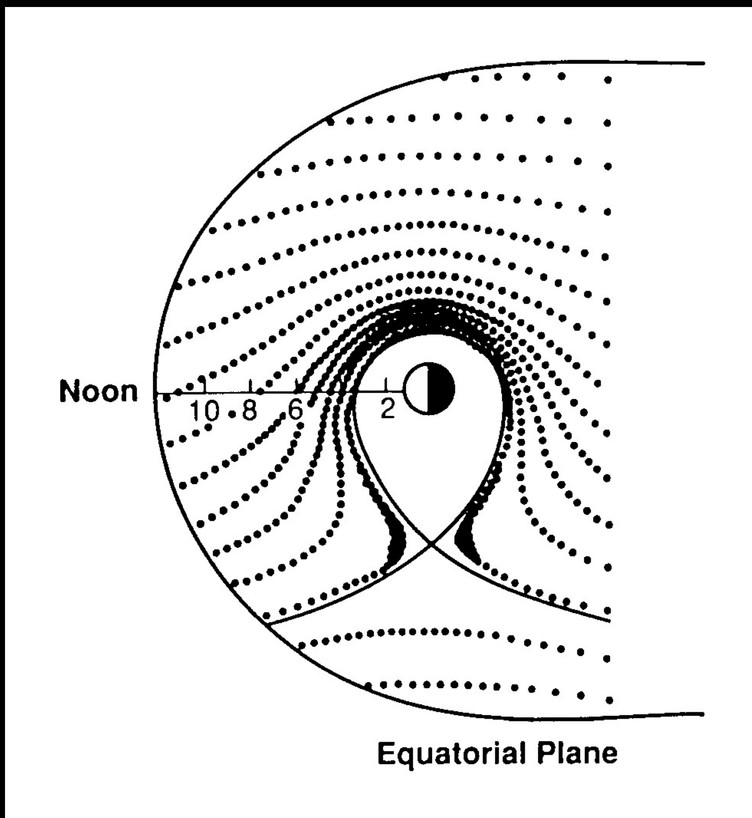
Plasma Convection

- Convection (Dawn-Dusk Electric Field)
- Corotation (Earth's Field Exerts a Torque)
- Gradient/Curvature Drift

$$V_D = \frac{B \times \nabla \Phi_{eff}}{B^2}$$

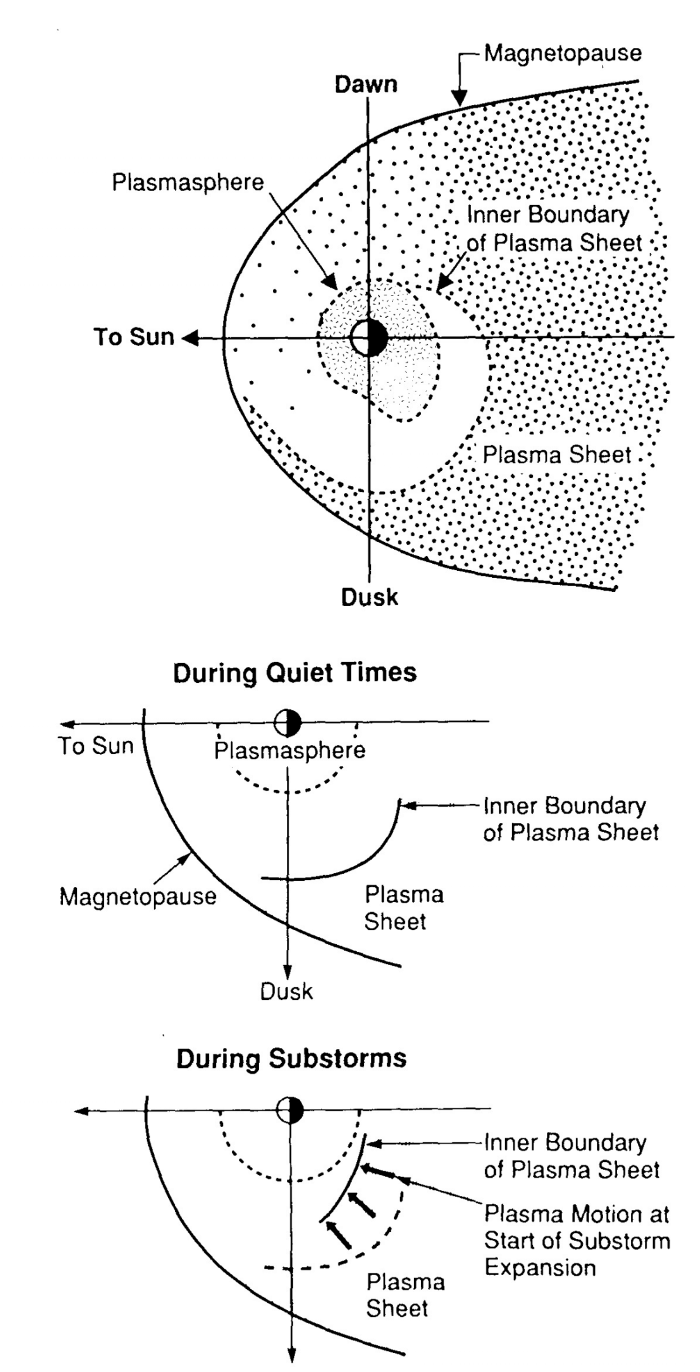
$$\Phi_{eff} = -E_0 r \sin\varphi + \frac{\mu B_0 R_E^3}{q r^3} - \frac{\omega_E B_0 R_E^3}{r}$$

Origin of Plasmasphere

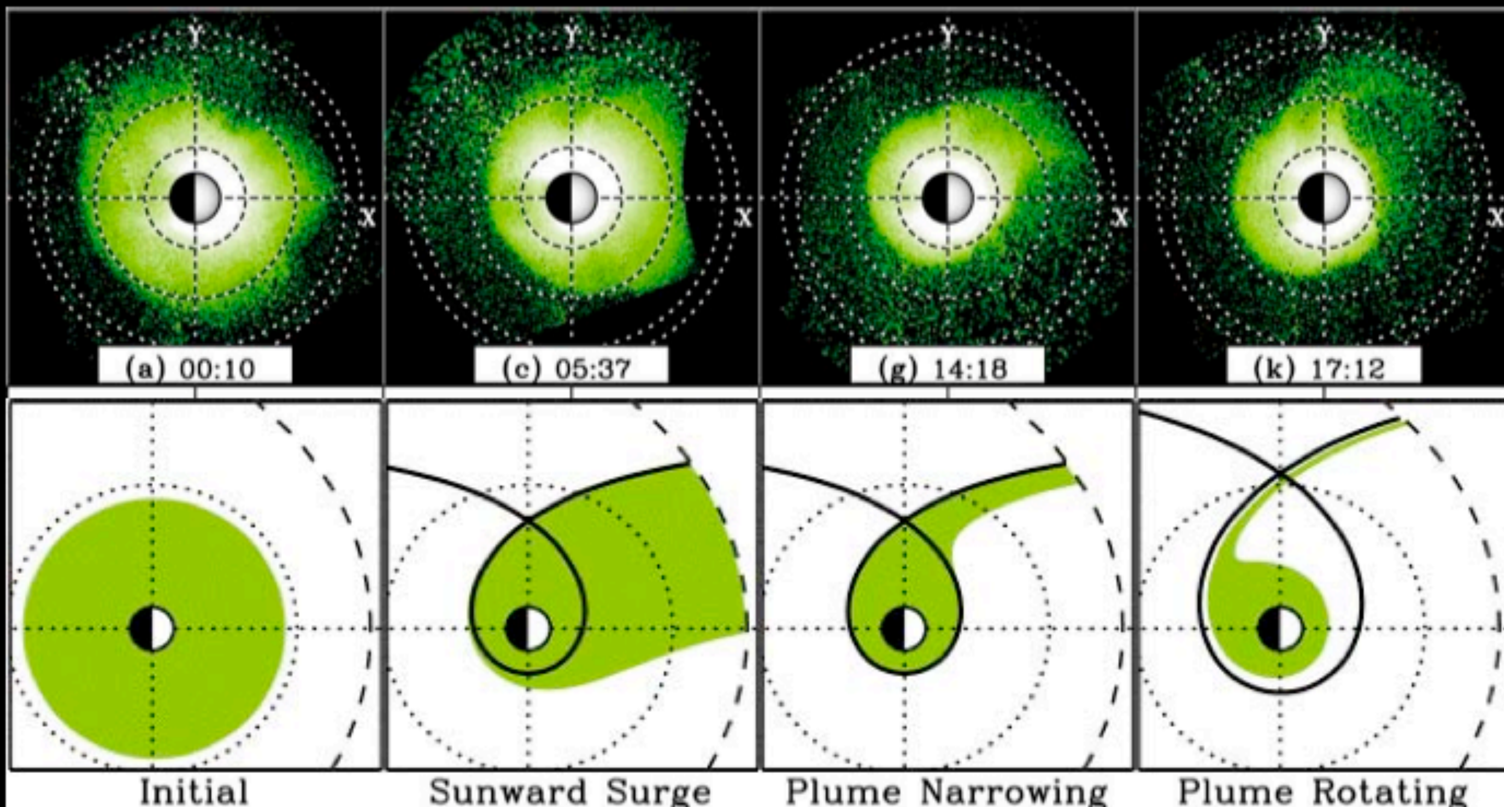


- Cold Particles
- $r > r_0$ Convected to Magnetopause
- $r < r_0$ Trapped
- Bulge is Observed
- Plasmasphere Shrinks when Magnetosphere Active

Plasmasphere Observed



Plasmasphere Erosion, 18 June 2001



Quiet

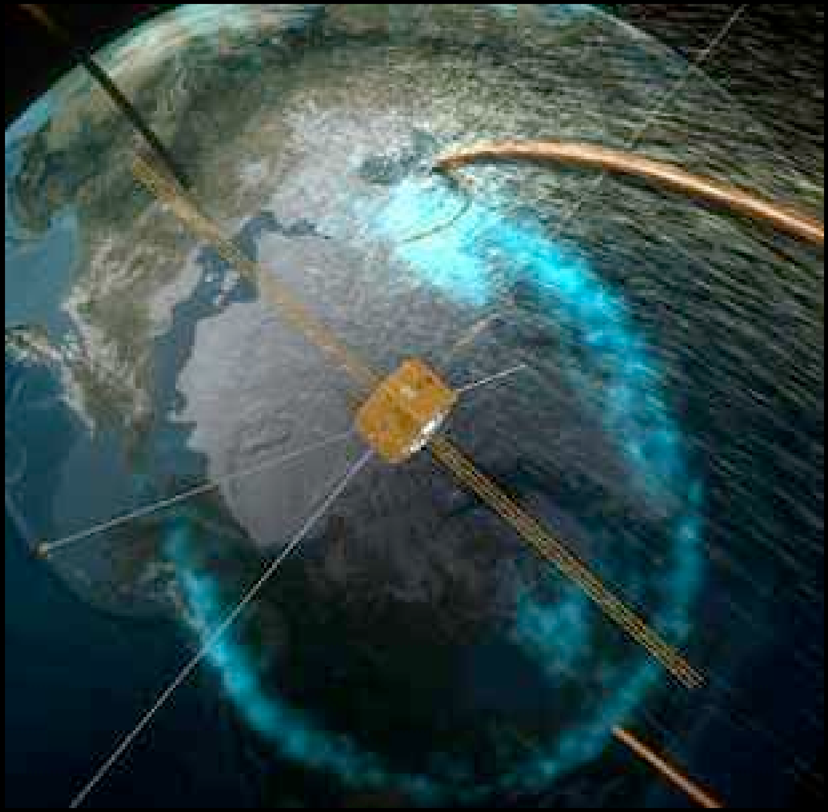
Erosion Onset

Plume Narrowing

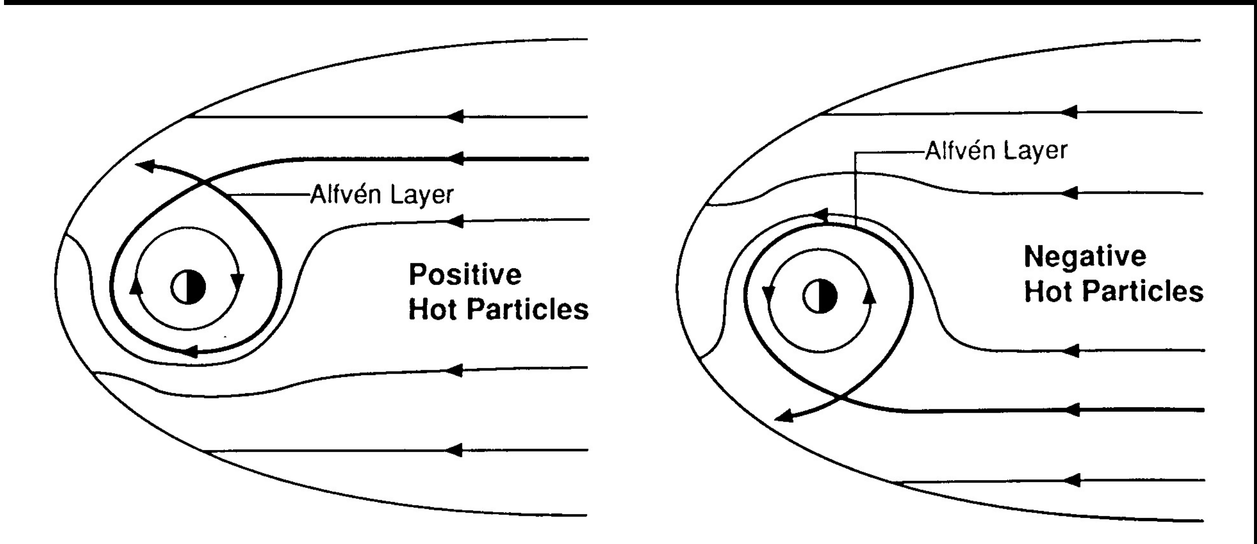
Plume Wrapping

[Goldstein, 2001]

Plasmaspheric Plumes and Aurora



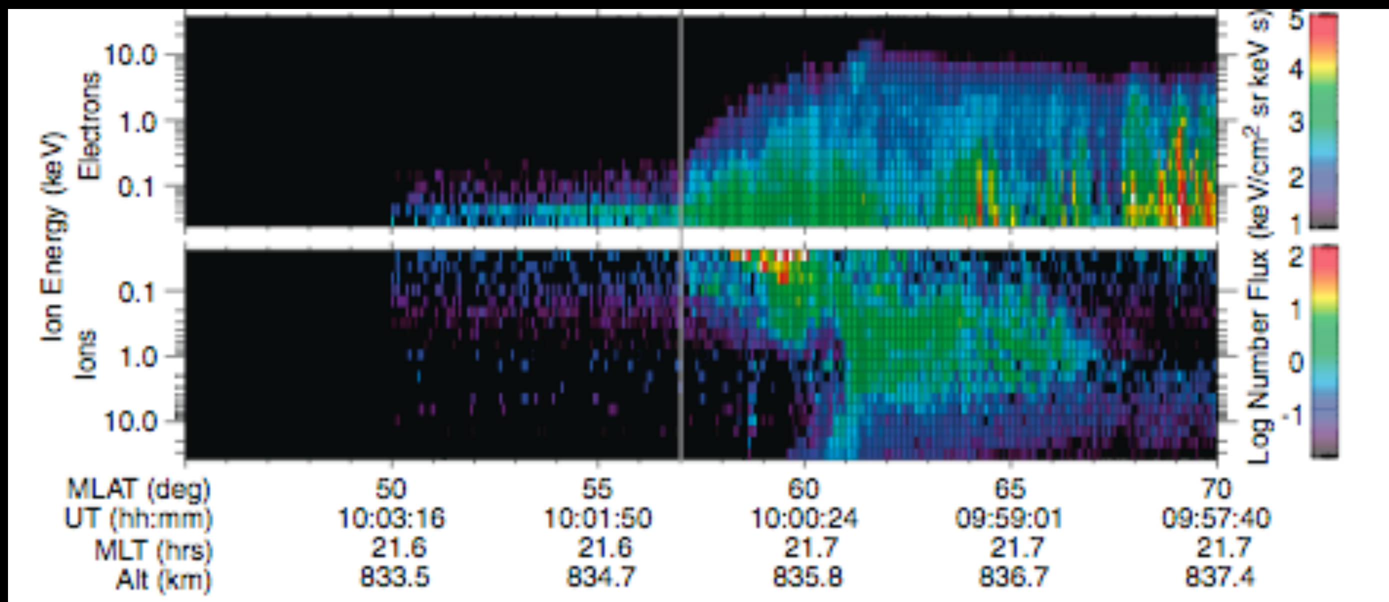
Alfven Layers

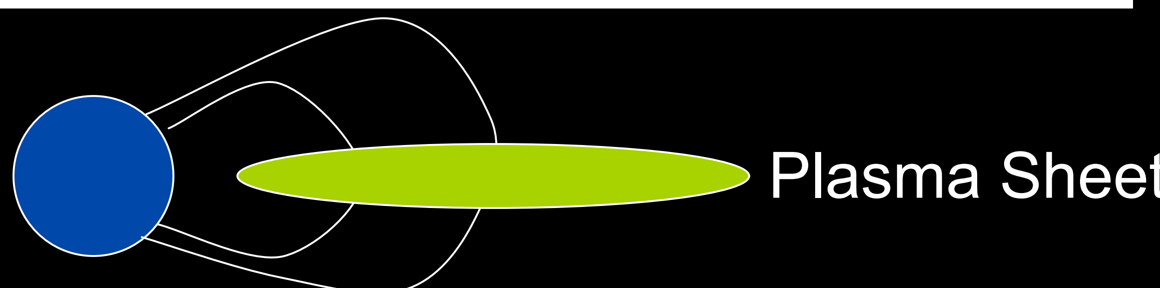


- Hot Particles
- More Energetic Particles drift to MP
- Increased Convection can Inject Energetic Particles where they can be Trapped
- Electron Edge Closer at Dawn, Ions at Dusk

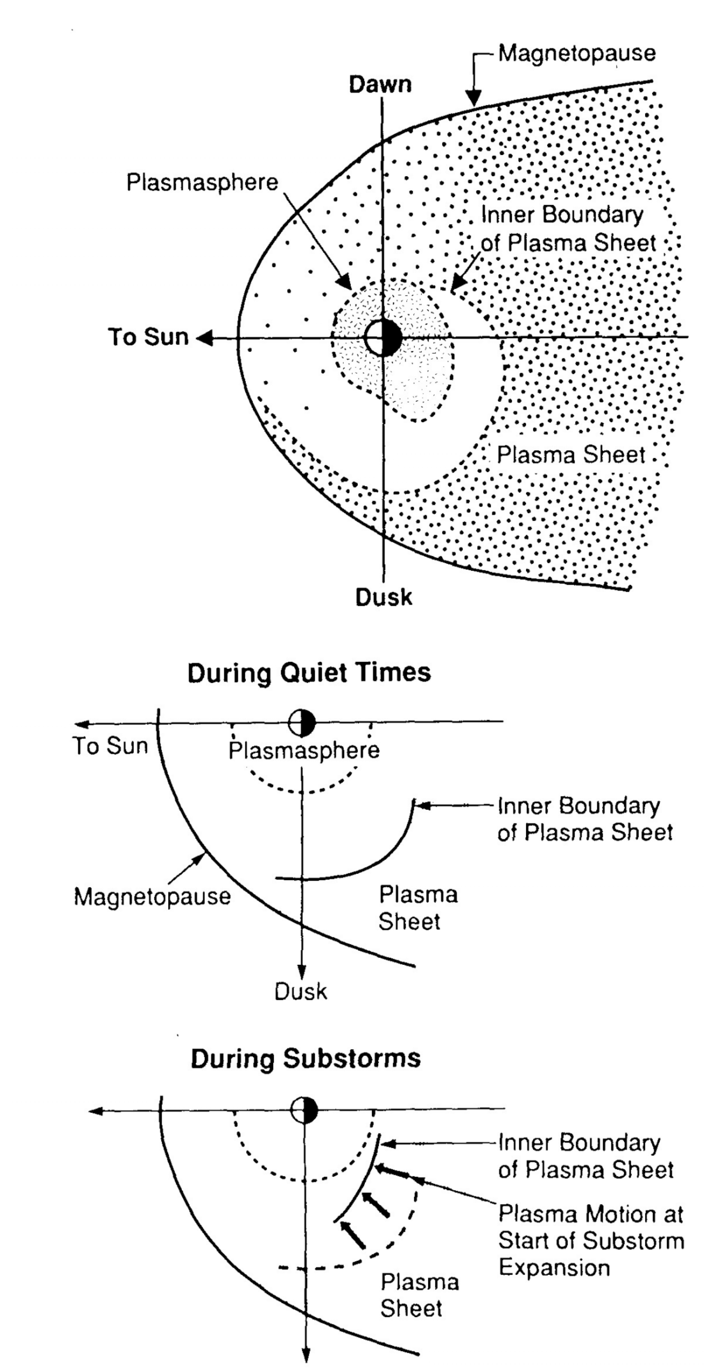
Alfven Layer--energy dependence

Low Latitude High Latitude



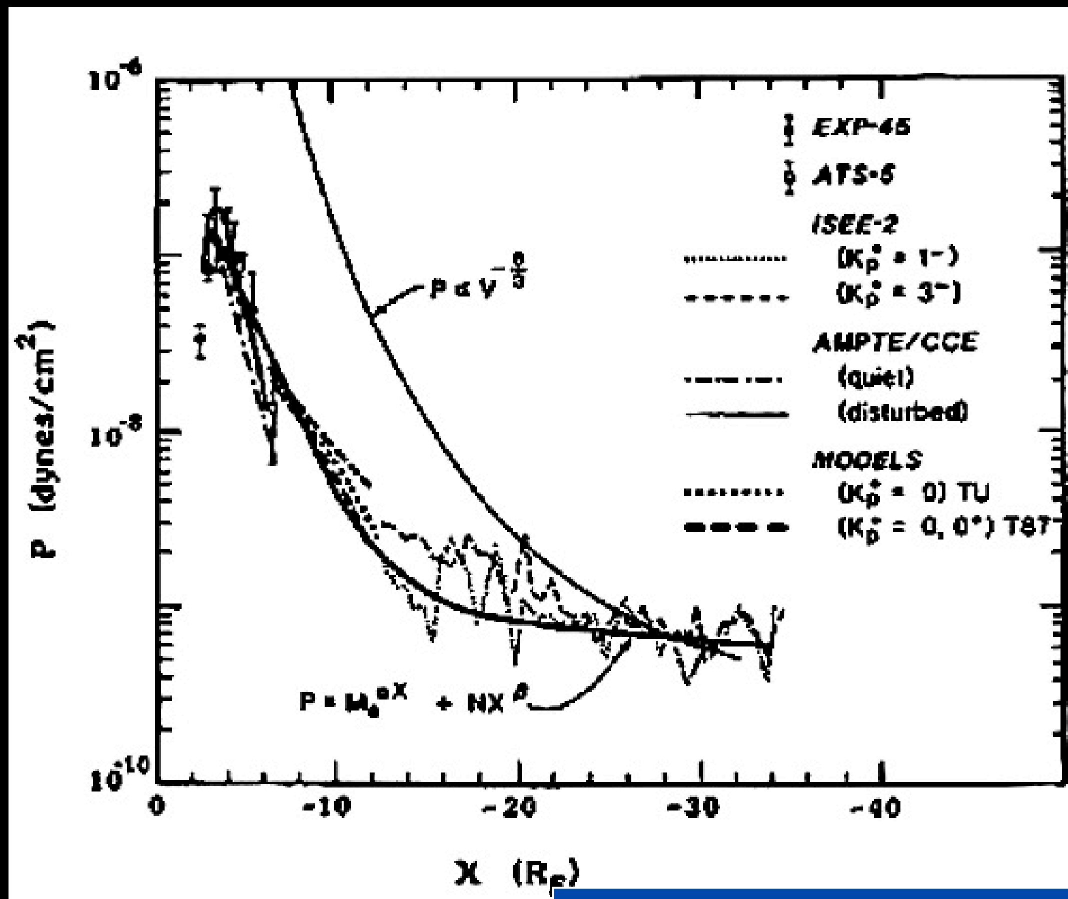


Inner Edge of Plasma Sheet Electrons

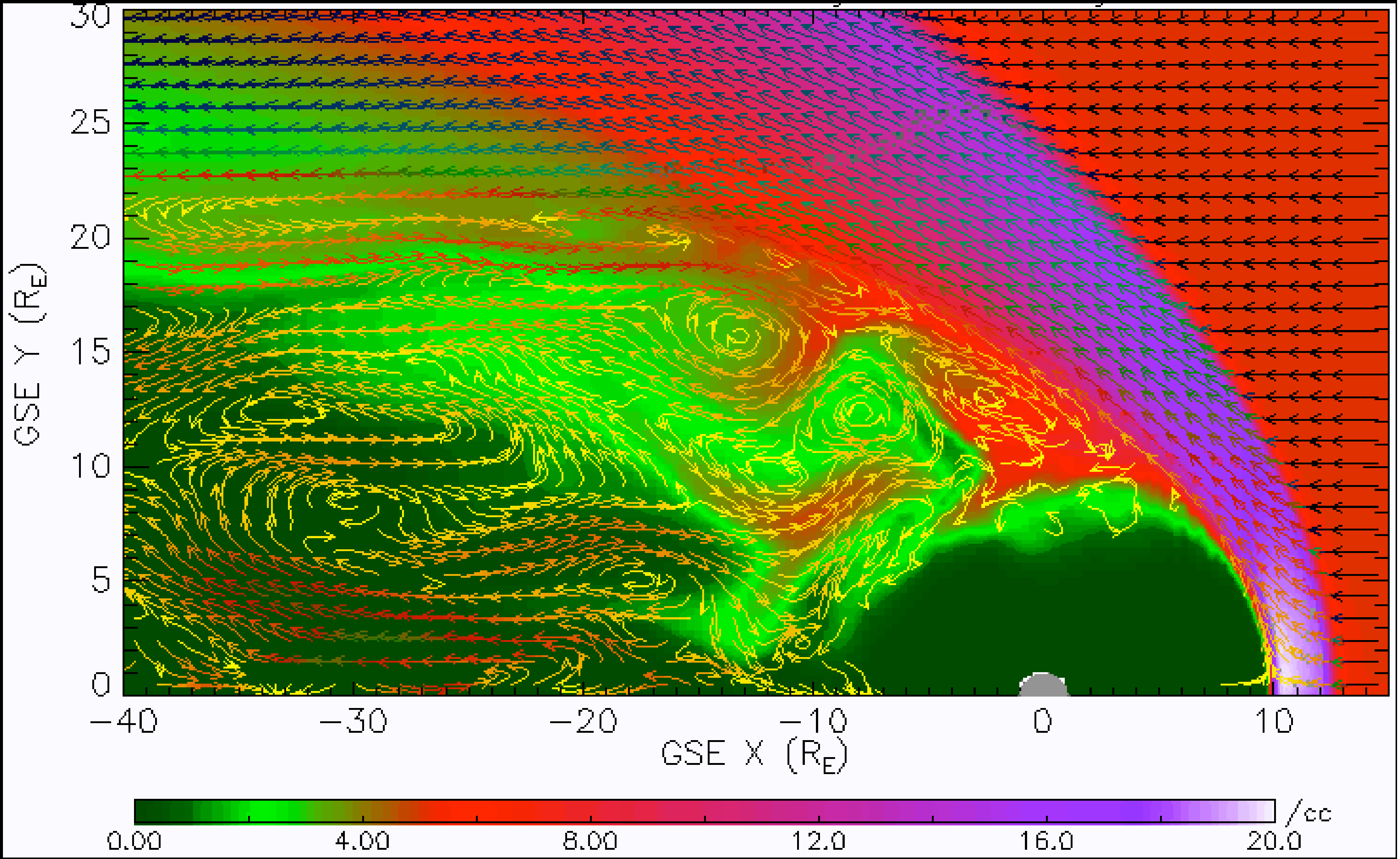


Convection Model and Pressure Crisis

- Losses
  - Kinetic drifts
  - Ionosphere
  - Near Earth Reconnection
  - Bursty Bulk Flows



Garner et al, 2003



Snapshot from ISM simulation of the magnetosphere (courtesy of Bill White [2001]).

Inferring Plasma Sheet Properties

Based on:

•Isotropy of pdf

(observed >8-10 R_E)

[Kistler et al., 1992; Spence et al., 1989; Huang and Frank, 1994]

(Theory: PAS $\rho_i > R_C/8$)

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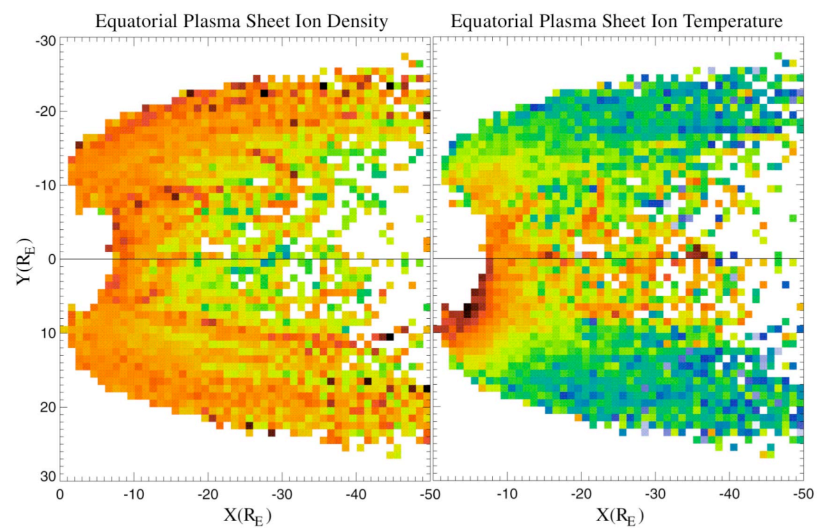
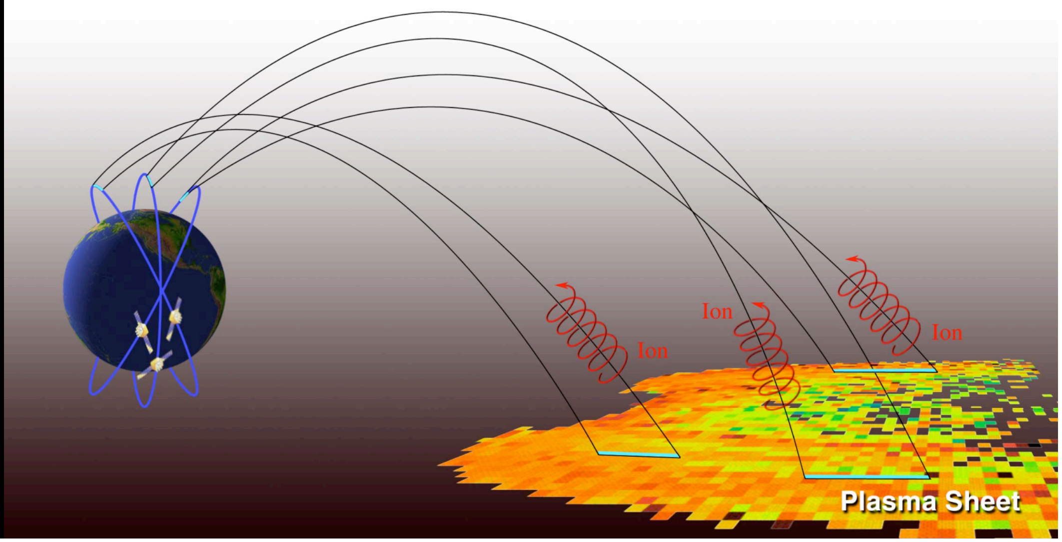
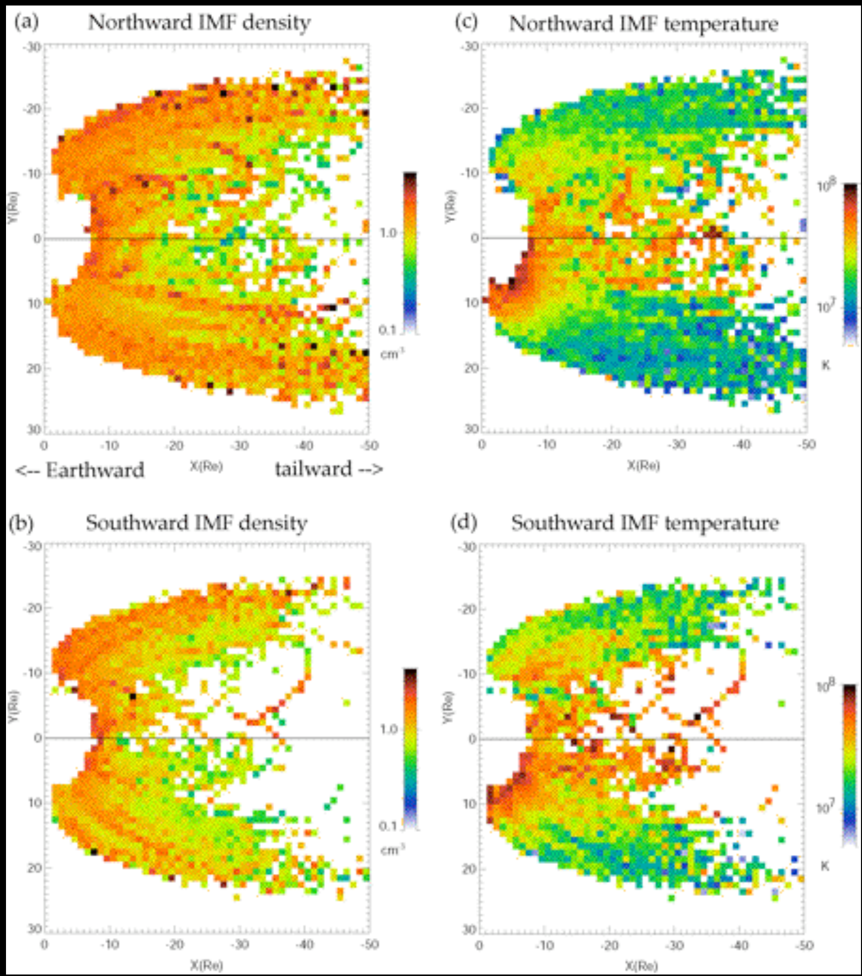




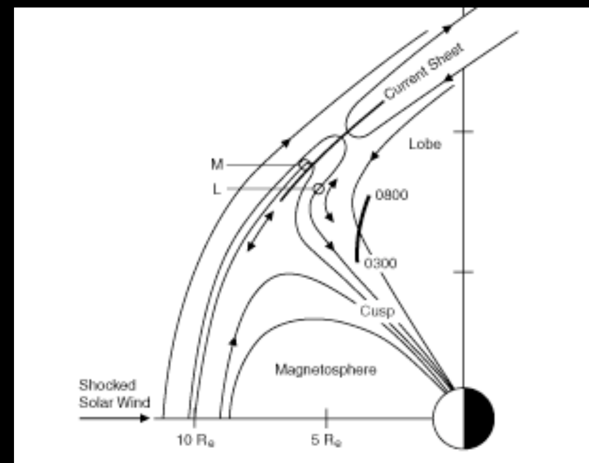
Plasma Entry

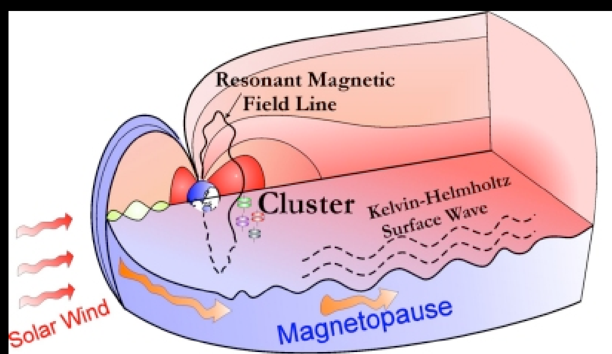
- Northward IMF
- Plasma Sheet
  - Colder
  - Denser

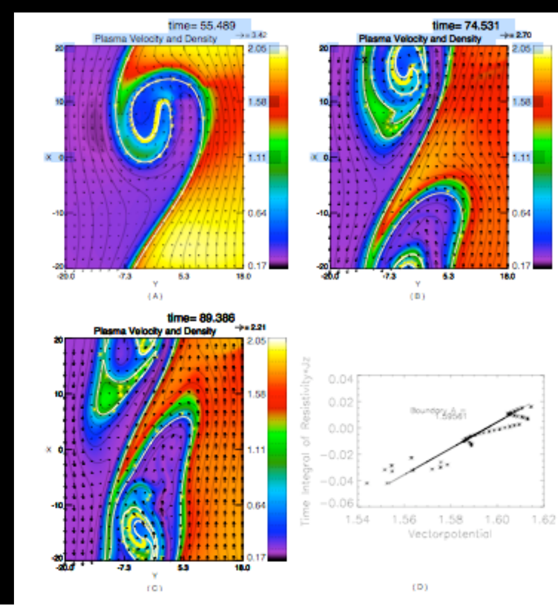


Plasma Entry

- Cusp Reconnection
- Wave induced entry







Dynamical Issues

- Storms
- Substorms
- Aurora
- Space Weather

Magnetospheric Dynamics

- Storms (1-5 days) (Dst)
  - Associated with Intense Solar Disturbances
  - Initial Phase (increase of B)
    - Compression
    - 0-25 hours
  - Main Phase (decrease of B)
    - Growth of Ring Current
    - 1 day
  - Recovery Phase (gradual increase of B)
    - Dipolarize
    - many days
- Substorms (AU,AL)
  - Associated with Earth's Response to Local Conditions
  - Growth Phase (30 min)
    - Storage of Solar Wind Energy
  - Expansion Phase (20 min)
    - Sudden Release of Magnetic Energy
    - Current Disruption
  - Recovery Phase (hours)
    - Return of Magnetosphere to Original Condition

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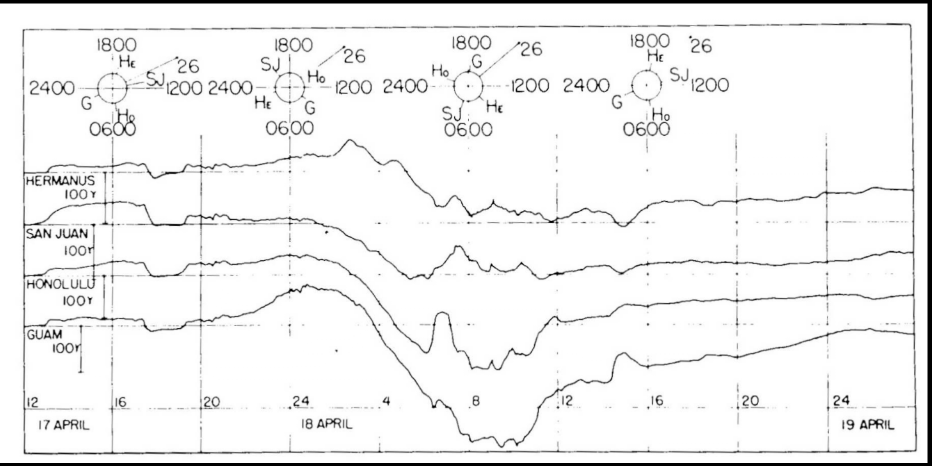


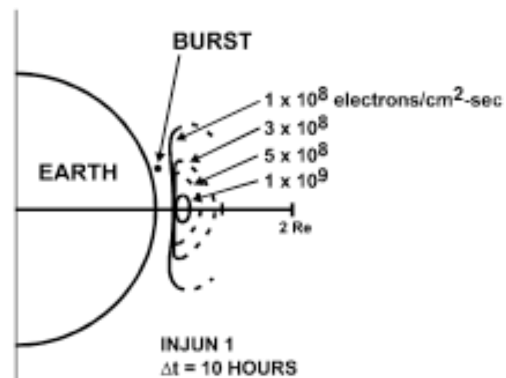
Critical Storm Issues

- Predictability of energetic particle fluxes

Hazard of Trapped Radiation Belts

- Electrical and electronic components of spacecraft are vulnerable to —
  - Spacecraft charging and resultant discharge;
  - Deep dielectric charging and resultant discharge;
  - Electronic effects (single event upset; noise spikes);
  - Cumulative radiation damage.

- Vulnerabilities well documented, e.g.,
  - Loss of Ariel, Traac, Transit 4B, Cosmos V, Injun I following Starfish nuclear detonation on July 9, 1962.
  - Loss of various commercial satellites to effects from natural radiation belts (e.g., Telstar 401 in January 1997).
  - Permanent damage and performance degradation to radiation-hardened military satellite.

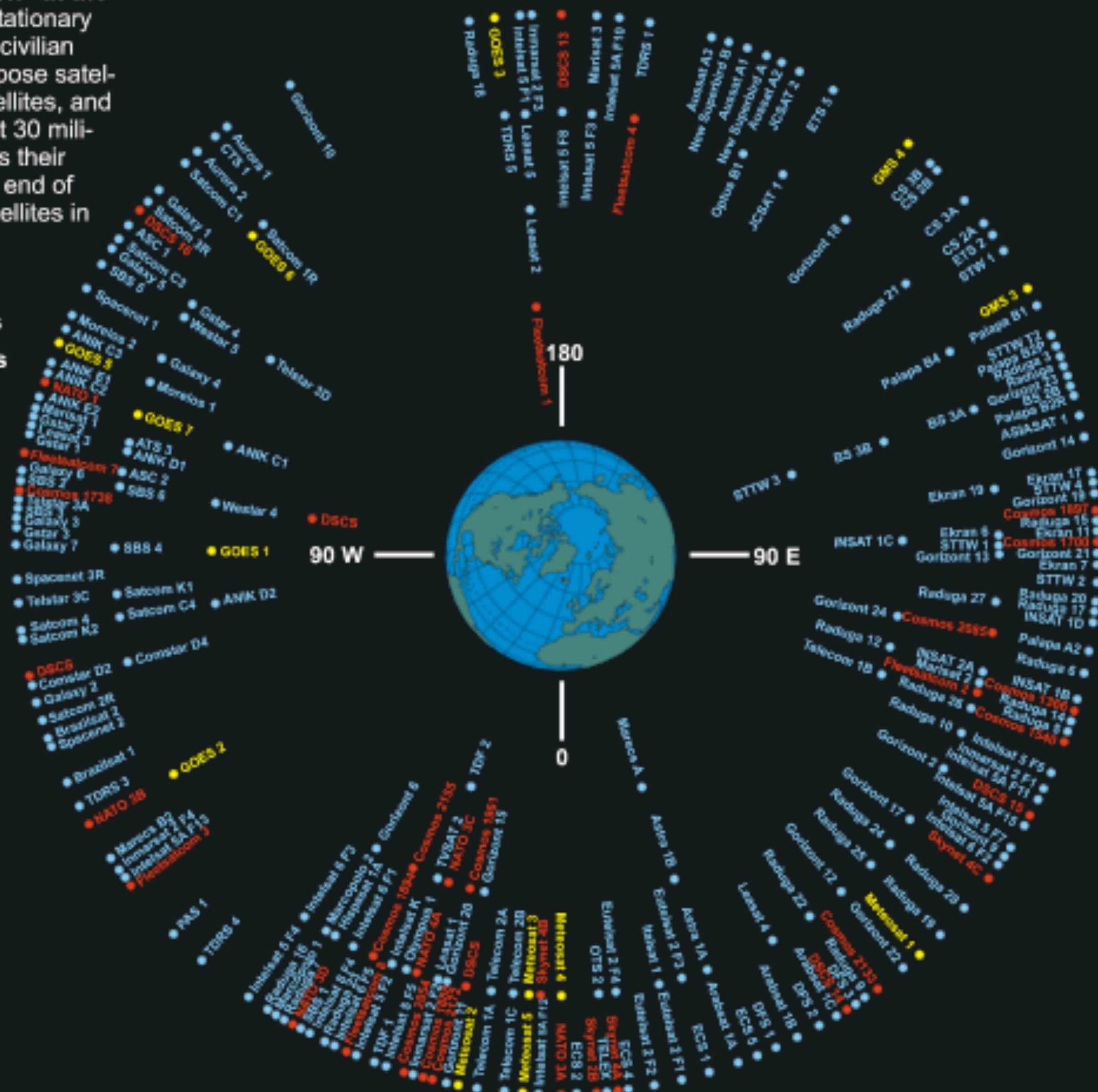


Flux contours 10 hours after Starfish, as determined from INJUN 1 data.

Assets at Risk: Geosynchronous Satellites

The geostationary "population" at the end of 1996. Of the 249 geostationary satellites shown here, 199 are civilian communications and multi-purpose satellites. 13 are meteorlogical satellites, and 37 are military satellites. About 30 military satellites are not shown, as their positions are classified. At the end of 1996 there were about 280 satellites in the geostationary ring.

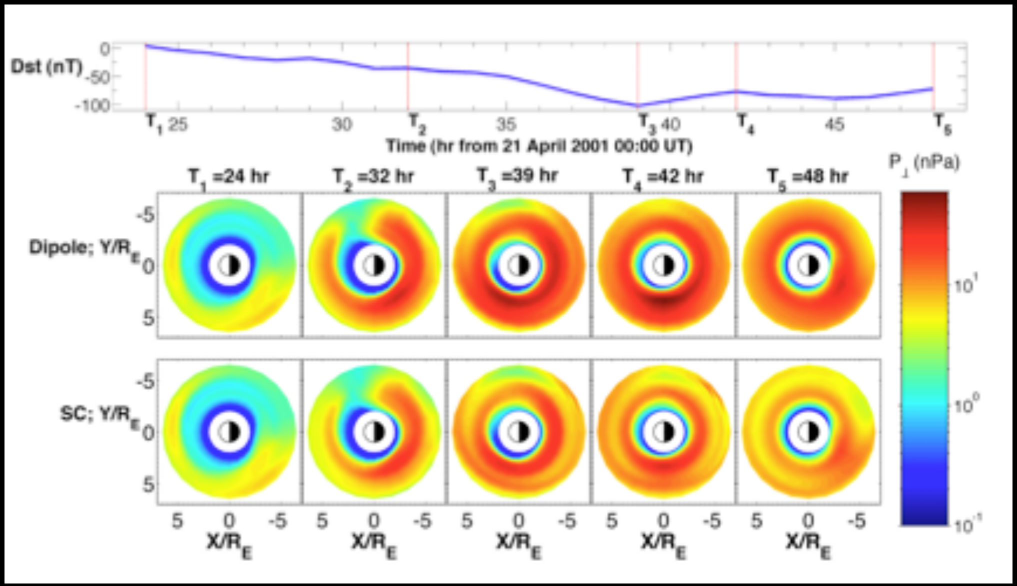
- Meteorological Satellites
- Civilian Communications Satellites
- Military Satellites



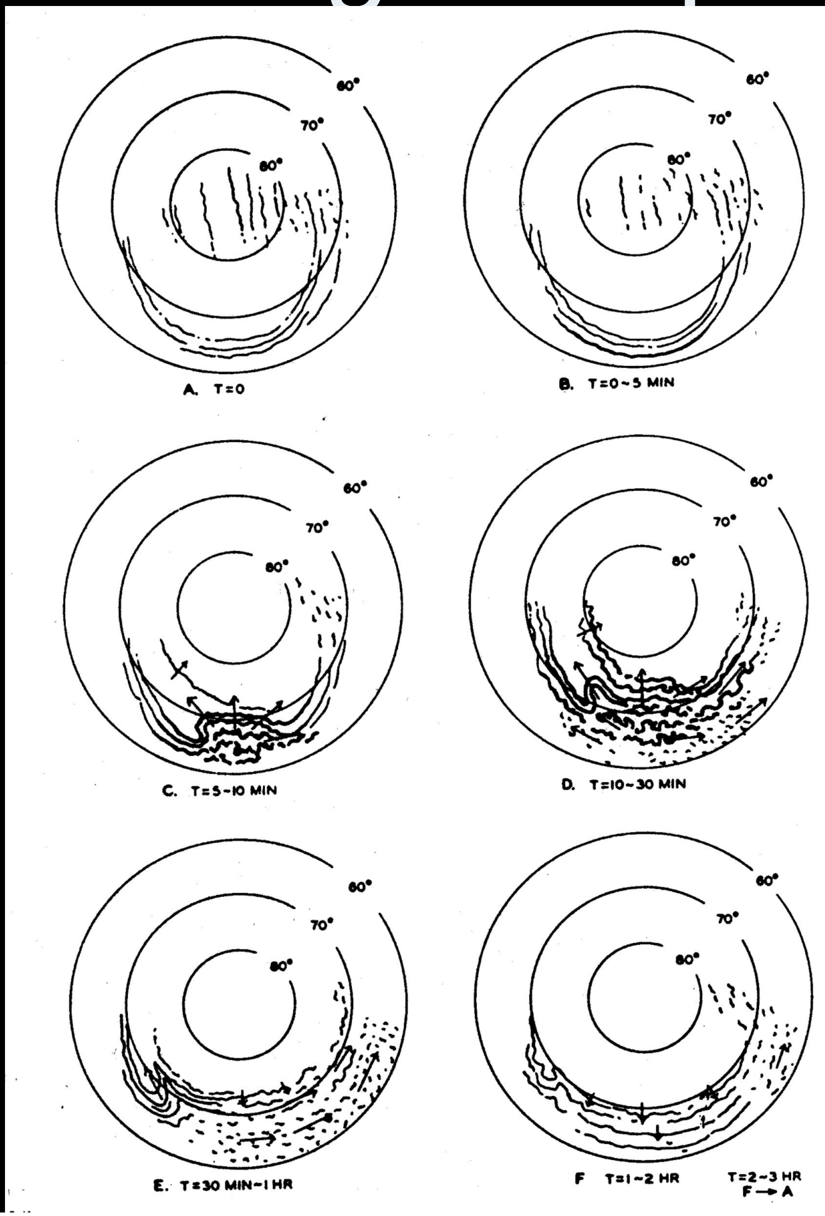
Critical Storm Issues

- Inner magnetosphere models
  - Plasma injections
  - Loss mechanisms (wave-particle, precipitation)
  - Self-consistency

[Zaharia et al., 2006]



Magnetospheric Dynamics



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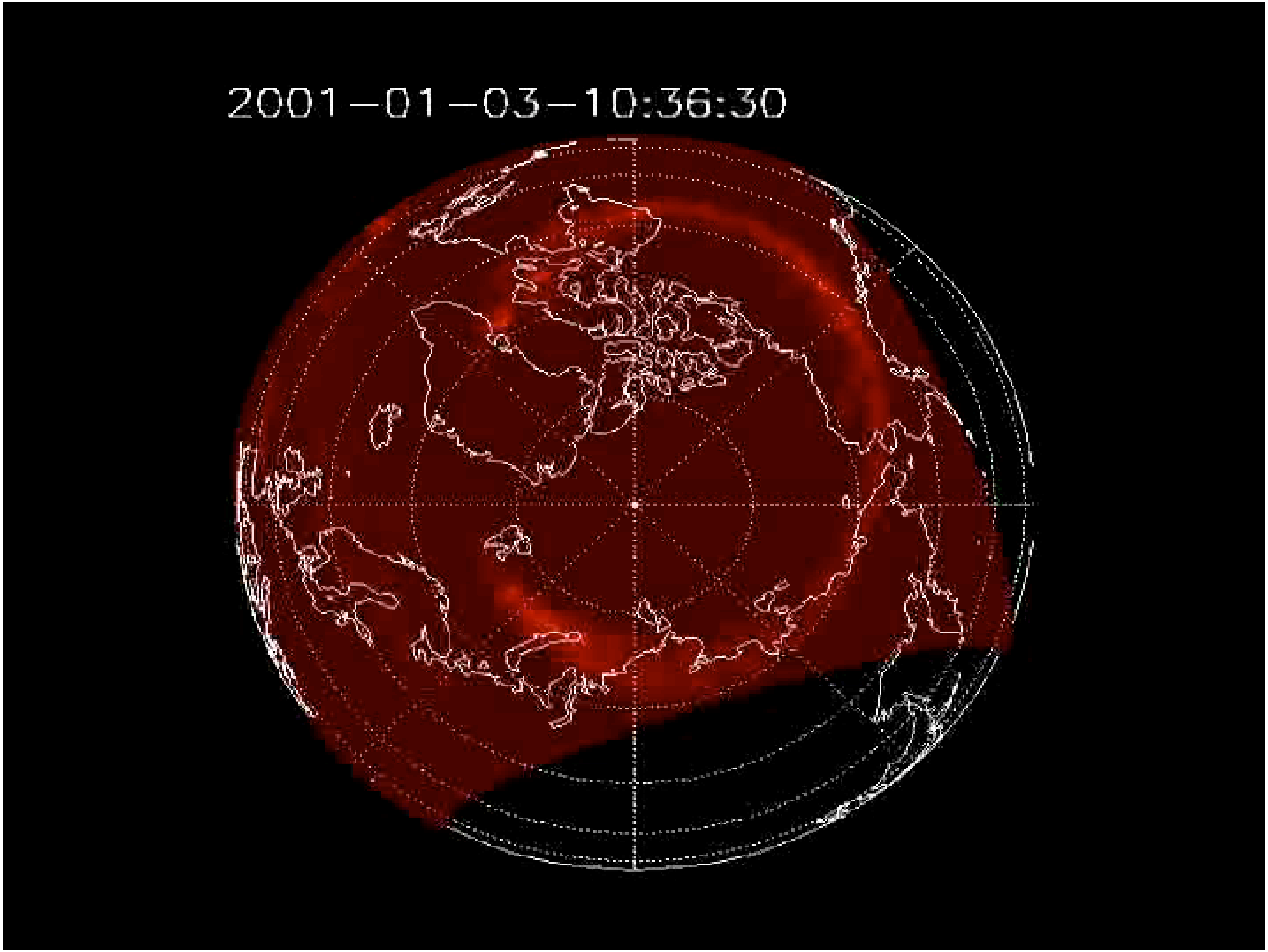
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Based on:

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(observed >8-10 R_E)

[Kistler et al., 1992; Spence et al., 1989; Huang and Frank, 1994]

(Theory: PAS $\rho_i > R_C/8$)

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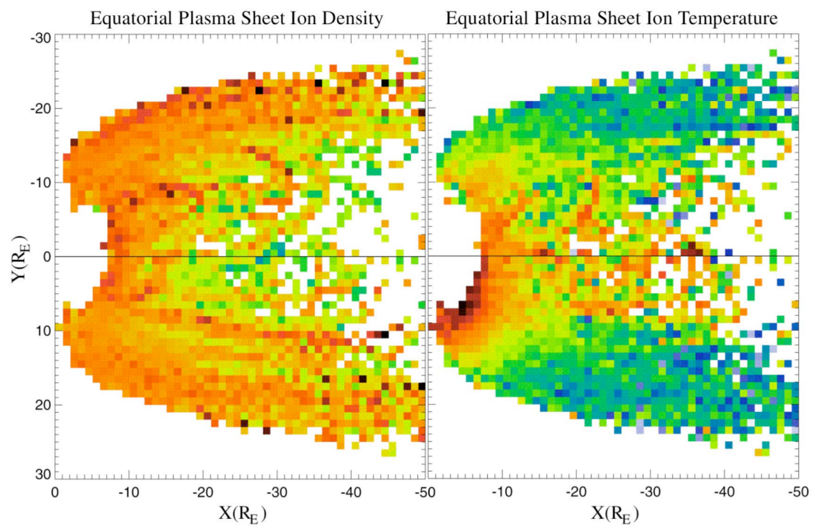
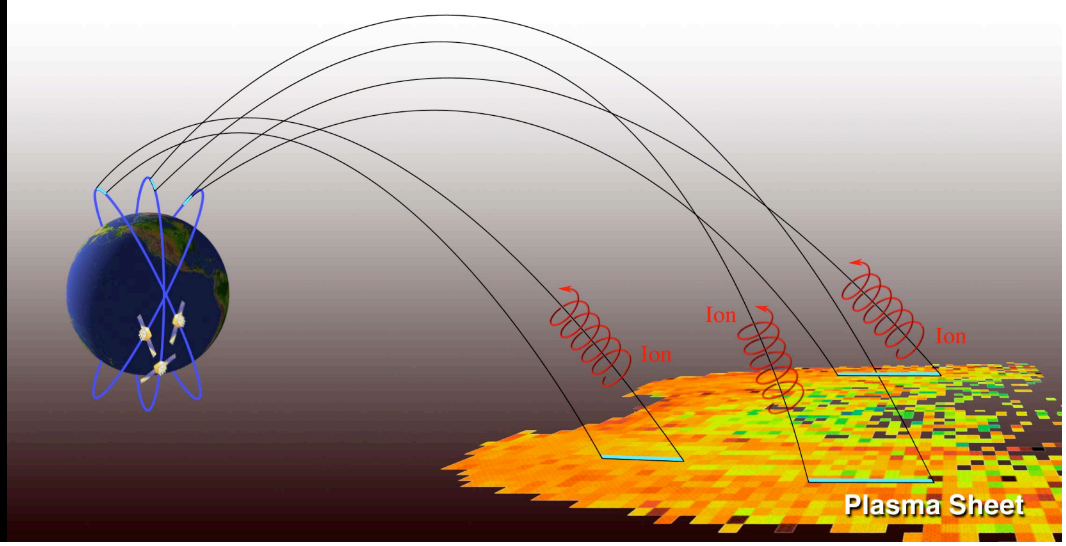
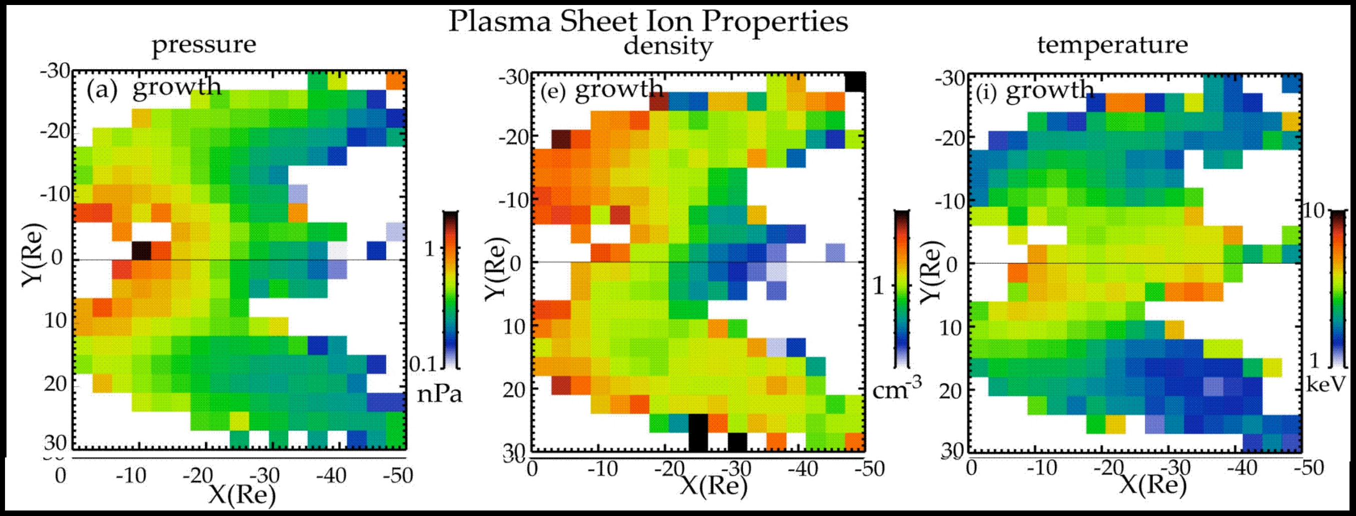




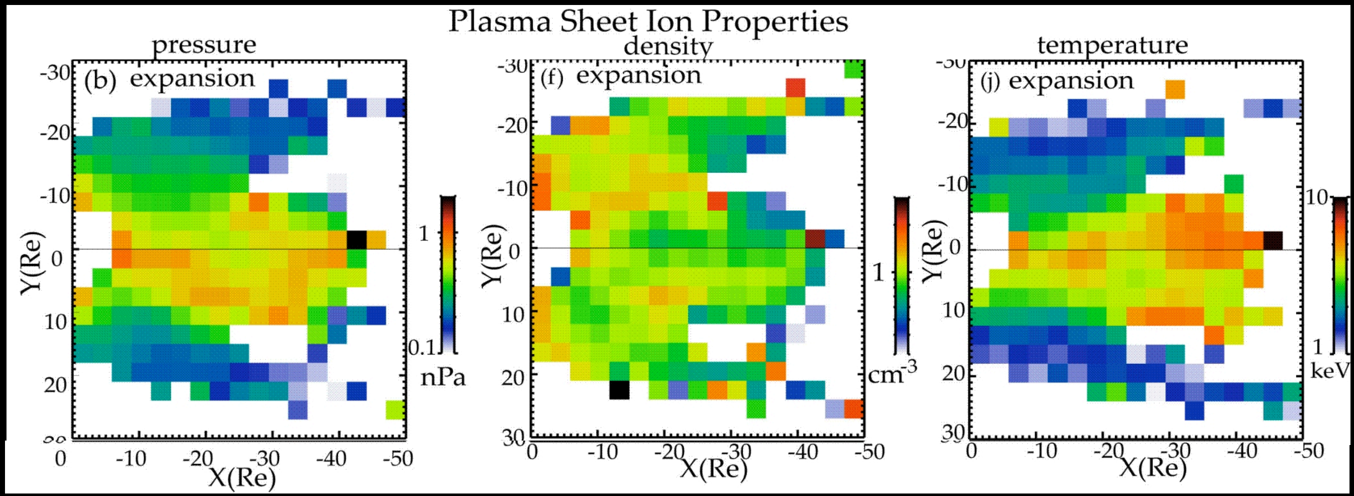
Substorm Analysis: Statistical Profiles



Growth Phase

- The pressure peaks nearly symmetrically at all local times at the inner edge of the plasma sheet;
- The premidnight pressure peak at is associated with enhanced temperatures whereas the postmidnight peak is associated with enhanced densities. This is in agreement with Spence and Kivelson [1983], Wing and Newell [1998], Friedel et al. [2001], Wang et al. [2004]

Substorm Analysis: Statistical Profiles

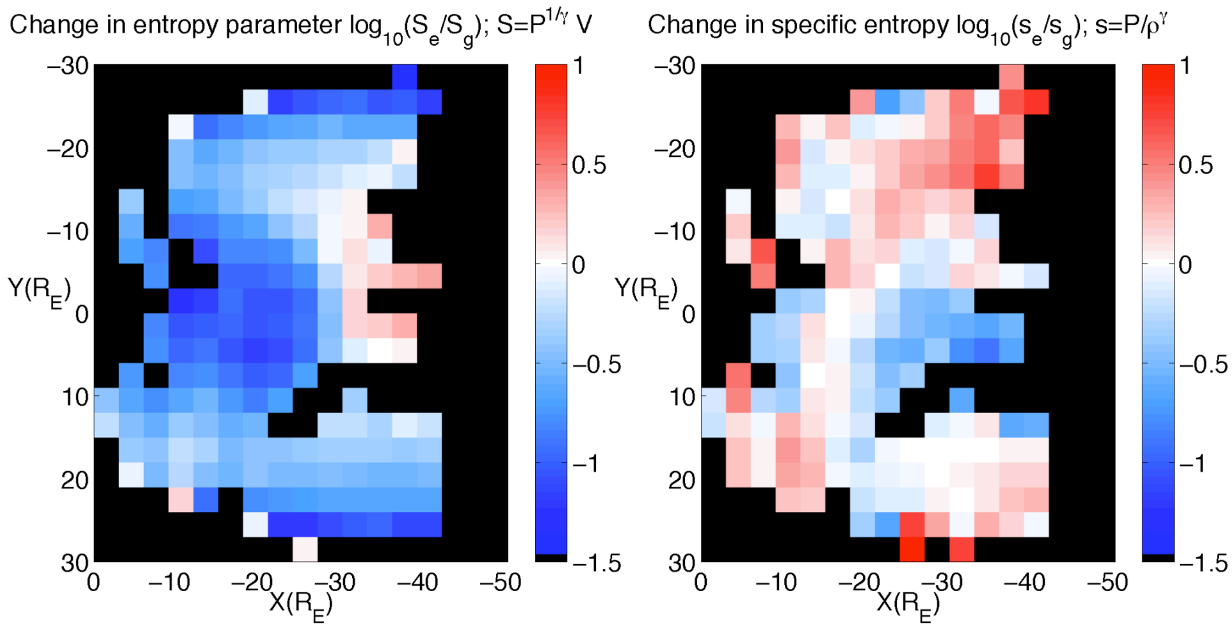


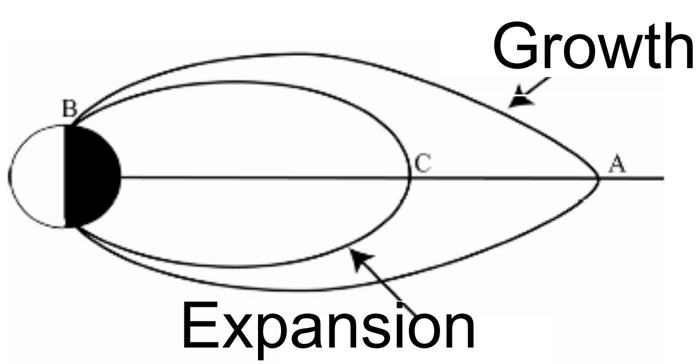
Expansion Phase

- Compared to the growth phase values at premidnight, the pressure diminishes at the inner edge, but the pressure peaks at premidnight (X∈[-10,-40] R*E*, Y∈ [0,10] R*E*), which is primarily associated with a temperature enhancement;

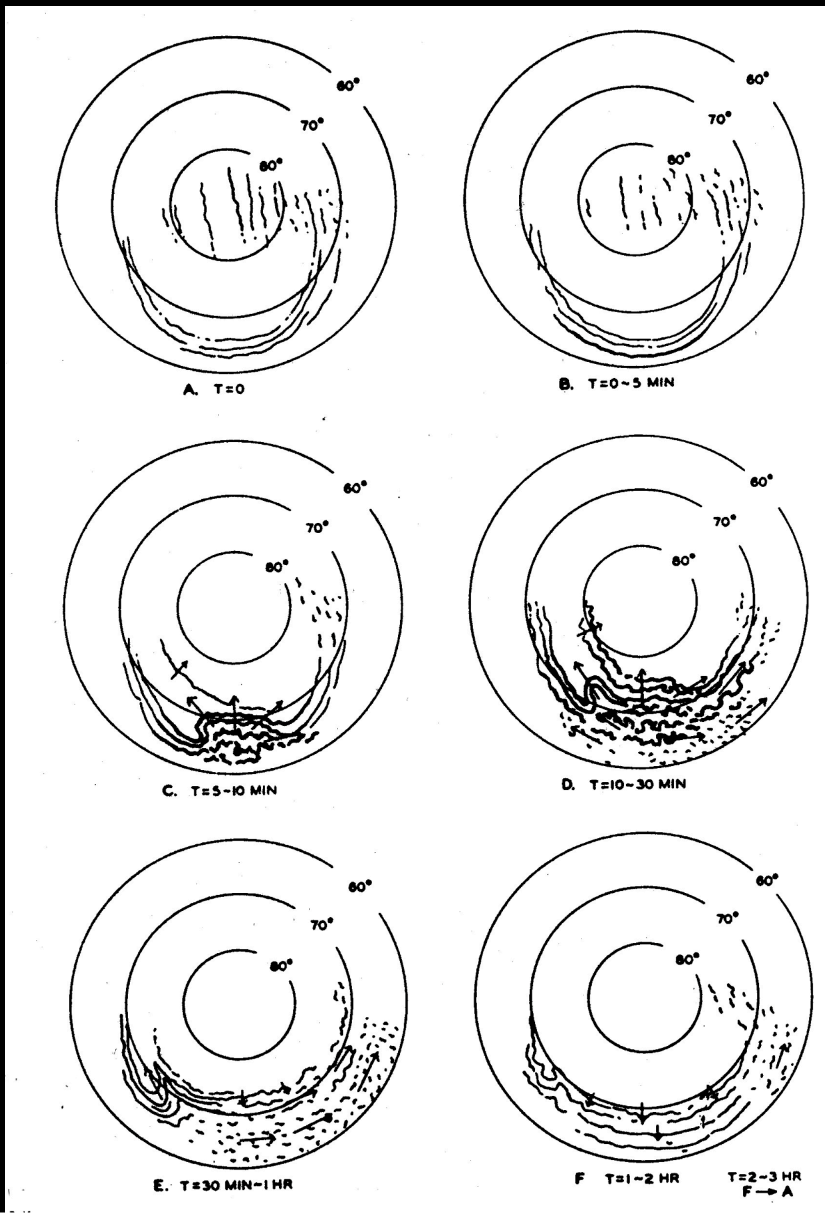
- Near midnight meridian, at the inner edge, the density decreases, while at the mid-tail region, the density increases from values at the growth phase.

Entropy Convervation (growth → expansion)



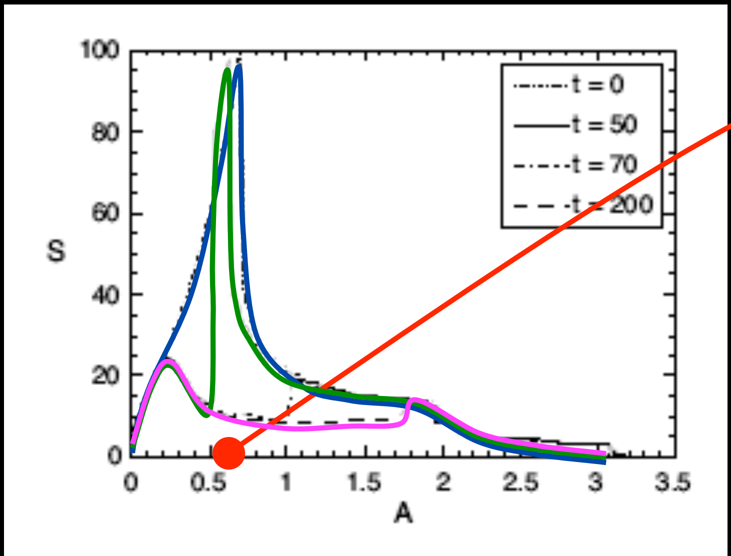


Outstanding Substorm Issue



- How is entropy/plasma content lost?
- Model 1: Near Earth ($9R_E$) Due to Instability Associated with Current Disruption
- Model 2: Tail Reconnection (Near Earth Neutral Line)

Entropy Loss due to Plasmoid



[Birn et al., 2006]

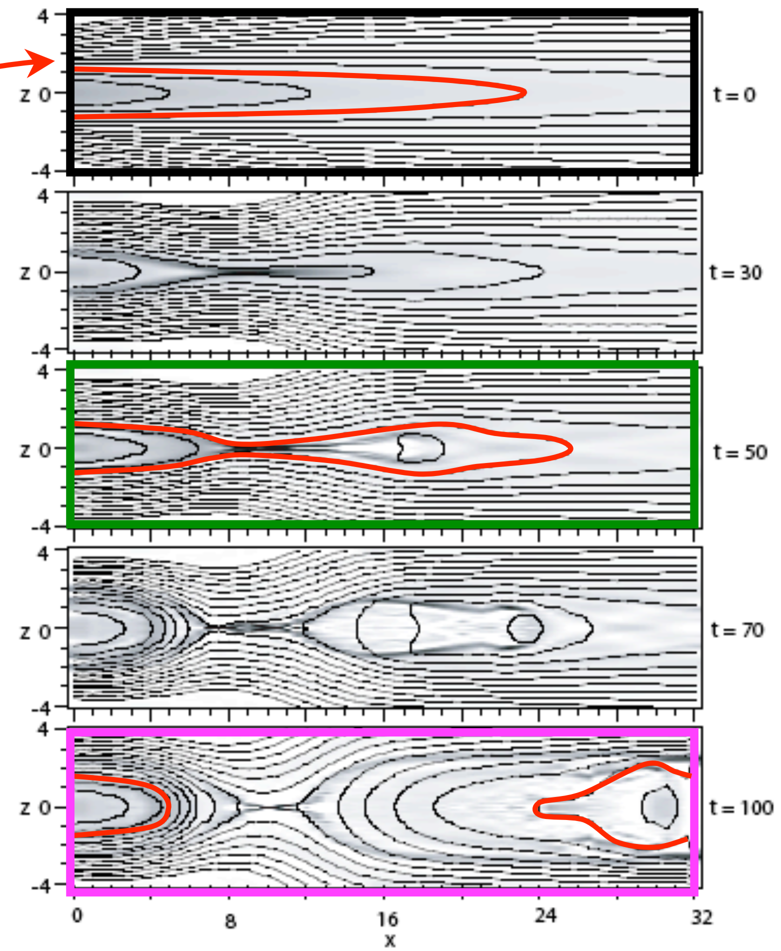
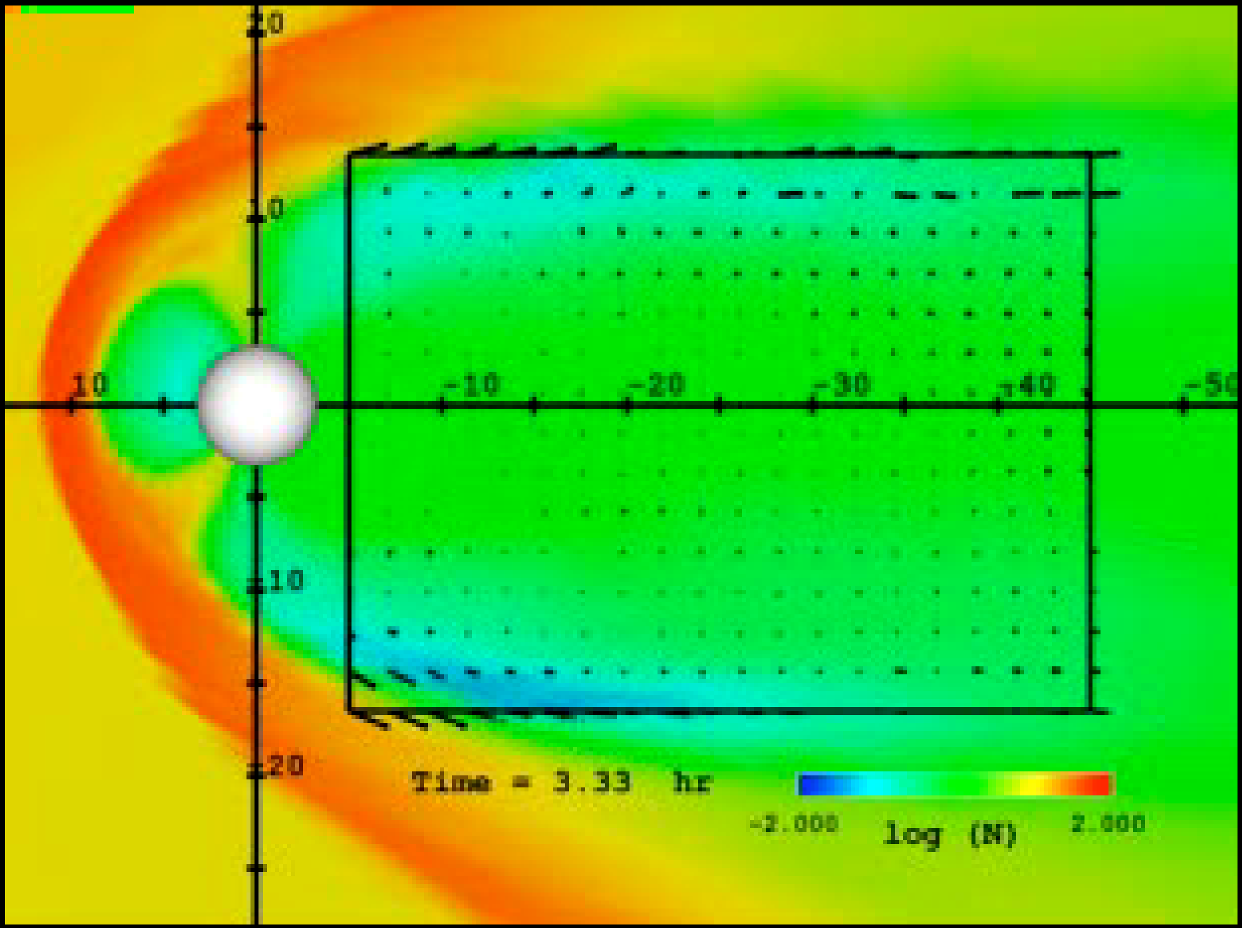
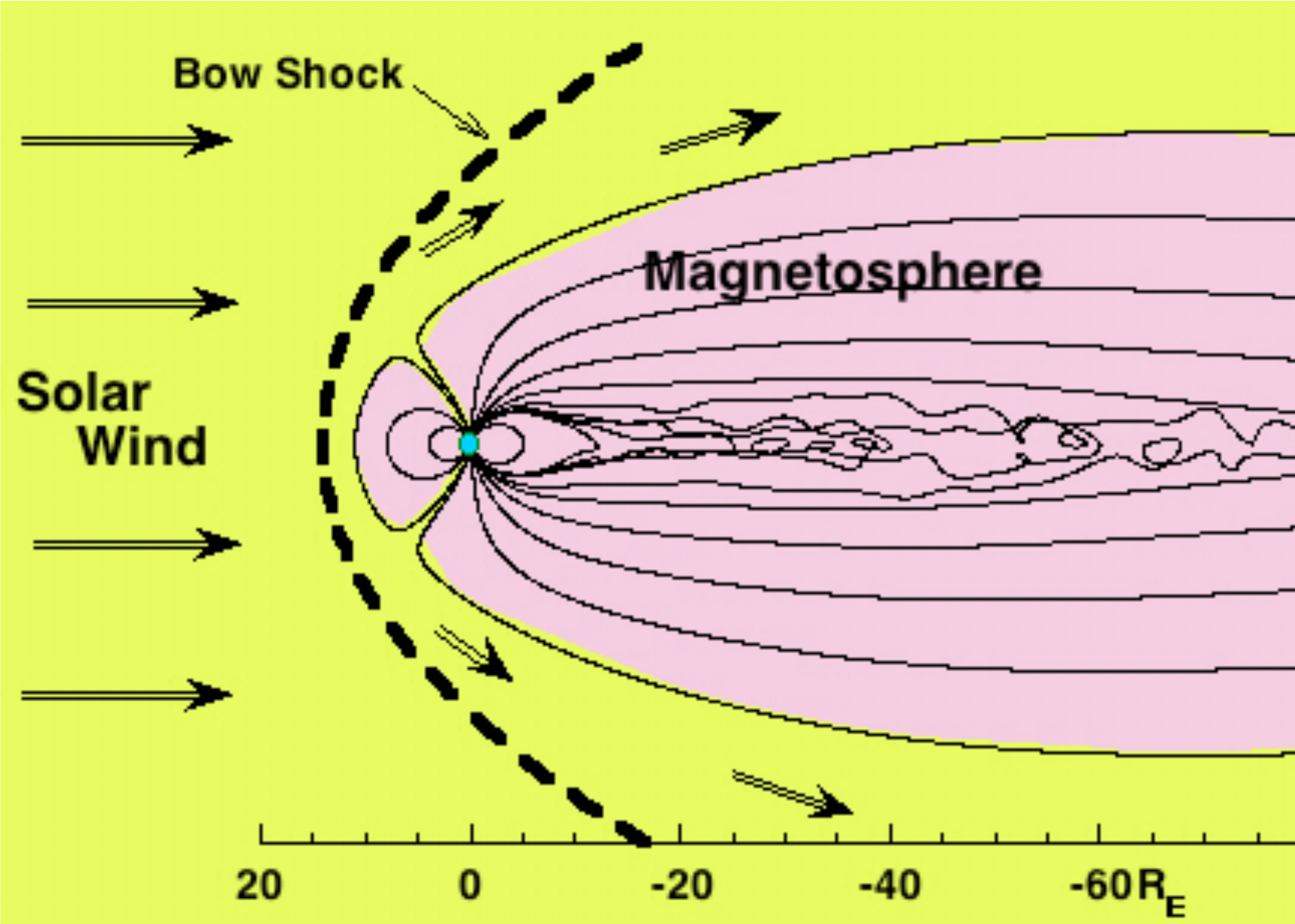


Fig. 2. MHD simulation of thin current sheet formation and plasmoid ejection in the tail, resulting from boundary deformation in the near tail. The gray scale indicates the current density.

Global MHD Simulation

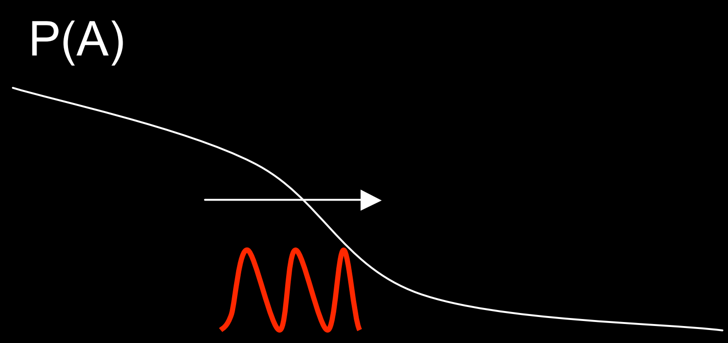




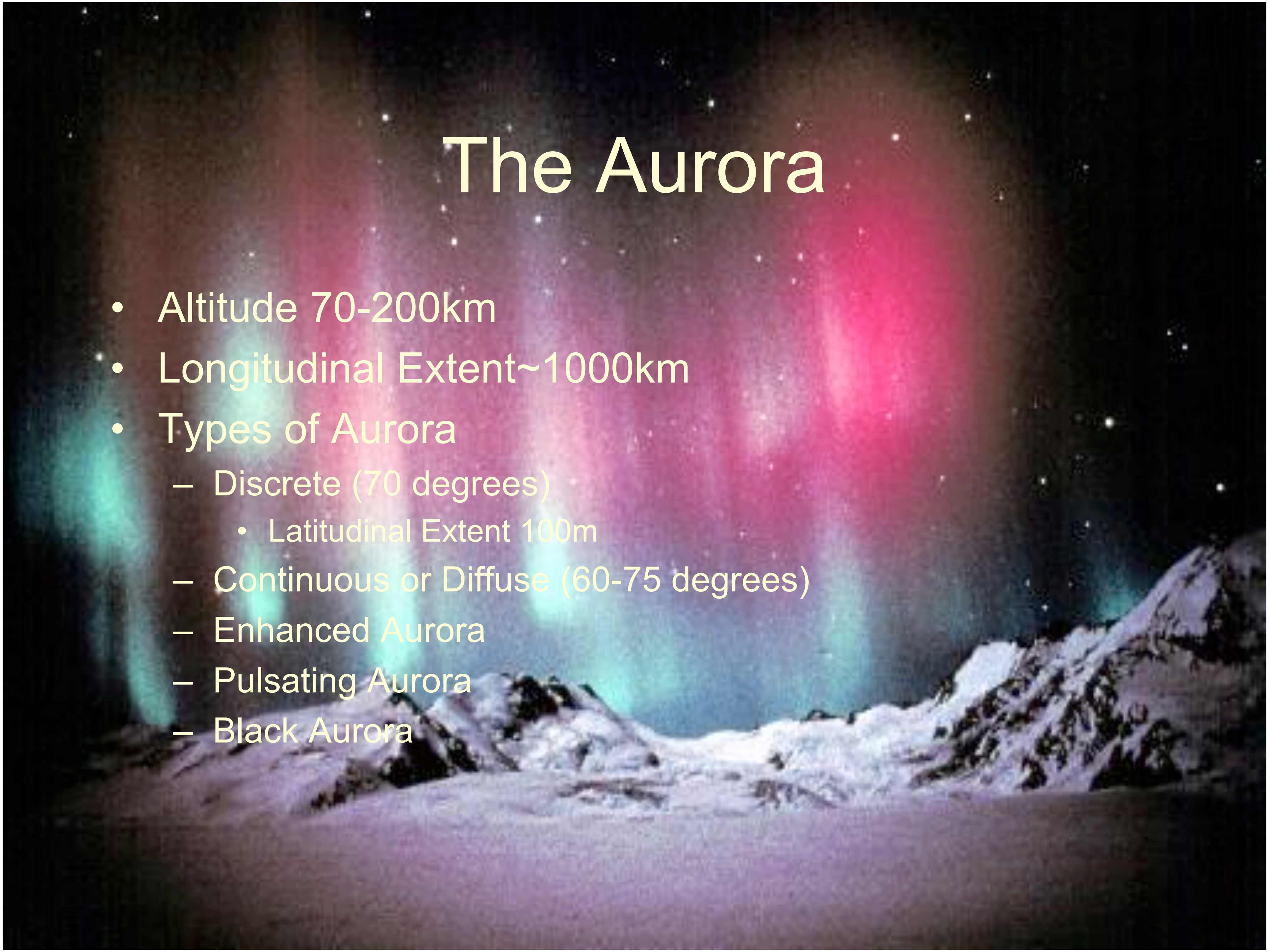
T96 magnetic-field model with noise added in. Noise has same statistics (amplitude and correlation length as that measured by ISEE-2).

Entropy Loss via WPI

- Mass diffusion results from wave particle interaction
- Leads to reduction of entropy and dipolarization
- Could explain S↓, but s~const?
- Dawn-dusk asymmetry in P/ρ^{γ}?



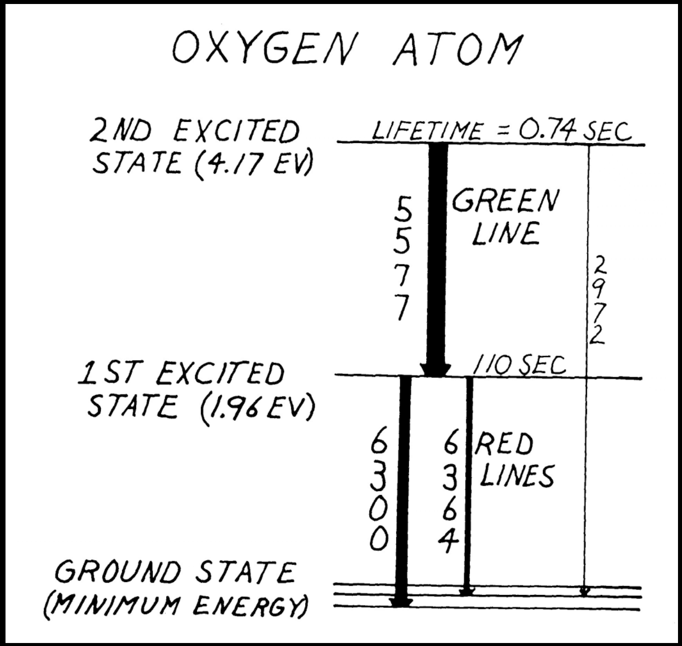
$\delta B/B = -\beta\ \delta P/P$



The Aurora

- Altitude 70-200km
- Longitudinal Extent~1000km
- Types of Aurora
  – Discrete (70 degrees)
    - Latitudinal Extent 100m
  – Continuous or Diffuse (60-75 degrees)
  – Enhanced Aurora
  – Pulsating Aurora
  – Black Aurora

Auroral Colors and Altitude



- At 200 km collision rate is low > Red Aurora
- Blood Red Aurora Occurs when Electron Beam Energy < 500eV

Auroral Colors and Altitude

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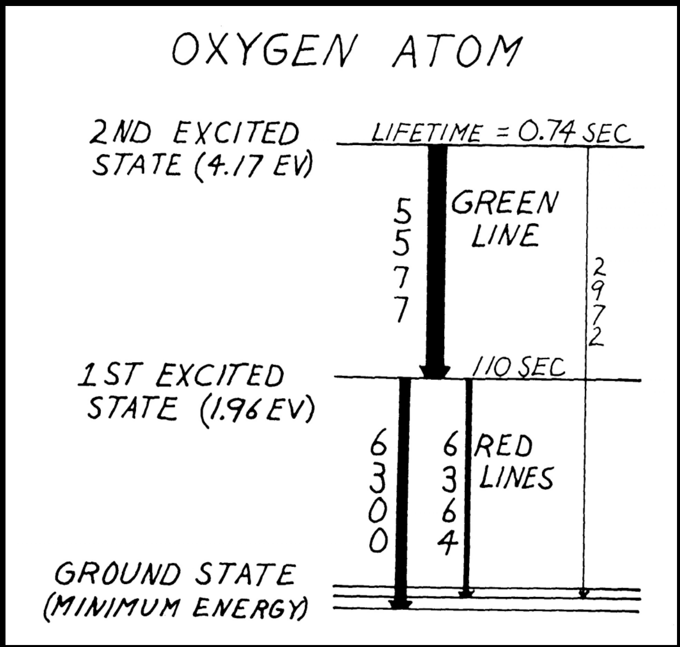
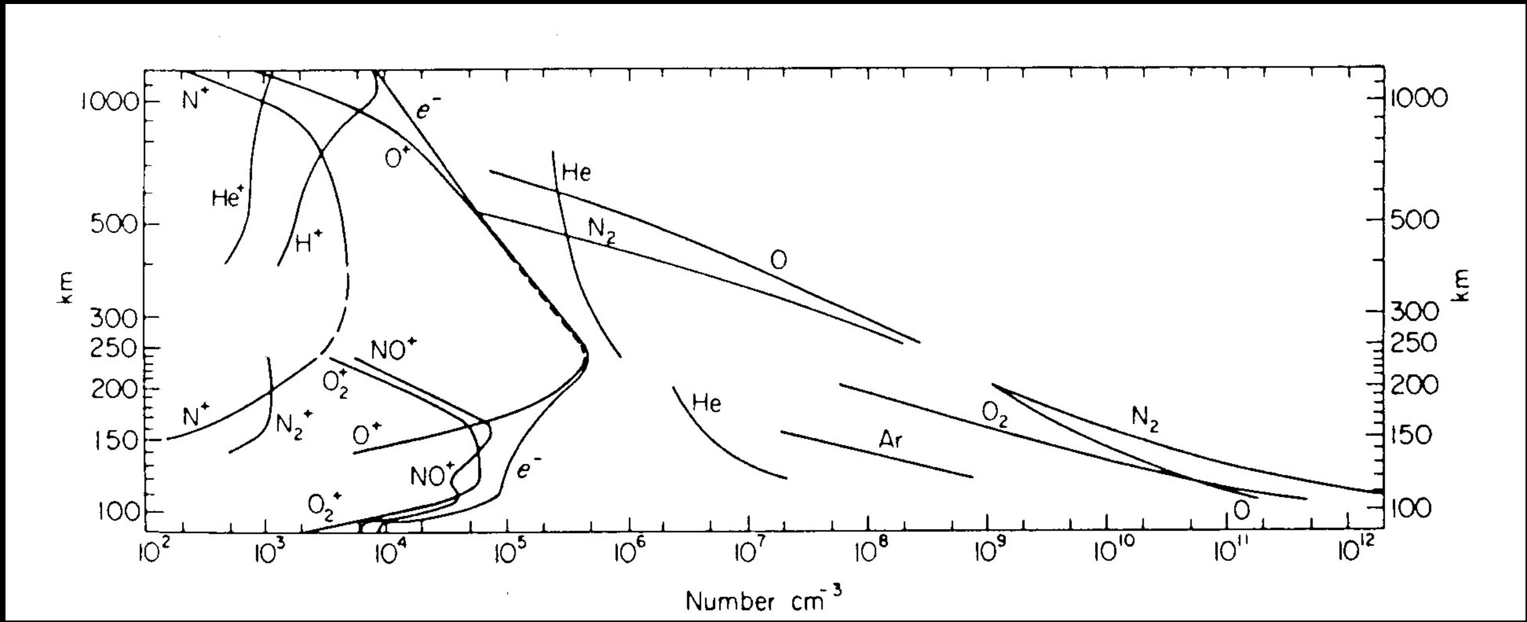
Auroral Colors and Altitude



- At 100-150 km collision rate too large so emission from metastable state quenched >> Green 5577
- Electrons about 10 keV

Auroral Colors and Altitude

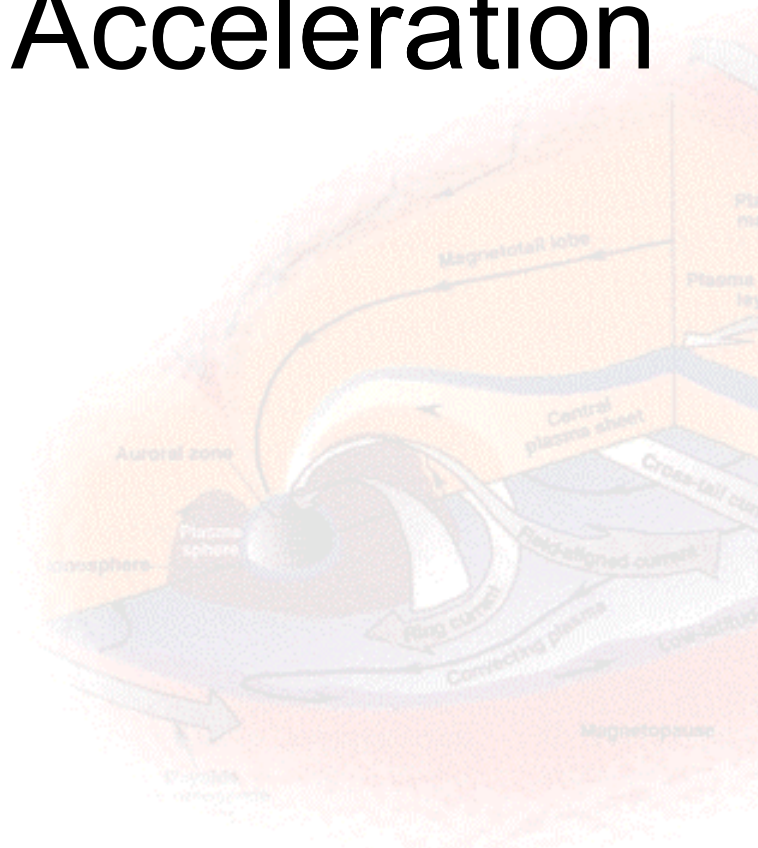


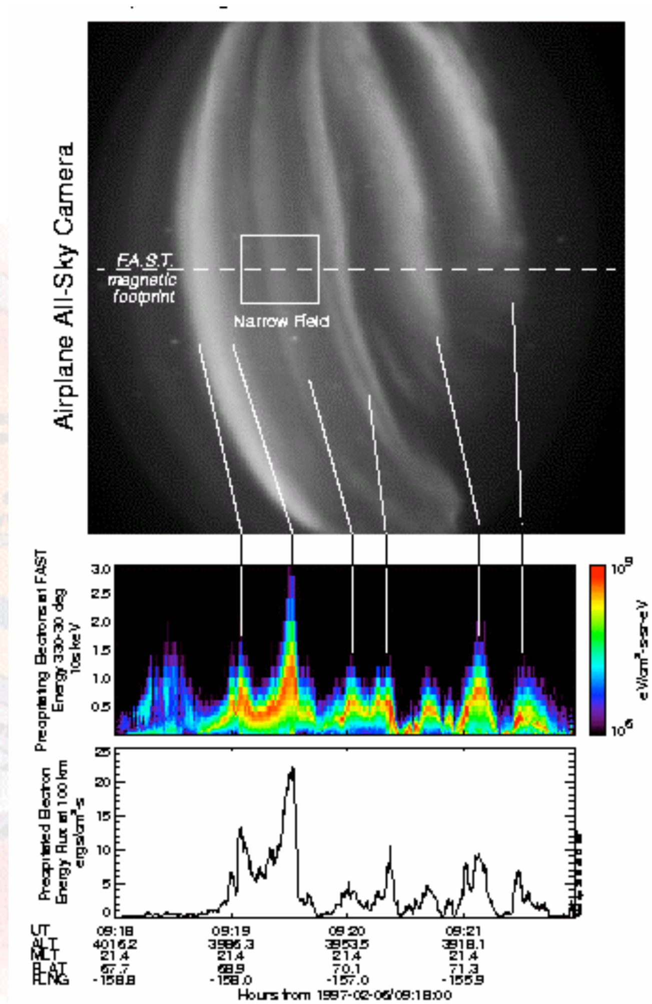
- Below 100 km N_2 can dominate O emission, so red emission seen at lower edge of arc

Diffuse (Continuous) Aurora

- Diffuse Aurora from DE-1 and from the Ground
- Widespread in Latitude, Connects to Plasma Sheet
- Results From Wave Particle Scattering of Electrons and Ions into Loss Cone (< 3 degrees)

Auroral Acceleration





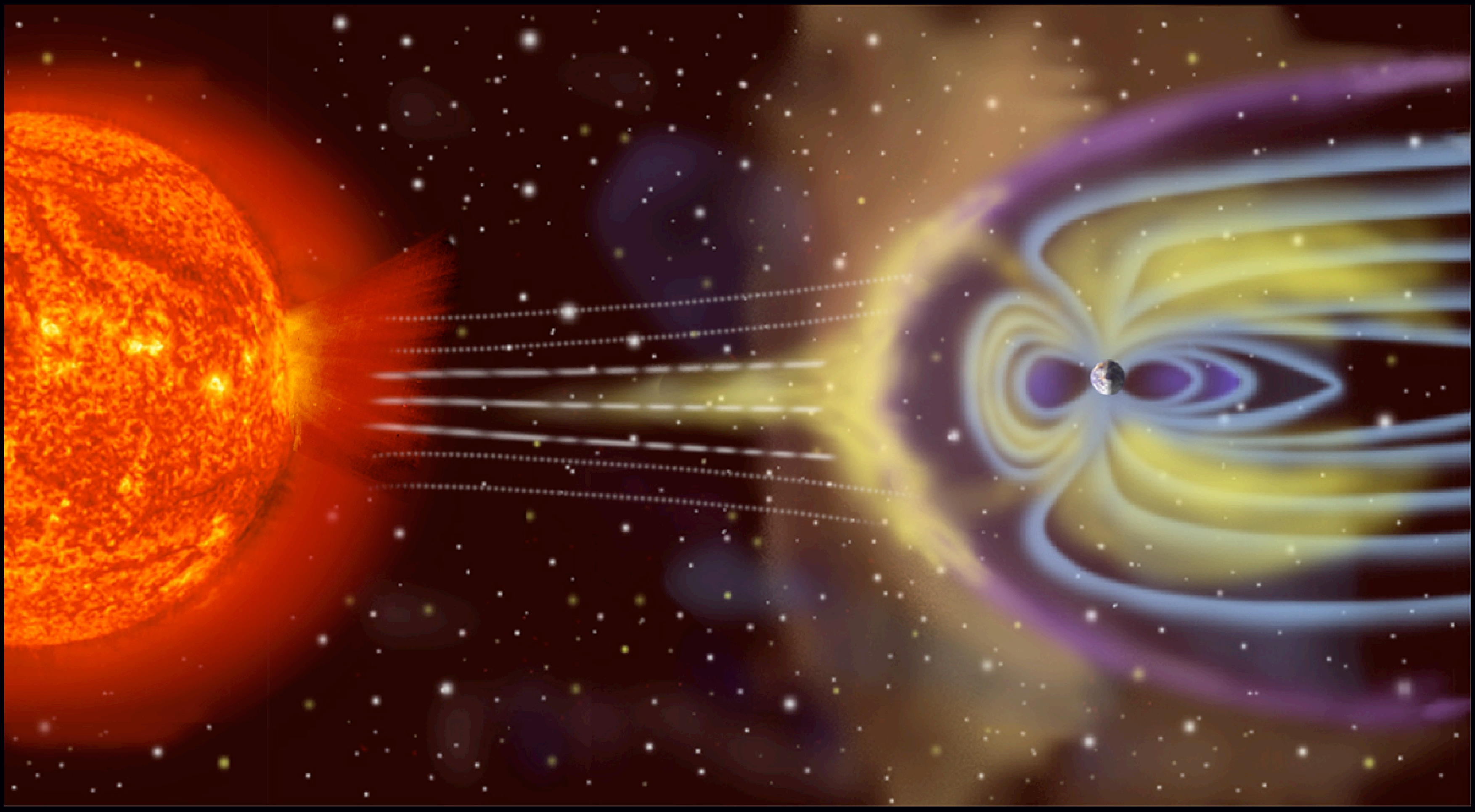
Auroral Challenges

- What is the auroral acceleration mechanism?
  - Double layers
  - Alfven waves
- Why are auroral arcs so thin (100m)?
- How do you include auroral physics in a global model?

Space Weather Models

- Physics-based models
  - First principles
    - MHD---physics deficient
    - Kinetic---computationally unfeasible
  - Empirical
    - Biased
    - Too many parameters
- Statistics-based models
  - Neural network
  - Information-theoretical

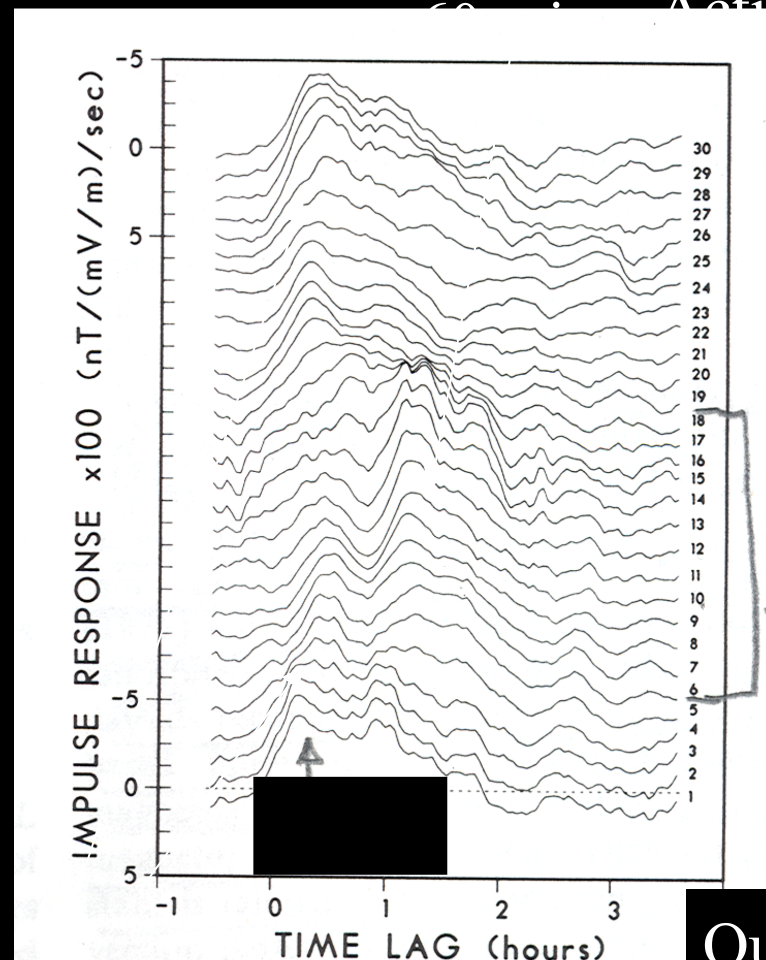
The Magnetospheric Response to the Solar Wind



Bargatze's Linear Filter (1985)

- Examined AL index response to IMP8 velocity
- O(T)=∫H(t)I(t-T)dt
- 20 min response at quiet and active times
- 60 min response for moderate activity

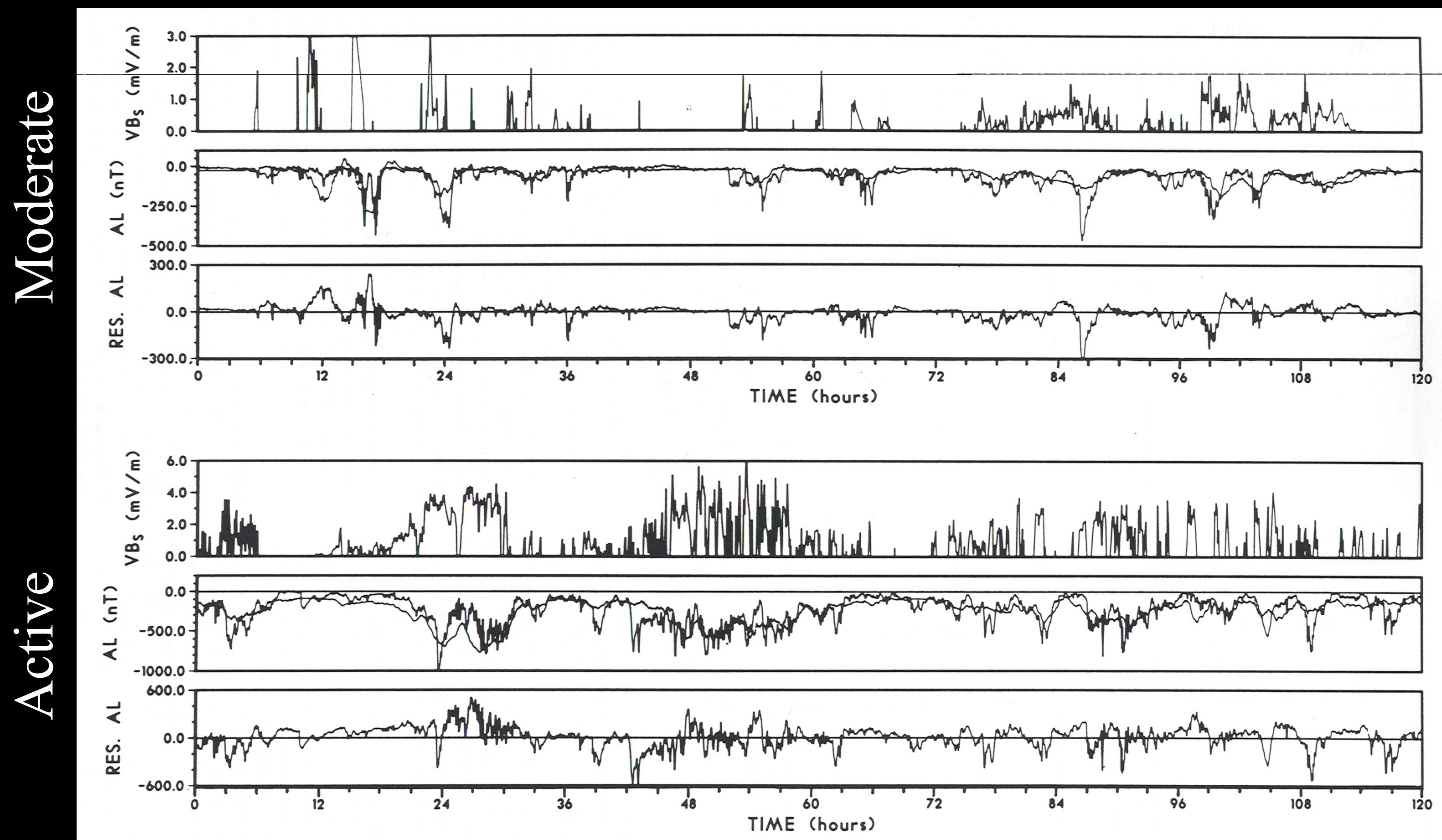
Active



Quiet

20 min

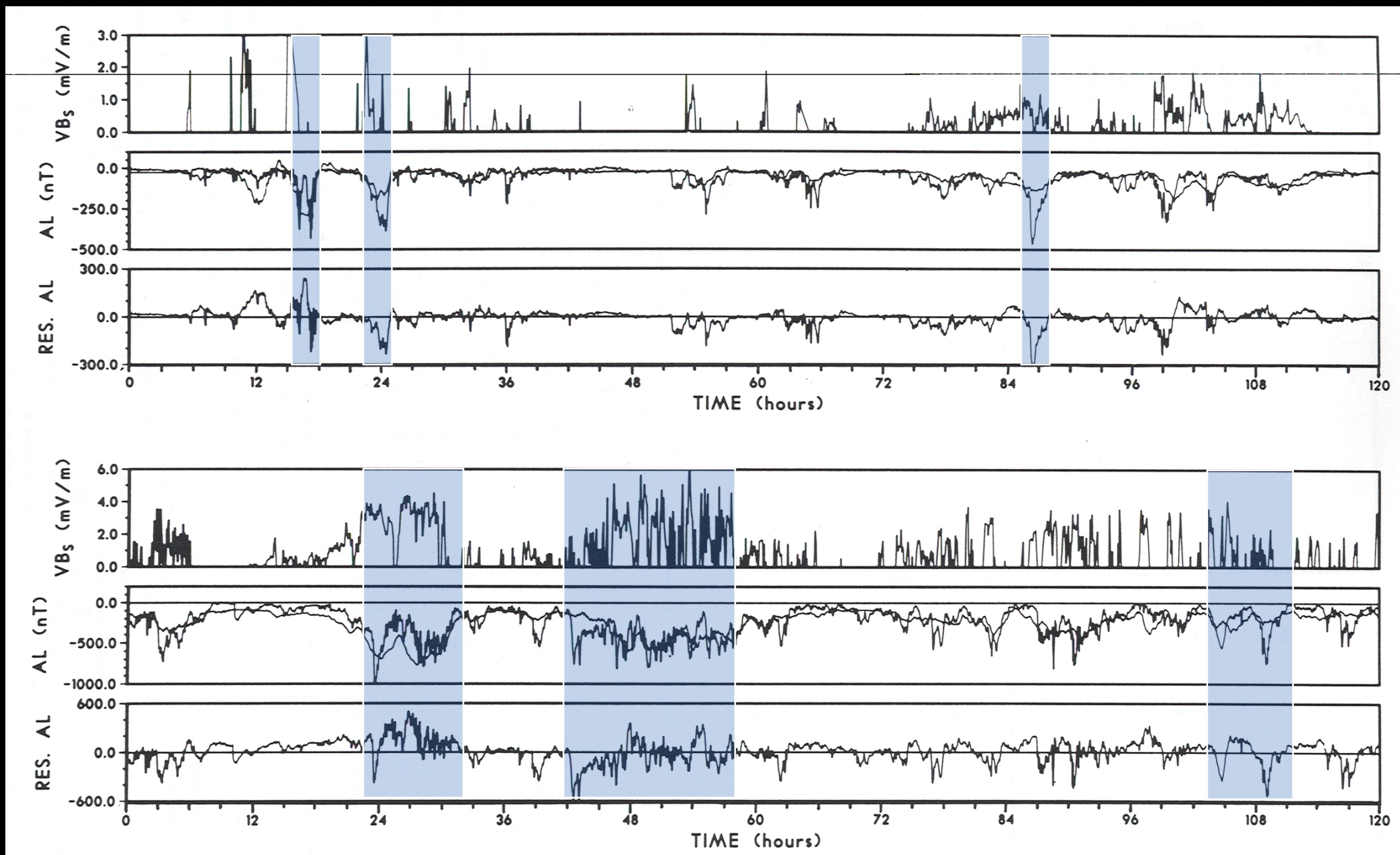
Is the Dynamics Linear?



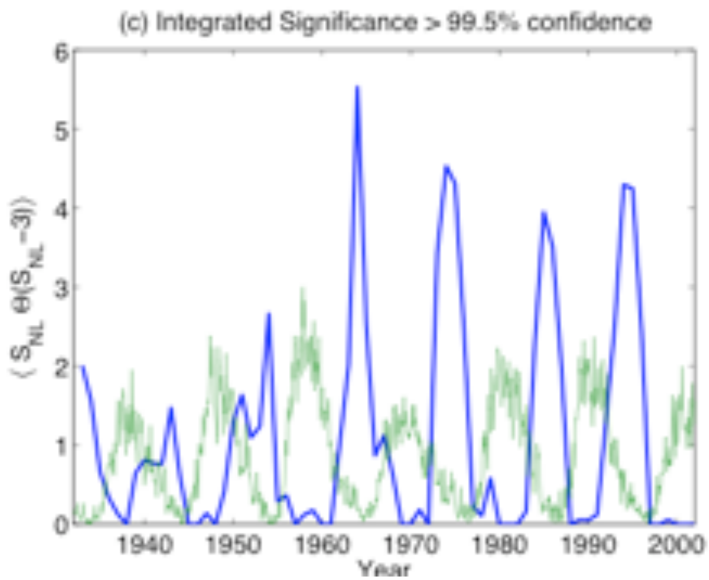
Is the Dynamics Linear?

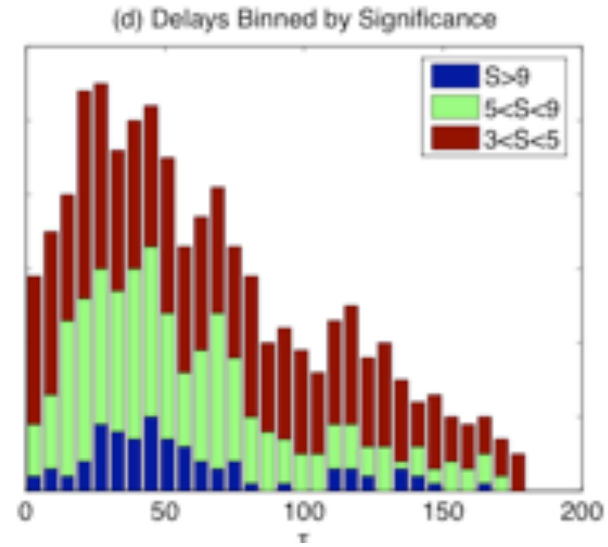
Moderate

Active



Cumulant Measure of Nonlinearity





Summary

- We have good physical understanding of the magnetosphere

BUT

- Many important issues are not yet resolved
  - Where does the plasma come from?
  - Substorms
  - Auroral acceleration
  - Nonlinear Solar Wind/Magnetosphere/Ionosphere Feedback