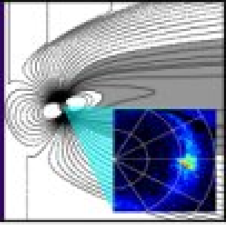
Perspectives on Geospace Plasma Coupling



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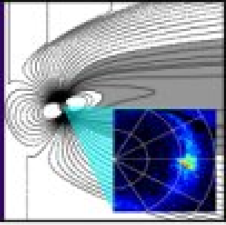
Acknowledgements to the Organizing Committee, notably Dimitris Vassiliadis

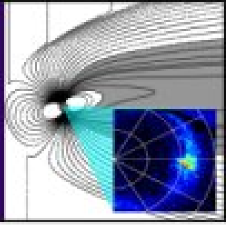
Special thanks to Dennis Papadopoulos for his remarkable career and contributions

Outline of Presentation



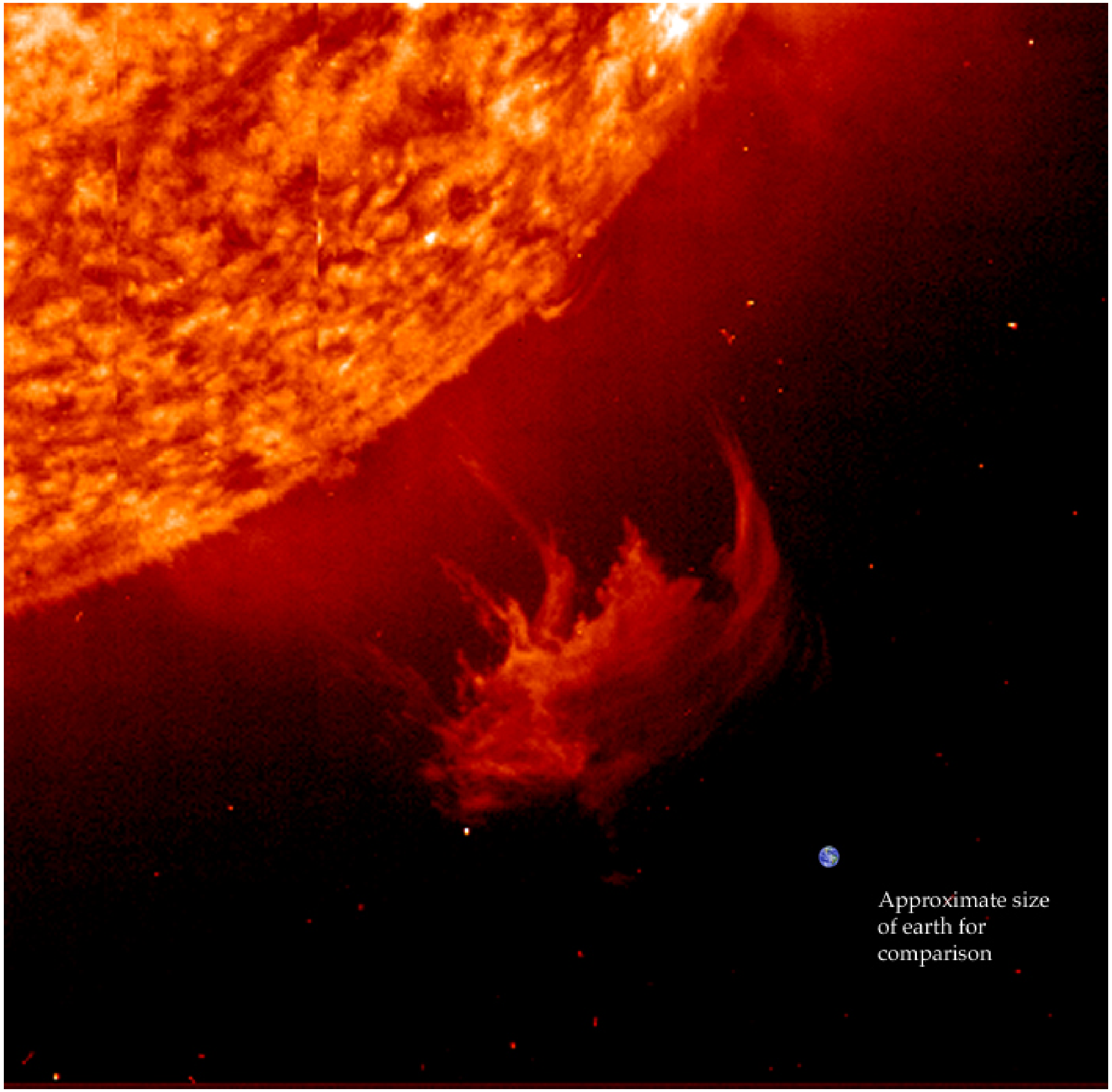
- Introduction
- Solar Wind-Magnetosphere Coupling
- Nonlinear Magnetospheric Dynamics
- Future Directions
- Some Reflections

Nonlinear Dynamics and Complexity



- Nonlinear Systems:
  - Output not proportional to input
  - Often have feedback (output influences input)
  - Can exhibit (apparently) random behavior
  - Can be low-dimensional (“deterministic chaos”)
- Nonlinearity can give rise to:
  - Self-organization (“Order emerging from chaos”)
  - Randomness and order in a single system
  - Homeostasis (when different types of “systems” interact strongly)

Solar Eruptive Disturbances

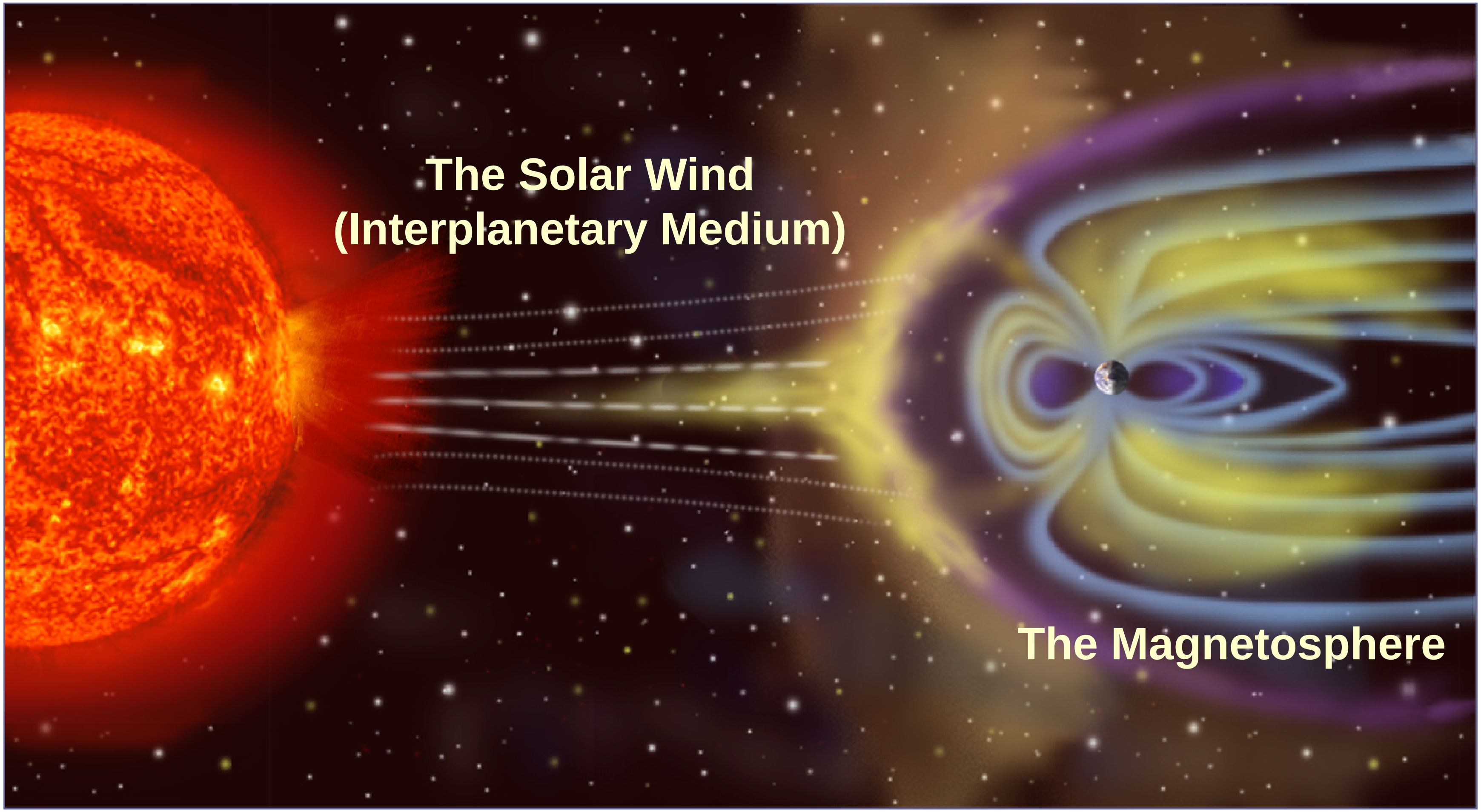


The relative size of the Earth:

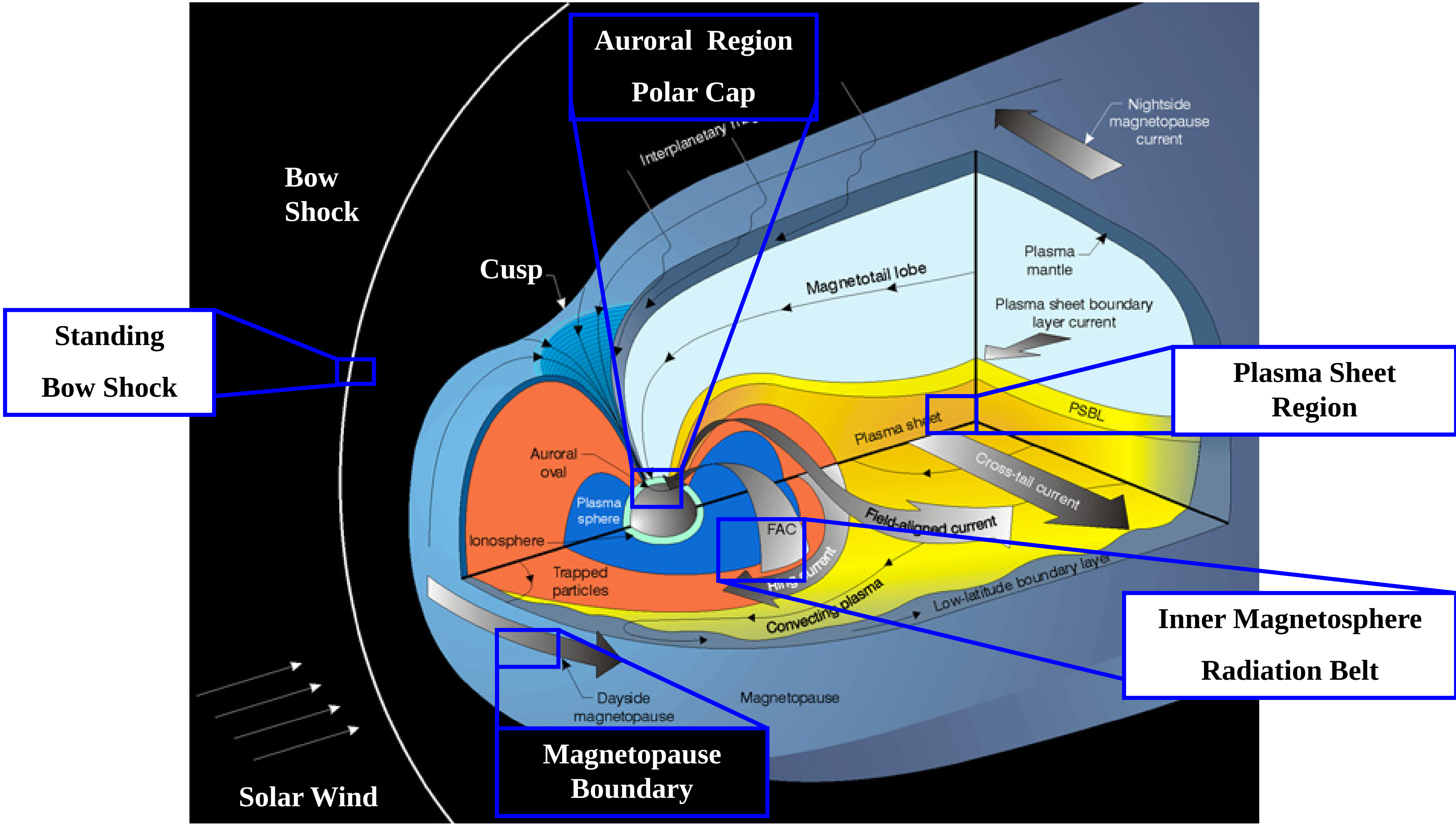
The way things really are…

Earth's Space Environment

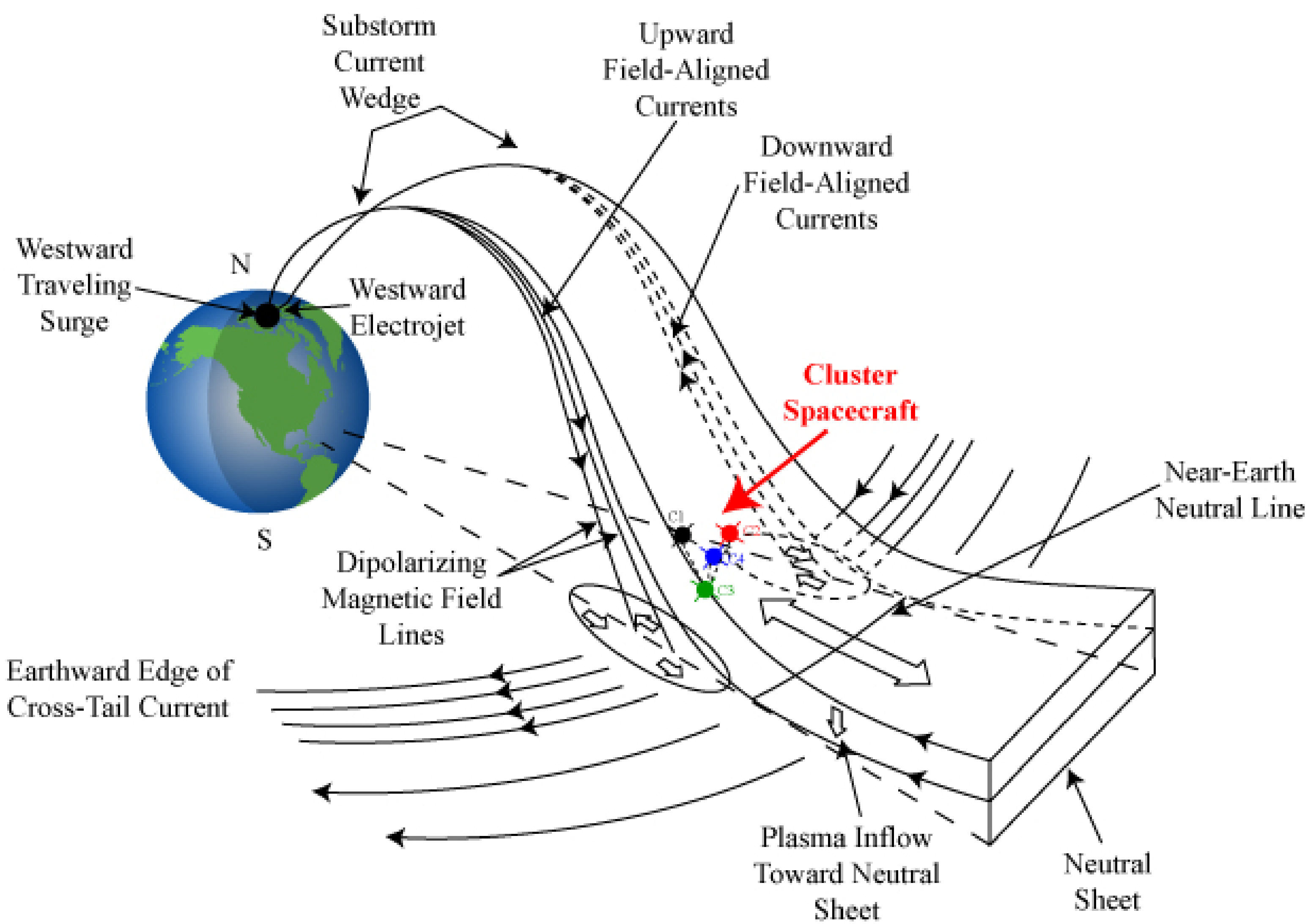
The way geospace people see it…



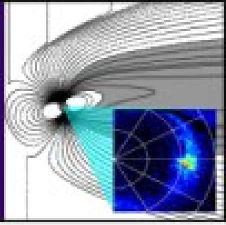
Key Regions of the Magnetosphere



Substorm Currents and Plasma Flow



Magnetospheric Dynamical Sequence



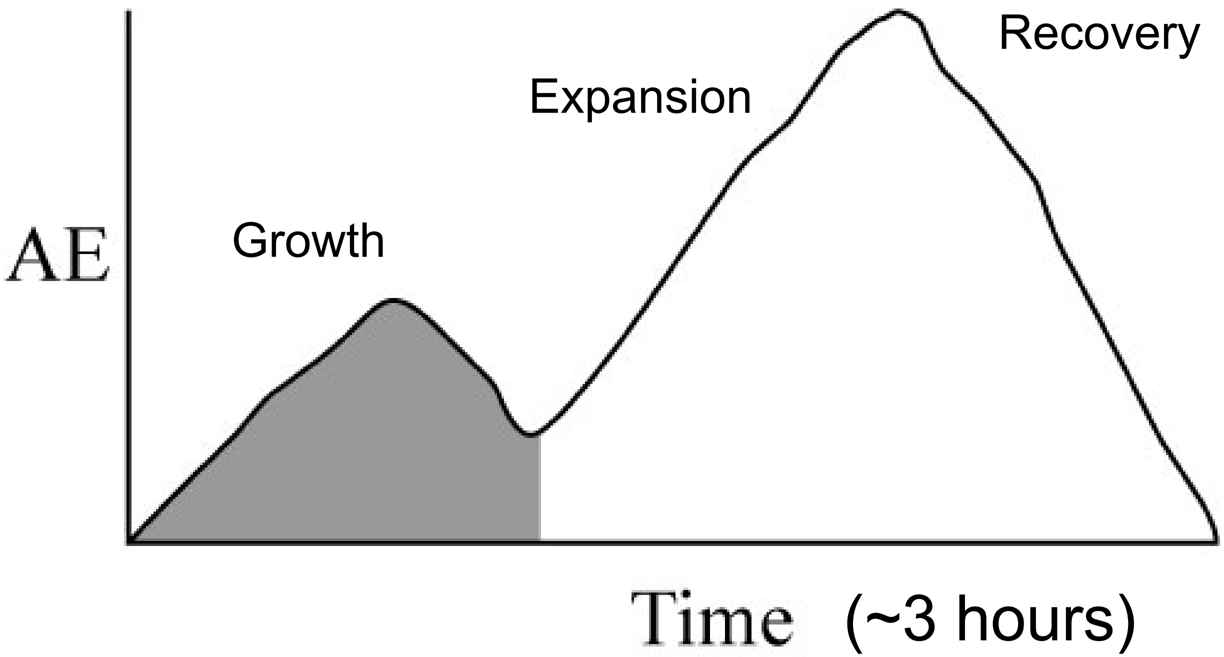
Southward IMF → (Dayside Reconnection) → Electrojets Grow; Auroral Oval Expands; Tail Field Increases → (Tail Energy Storage) → Near-Earth Plasma Sheet Thins; Flux Dropout (Cigar Phase) at 6.6 R_E

↓ Enhanced Cross-Tail Current

Pseudo-Breakups, BBFs

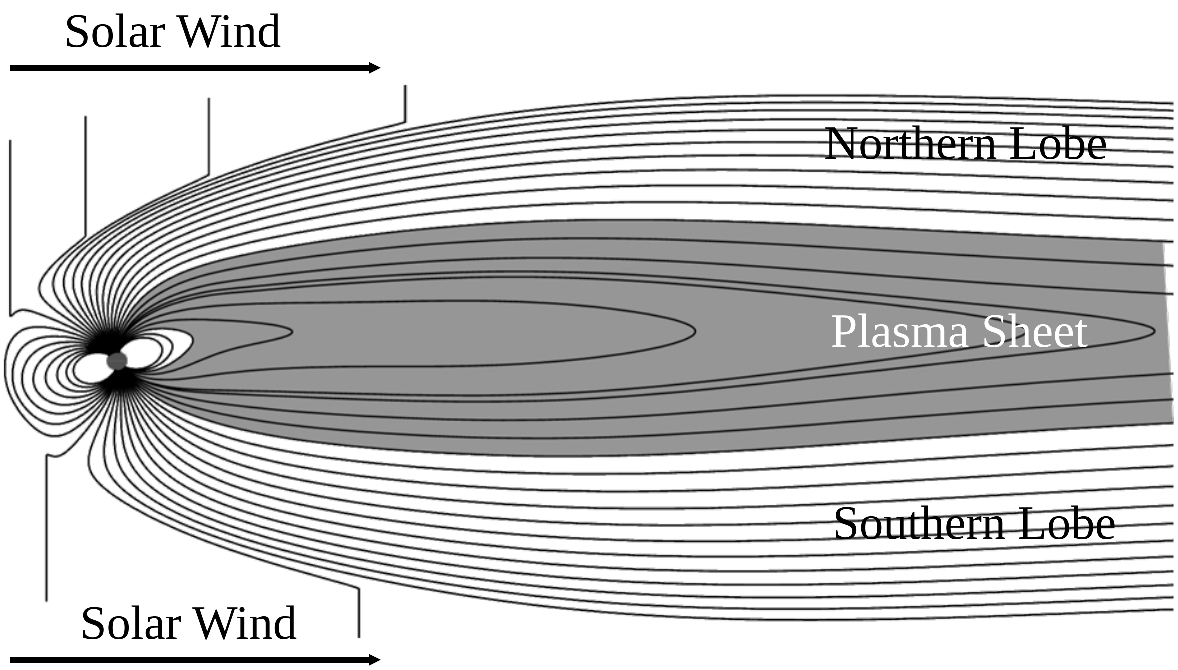
↓ Plasma Sheet Instability Growth

Substorm Expansion Phase Onset



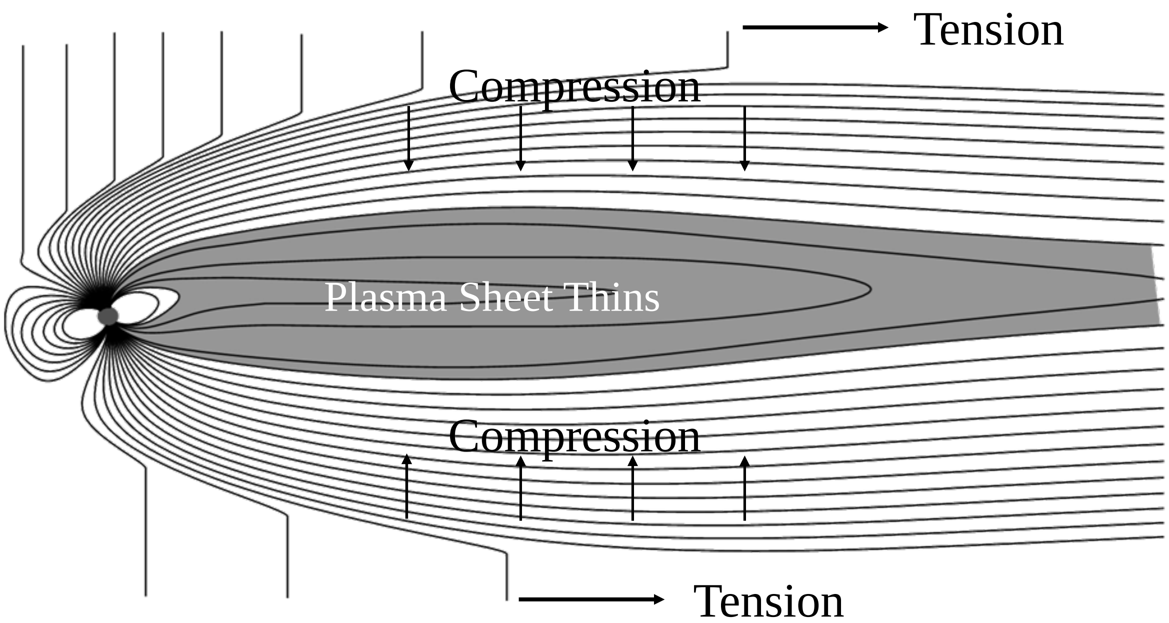
Magnetospheric Configuration

Initial State



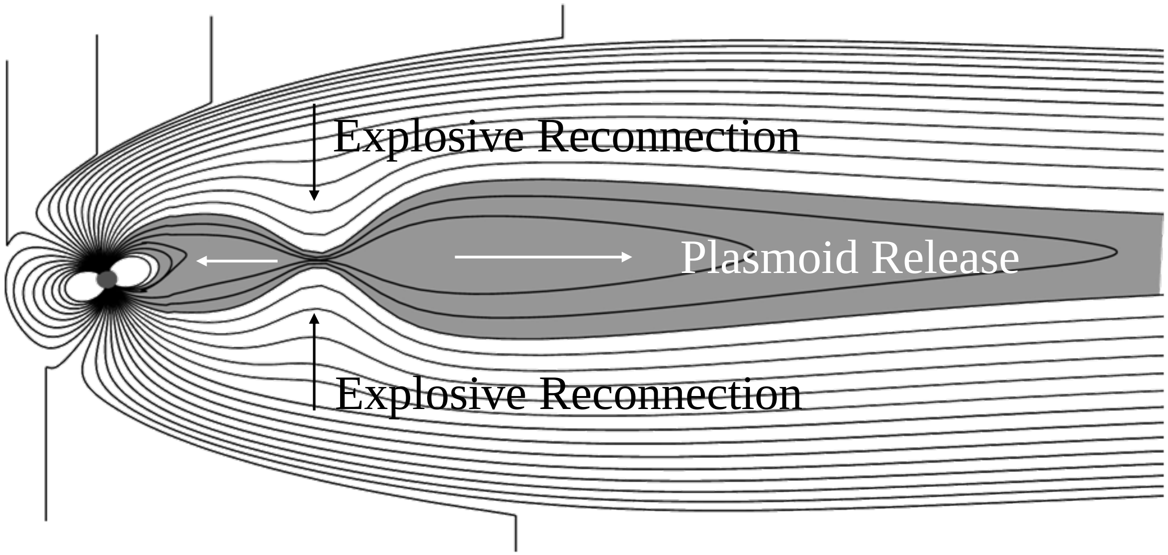
Interplanetary field turn southward and merges with Earth’s dayside field.

Substorm Growth Phase



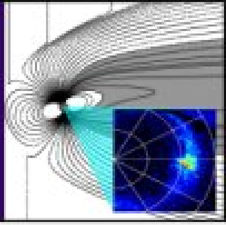
Interplanetary field continues merging with Earth's dayside field. Magnetic flux is loaded into lobes. Plasma and current sheets thin. Growth lasts ~ 1 hour if interplanetary field remains southward.

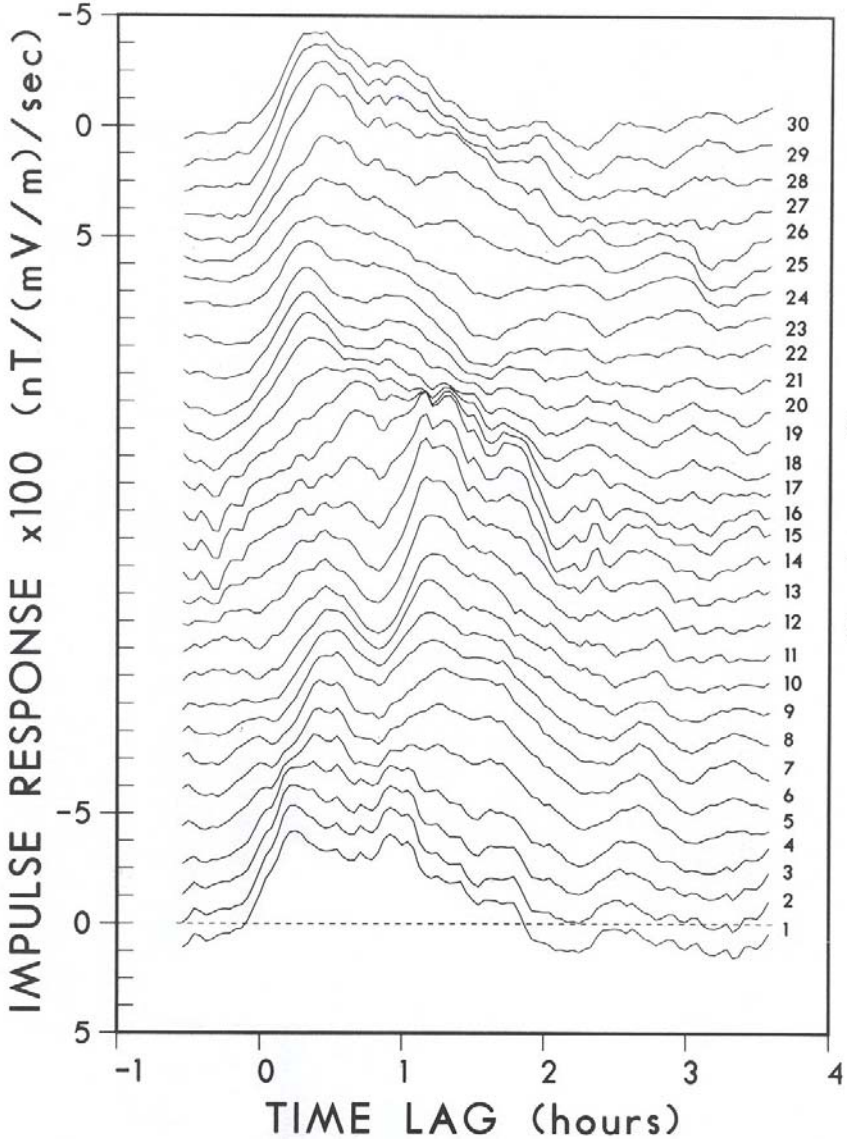
Substorm Expansion Phase



Explosive reconnection. Plasmoid release.
Inner field dipolarization and current diversion.
Auroral expansion poleward.

Linear Prediction Filter Technique





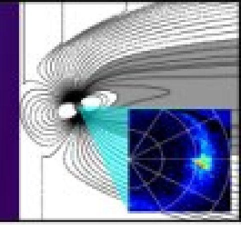
$$O(t) = \int_0^\infty ds\, h(s)\, I(t-s)$$

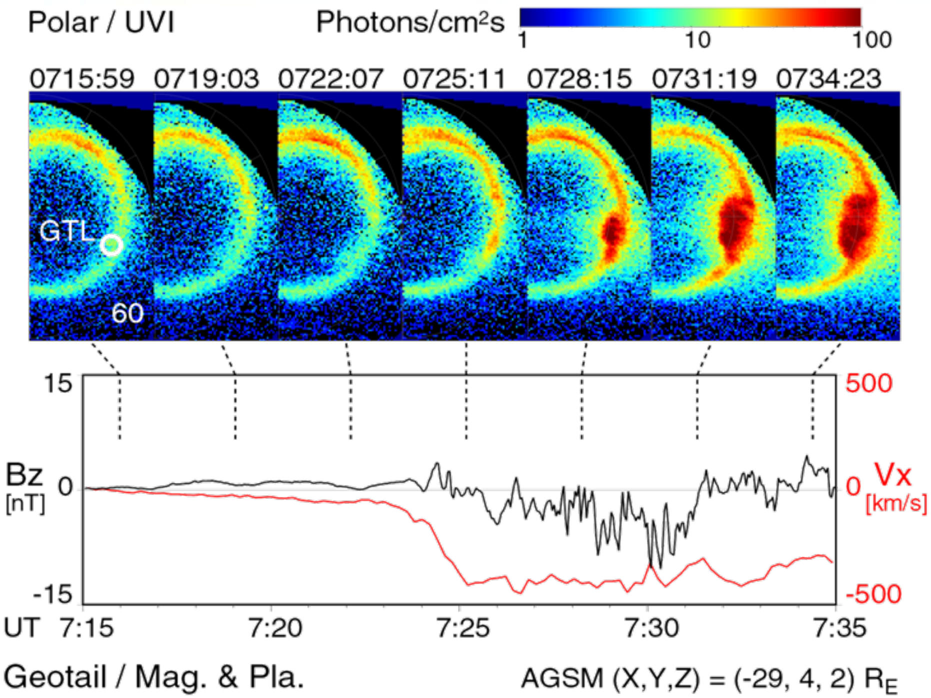
$$I(t) = VB_s$$

$$O(t) = \text{ AL index}$$

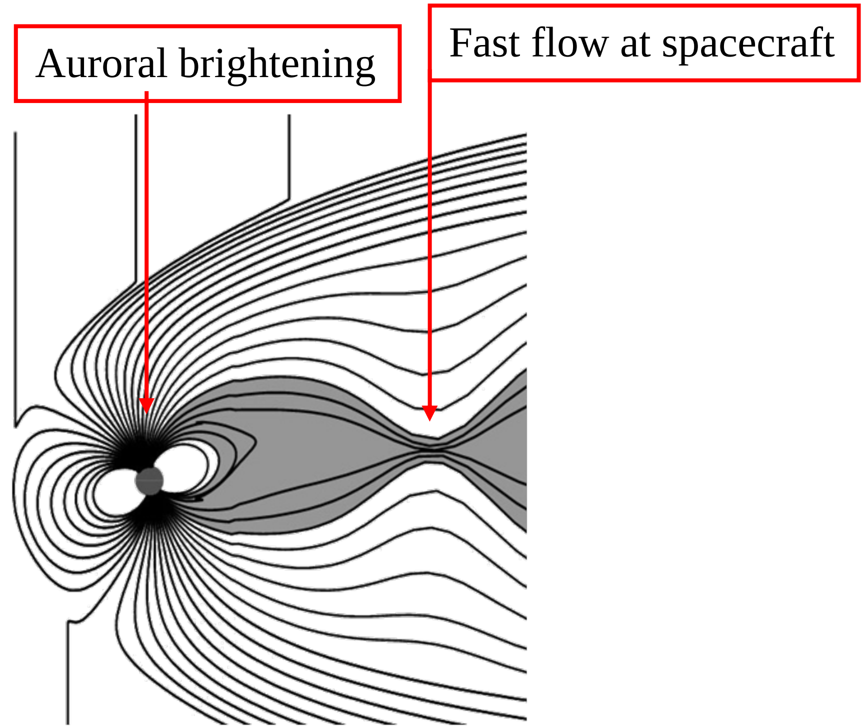
Bargatze, Baker, McPherron & Hones (1985)

Fast Flows and Auroral Brightening





Ieda et al., JGR, 2001

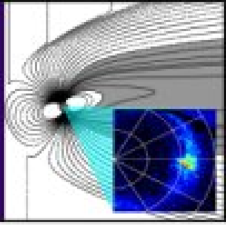


<u>Field Line Mapping</u>:

-Find fast flow at spacecraft in tail

-Map spacecraft position to ionosphere using magnetic field model

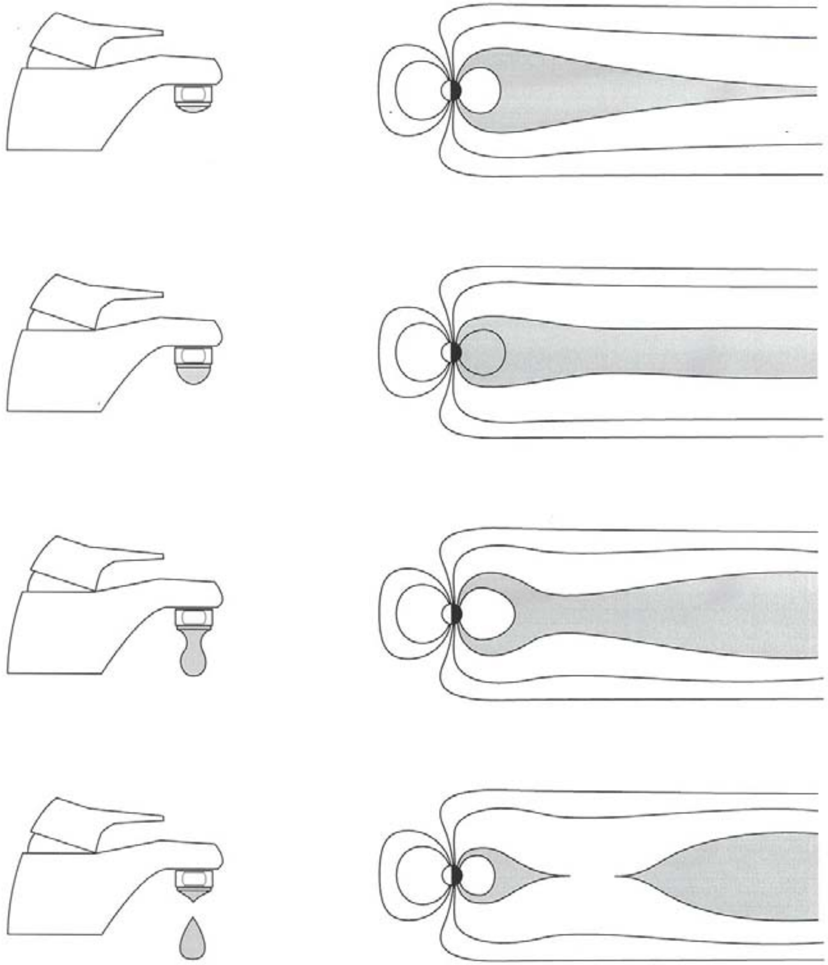
Fundamental Magnetotail Dynamics



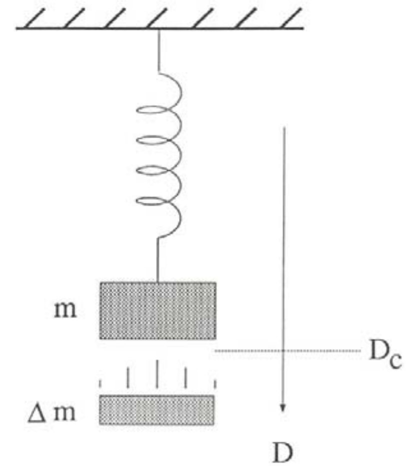
- Spatially distributed loading-unloading system
  - Hypothesis: magnetic flux is relevant conserved quantity
- Threshold instability
  - Current driven, tearing, etc., produce localized reconnection
- Criticality
  - Localized reconnection broadly distributed spatially and temporally indicates plasma sheet region generally near instability
  - Global coherence
- Scale-free avalanche distributions
  - Localized reconnection, pseudo-breakups, substorms
  - Auroral avalanche distributions

Klimas et al.,2000

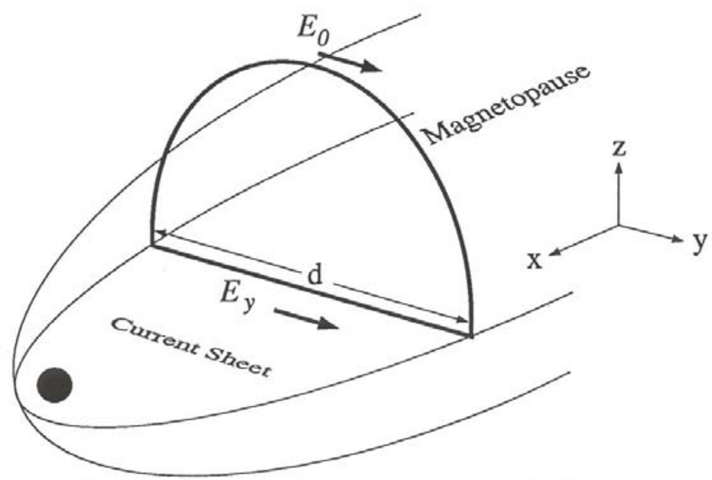
Dripping Faucet Analogue Models



Analogy of **plasmoid formation** to a leaky faucet [Hones, 1979]

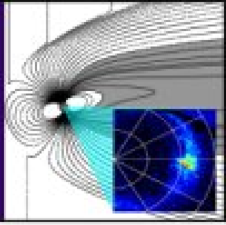


Dripping Faucet analogue
[Shaw, 1984; Baker *et al.*, 1990]



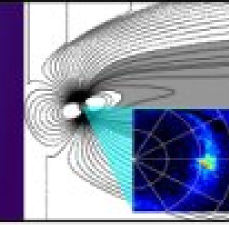
Faraday Loop nonlinear analogue model of loading-unloading processes [Klimas *et al.*, 1992; 1996]

An Assessment of Substorms *(Baker et al., JGR, 1999)*



- "It is important to realize, however, that many fundamental issues remain to be resolved concerning substorms. Why, for example, is the magnetotail stable most of the time…? What allows the violation of the frozen-flux constraint necessary for an efficient energy release by reconnection in the course of substorms? How do recent observations of small-scale turbulence and suggestions of localized reconnection in the plasma sheet play a role in the issue of global stability versus instability? What are the mechanisms of organization that lead to the global coherence of the magnetospheric substorm phenomenon? How do external triggering and changes in boundary conditions ultimately play a role in substorm behavior?"
- "There clearly is much more to learn about pseudobreakups, convection bay events, and other variants of the 'normal' substorm sequence than has been addressed in this paper..."

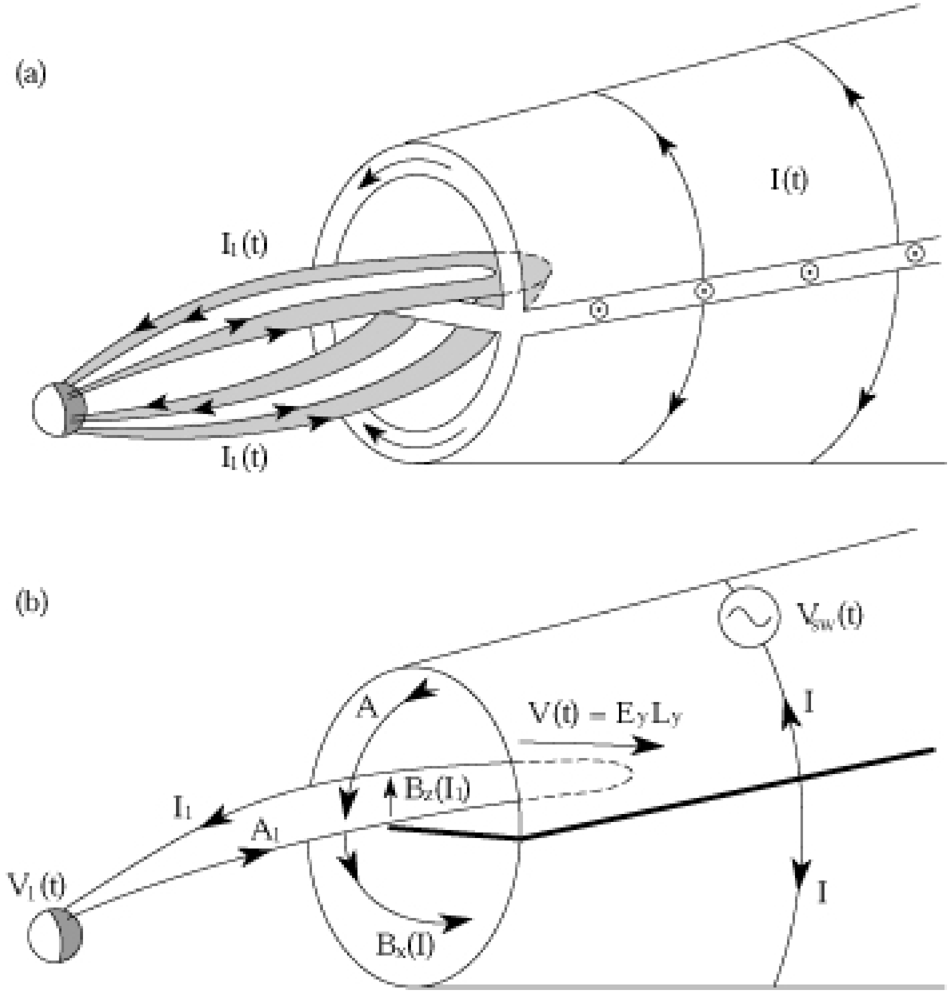
Self-Organization



“The concept of self-organization originated in the study of nonlinear physical and chemical systems, such as convection flows and chemical reactions that form waves. In these systems, global patterns emerge from local interactions among many subunits. ***The interactions are typically shaped by multiple feedback loops, including positive ones that amplify emergent dynamics and negative ones that modulate and constrain them***.”

(J.W. Pepper and G. Hoelzer, Science, 2001)

UT WINDMI Model

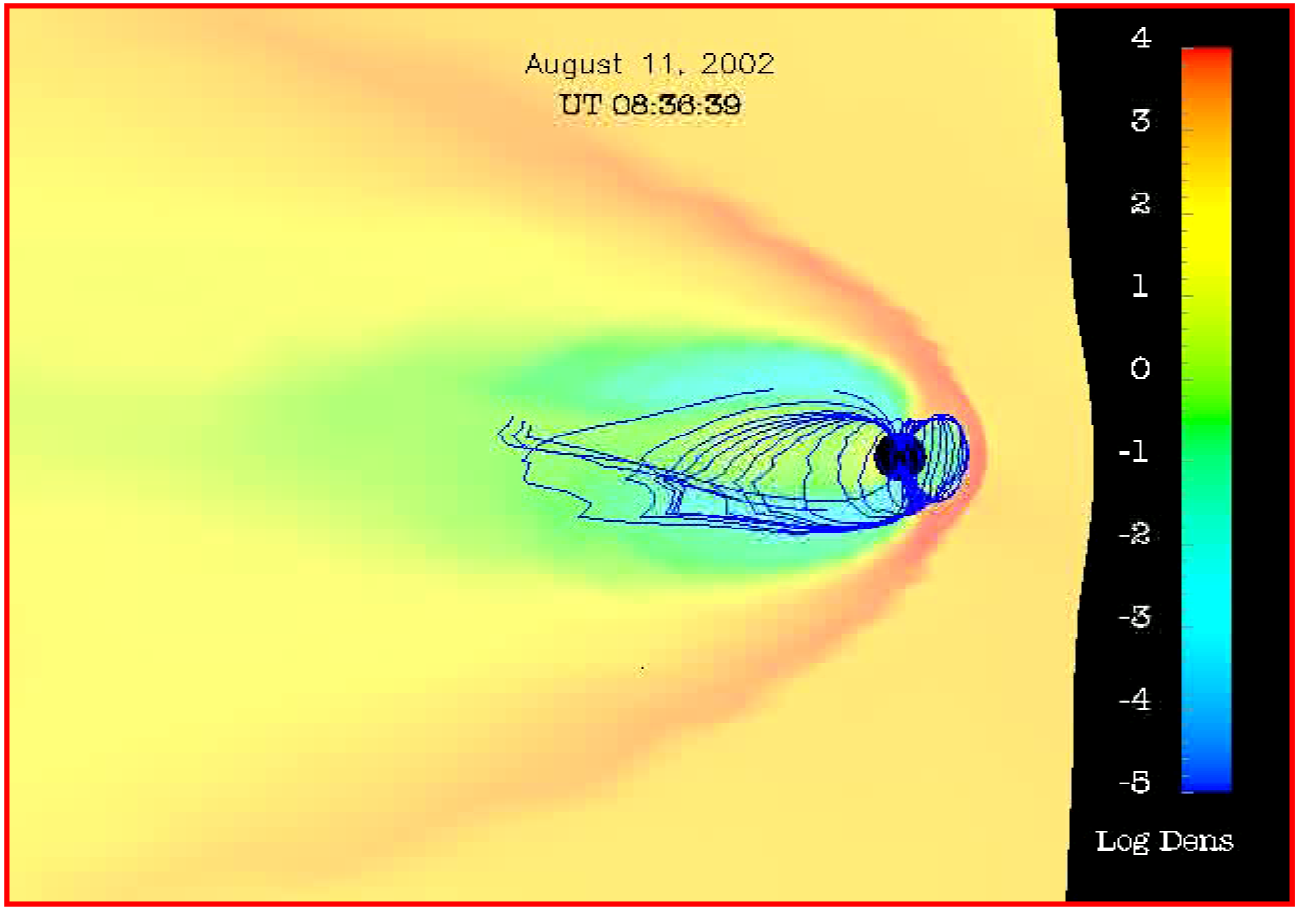


General Characteristics of Sandpile Models Near SOC

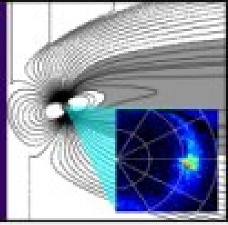
- Loading-unloading system
- Threshold instability
  - A **local** phenomenon
  - Dependent on local state; e.g., local gradient
- Criticality
  - A **global state** on the verge of instability everywhere
  - Systems self-organize toward this limiting critical state
  - Criticality produces a stable global configuration
- Scale-free avalanche distributions
- Sensitivity to external disturbances

Chapman et al.,1998

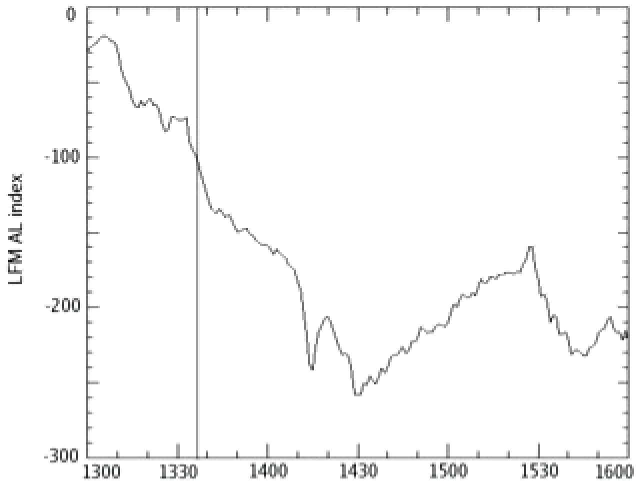
LFM Model: Density and Magnetic Field Lines

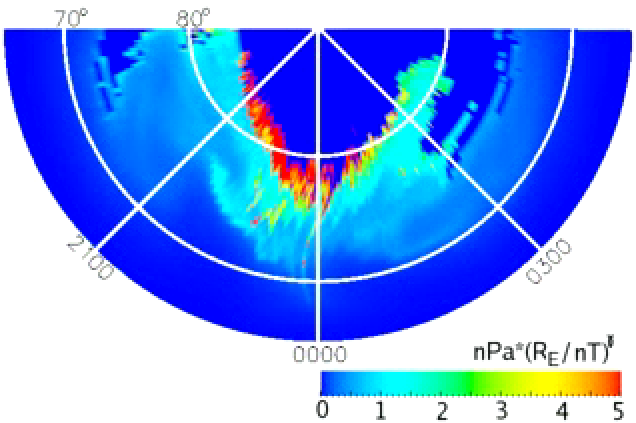


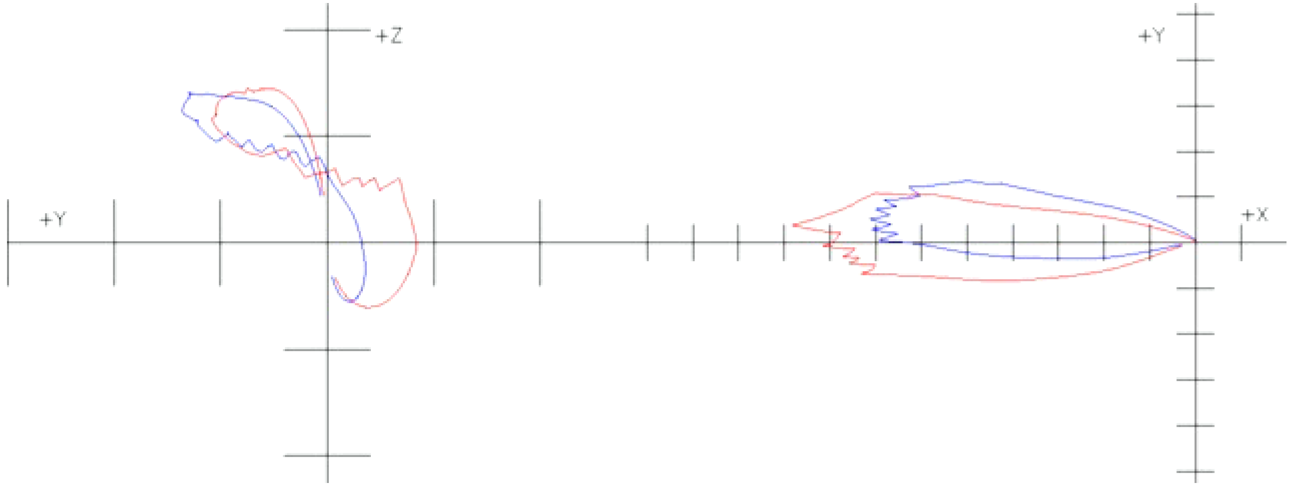
Simulated Flux Rope in LFM Model



Farr, Baker, and Wiltberger [2009]



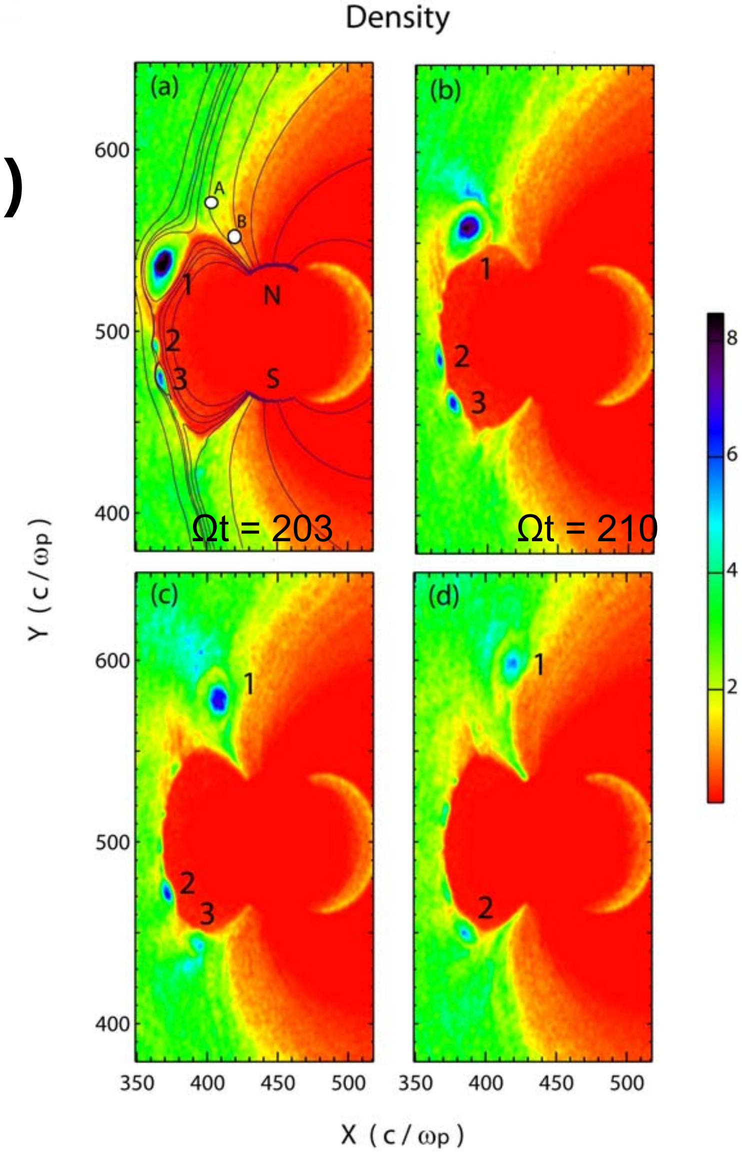




Hybrid modeling of dayside reconnection

Formation of FTEs with variety of sizes (three labeled) during southward IMF

- **Their poleward motion with time**
- **FTE degradation due to passage through cusps**

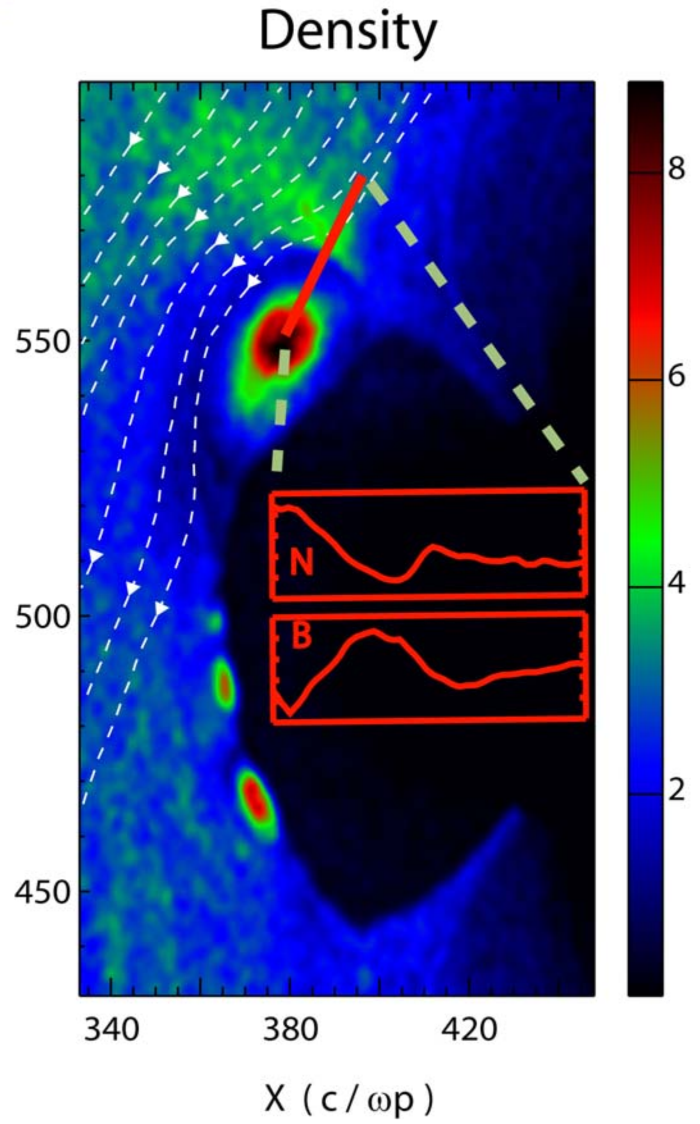


Omidi and Sibeck (GRL, 2007)

FTE Evolution

Considering the large FTE, figure on the right shows:

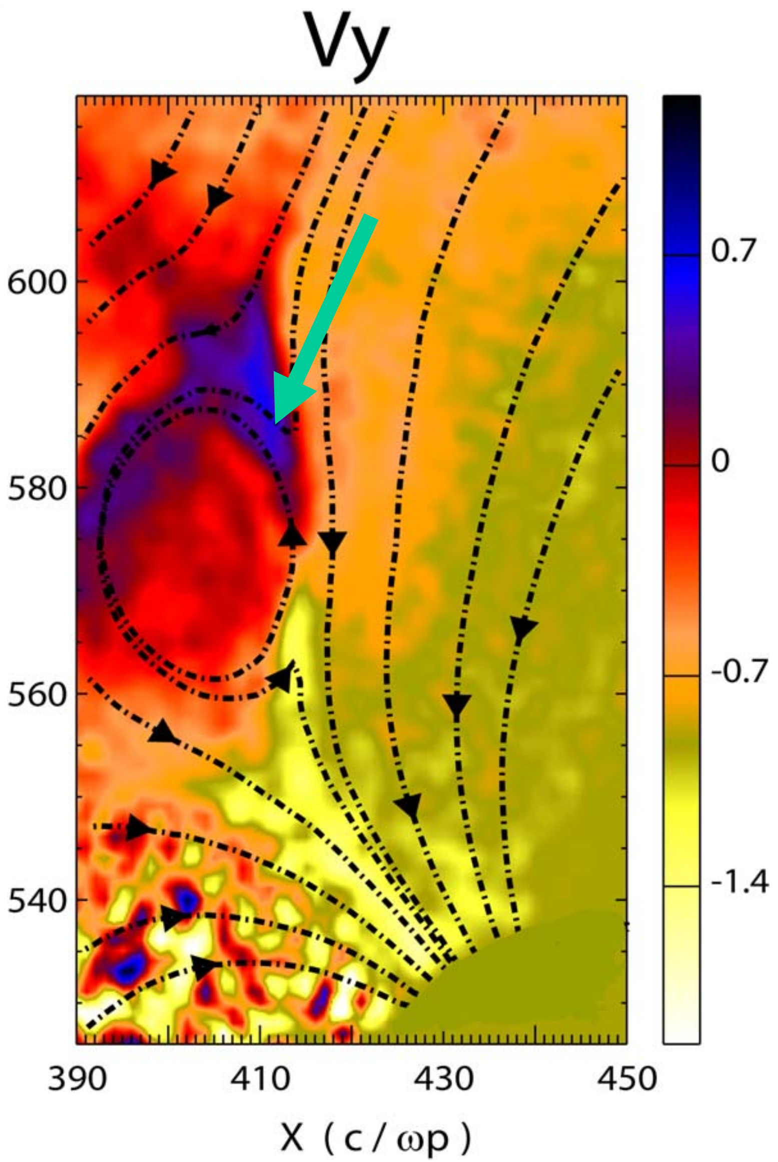
- **Flow lines in the rest frame of the FTE**
- **Flow deflection associated with asymmetric density enhancement upstream of the FTE; formation of a bow wave**
- **Anti-correlation between N (density) and B (magnetic field), i.e. a slow-mode bow wave**



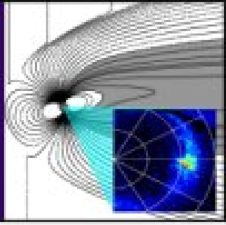
FTE Role in Coupling

Figure shows:

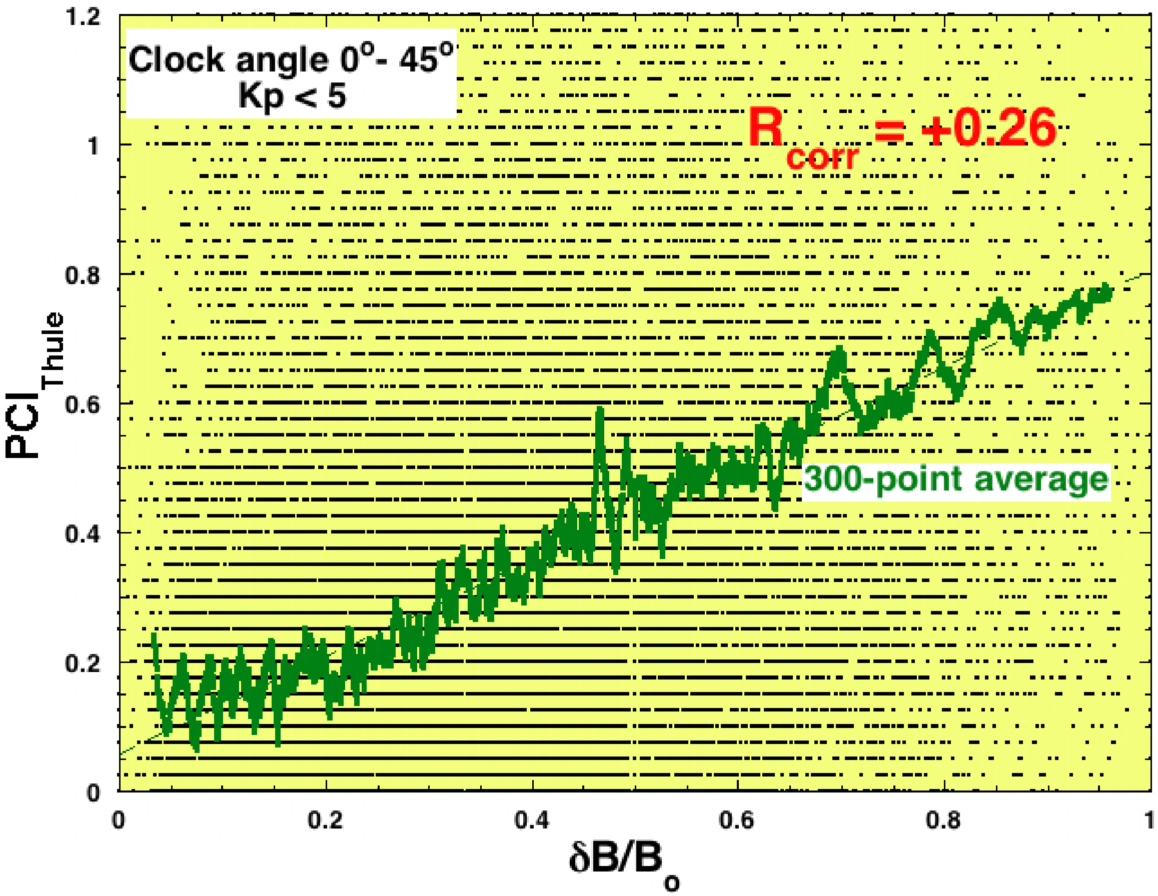
- **Ion flow speed in Y direction normalized to Alfven speed**
- **Magnetic field lines**
- **Plasma jetting due to magnetic reconnection as FTE enters the cusp**



Variation of Geomagnetic Indices with the Amplitude of Upstream Turbulence



Borovsky and coworkers

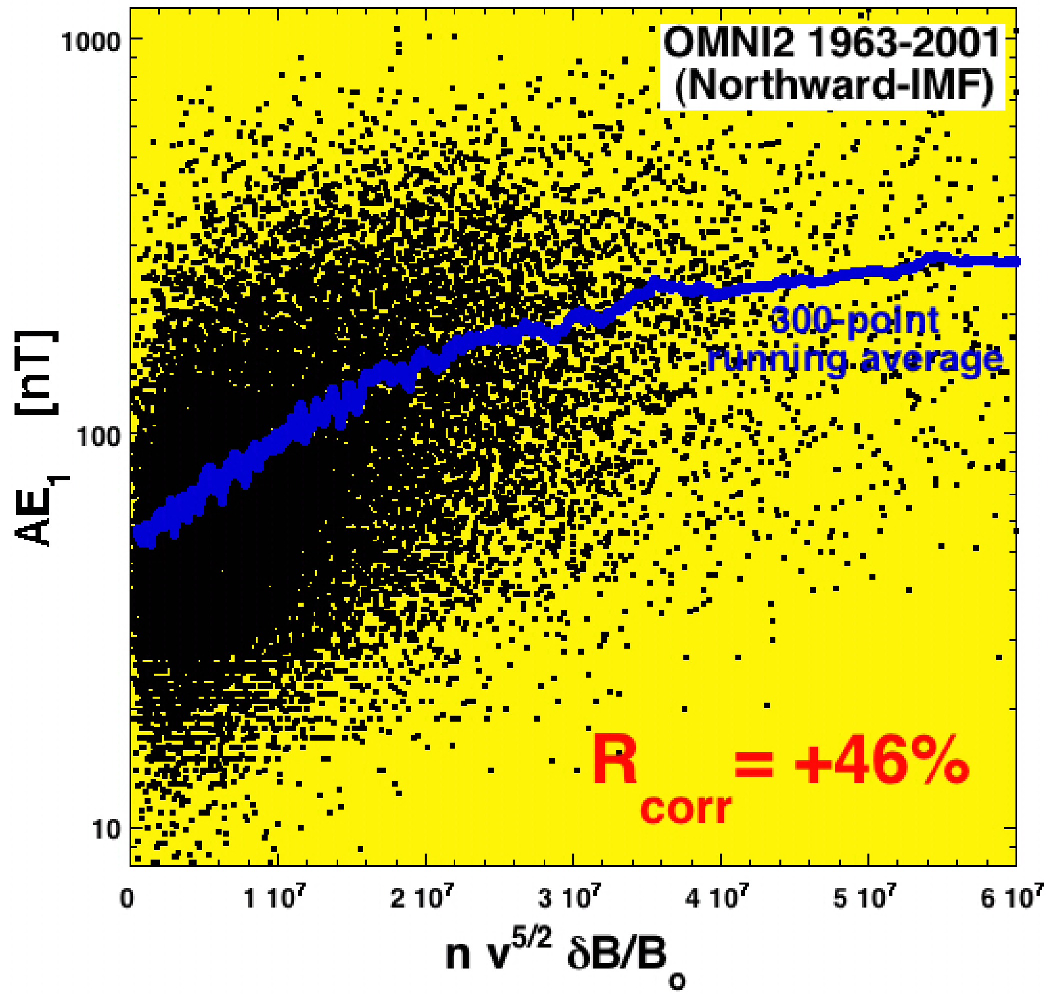


With reconnection turned off, the "turbulence effect" is easily discernable.

The effect is also discernable when the IMF is southward.

Proxy effects can be removed: the answer is the same.

Variation of Geomagnetic Indices Versus Viscous Driver Function



When a coupling function based on turbulent viscosity is used, the correlation coefficient increases.

Conclusions of the Coupling Studies

Studies: Borovsky and Funsten, JGR, 2003
Borovsky and Steinberg, AGU Monog., 2006
Borovsky, Phys. Plasmas, 2006

Increasing the level of upstream fluctuations in the solar wind increases solar-wind/ magnetosphere coupling.

This is consistent with the aerodynamic "upstream effect".

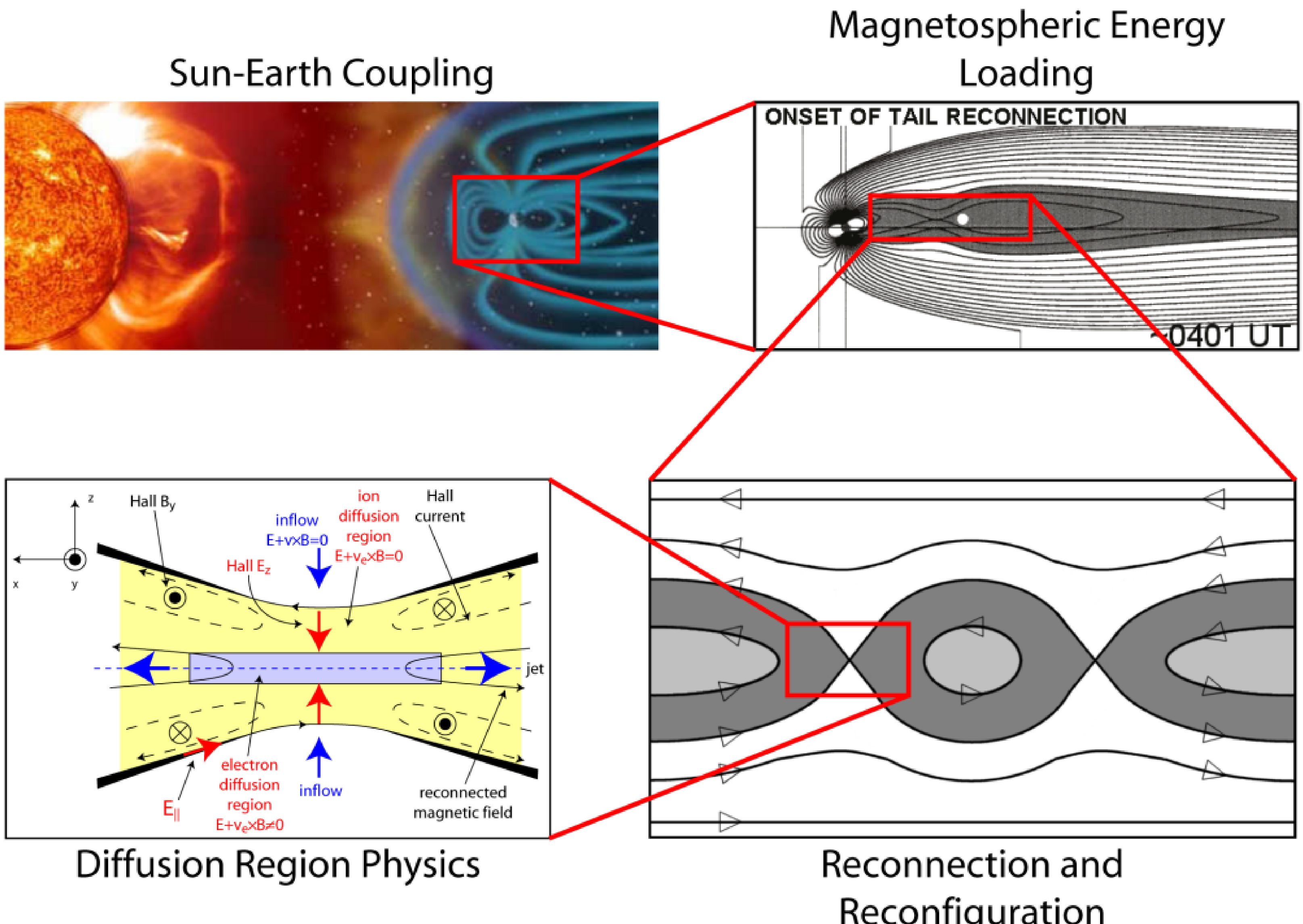
1) an eddy-viscosity dominance of the viscous interaction
2) solar-wind-turbulence control of the eddy viscosity

The "turbulence effect" is:

- responsible for ~150 nT of the AE index
- the dominant driver of the magnetosphere during quiet times
- a 5-10% driver during geomagnetic storms.

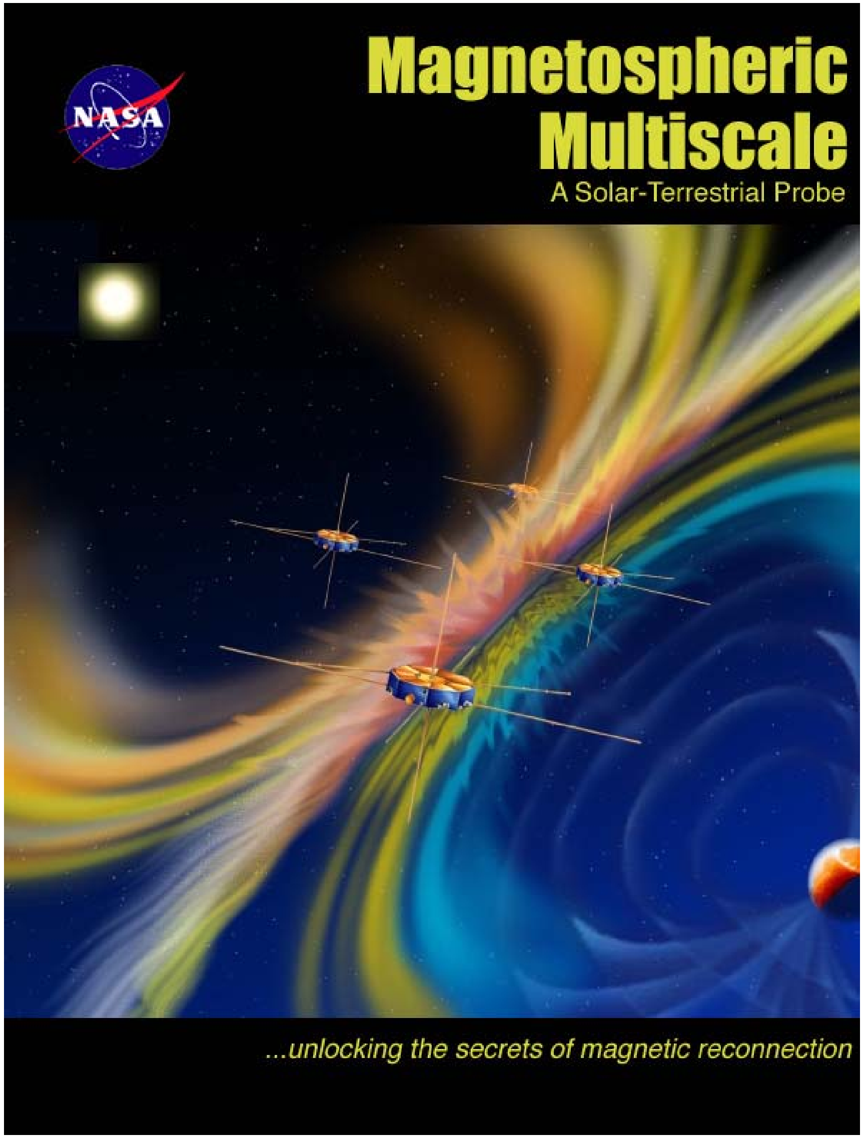
Important assertions about the role of turbulence
"Structure" must be separated from "turbulence" in $\delta B/B_o$ measures.

Multi-Scale Phenomena in Magnetospheric Substorms

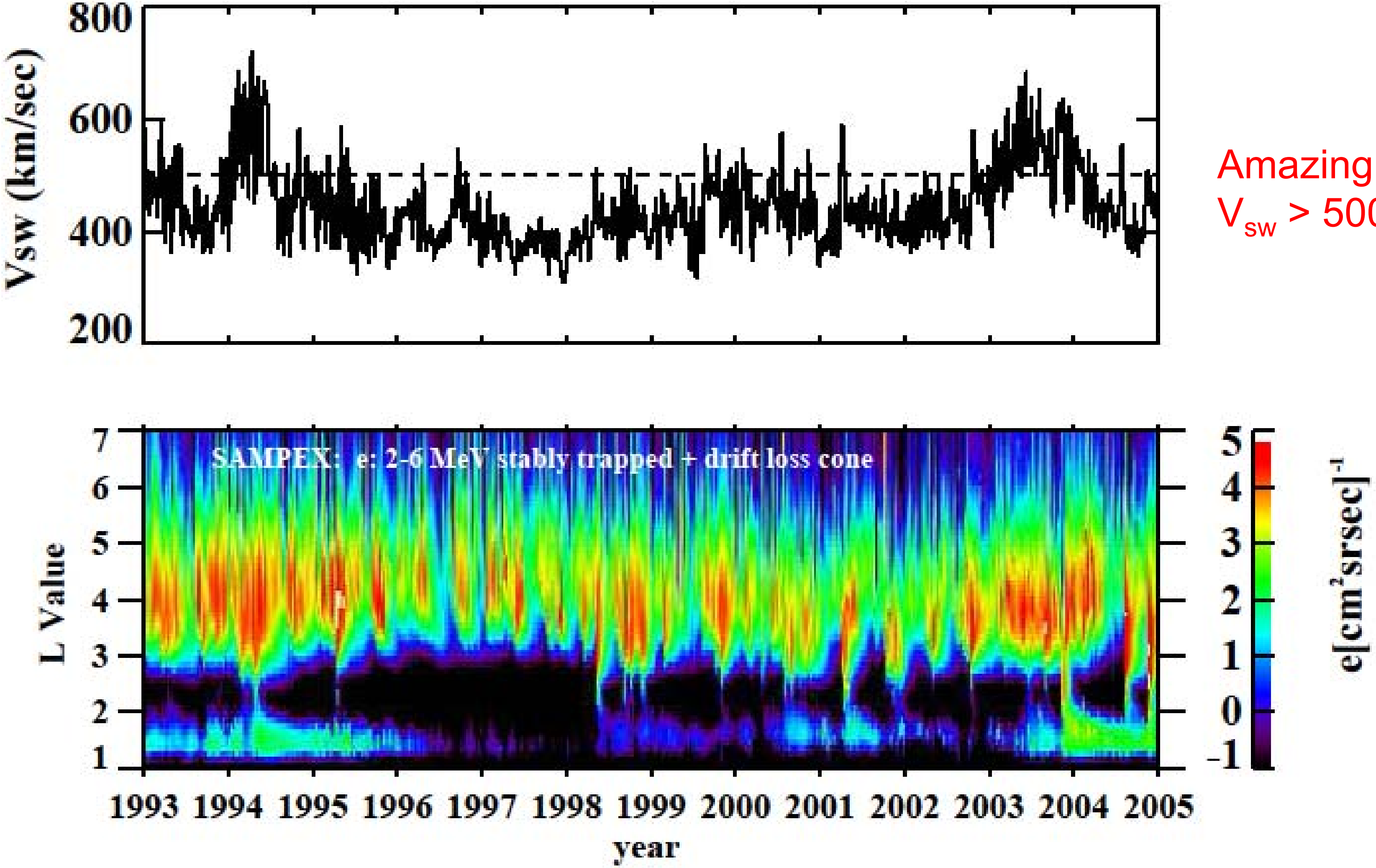


What Must We Learn?

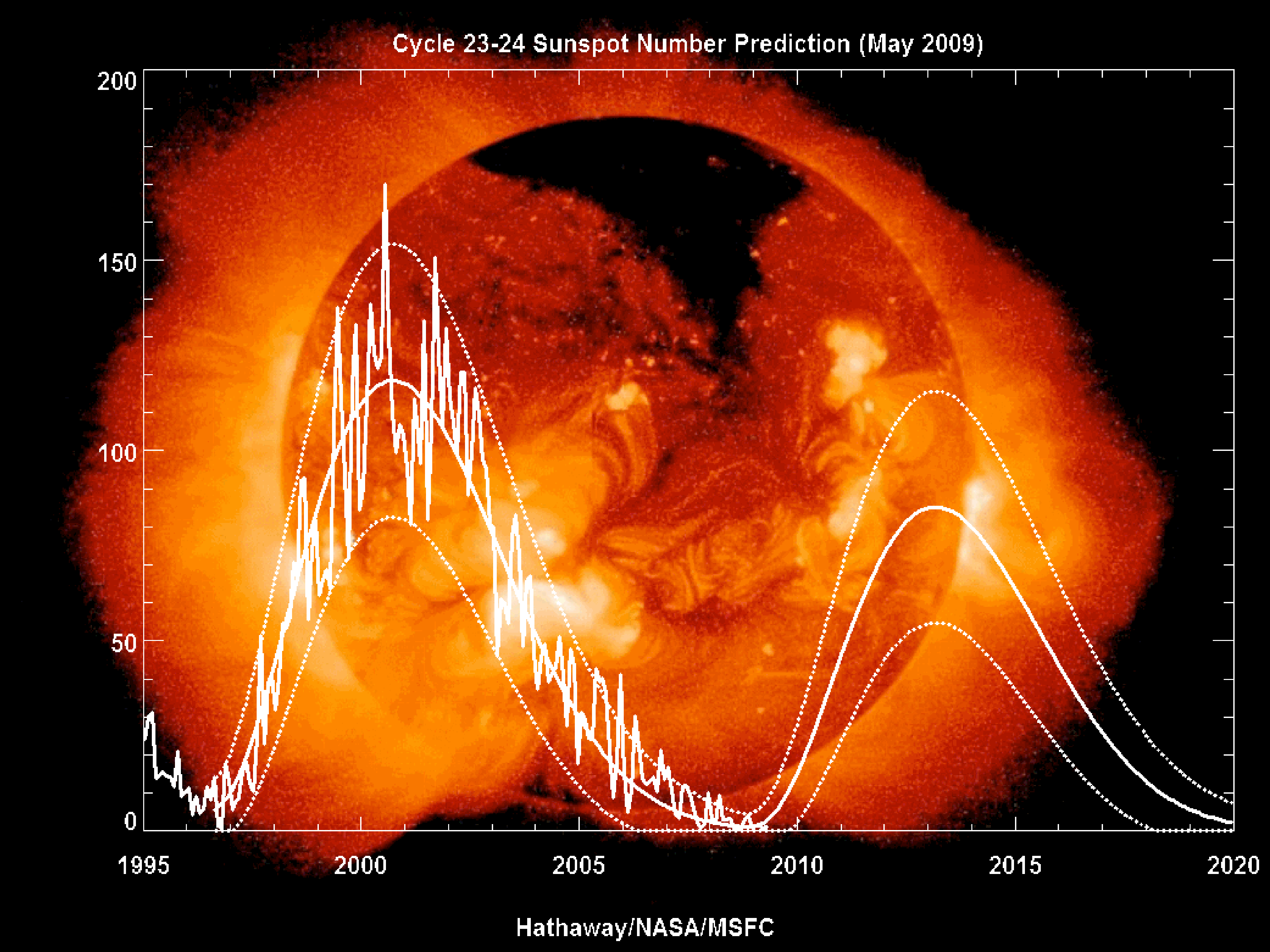
- We need to learn:
  - How complex systems catastrophically reconfigure themselves
  - How local (multiscale) turbulence relates to global-scale system instability: MMS
  - How the progression of geomagnetic disturbances relate to one another (and ultimately lead to global dynamical changes)



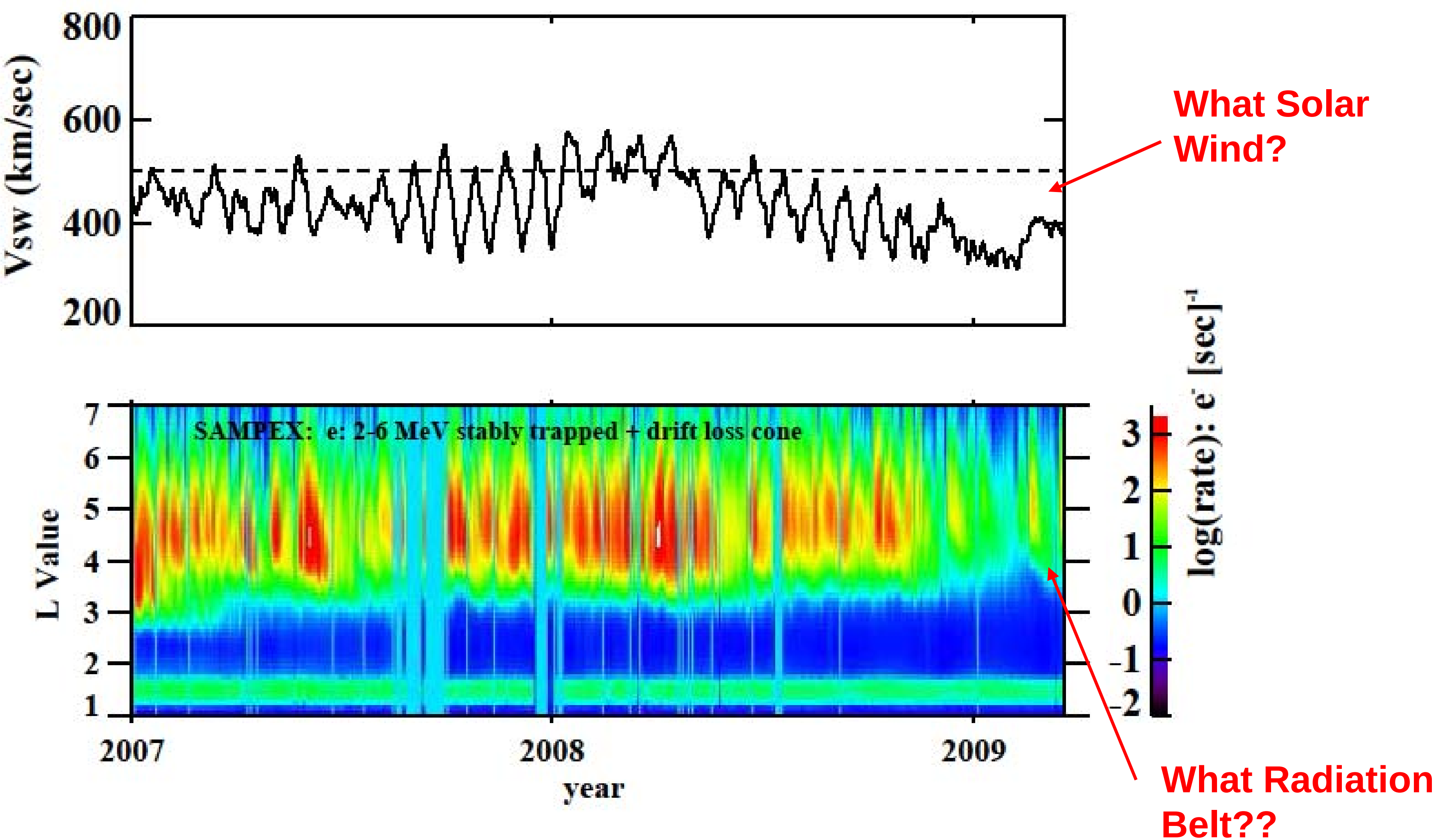
Solar Wind Control of Radiation Belts!

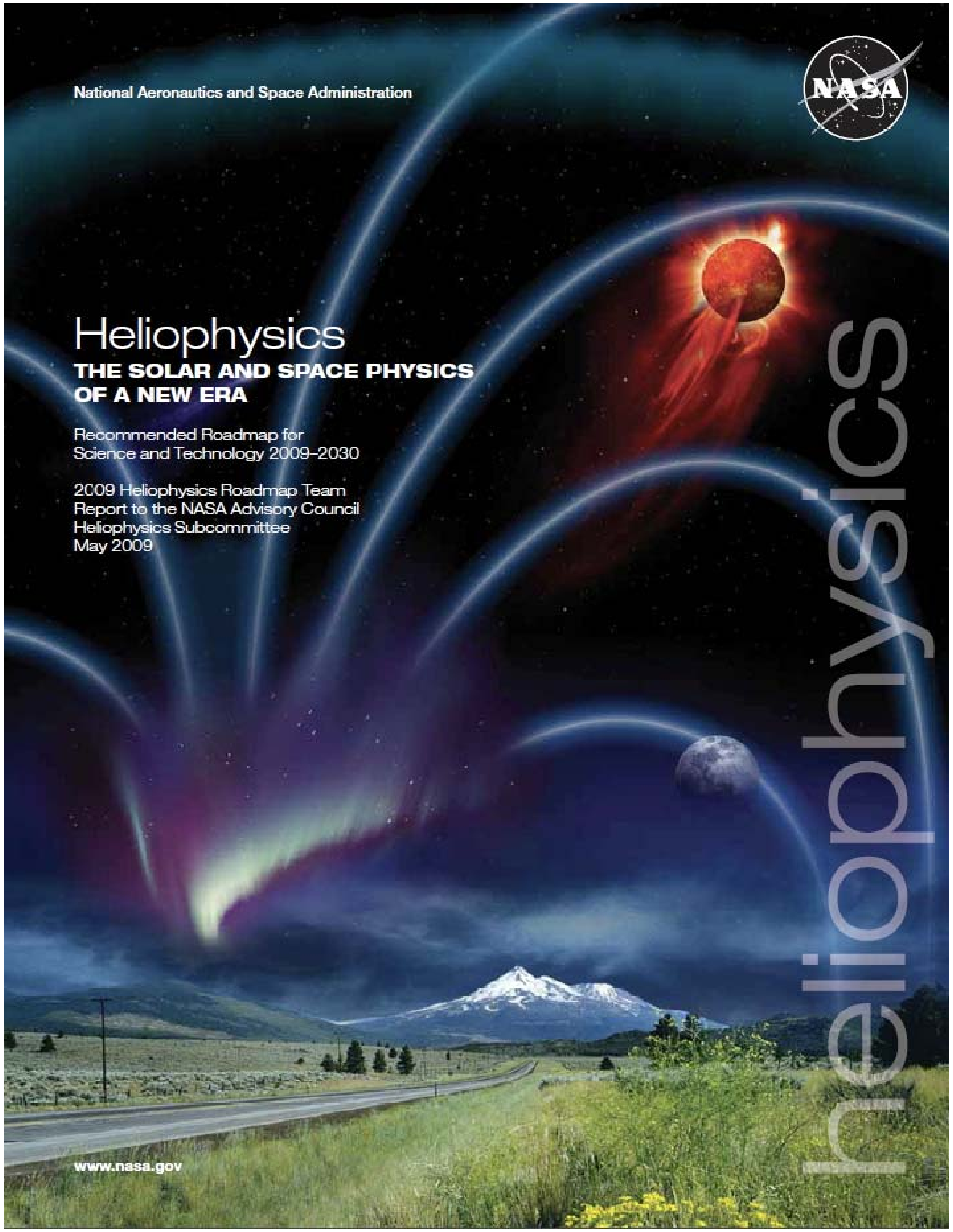


Amazing control:
V_{sw} > 500 km/s!!


Cycle 23-24 Sunspot Number Prediction (May 2009)
200
150
100
50
0
1995
2000
2005
2010
2015
2020
Hathaway/NASA/MSFC

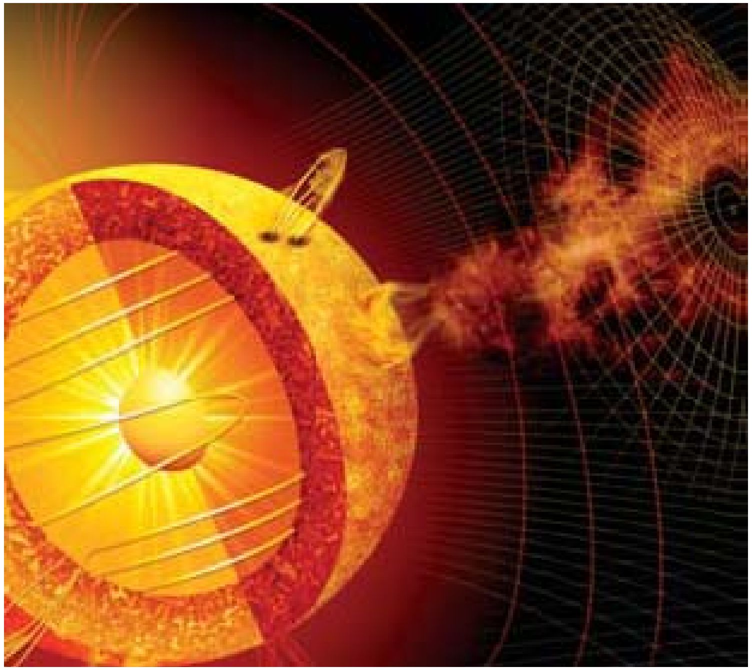
Nature's Remarkable Experiment!





2009 Heliophysics Roadmap

Heliospheric Magnetics



Understand the flow and dynamics of transient activity from the solar interior to Earth.

The causes and effects of transient solar activity are a main focus on the path to identifying the precursors and impacts of major solar eruptions.

The solar tachocline and convection zone are the origins of strong dynamo magnetic fields.

Detailed understanding of magnetic field formation and transport to the visible solar surface is crucial for the identification of triggers of sudden solar activity.

Trigger mechanisms may then be linked with the propagation and evolution of existing plasma and fields in the solar corona and inner heliosphere.

The synthesis of these elements leads to better physics-based predictive capabilities of space weather.

A systematic approach is needed, one that combines the physics of the solar interior with the evolution of the inner heliosphere, ideally from a location that permits observations of the Sun-Earth line.

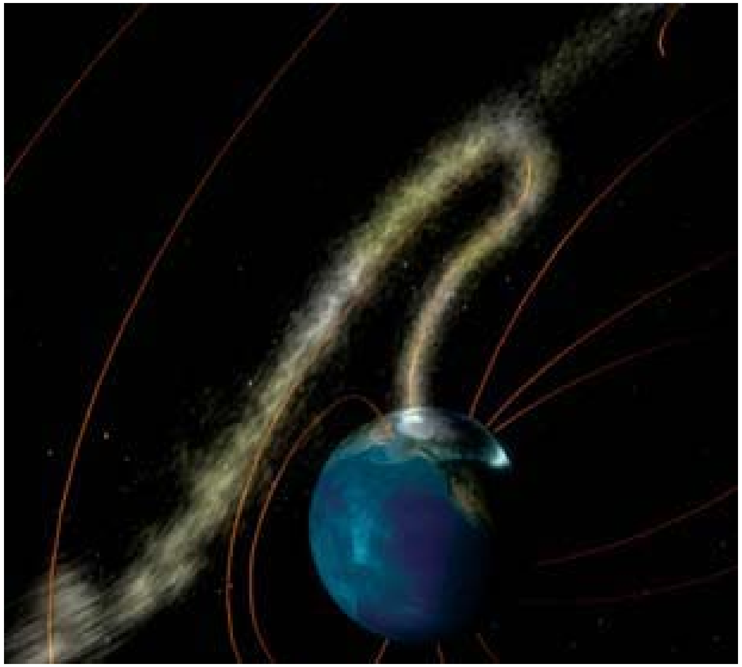
Measurements over a range of spatial and temporal scales should include:

- Helioseimology and vector magnetic field.
- Heliospheric imager.
- Coronal X ray imaging and spectroscopy.
- In situ solar wind plasma and magnetic field measurements.
- Energetic particle instruments.

Note that this is not a prioritized or complete list.

Recommended Mission Class: Medium

Dynamic Geospace Coupling



Understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.

The coupled ionosphere-magnetosphere system is highly nonlinear and dynamic. Scientists have catalogued the responses of different parts of the system and the general nature of the connections between them. Yet the processes that control the coupling or how the dynamics of one region of this systems of systems drive the dynamics in other regions are not understood.

The next scientific step is to simultaneously probe the dynamics in the magnetosphere and ionosphere.

Magnetospheric dynamics can be understood through in situ measurements across spatial scales characteristic of global circulation, while ionospheric dynamics can be remotely probed through auroral imaging.

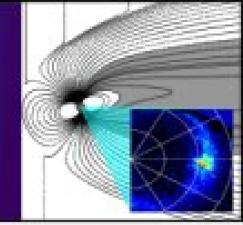
Auroral acceleration and heating change both ionospheric and magnetospheric currents as well as providing ionospheric plasma to the magnetosphere.

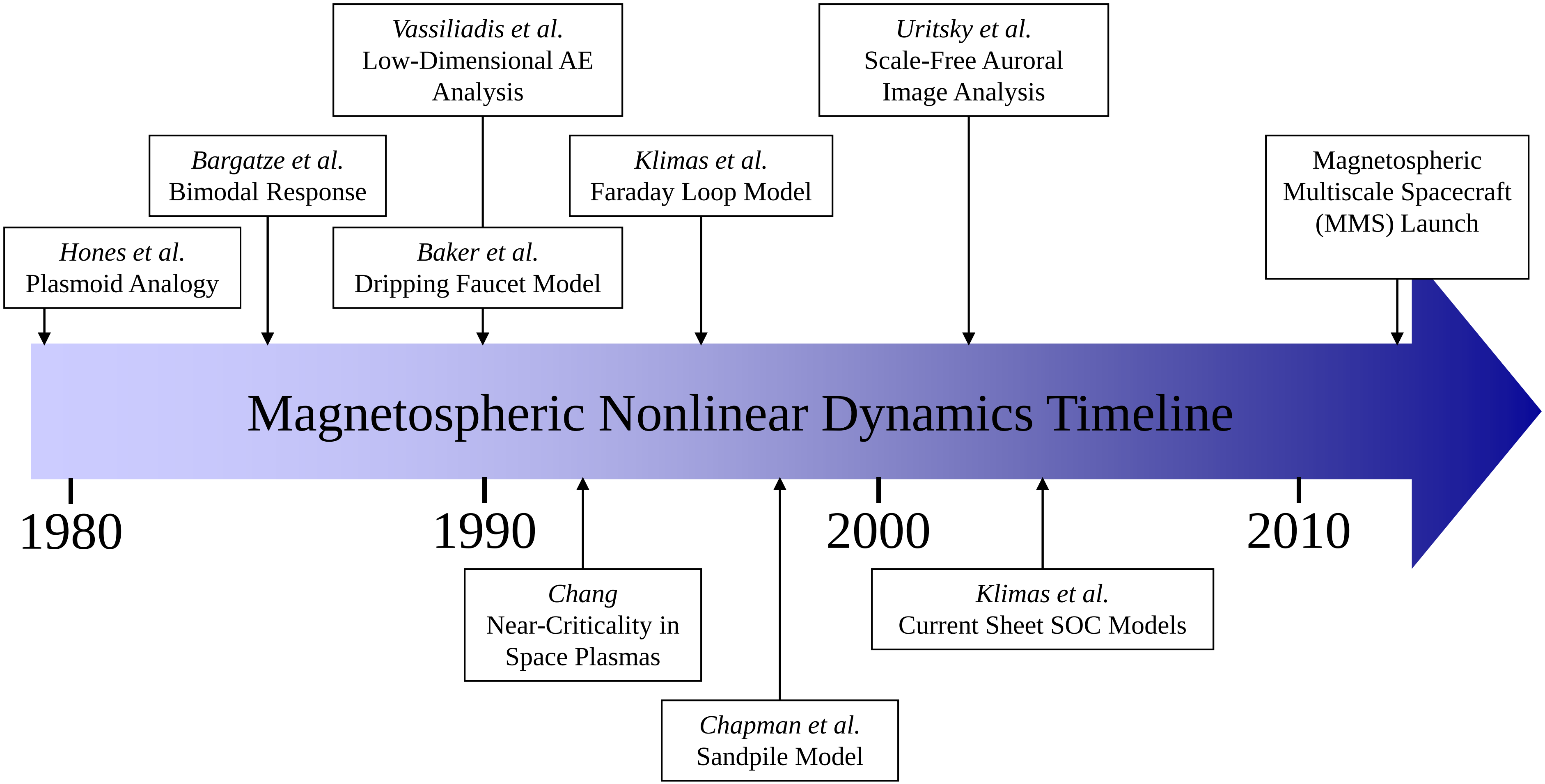
The nature of these processes, their linked responses to solar wind driving, and the interrelationships between different regions are the key to understanding dynamic geospace coupling.

To understand coupling between the ionosphere and magnetosphere systems it is necessary to make measurements of the dynamics of both. Magnetospheric dynamics are best measured by probes at multiple locations within the system separated spatially on scales that are characteristic of global circulation.

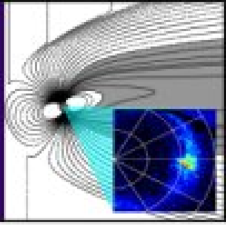
Recommended Mission Class: Medium

30 Years of Nonlinear Thinking





What Has Geospace Study Taught Us?

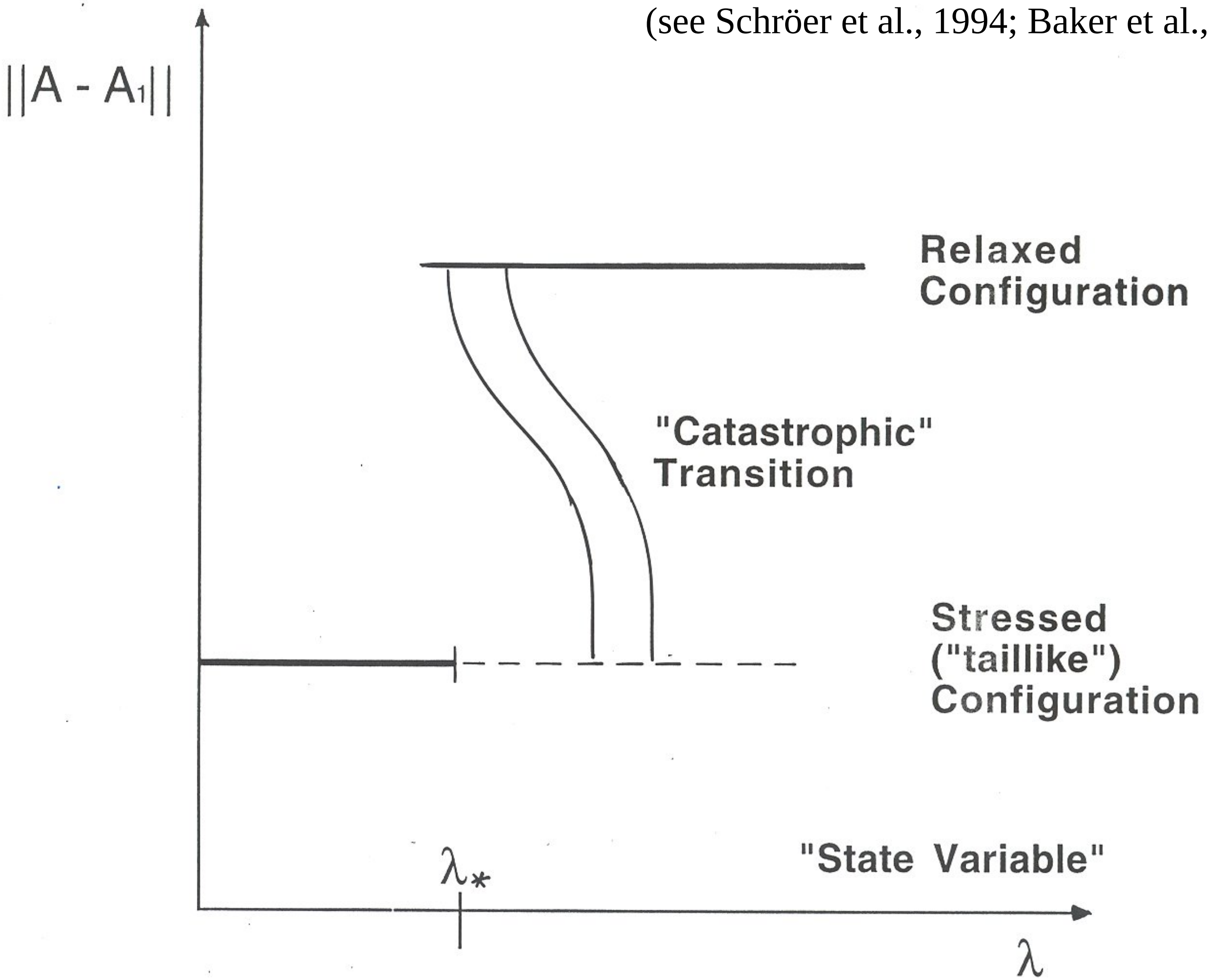


- Solar wind – magnetosphere – ionosphere system is characterized by nonlinear dynamics
- Methods borrowed from other branches of physics, chemistry, and biology can offer useful—if imperfect—analogies
- Ultimately, space plasma physics must depart from idealized local “stability” analyses to consider true system responses

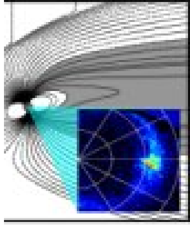
Thank you, Dennis, for your leadership!

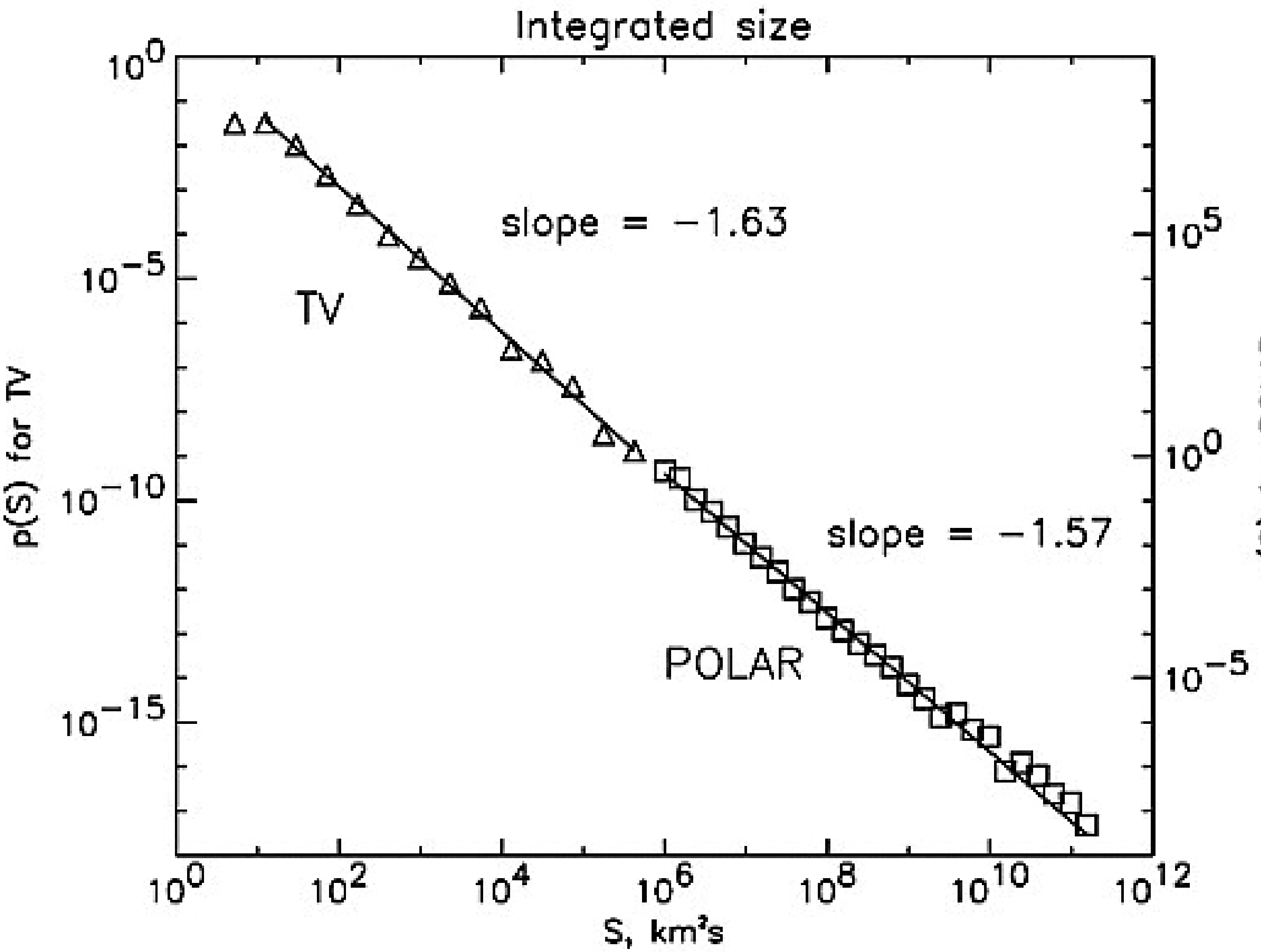
Catastrophic Magnetotail Transitions

(see Schröer et al., 1994; Baker et al., 1999)



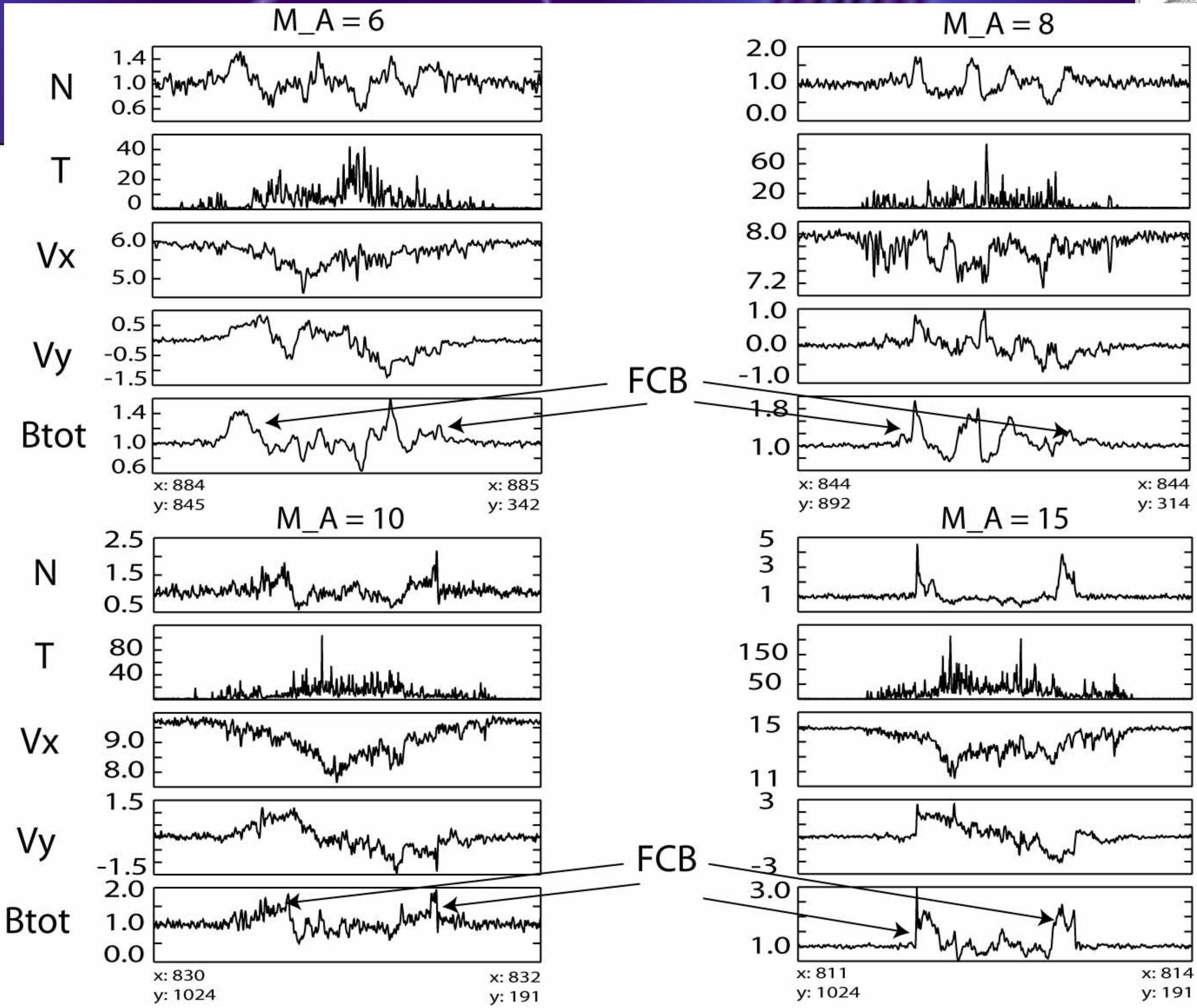
A, km²




Integrated size
slope = −1.63
TV
slope = −1.57
POLAR
p(S) for TV
p(S) for POLAR
S, km²s
10^0
10^−5
10^−10
10^−15
10^5
10^0
10^−5
10^0
10^2
10^4
10^6
10^8
10^10
10^12

NEXT SLIDE SHOWS:

Variations of density (N), ion temperature (T) and velocities Vx and Vy and total magnetic field (B) along cuts nearly parallel to Y axis from one side of the foreshock to the other for Mach numbers 6-15.

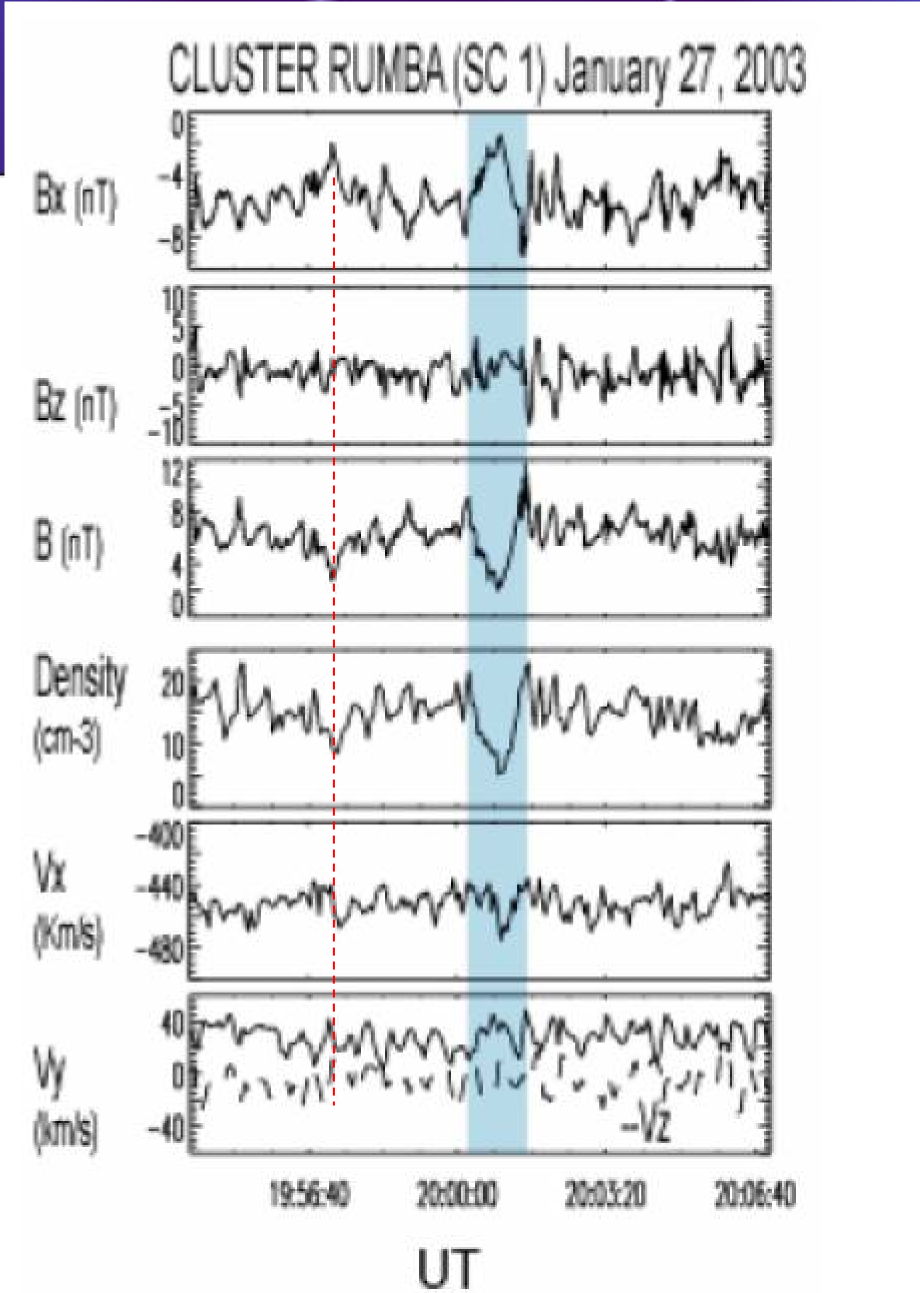


M_A = 6
N
1.4
1.0
0.6
T
40
20
0
Vx
6.0
5.0
Vy
0.5
-0.5
-1.5
Btot
1.4
1.0
0.6
x: 884
y: 845
x: 885
y: 342
M_A = 8
2.0
1.0
0.0
60
20
8.0
7.2
1.0
0.0
-1.0
1.8
1.0
x: 844
y: 892
x: 844
y: 314
FCB
M_A = 10
N
2.5
1.5
0.5
T
80
40
Vx
9.0
8.0
Vy
1.5
-1.5
Btot
2.0
1.0
0.0
x: 830
y: 1024
x: 832
y: 191
M_A = 15
5
3
1
150
50
15
11
3
-3
3.0
1.0
x: 811
y: 1024
x: 814
y: 191
FCB

NEXT SLIDE SHOWS:

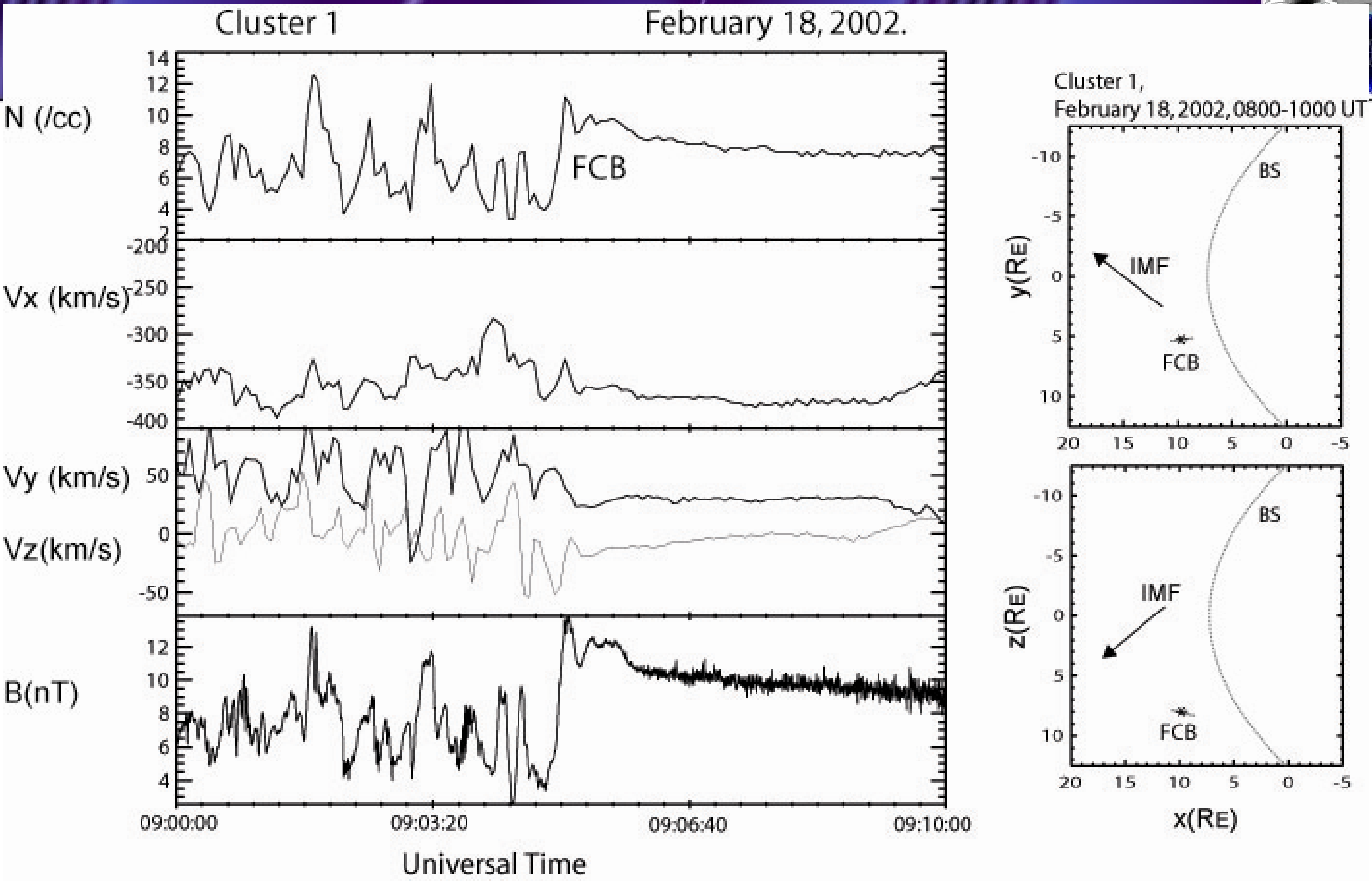
A simple fluid picture for the formation of the FCB is that the presence of the backstreaming ions in the foreshock results in enhanced pressure compared to solar wind pushing it outward (perpendicular to flow). As the Mach number increases this pressure becomes larger and FCB becomes stronger.

The kinetic reason for the formation of FCBs is the nonlinear evolution of ULF waves and formation of regions of density and magnetic field drop by ~ 50%. We have named these Foreshock Cavitons and have found numerous examples in the Cluster data. Next slide shows examples of a fully developed Caviton and one in the process of formation. The size of Foreshock Cavitons is ~ > R_E



From :
Blanco-Cano et al. (2009) JGR

Simulations show that FCBs form over a broad range of cone angles. Cluster observations confirm the model predictions as shown in the example in the next slide

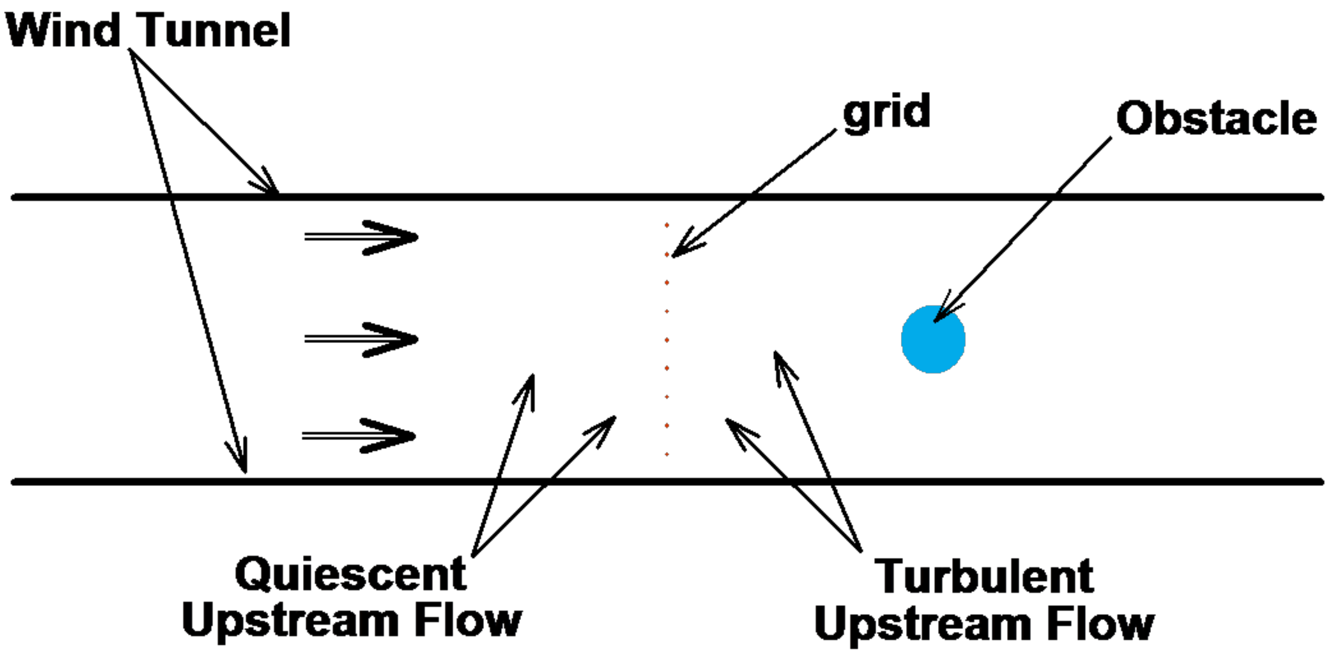


Omidi et al. (2009) JGR, in press

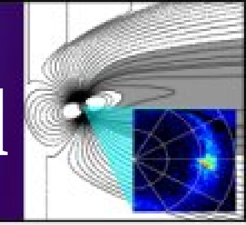
Upstream Turbulence in Aerodynamics

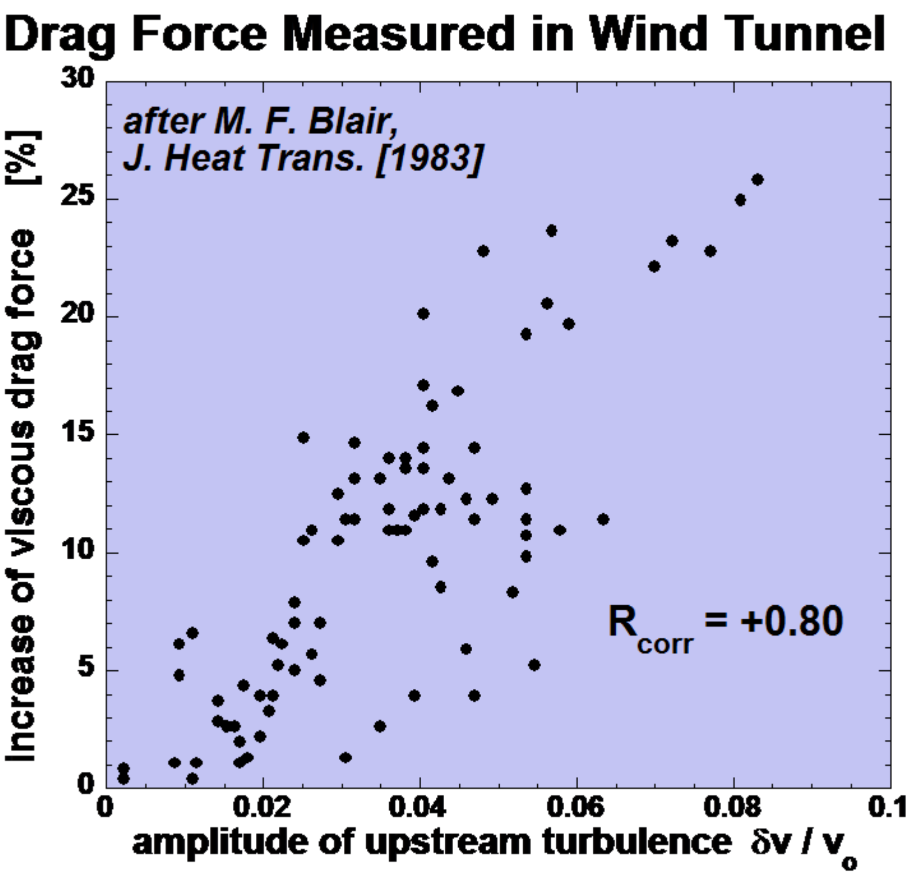
The presence of ambient turbulence in a fluid affects the manner in which a flow couples to an obstacle:
1) It can lead to an increased surface drag [*Jeffreys*, 1925]
2) It can change the flow pattern around an obstacle [*Castro* + *Robbins*, 1977].

The "upstream effect" is quantified in a wind-tunnel experiment:



Drag Force Measured in Wind-Tunnel





An increased level of upstream turbulence increases the coupling of a fluid to an obstacle.

Explanation: The eddy viscosity of the wind is controlled by the level of turbulence in the wind.

Theoretically, MHD fluids can also have eddy viscosity.

¿Does this work for the coupling of the turbulent solar wind to the Earth's magnetosphere?

Origin of Near-Earth Plasma (ONEP)

Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.

Plasma of ionospheric origin is now widely ecognized as a critical constituent of magnetospheric dynamics, providing the primary source of plasma for the ring current and plasma sheet during active conditions.

The key unknown is how this plasma is heated and accelerated so that it may escape Earth’s gravitational bounds.

Candidate heating processes include Joule dissipation through ion-neutral collisions, energetic particle precipitation, and wave heating.

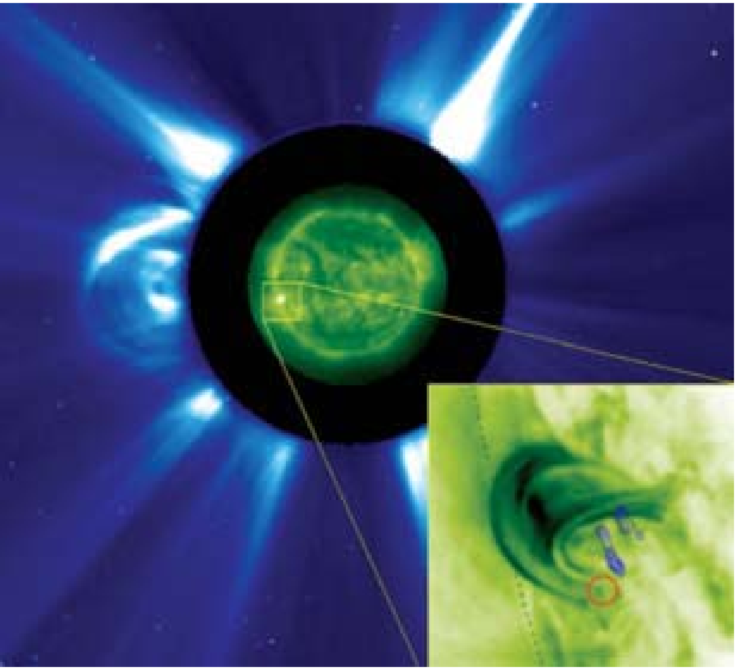
Information is needed on the sources of energy, the heating and dissipation processes, and characterization of the modes of energy transfer from above and below.

- Ion and neutral composition - thermal energies
- Ion and neutral fl ow velocities
- Ion energy and pitch angle distribution - up to 20 keV
- Electron energy and pitch angle distribution - up to 20 keV
- Magnetic fields DC - 1 kHz
- Electric fields DC - 1kHz
- Plasma density, electron temperature

Note that this is not a prioritized or complete list.

Recommended Mission Class: Small

Solar Energetic Particle Acceleration and Transport



Understand how and where solar eruptions accelerate energetic particles that reach the Earth.

Solar activity is often linked to the release of highly energetic particles, including heavy ions.

The origin and the mechanisms that accelerate particles to high energies

close to the Sun are neither fully identified nor understood.

Heavy-ion charge states form an equilibrium shaped by the constant interaction with electrons in the strong solar magnetic fields.

They are a unique identifier for the site of acceleration

and processes between the Sun and the spacecraft.

A strategy for a breakthrough in the area of solar particle acceleration is a mission that can separate the effects of particle transport from pure acceleration signatures.

Thus, in situ measurements of energetic particles from multiple vantage points in the inner heliosphere, coupled with advanced particle transport modeling and theory, are needed to resolve this long-standing problem.

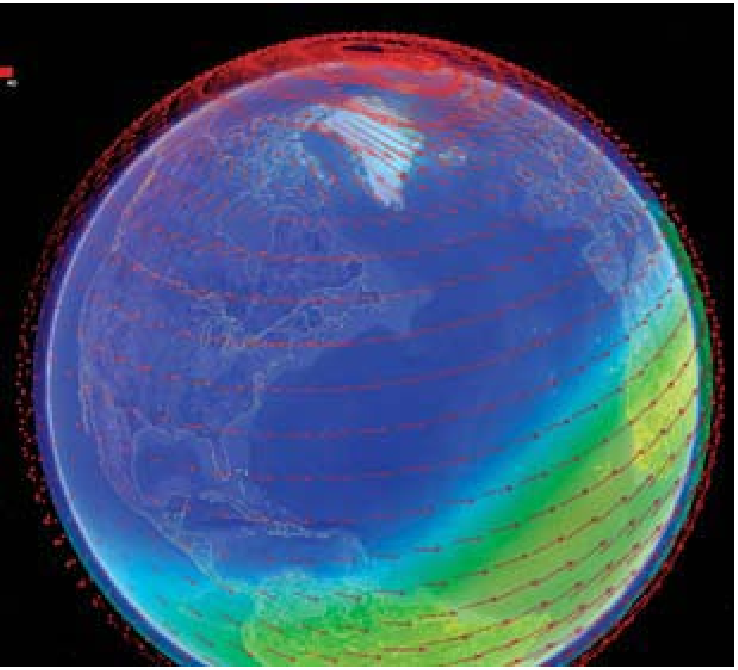
Measurements over a range of spatial and temporal scales could include:

- Energetic Particle Intensity, Anisotropy, Composition, and Charge State.
- Solar Radio Observations.
- Solar Wind and Interplanetary Magnetic Field.
- Coronal Soft X-ray Imaging/Timing.

Note that this is not a prioritized or complete list.

Recommended Mission Class: Small

Ion-Neutral Coupling in the Atmosphere



Understand how neutral winds control ionospheric variability

Measurements of neutral winds are crucial for understanding ionospheric variability; the paucity of such measurements represents the greatest experimental impediment to progress.

Previous missions discovered that coupled parameters must be measured to understand the system and showed that the ion and neutral motions depend on prior history of the system, not just the present state.

There are almost no observations of the ionospheric density, composition, and the altitude variation of the neutral winds below 250 km.

At low latitudes near 300 km, there are indications that the variability about the mean value is of the same order as the mean value itself.

At high latitudes near 300 km, the neutral winds appear to be strongly driven by collisions with ions and electrodynamic coupling to the magnetoshphere.

- IT winds and temperatures.
- Altitude profiles of neutral and ion properties.
- Lower atmospheric waves.
- DC E fields and ion drifts.
- Knowledge of E-field with neutral wind.
- Knowledge of neutral winds with ion density.
- Gravity waves in the middle atmosphere.
- Range of spatial and temporal scales

Recommended Mission Class: Medium

Climate Impacts of Space Radiation

Understand out atmosphere's response to auroral, radiation belt, and solar energetic particles and the associated effects on ozone.

Generation of odd nitrogen in the thermosphere, especially at high latitude, is well known, but transport processes to the middle atmosphere are poorly understood due to a paucity of measurements.

Changes of odd nitrogen and ozone in response to solar energetic particle events have been observed but are not yet understood.

Radiation belt particles penetrate into the mesosphere but the causal linkage with middle atmospheric chemistry is speculative.

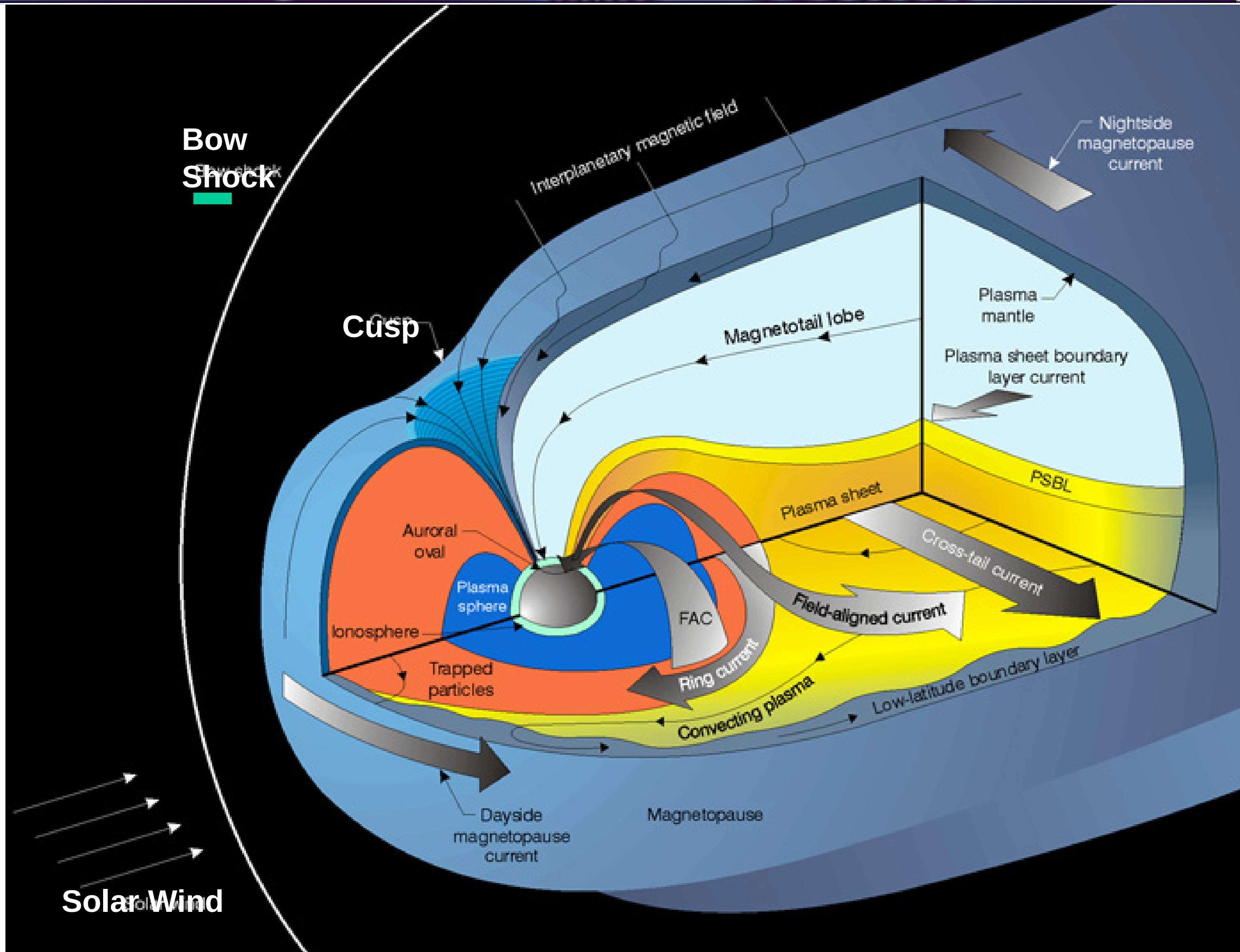
Changes in ozone alter the thermal budget of the middle atmosphere so that a climate linkage is possible, but, without observations, this cannot be explored.

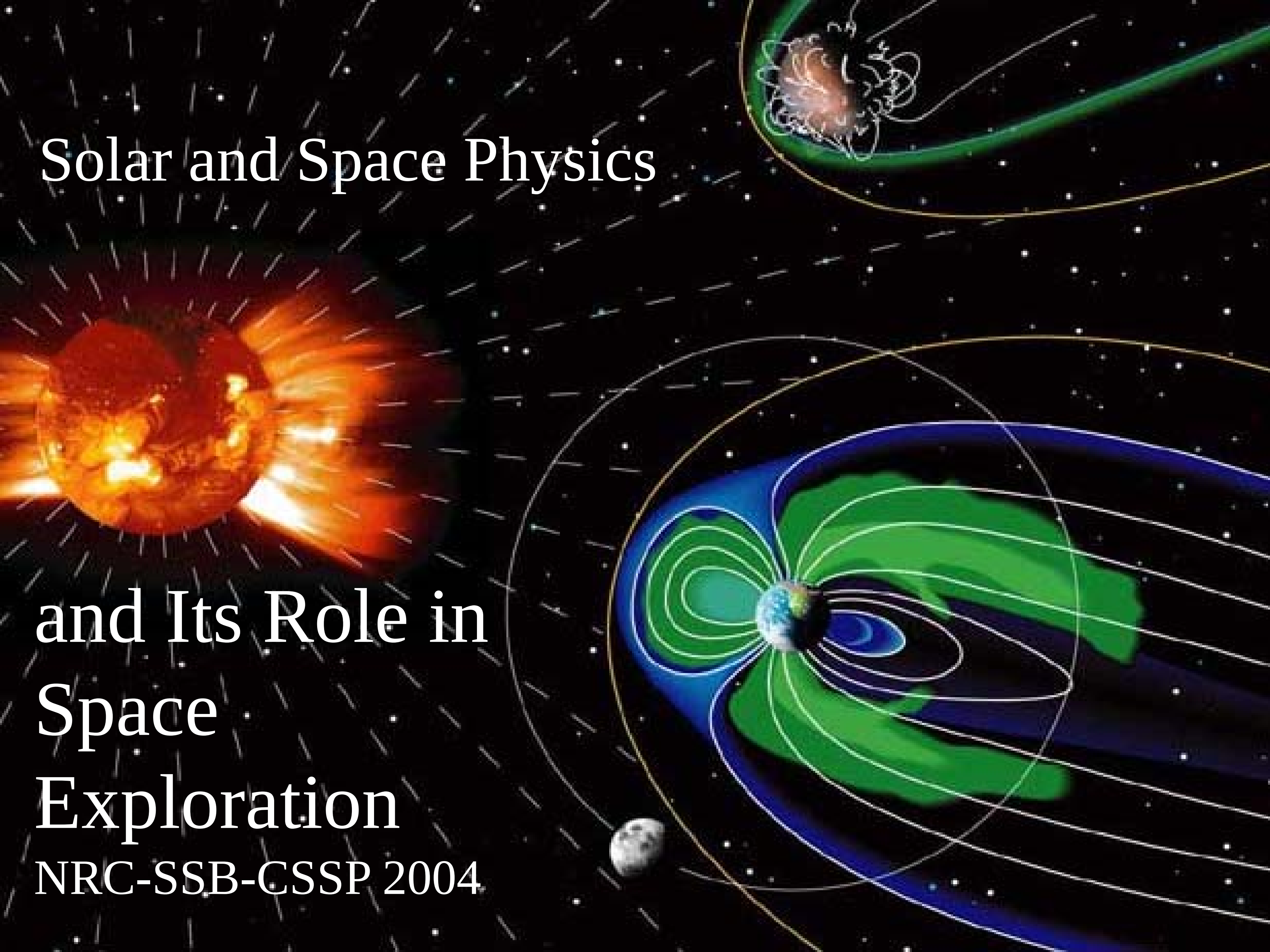
Measurements over a range of spatial and temporal scales could include

- High-energy particle inputs to the upper atmosphere.
- Auroral particle inputs to the upper atmosphere.
- Reactive chemical distribution, including ozone and various odd-nitrogen compounds.
- Upper- and middle-atmosphere temperature profiles.
- Upper- and middle-atmosphere neutral winds.

Recommended Mission Class: Small

Earth’s Magnetospheric System



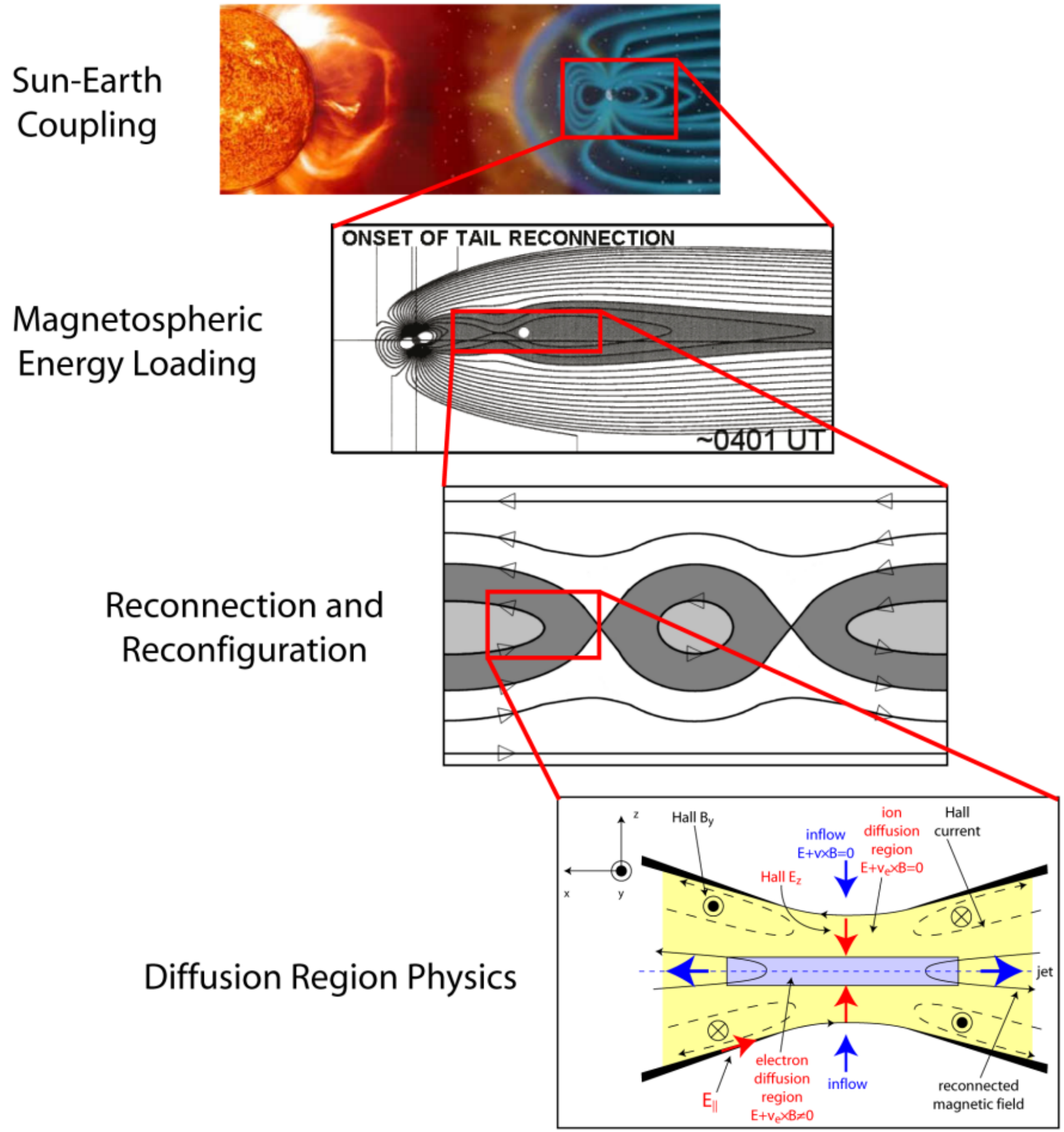


Solar and Space Physics

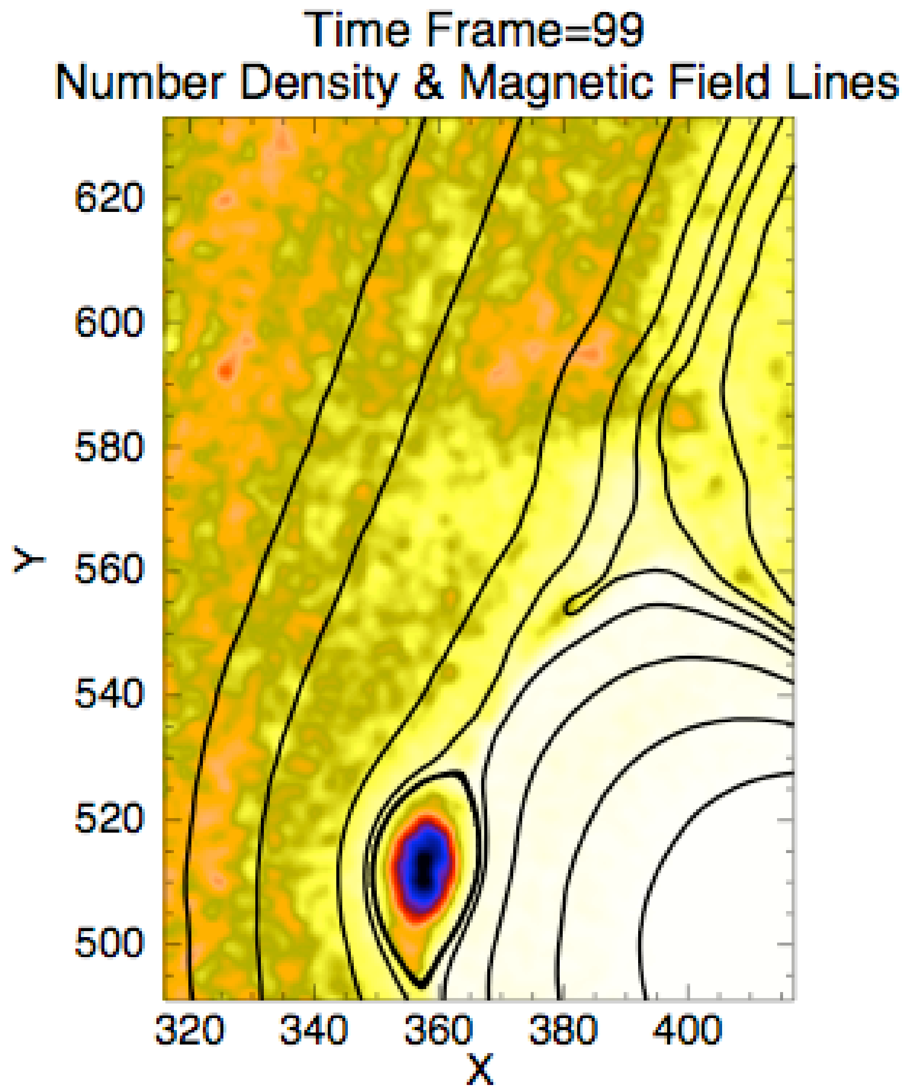
and Its Role in Space Exploration

NRC-SSB-CSSP 2004

Multi-Scale Phenomena in Magnetospheric Substorms



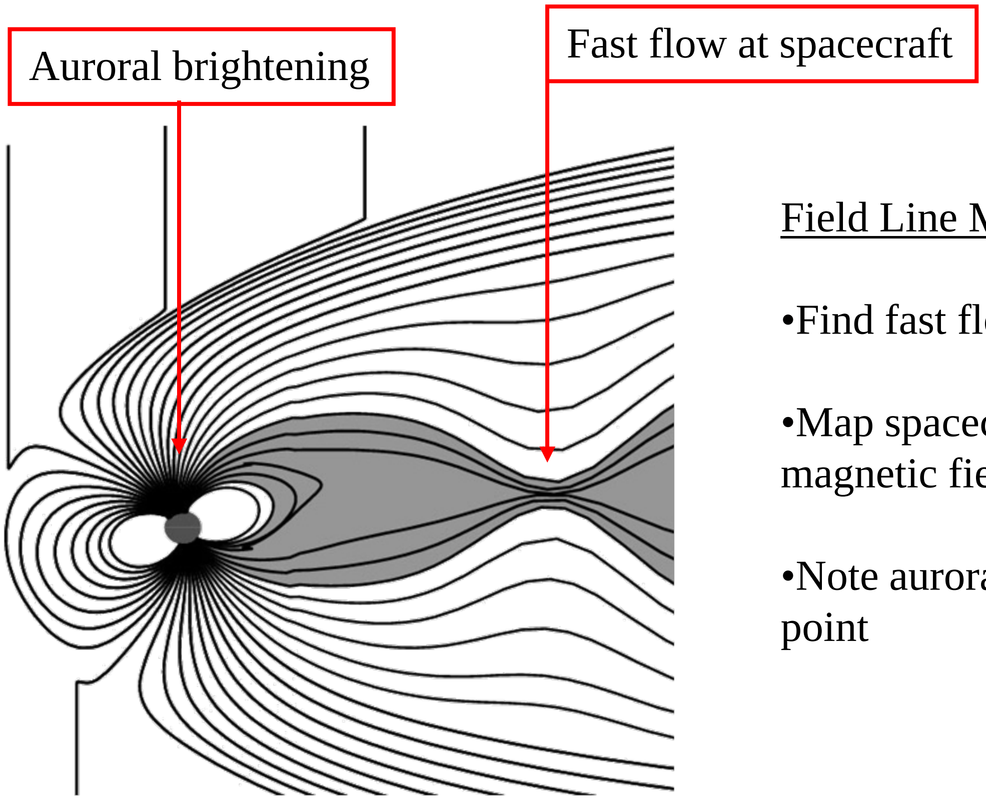
Flux Transfer Events

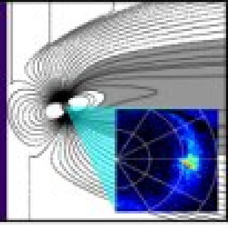


FTEs in Simulations

Omidi & Sibeck [2007]

Bursty Bulk Flows, Fast Flows, and Auroral Brightening





Field Line Mapping:

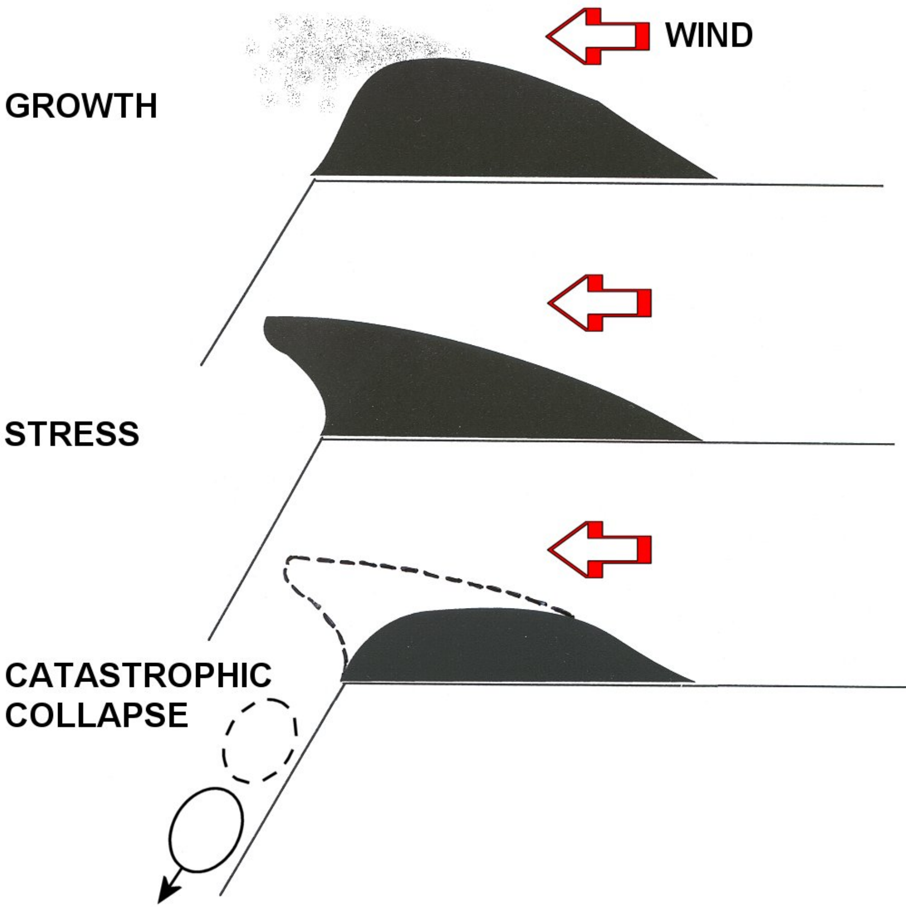
•Find fast flow at spacecraft in tail

•Map spacecraft position to ionosphere using magnetic field model

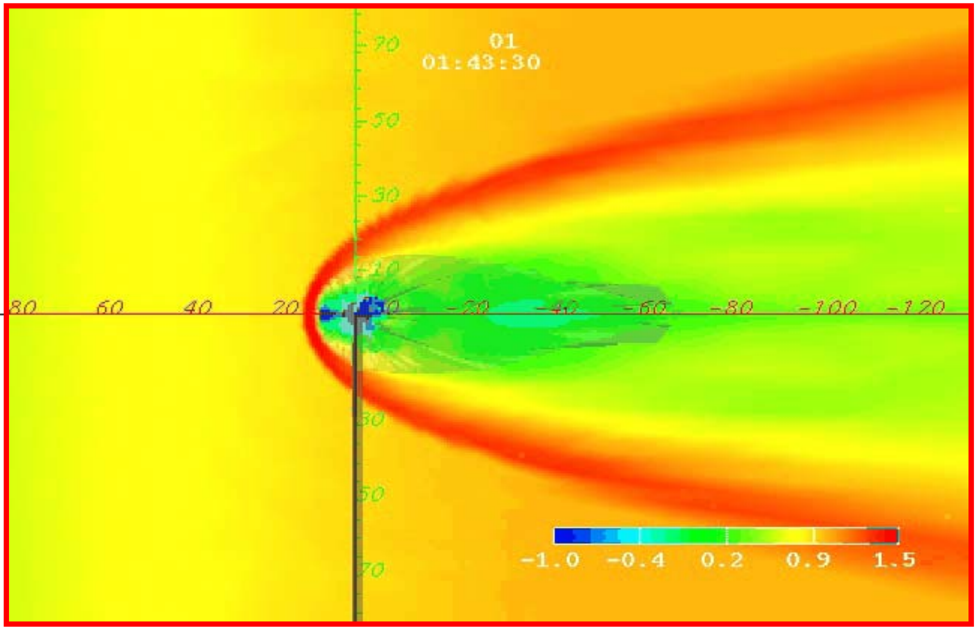
•Note auroral brightening at field line foot point

Catastrophic Magnetotail Transitions

A Sand Dune Analogy *(Baker et al., 1999)*



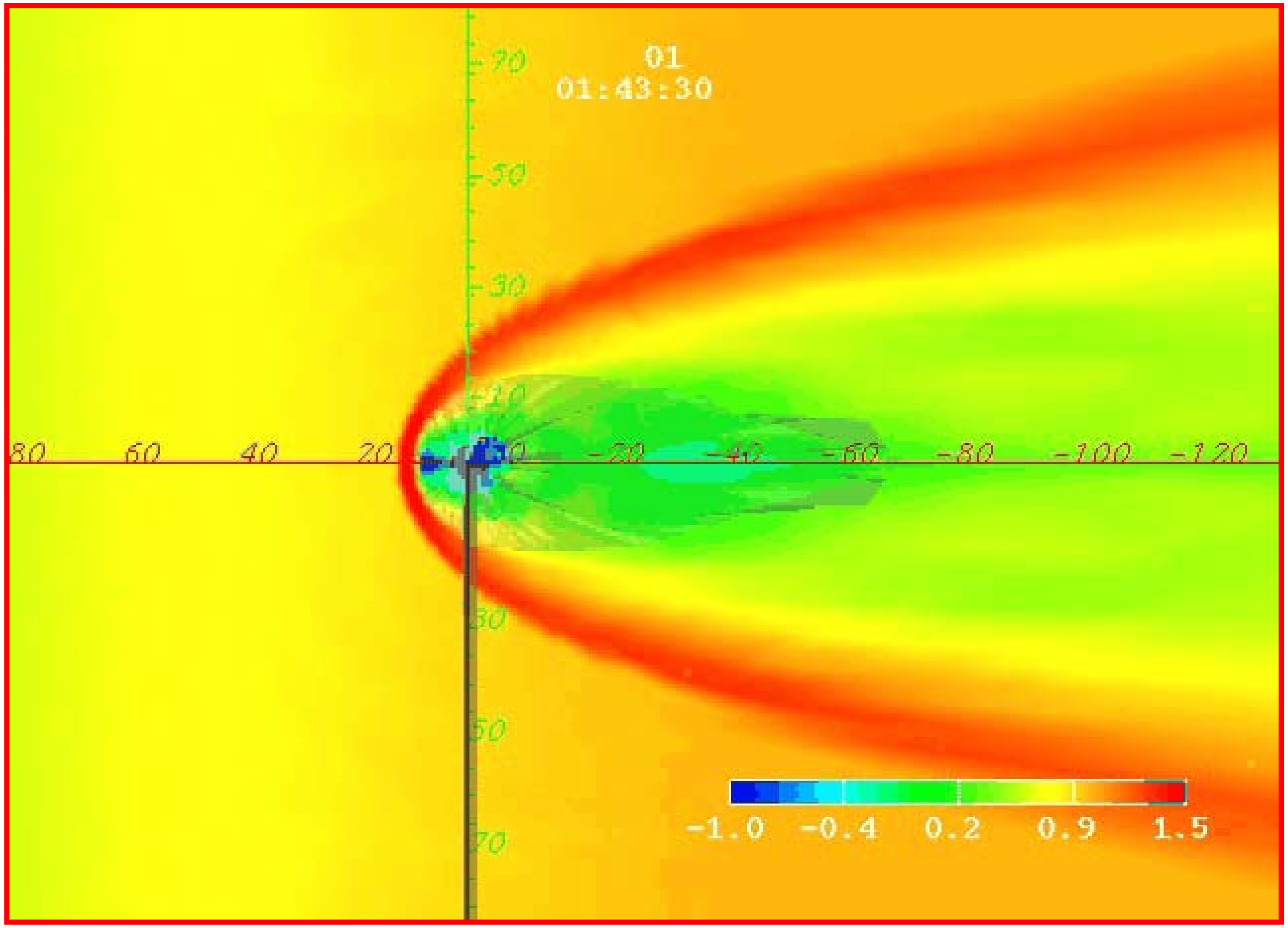
An MHD Numerical Simulation



Analogous Magnetotail Characteristics

- Loading-unloading system
- Threshold instability
- Criticality
  - Localized events distributed spatially and temporally indicates plasma sheet region generally near instability
- Scale-free avalanche distributions
  - Localized reconnection, pseudobreakups, substorms
- Sensitivity to external disturbances
  - Externally triggered substorms

Advanced Numerical Simulations

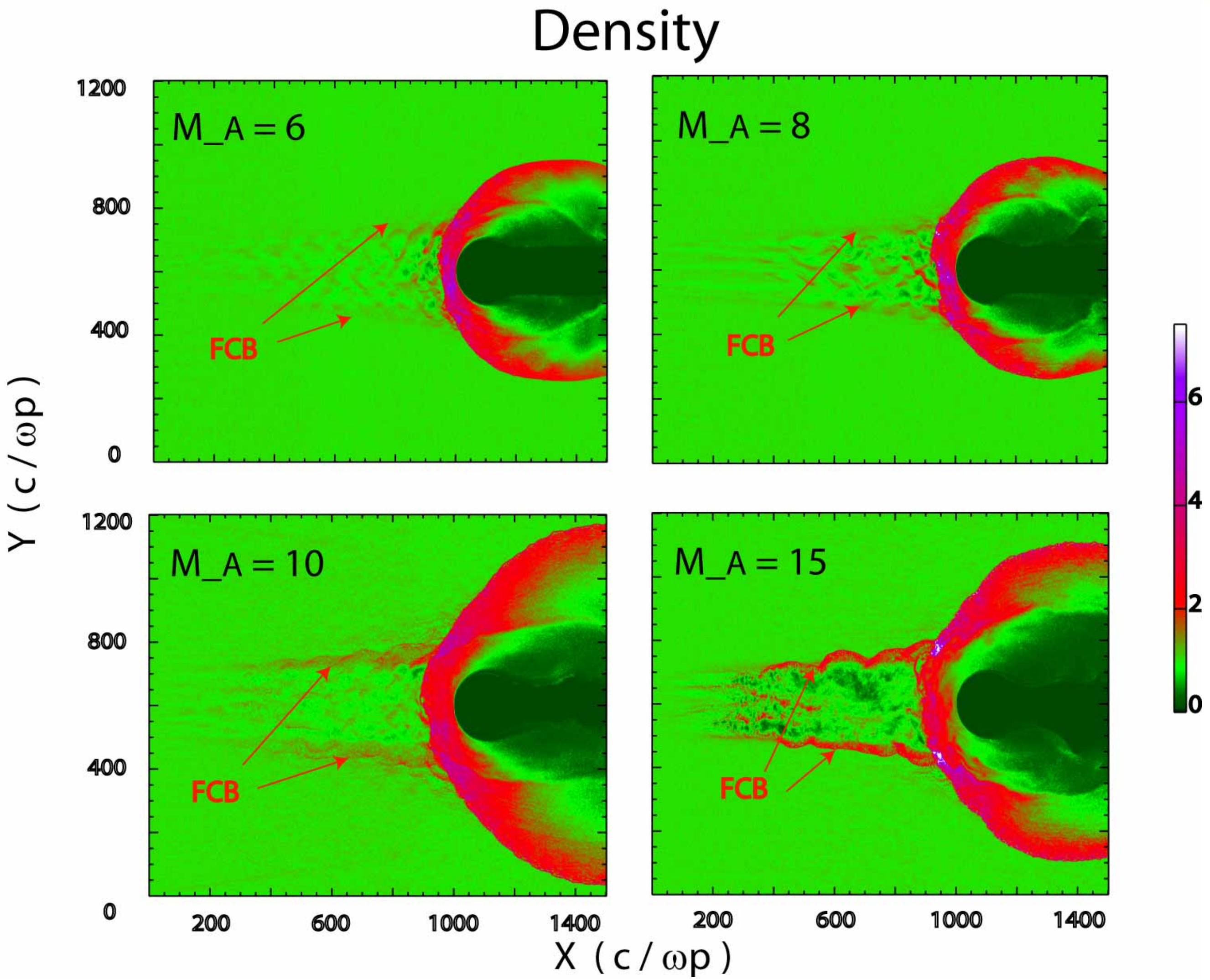


NEXT SLIDE SHOWS:

Plots of density from four runs corresponding to solar wind speeds of 6 to 15 V_A during radial IMF. It demonstrates the formation of the Foreshock Compressional Boundary (FCB). This boundary becomes stronger with increasing Mach number and transitions from a fast magnetosonic pulse to a true shock wave with normal nearly perpendicular to the flow.

In general FCB and the ion beam and ULF foreshock boundaries do not coincide and are different.

Radial IMF



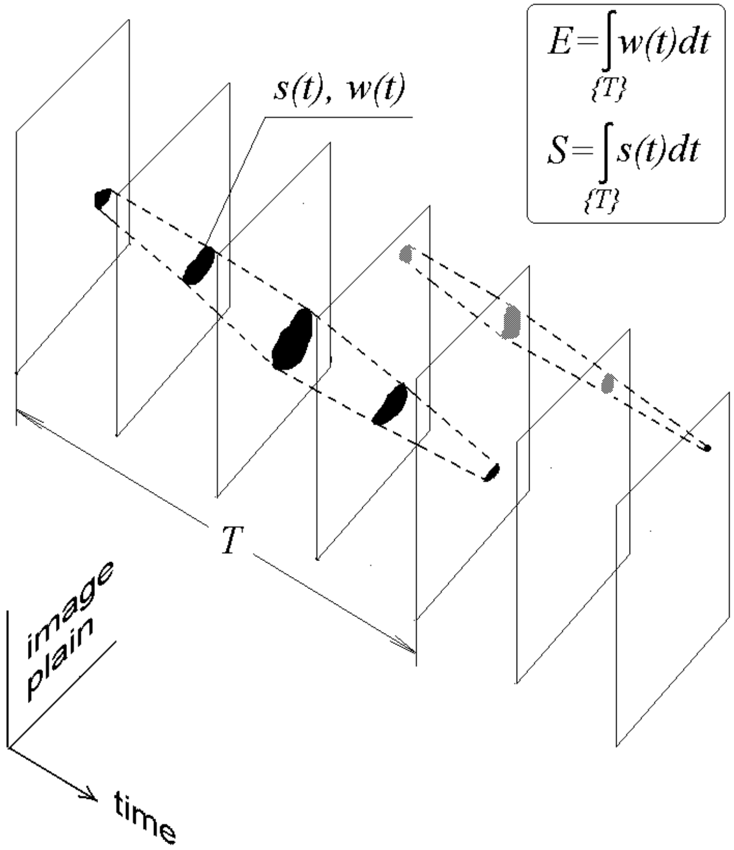
Omidi et al. (2009) JGR, in press

FTE formation and interaction with the cusps

From Omidi and Sibeck (2007) GRL

Auroral Bright Spots

Plasma Sheet Avalanche



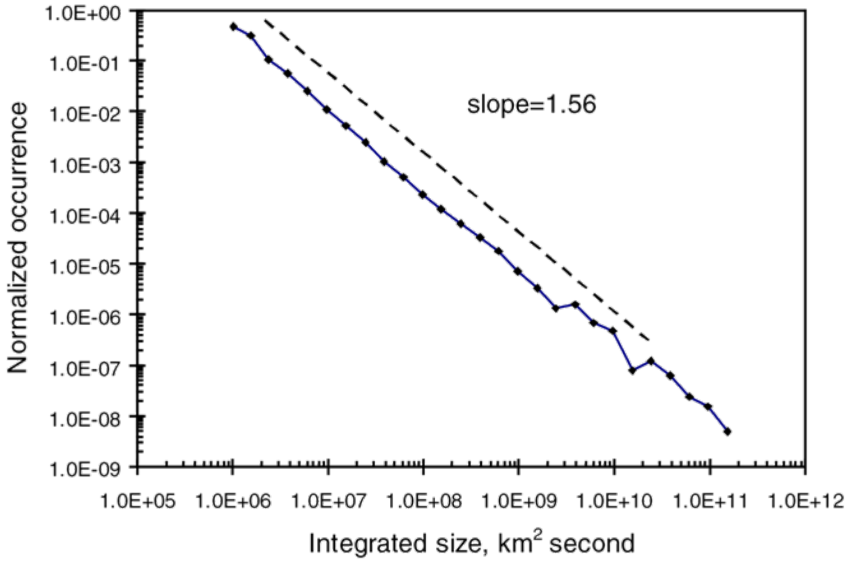
Distributions of bright spot sizes and emitted energies are examined for evidence of scale-free avalanche activity

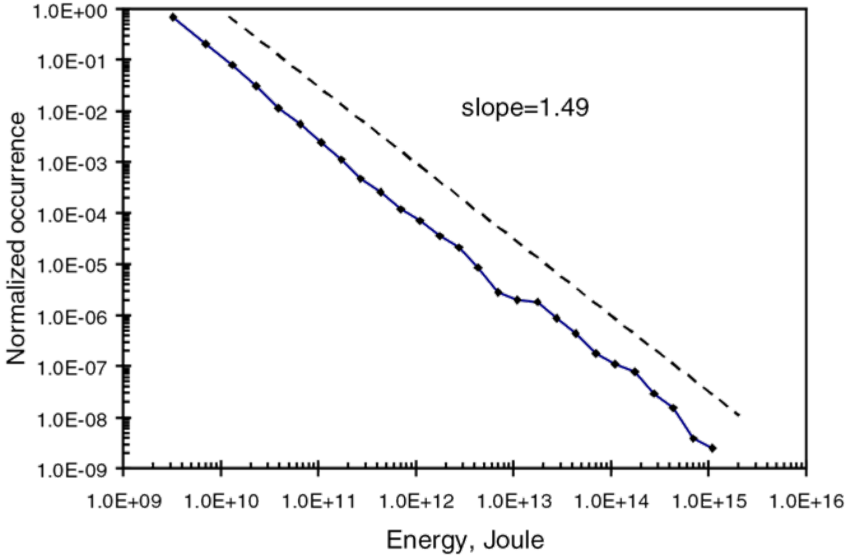
Avalanche activity must be analyzed using methods that show SOC in sand-pile models

Each avalanche must be tracked from beginning to end to determine its total size and energy emission

(Uritsky et al., JGR, 2004)

Burst Size and Energy Distributions





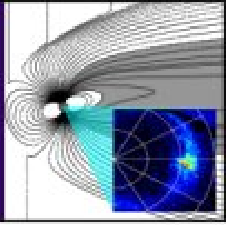
The range of scale invariance in these distributions is exceptional

One of the very few examples of such broad-band self-similarity in nature

Strong evidence in support of self-organized criticality

(Uritsky et al., JGR, 2004)

Ionospheric Consequences

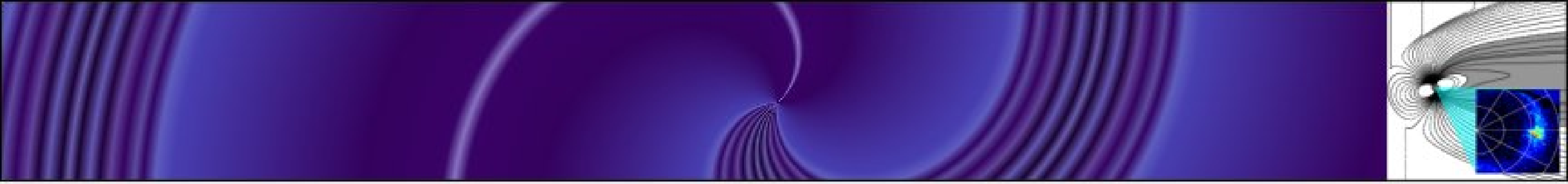


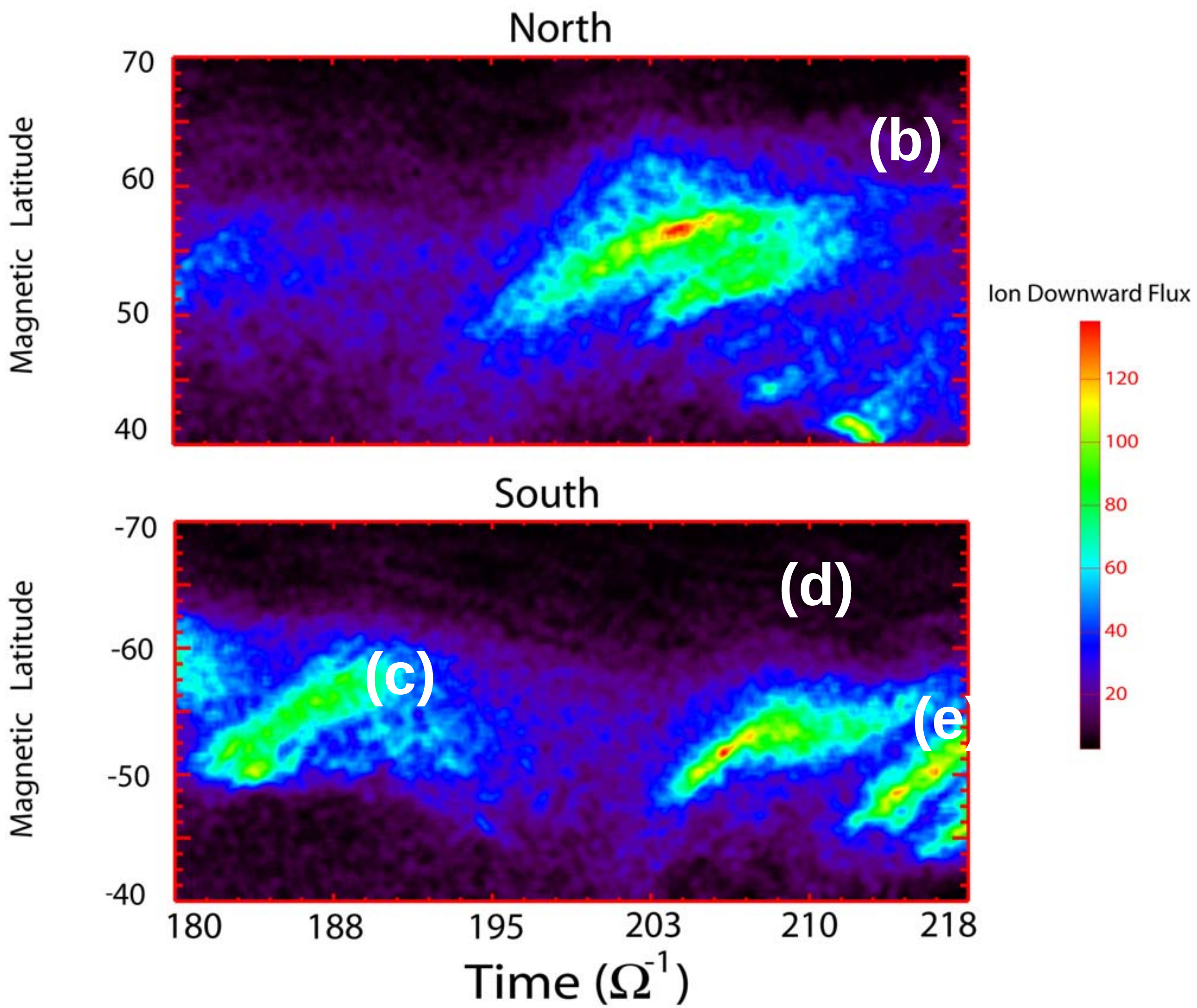
- It is believed that poleward moving auroral forms (PMAFs) are the consequence of FTEs in the cusp

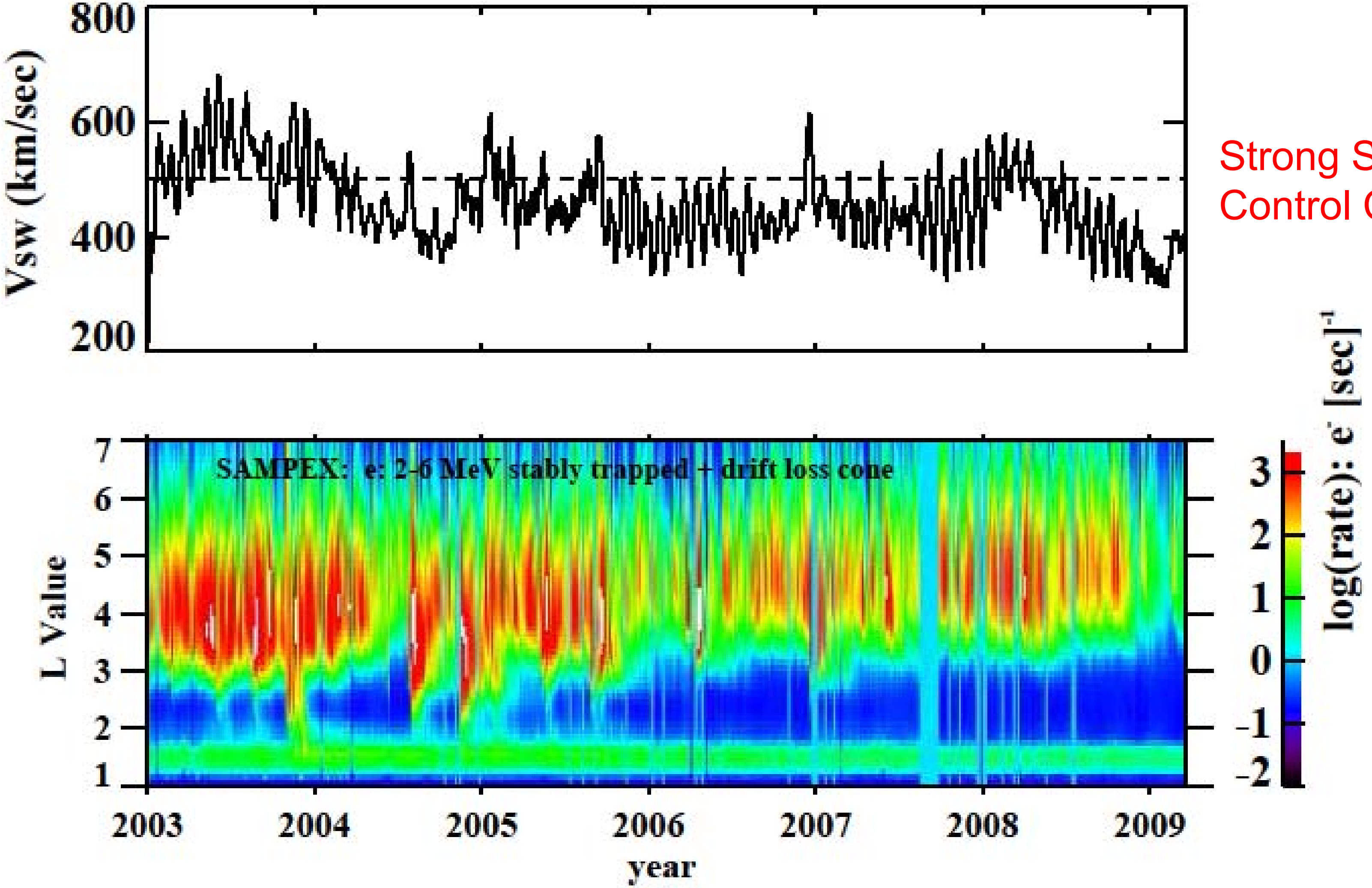
- Fasel et al. [1994] identified three classes of PMAFs based on their motion and brightening history. PMAF1 move into the polar cap and fade, while PMAF2 rebrighten as they move poleward. PMAF3 are similar to PMAF2 except that they slow down and stop (at the same latitude) while rebrightening

- We examine the ionospheric consequences of FTEs by looking at the downward flux of 0.25 keV ions as a function of time and latitude at low altitude

- Next figure shows 6 enhancements in the downward flux of ions labeled (a) – (f)
- Feature (a) is due to the passage of FTE#1 and resembles PMAF3
- Feature (b) is due to a much smaller FTE and resembles PMAF1
- In general we find that both the size and level of density enhancement within an FTE determine its ionospheric signatures. This suggests that PMAF classifications are tied to these characteristics of FTEs

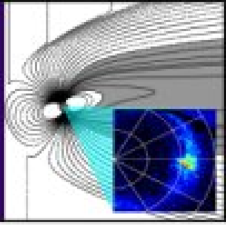



North
Magnetic Latitude
70
60
50
40
(b)
South
-70
-60
-50
-40
(c)
(d)
(e)
180
188
195
203
210
218
Time (Ω-1)
Ion Downward Flux
120
100
80
60
40
20



Strong Solar Wind Control Continues

UVI Image Analysis



- Scale-Free auroral emission avalanche distributions
  - Upper limit – finite scale size measured (Uritsky et al., 2006)
  - Lower limit – elementary avalanche: 70 km → few meters
  - Range – > 7 orders of magnitude (Kozelov et al., 2004)
- Localized reconnection in plasma sheet maps to auroral emission sites
  - Relationship is 1-to-1 and well accepted in space physics community
- Conclusion:
  - Plasma sheet is avalanching system
  - Plasma sheet dynamics closely related to SOC