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Entropy Constraints on Particle Entry and Tail Transport from DMSP Measurements

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What is Entropy?

- A measure of the unavailability of a system to do work
- Additive and positive
- Number of possible microscopic configurations of a system
  - $S = - N k \Sigma p \log p$ or $- \Sigma p \log p$
- Macroscopic connection from a distribution function characterized by measureable variables:
  - $P_j(\varepsilon) \sim \exp(-\varepsilon/2kT)$, N particles

What is Entropy?

- S=kN[3/2 log(T) - log(n) + σ_0];
- Adiabatic Gas Law
  - P/n^γ = constant if S conserved
- Entropy per unit flux
  - Related to frozen in condition

$$S = \int p^{1/\gamma} ds / B \sim M = \int \rho dV = \int \rho ds / B, \quad M = \gamma = 5/3$$

- Relation to entropy of the flux tube

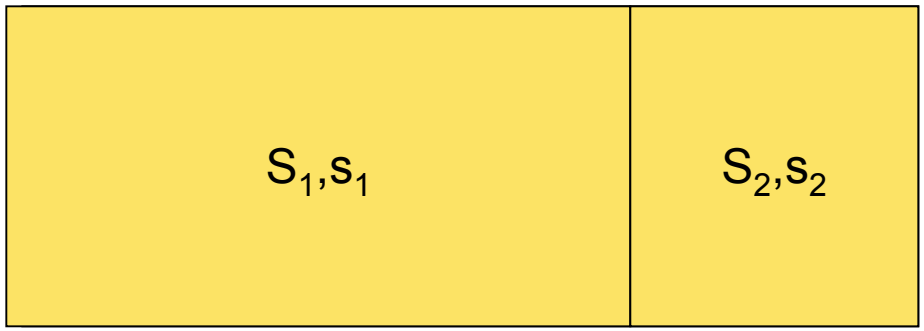
$$\Sigma = \int \int \rho \log(p^{1/\gamma} / \rho) dV = \quad CM \log(S/M)$$

Intensive/Extensive Properties

- Extensive (Total)
  - $S=p^{1/\gamma}V$ where V is the flux tube volume
  - Proportional to mass and field-line length
- Intensive (Specific)
  - $s=p/\rho^{\gamma}$ ---the adiabatic pressure law usually assumed in MHD

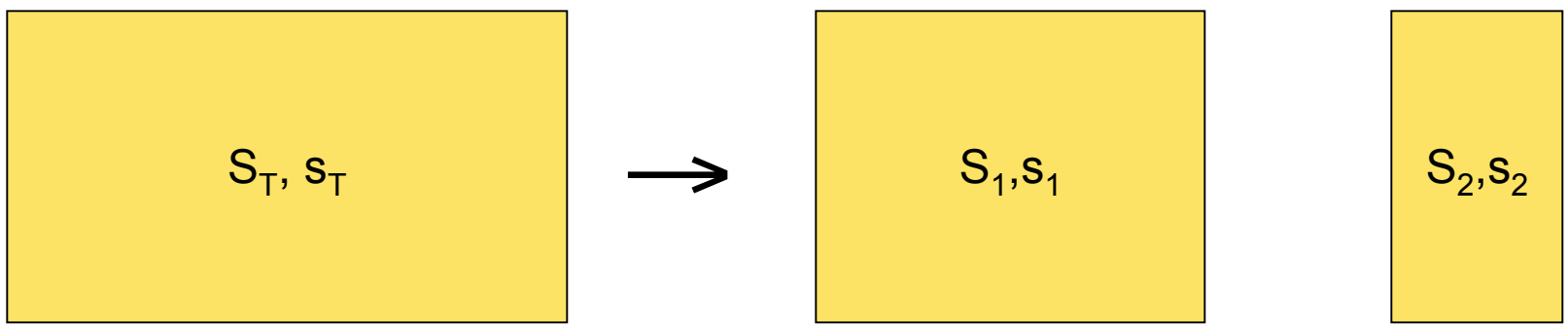
$S_1 + S_2 = S_T$

$s_1 = s_2 = s_T$



Why Look at Entropy?

- Changes are an indicator of:
  - a nonadiabatic process
  - mass loss from flux tubes
  - heat loss from flux tubes
  - integrity of the fluid element



Application to Space Systems

- Substorm phases

  Wing, Gjerloev, Johnson, Hoffman, GRL, 2007

  – In transport ideal during storm phases?
  – How does entropy change in the transition from growth phase to expansion phase?

- Plasma sheet during northward IMF

  – Are there different entropy signatures for hot and cold populations (integrity of the fluid element?)
  – What does this imply about plasma entry?

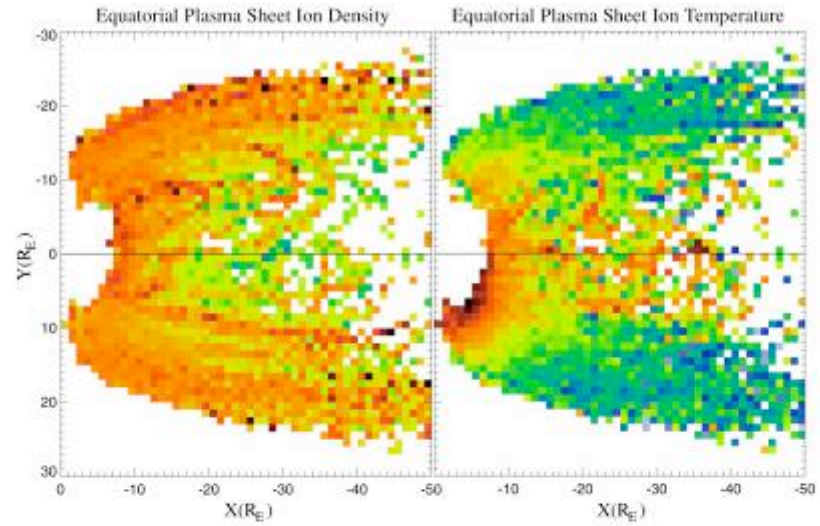
Substorm Entropy Profiles

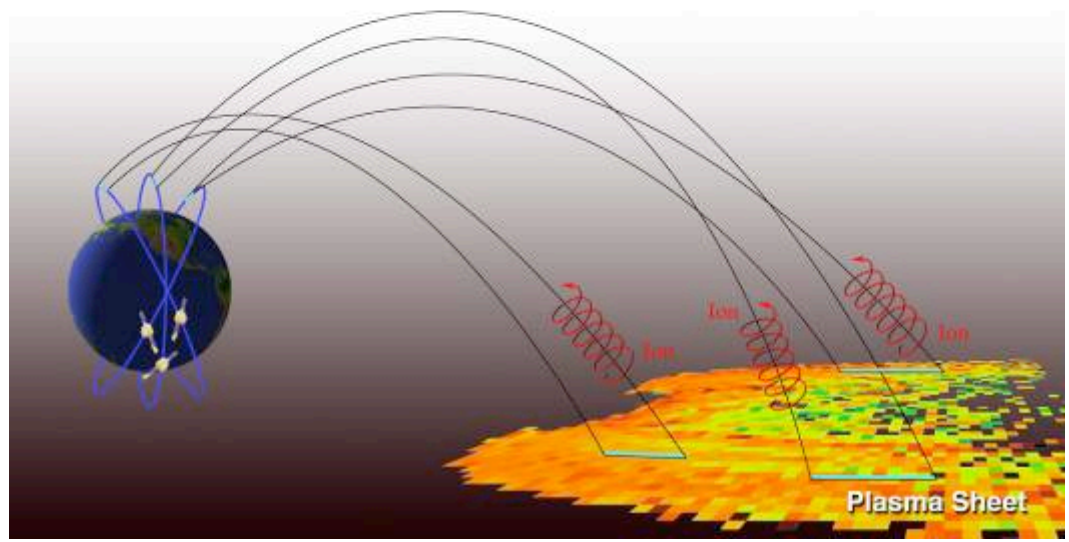
- Method of mapping plasma sheet properties from ion precipitation (DMSP)
- Application to substorms
  - Event Selection (illustrated by example)
  - Pressure, density, temperature, entropy
    - Entropy loss from growth → expansion
    - Cold ion population (apparently from ionosphere) appears at post-midnight during recovery phase and reduces entropy
- Interpretations

Inferring Plasma Sheet Ion Properties From Ionospheric Data

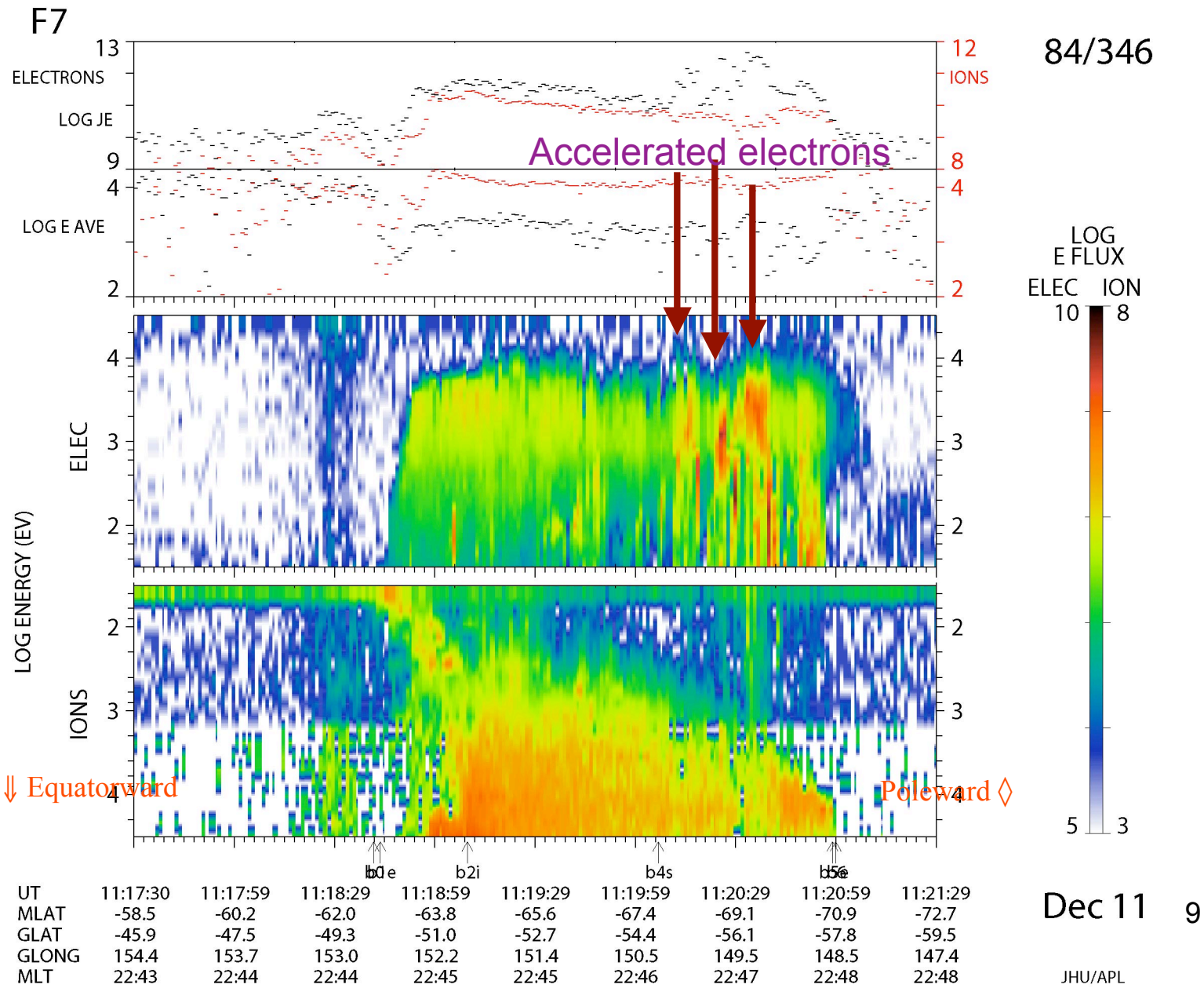
High-altitude satellites move slowly in the magnetotail but provide direct measurements.

Low altitude satellites cut through the foot print of the plasma sheet twice per ~100 min, 2D plasma sheet temperature and density profiles can be constructed, but the plasma sheet properties are deduced





Example: DMSP data



Inferring Plasma Sheet Properties

Based on:

•Isotropy of pdf

(observed >8-10 R_E)

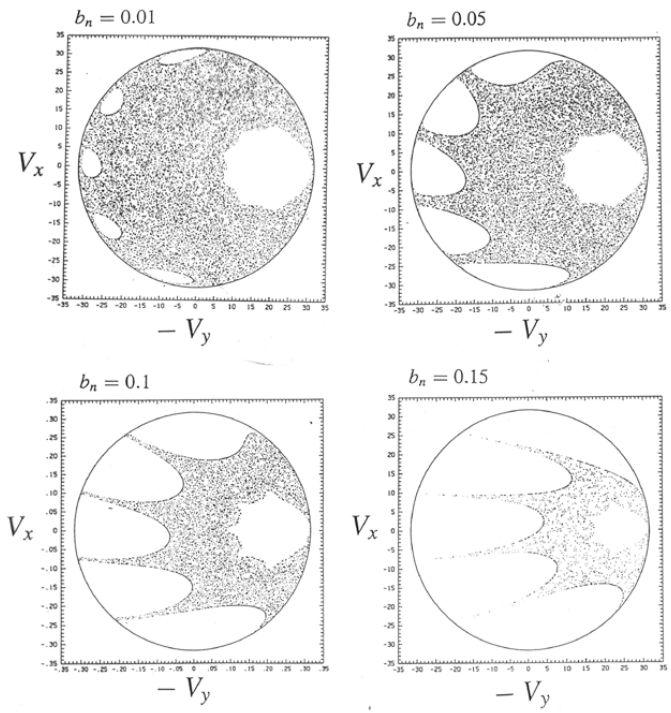
[Kistler et al., 1992; Spence et al., 1989; Huang and Frank, 1994]

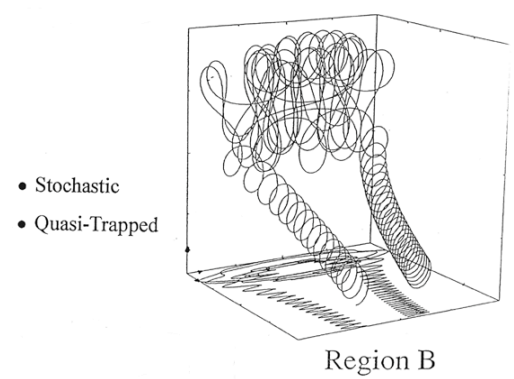
(Theory: PAS $\rho_i > R_C/8$)

[Lyons and Speiser, 1982; Sergeev et al., 1993, Chen, Burkart, Holland, …]

•Exclude electron acceleration events (parallel electric field)

•Mapping of field





Inferring Plasma Sheet Ion Properties From Ionospheric Data

Task:
Compute ion properties [density (n), temperature (T), and pressure (p)] from low altitude electron and ion precipitation data from DMSP

Method:
Eliminate electron acceleration events using automated algorithm developed by Newell et al. [1996].

Instead of computing moment, fit each ion spectrum to

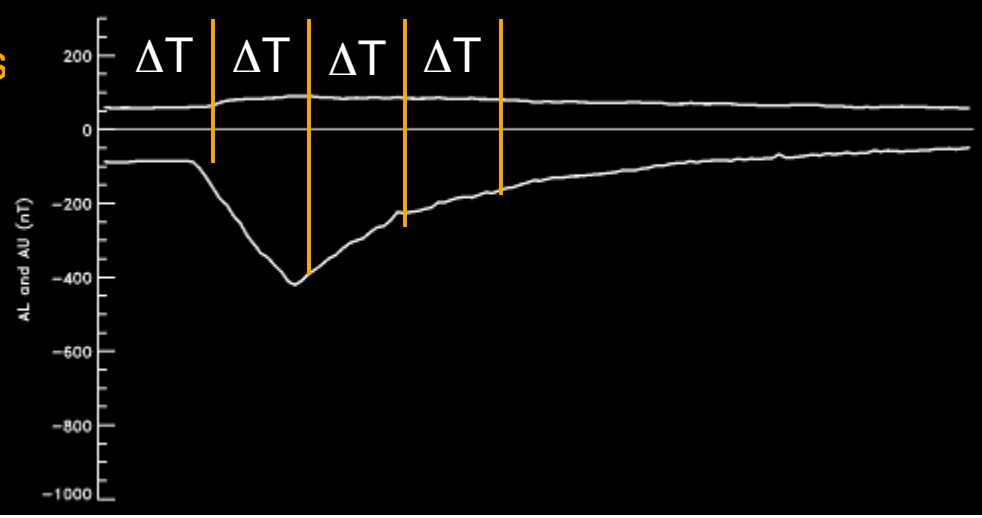
1. one-component Maxwellian.
2. two-component Maxwellian.
3. Kappa (κ) distribution [e.g., Vasyliunas, 1971; Christon et al., 1988, 1989]

Electrons contribute to only about 15% of total pressure [Baumjohann et al., 1989; Spence et al., 1989].

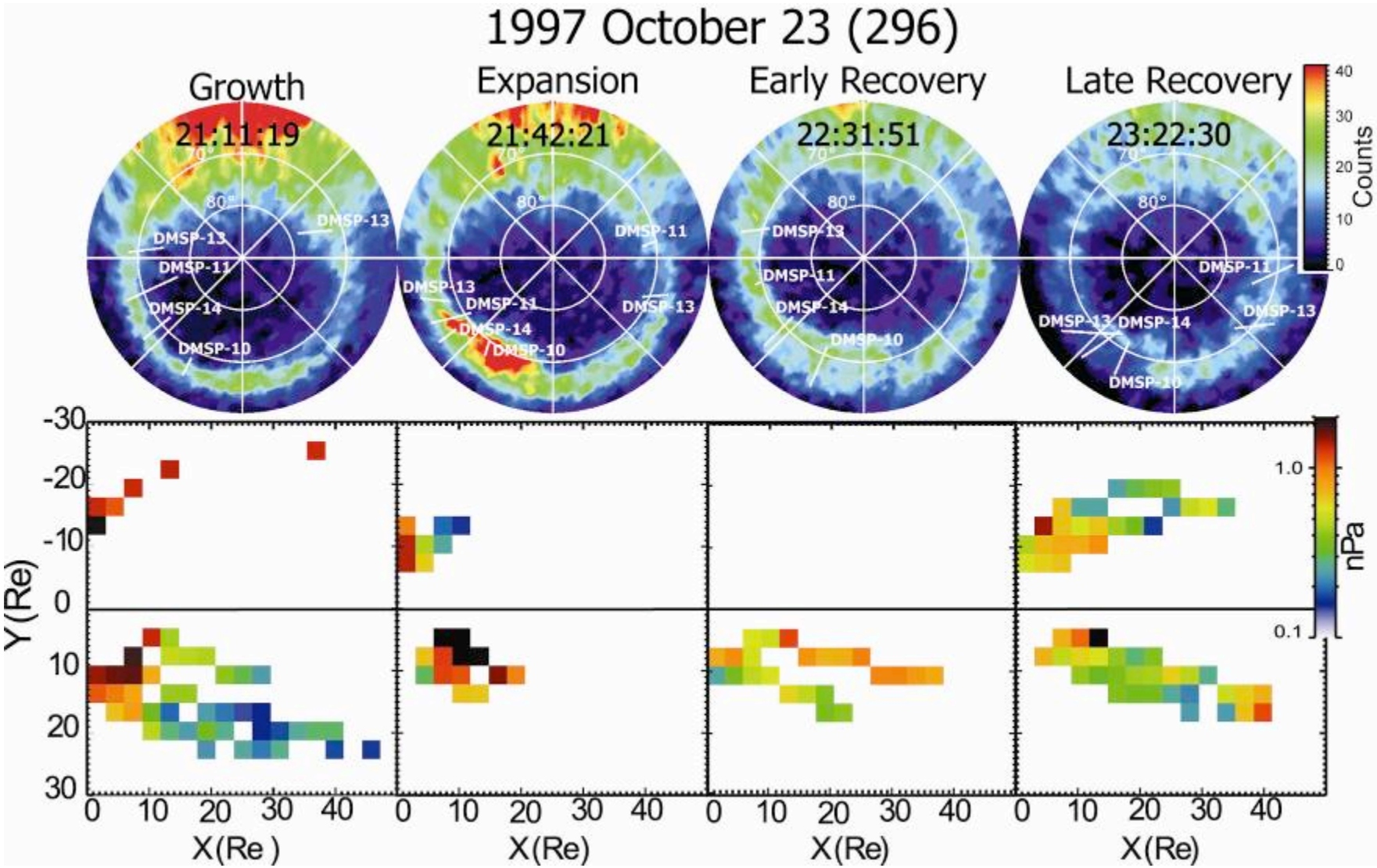
Substorm Analysis

- Isolated single event optically and magnetically;
- Poleward expansion from a localized onset;
- Single expansion and recovery phase (in case of a secondary expansion the event
  end is defined as the time of the second expansion);
- Entire auroral bulge in darkness and viewed by the imager;
- Not during magnetic storms (|Dst|<30 nT) or periods of long magnetic activity.

Five DMSP satellites operational, F10, F11, F12, F13, and F14 in 1997-2001 interval. Out of the 180 substorm events 132 events have simultaneous DMSP particle observations.



Event Example

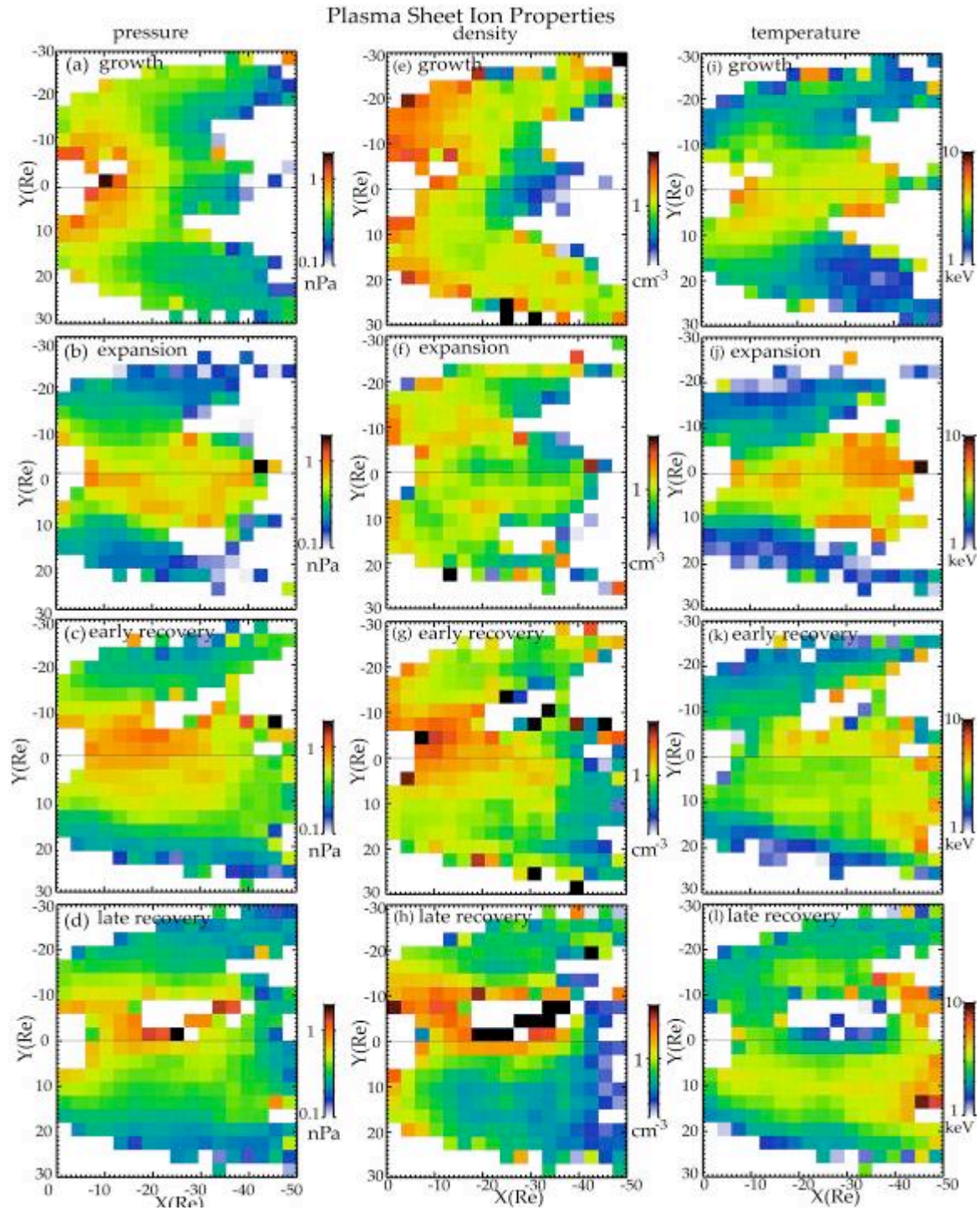


Pressure peaks at the inner edge of the plasma sheet in the growth phase

pressure and temperature increase at premidnight in the midtail in the expansion phase

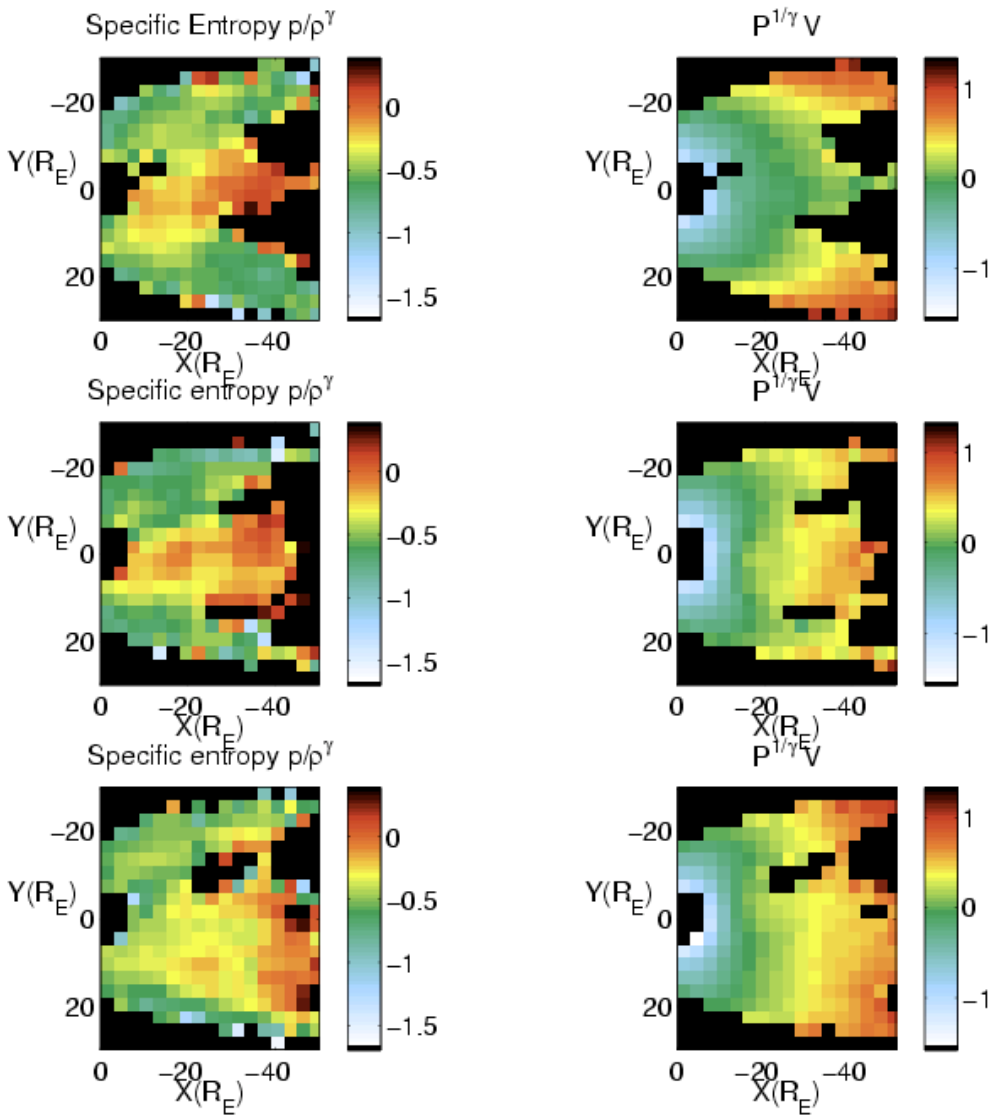
pressure peaks at postmidnight in the early and late recovery phases

cold dense ions at post-midnight during the early and late recovery phases

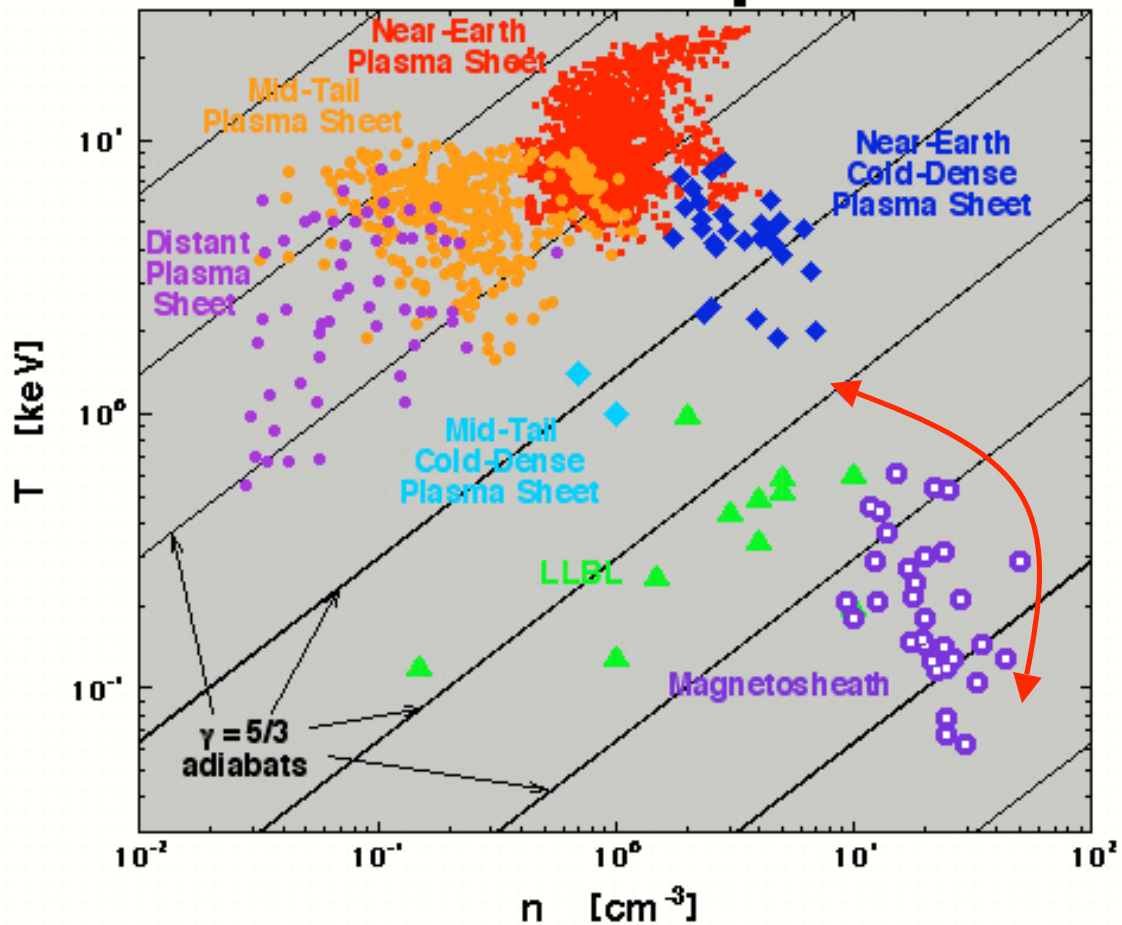


Entropy Features

- Growth
- Expansion
- Recovery



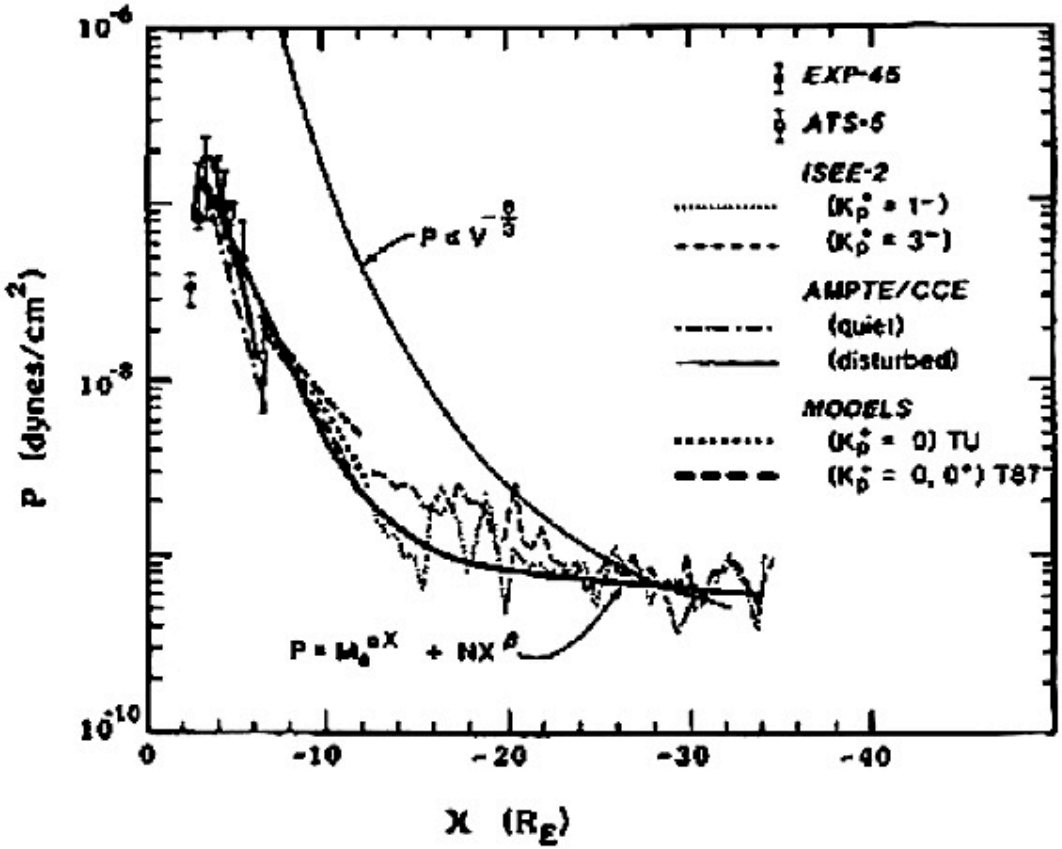
Entropy Density of Plasma-Sheet Populations



Borovsky

Convection Model and Pressure Crisis

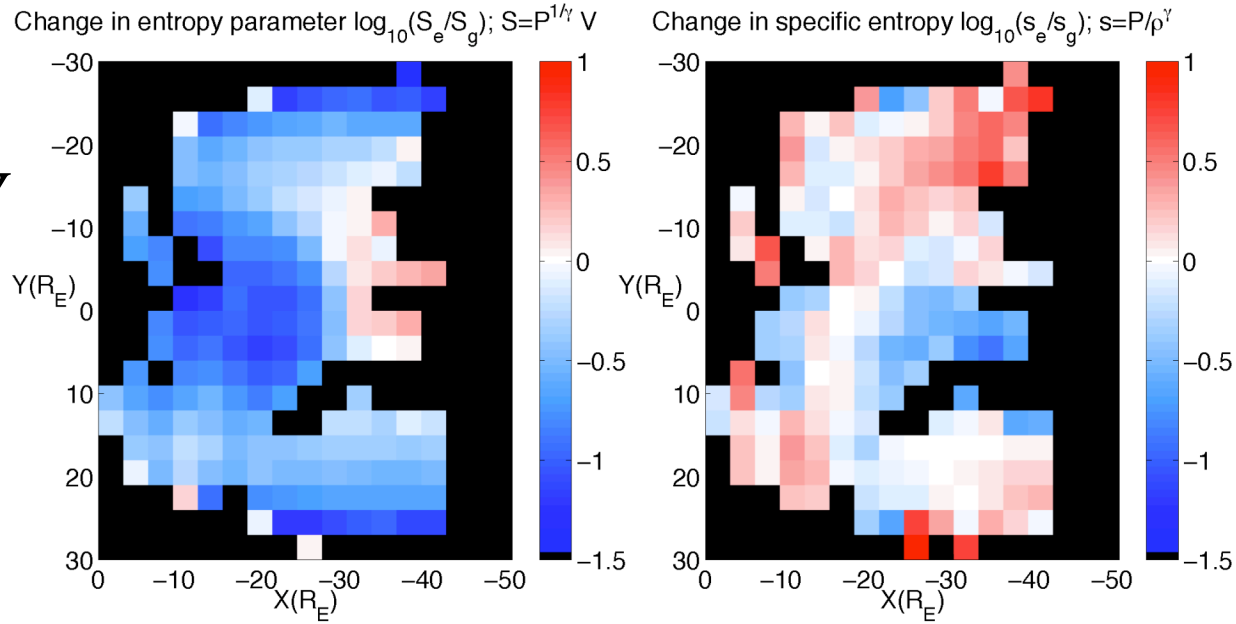
- Losses
  - Kinetic drifts
  - Ionosphere
  - Near Earth Reconnection
  - Bursty Bulk Flows

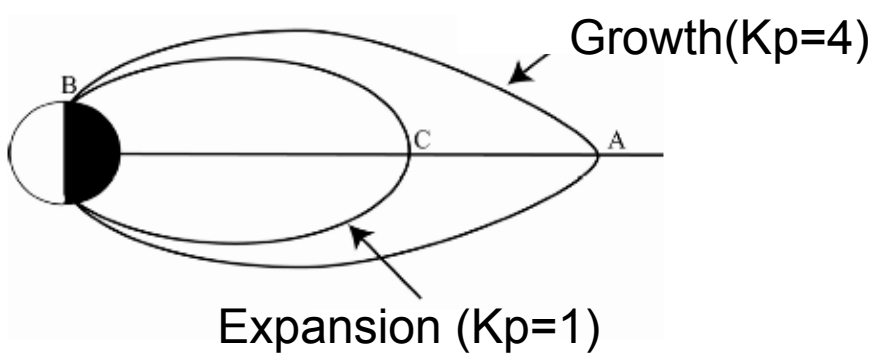


Garner et al, 2003

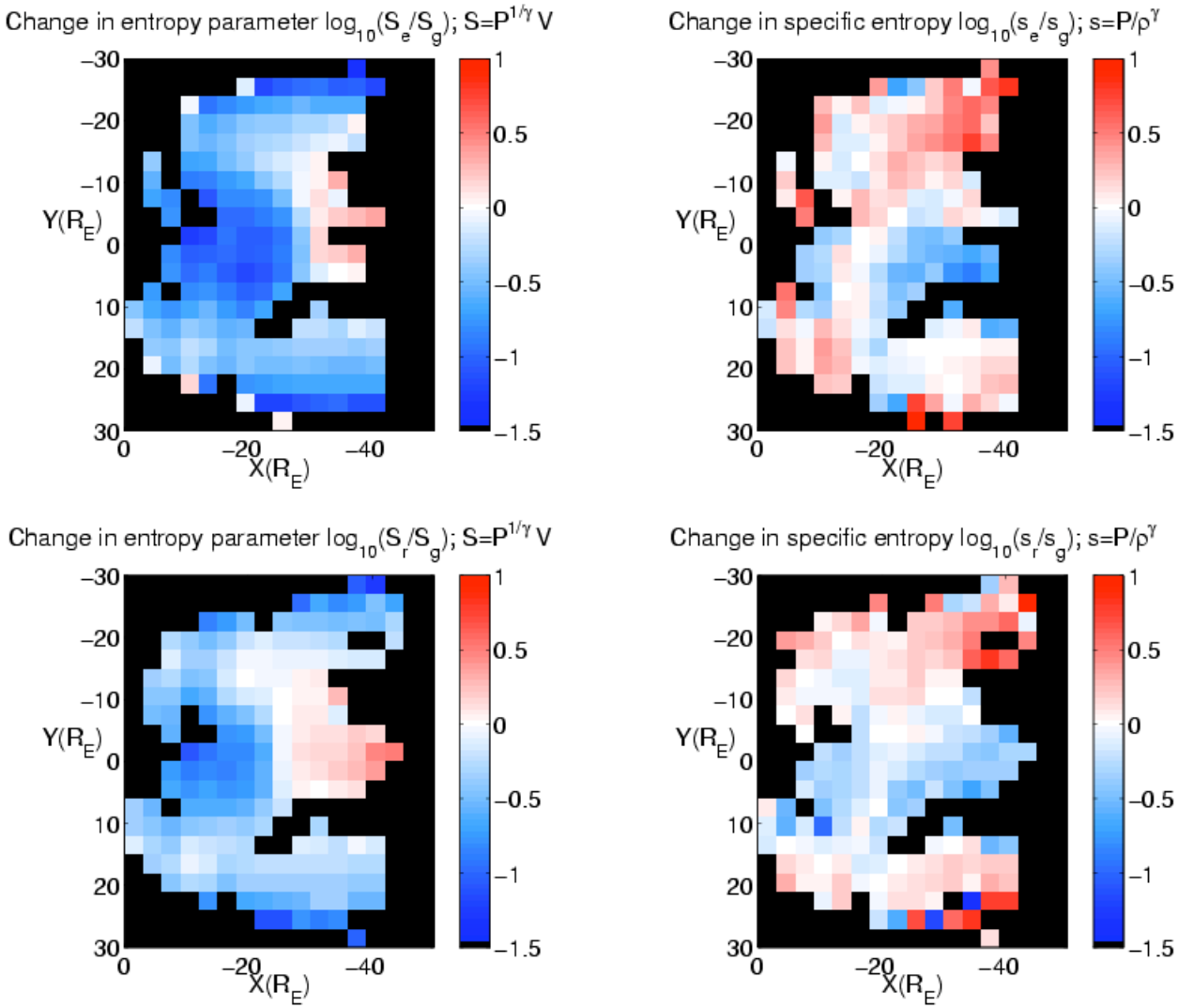
Entropy Convervation (growth → expansion)

$$S \sim p^{1/\gamma} V$$





Entropy Conservation



Entropy Loss (GEOTAIL)

- Pi2 activity
- Dipolarization
- Flow Burst
- Entropy Reduction

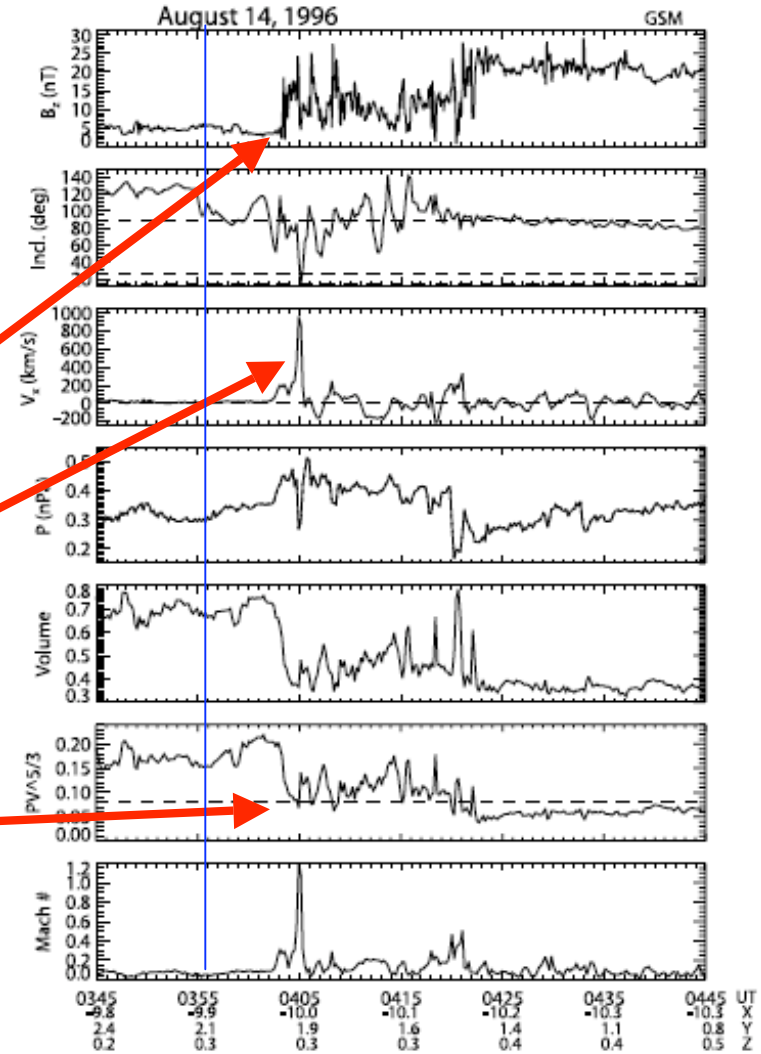
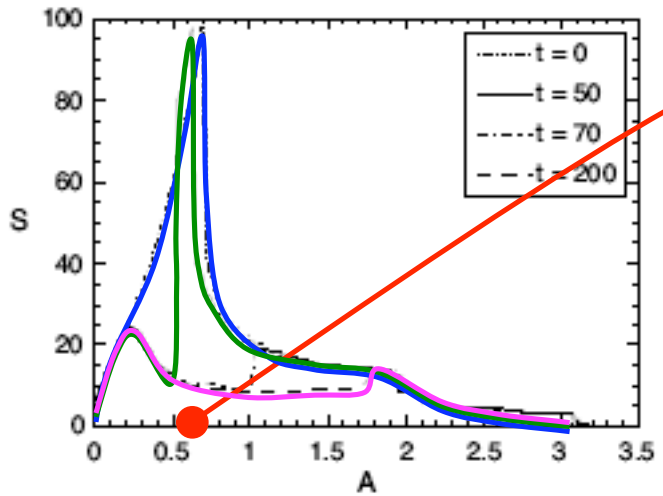


Figure 5. Application of flux tube volume formula to the substorm of 14 August 1996, observed by Geotail.

[Wolf et al., 2006]

Entropy Loss due to Plasmoid



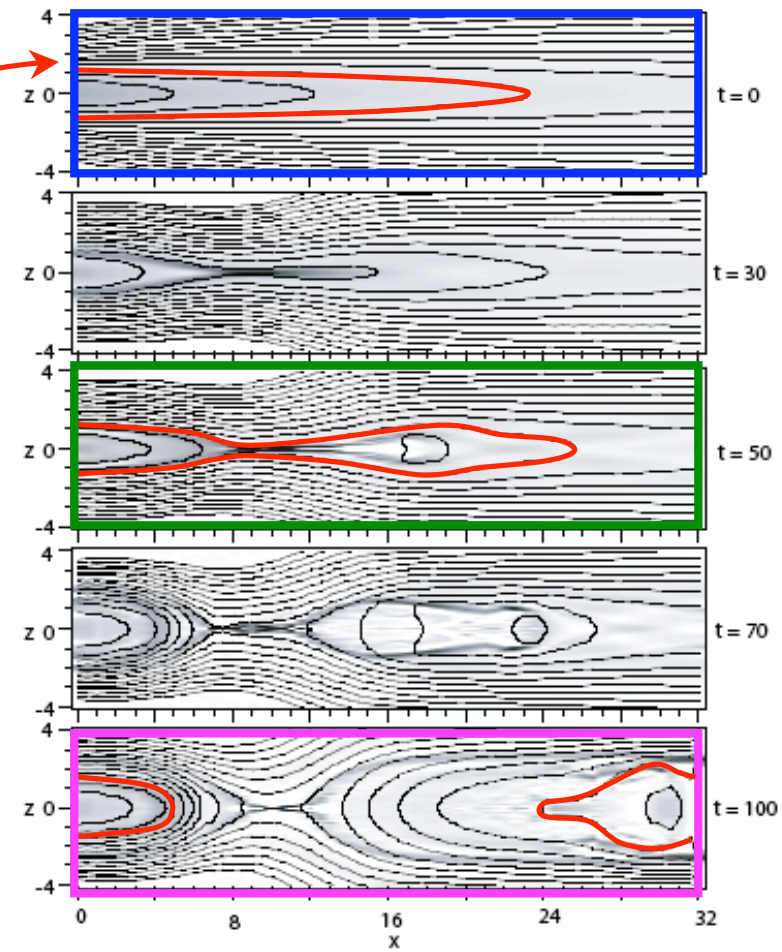
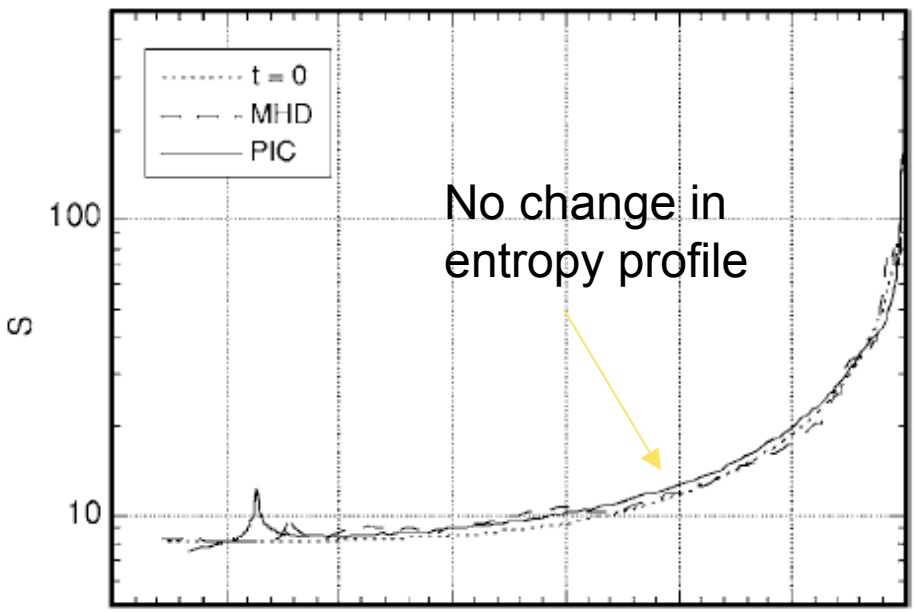


Fig. 2. MHD simulation of thin current sheet formation and plasmoid ejection in the tail, resulting from boundary deformation in the near tail. The gray scale indicates the current density.

[Birn et al., 2006]

$$S = \int p^{1/\gamma} ds / B, \quad \gamma = 5/3$$

Conservation of Entropy (Newton Challenge)



- Although S decreases, s would not change much

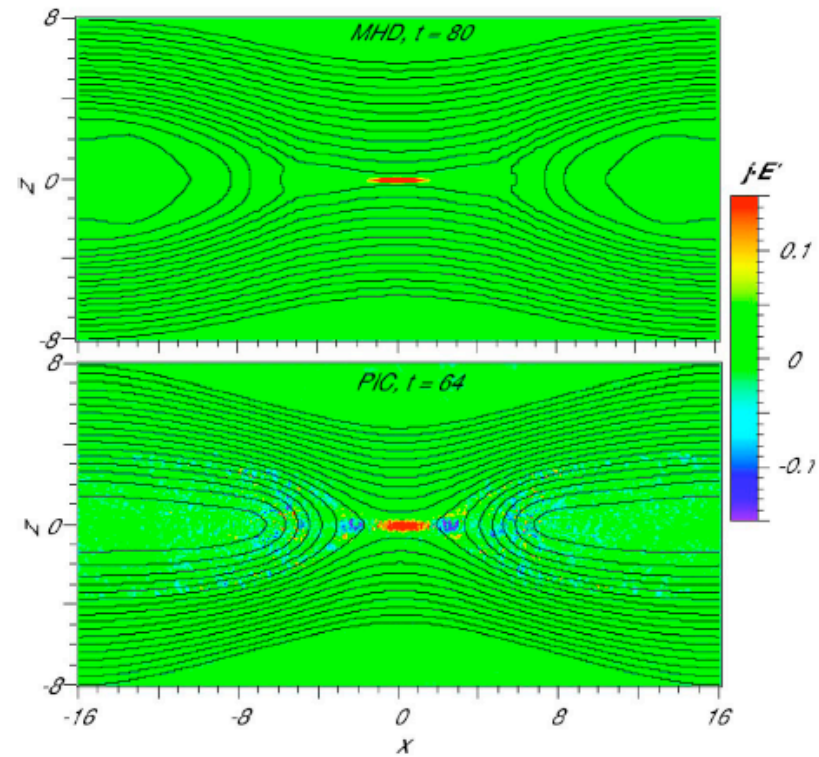
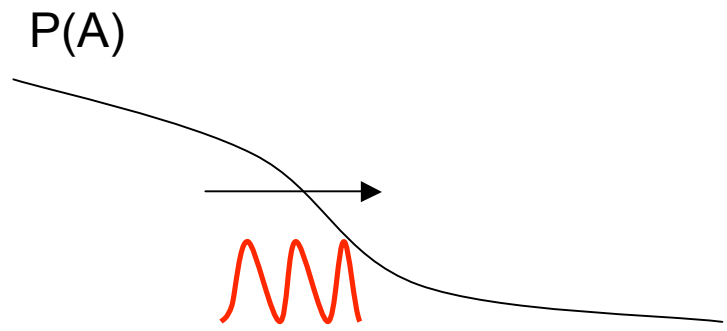


FIG. 3. (Color online) Joule dissipation $\mathbf{j}\cdot\mathbf{E}'$ (color scale), $\mathbf{E}'=\mathbf{E}+\mathbf{v}\times\mathbf{B}$, in the resistive MHD simulation (top) and the PIC simulation (bottom) at the times of fastest reconnection, showing the strong localization.

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} ?

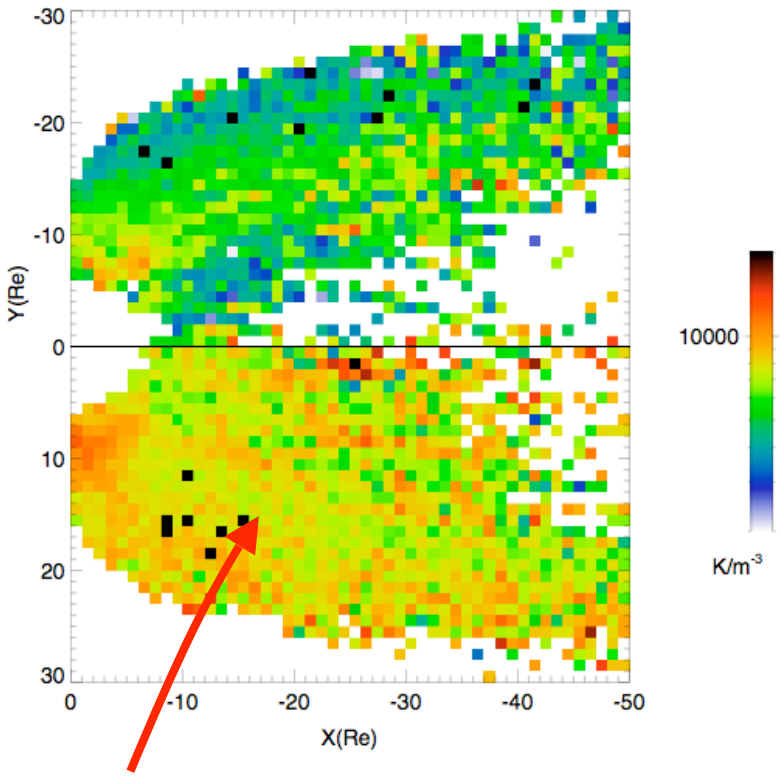


$\delta B/B = -\beta\, \delta P/P$

Entropy for Northward IMF

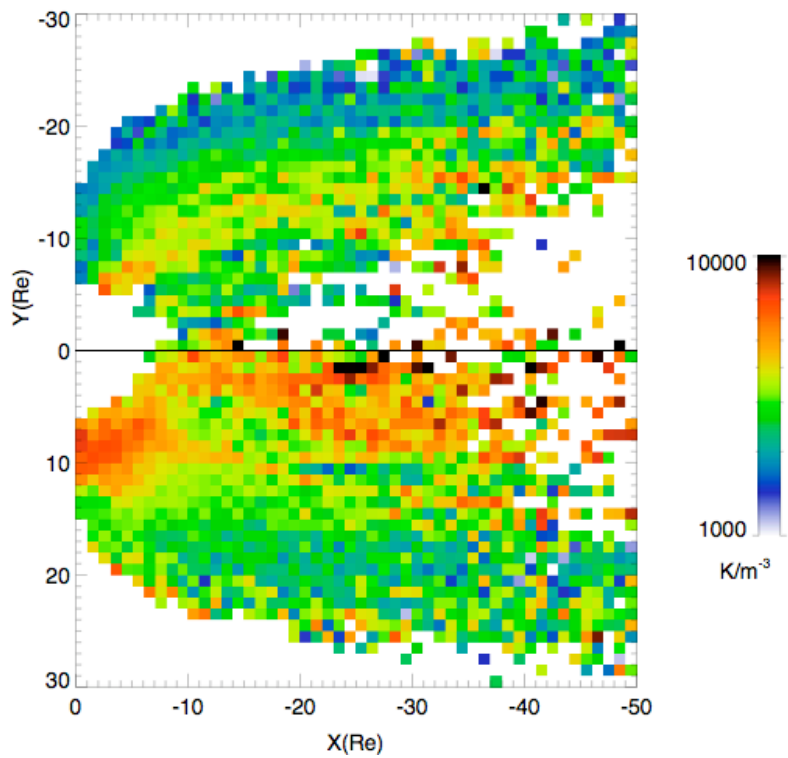
- Difference in the hot and cold population
- Increase of cold plasma entropy by a factor of 5 associated with a flux of cold sheath plasma that is slightly heated

Entropy



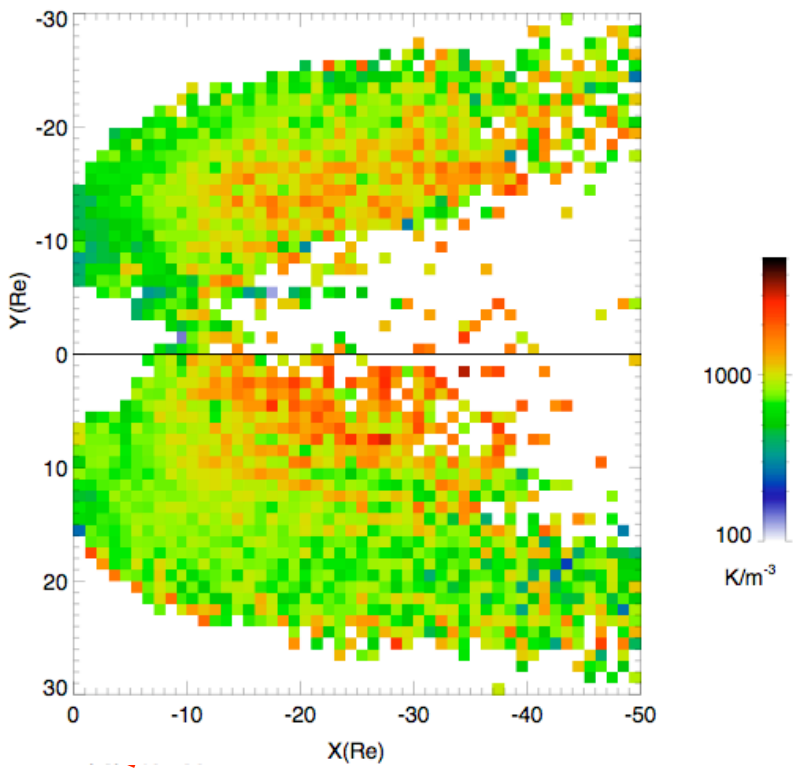
κ,∇B

Hot

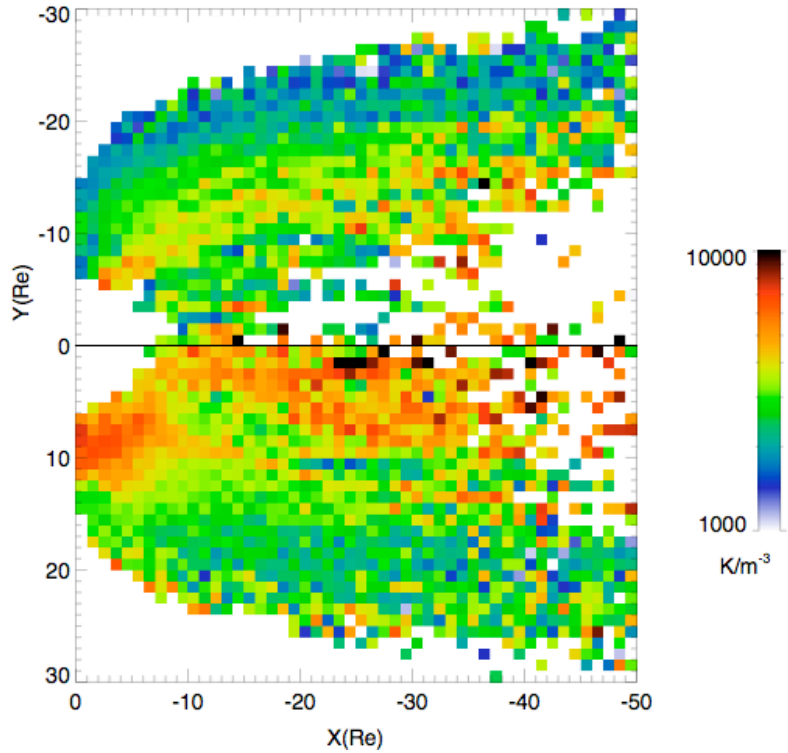


Total (Hot+Cold)

Entropy

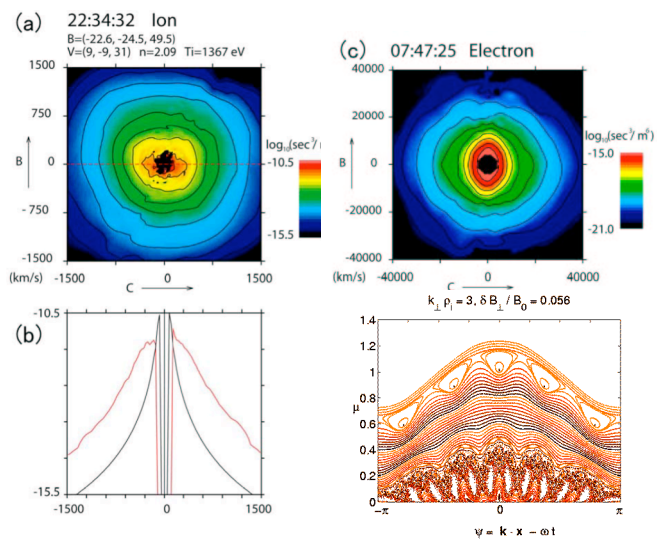


Cold



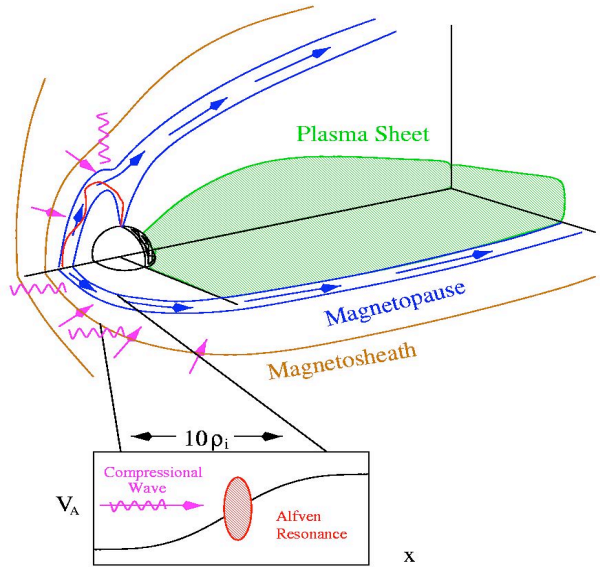
Total (Hot+Cold)

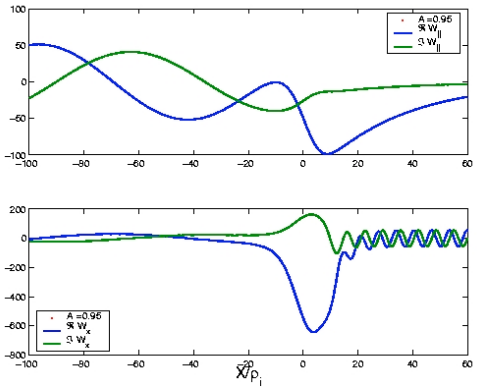
KAW as a source of transport



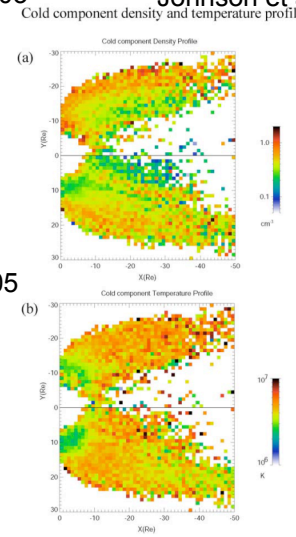
Hasegawa et al, 2003

Johnson et al, 2001

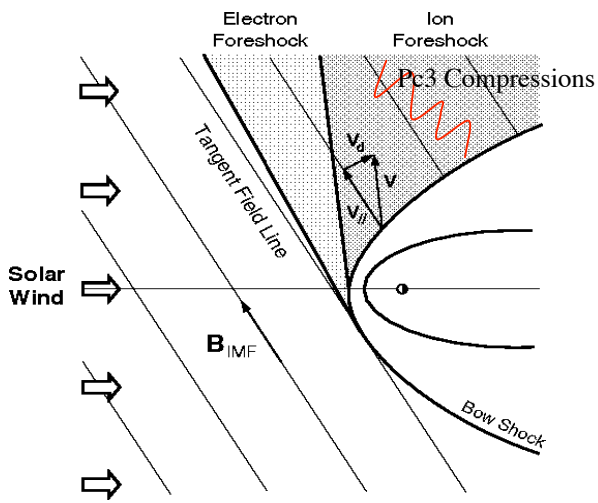


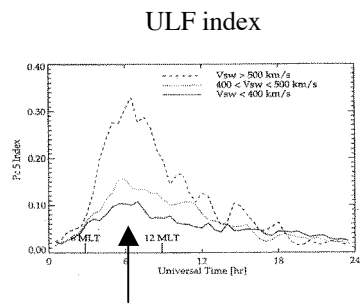


Johnson et al, 2001



Wing et al., 2005



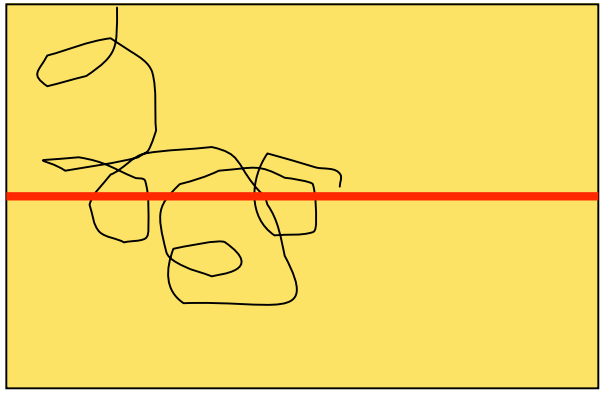


Engebretson, 1998

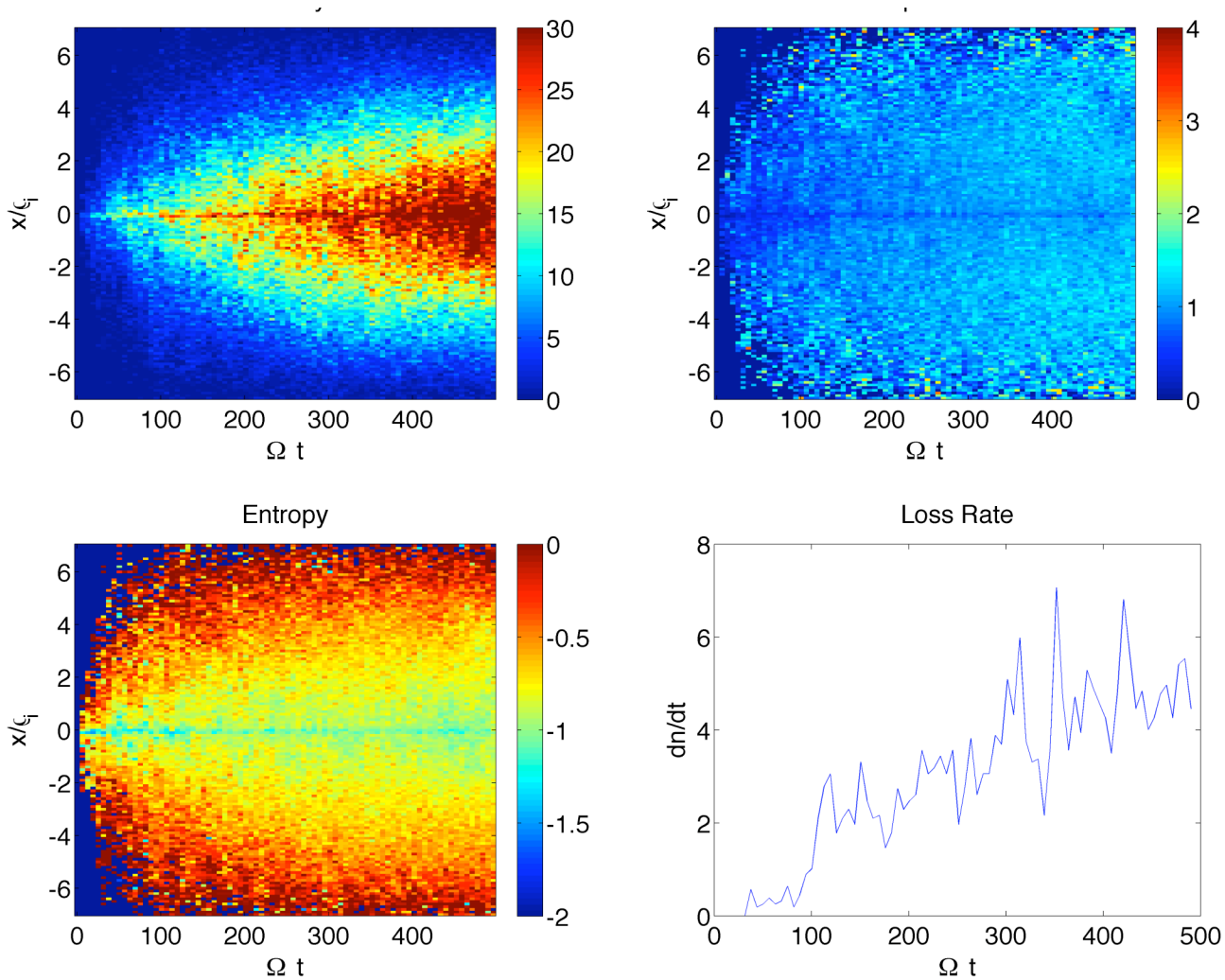
Ground Wave
Power Peaks
for 3hr<LT<9hr

Test Particle Estimate of Diffusion and Entropy Profile

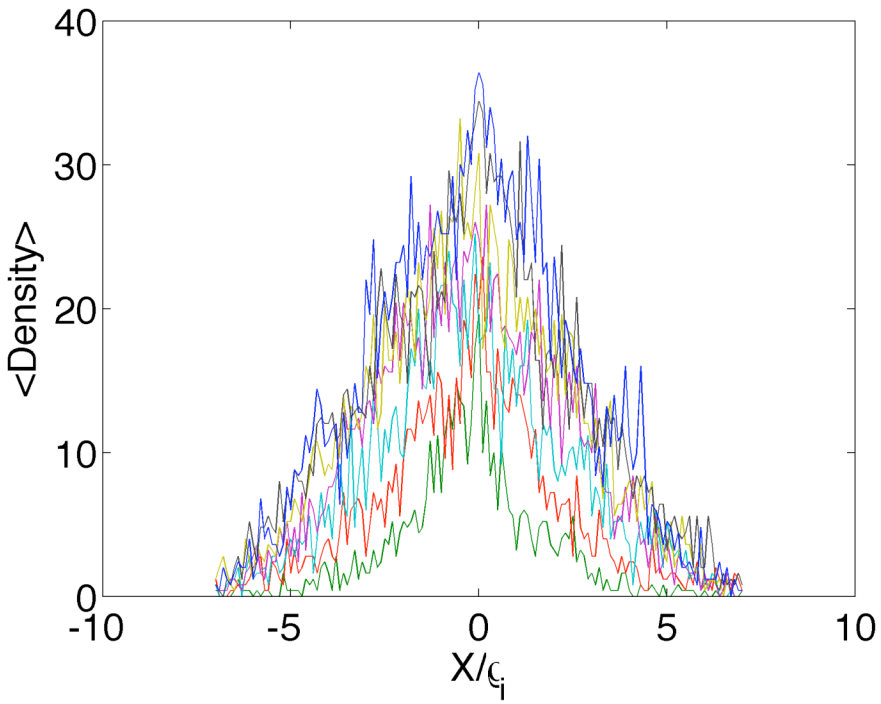
- Specify KAWs in region $\mathcal{A}$
- Add particles at a constant rate at a source location (magnetosheath)
- Allow a steady state to develop
- Perform statistics
- Extract D from flux
- Determine entropy profile



Diffusion due to KAW

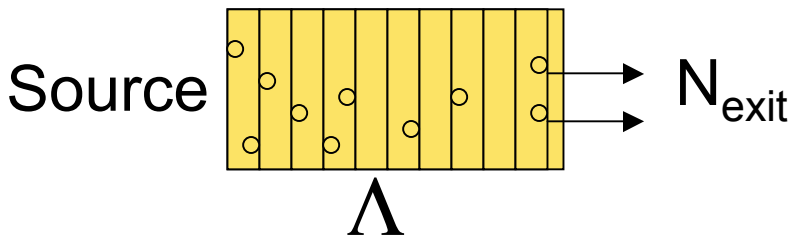


Diffusion Profile



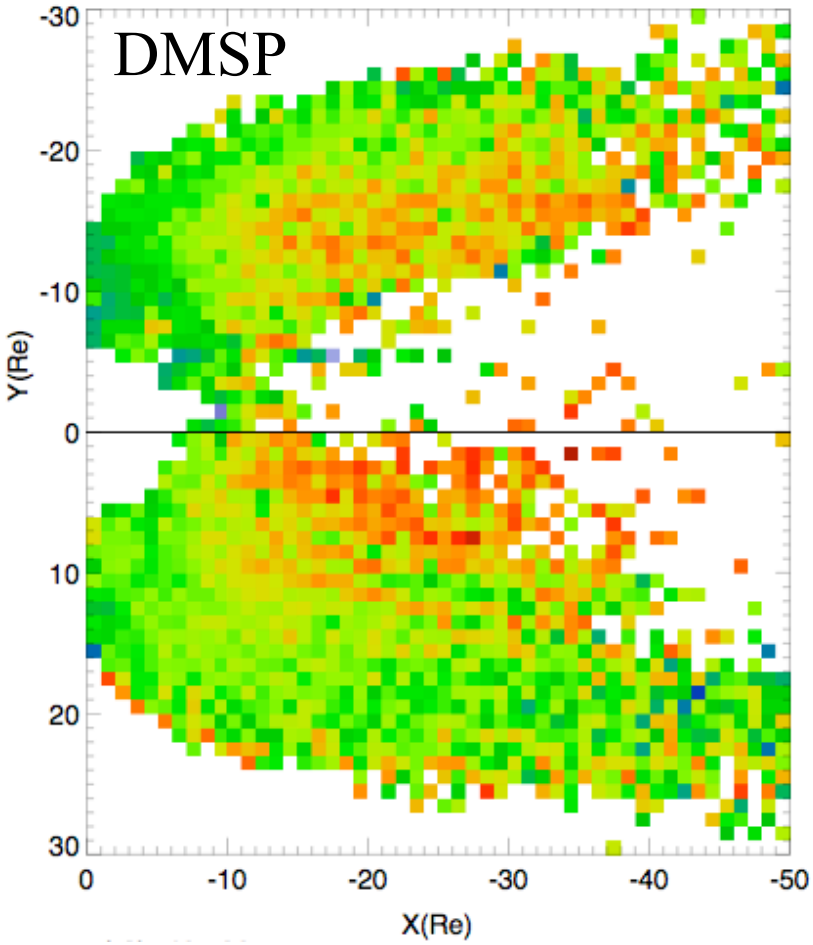
Diffusion Coefficient

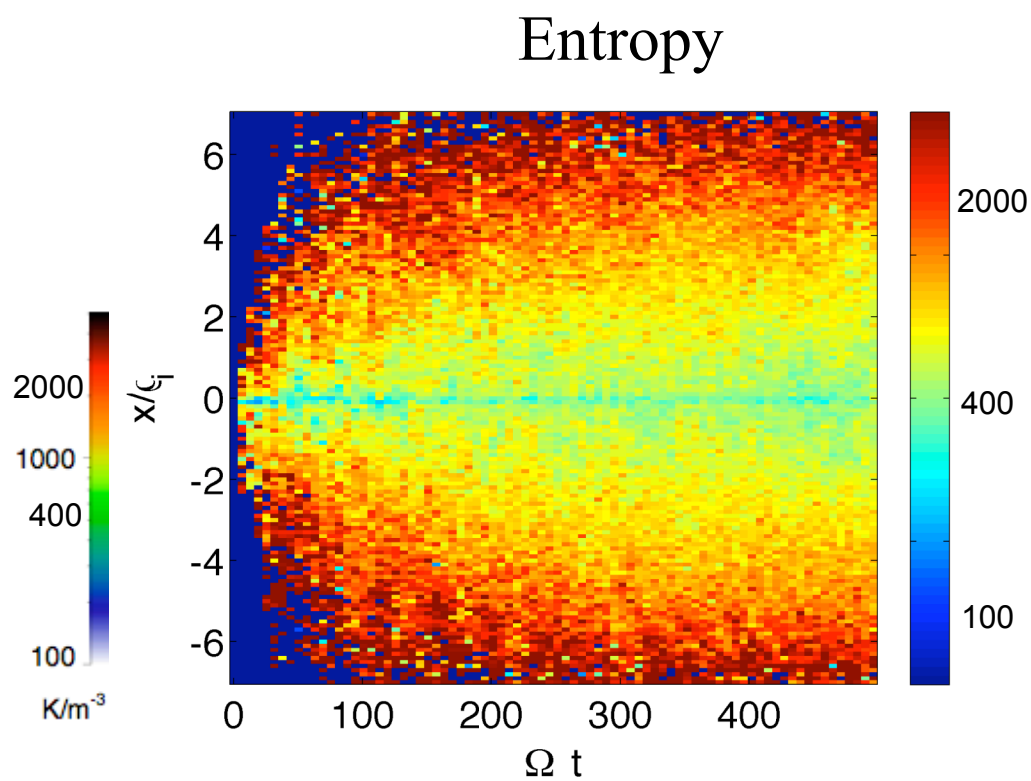
- Flux = D dn/dx



- $D \sim (N/time)_{exit}\, \Lambda \,/\, (N/\Delta x)_{source}$
- $D \sim 5\Omega_I (7\rho_I) / 20/(0.15\rho_I)$
- $D \sim 2 \times 10^9 m^2/s$

Specific Entropy (P/n^{γ})↑5





Simulation of KAW

Summary

- Entropy constraints on substorm models:
  - loss of total entropy
  - less significant changes in specific entropy
  - Azimuthal heat flux
- Entropy Constraints on plasma entry
  - Cold population enters and is heated leading to an increase in entropy by a factor of 5
  - Hot ions follow transport paths from the tail
  - Cold ions flux across the magnetopause
  - KAWs provide similar entropy changes