Investigation of Energy Conversion and Transfer in the Auroral Magnetosphere by Multi-Point Observations

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STIMM-2 Workshop, Sinaia, June 15, 2007

𝒜 Intro 𝒜

- Energy conversion:
  - Source of mechanical / elmag energy = sink of elmag / mechanical energy.
  - E·J < 0 => Generator => conversion mechanical → electromagnetic energy, e.g. associated with source regions of auroral arcs.
  - E·J > 0 => Load => conversion electromagnetic → mechanical energy, e.g. associated with source regions of bursty bulk flows.
- Energy transfer:
  - Electromagnetic transfer => like the Poynting flux in the auroral magnetosphere, from generator regions in the plasma sheet to the acceleration region and ionosphere.
  - Mechanical transfer => like the bursty bulk flows in the plasma sheet, which can be braked and possibly generate Poynting flux (e.g. Cluster / Double Star ongoing work by Martin Volwerk et al., EGU poster).
- The reference system is a key factor, since E is not invariant. A good system is the one where the irreversible energy dissipation takes place. For the auroral M–I this is the neutral wind system, which for our purpose is well approximated by GSE.

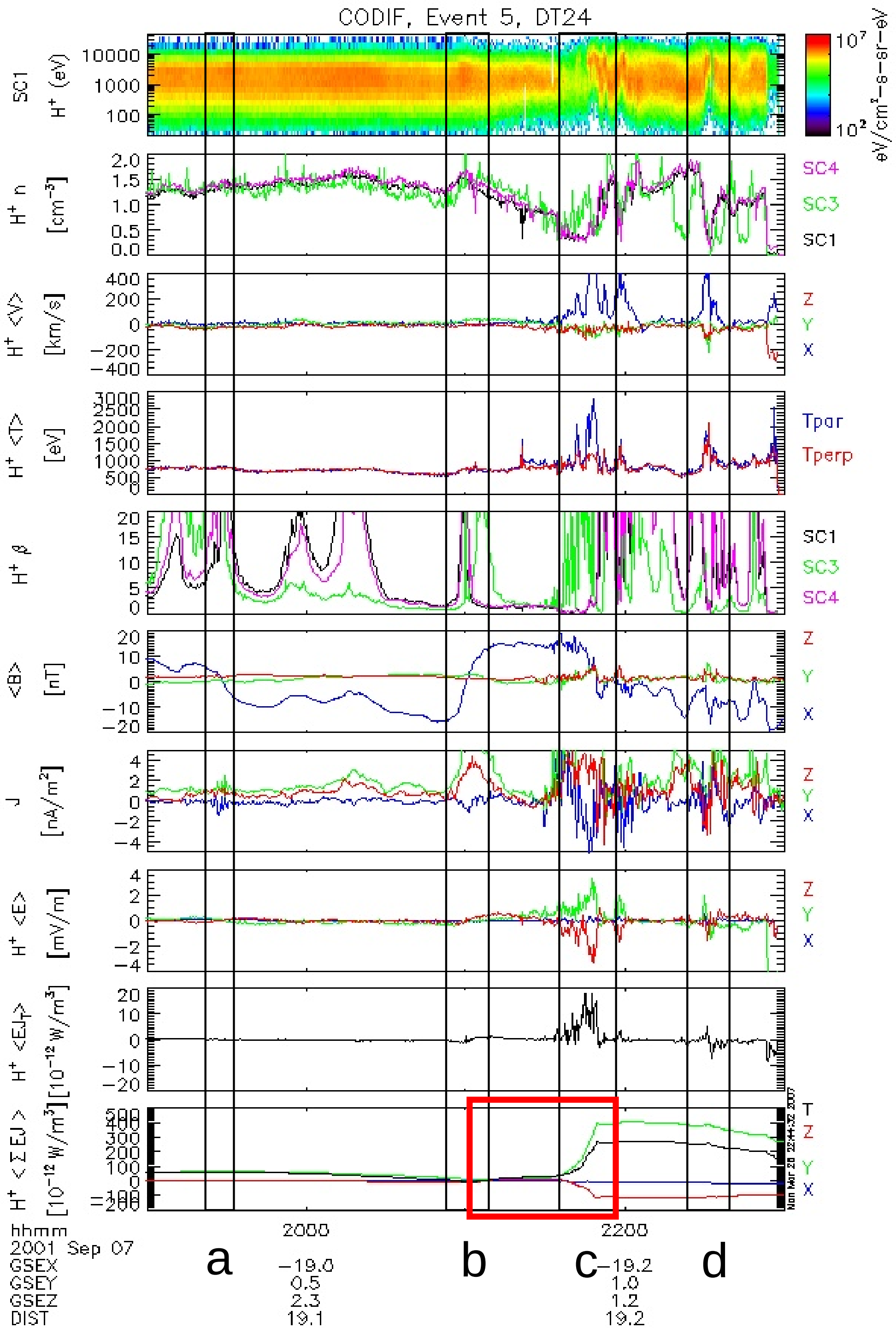
A Intro A

- With Cluster one can investigate local energy conversion, by computation of **E·J.** The sources and sinks of energy can be identified and examined by *in-situ* data.
- In the plasma sheet:
  - **E** can be inferred from two different experiments: CIS and EFW. Only CIS can provide estimates for the full electric field vector. Because **B** is almost parallel to the spin plane, EFW provides just the spin plane components. The duskward component, Ey, is used to cross-check CIS.
  - **J** can be computed by the Curlometer method from the magnetic field measured on the four satellites.
  - In GSE no coordinates transformation is needed for EFW data (booms plane nearly the same with $(x, y)_{GSE}$).

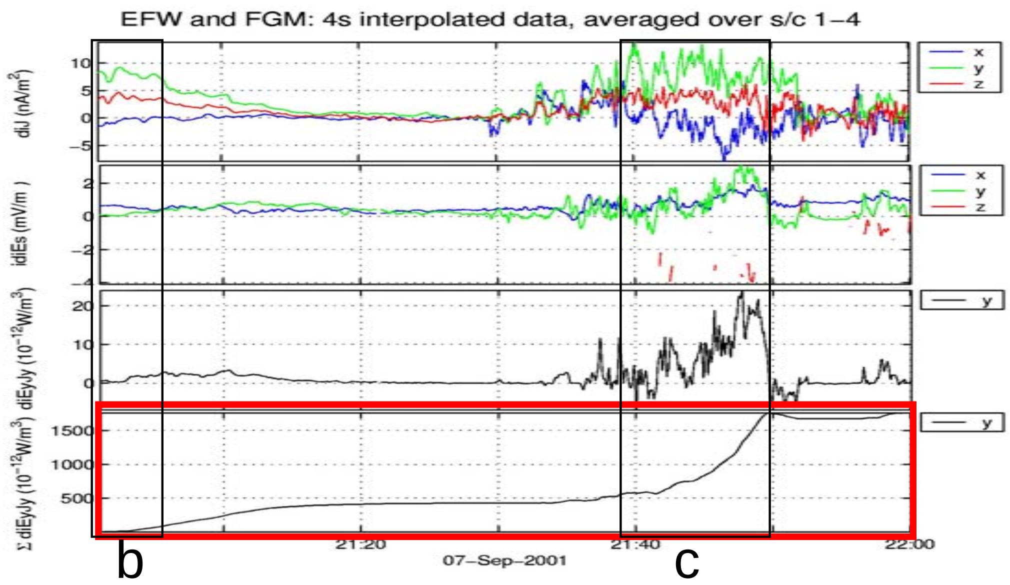
A Intro A

- We searched for energy conversion events between the end of August and the beginning of November, 2001. During this time the apogee of Cluster, at 19 R_E, was in the plasma sheet, moving from midnight to the dusk.
- Near Cluster apogee, the conversion of magnetic energy into mechanical energy, mostly by reversible ('motor') processes, is dominant, and the plasma sheet behaves, on average, as a load. The loads are rather concentrated (at least in z direction).
- The fact that plasma sheet behaves as a load is not a surprise. However, we do not know very well what is the structure of this load.
- Concentrated generator regions are also observed in the data – less frequent than the load regions and with lower power densities.
- For illustration we present one generator and two load events:
  - L1 from Sep. 7, 2001,
  - L2 from Aug. 29, 2001,
  - G1 from Sep. 19–20, 2001.

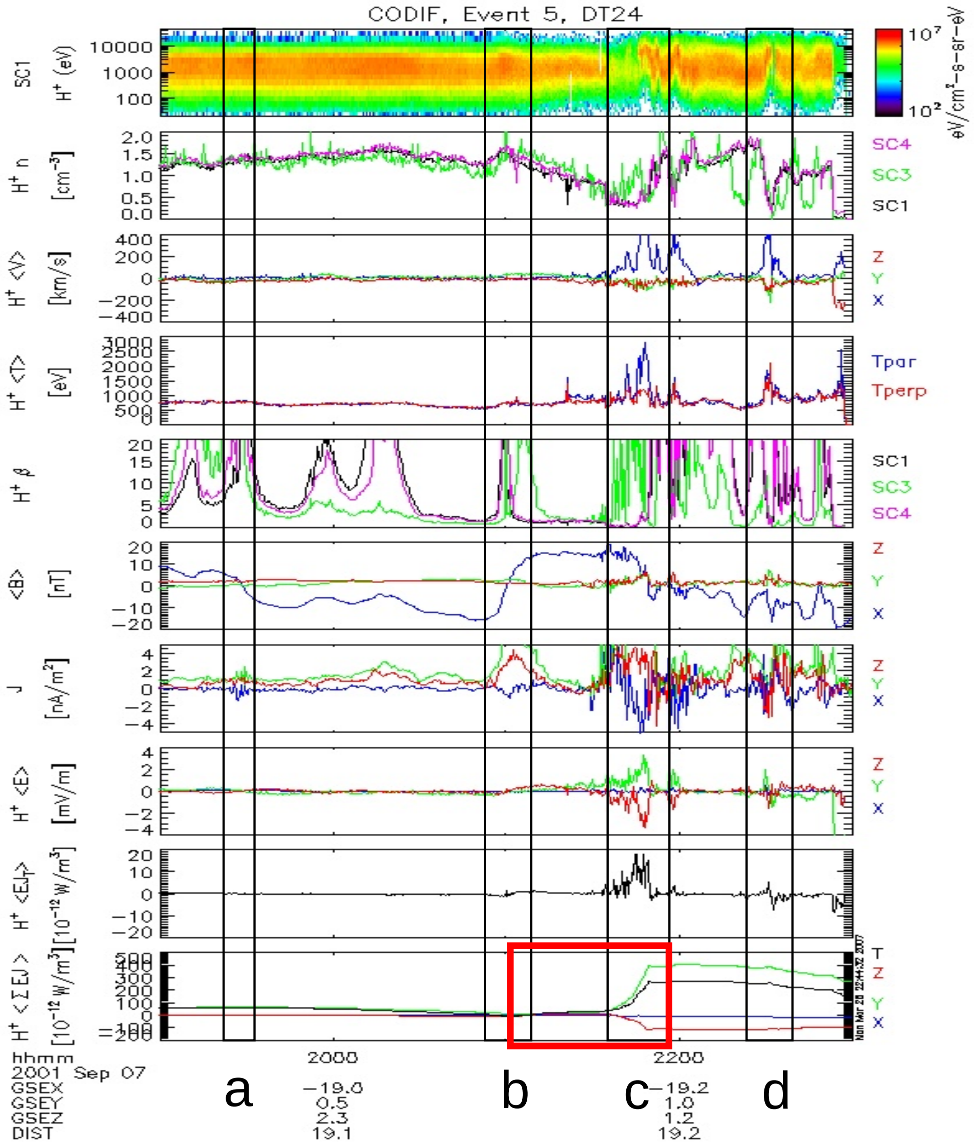
𝓑 Load Event L1: Data 𝓑

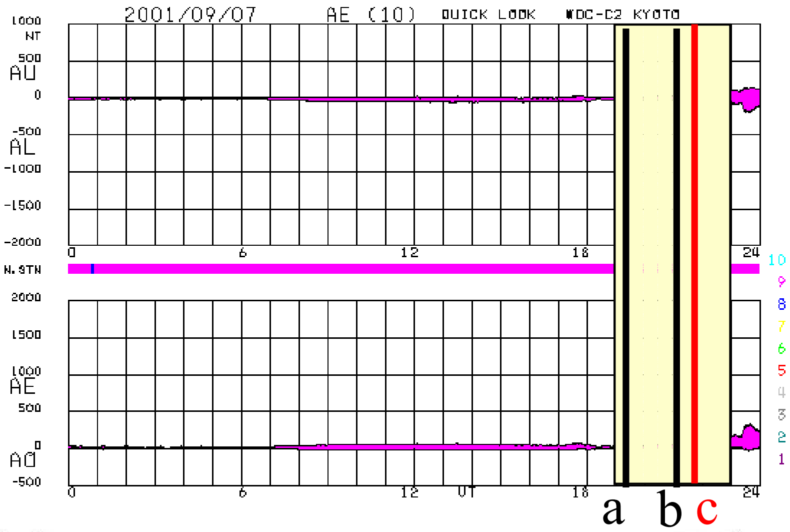


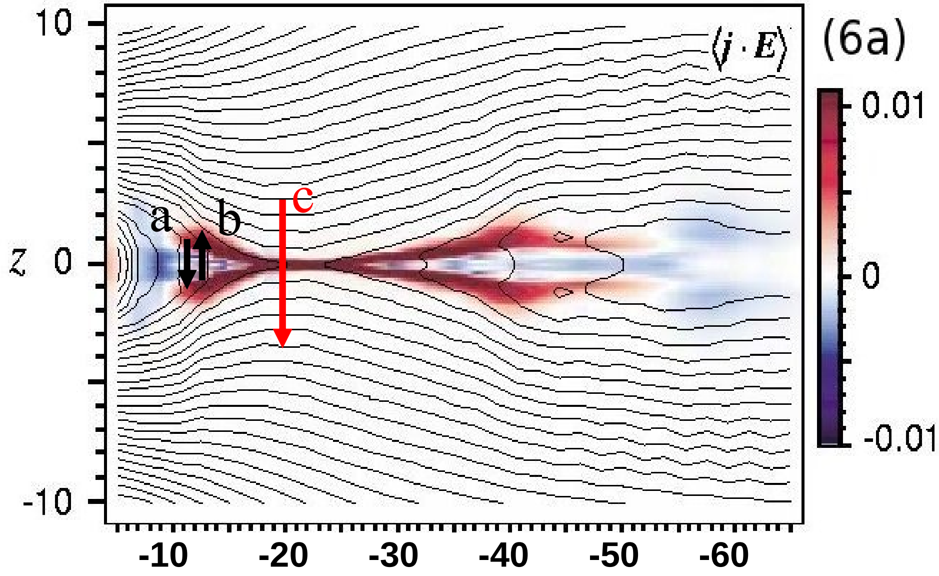
- ➤ Big load (L1c) close to the neutral sheet (high β) and midnight. L1c associated with bulk flow (mainly field aligned) and temperature anisotropy ($T_{\parallel} > T_{\perp}$).
- ➤ No significant load is observed near the neutral sheet when the bulk flow is missing (L1a, L1b).
- ➤ Bulk flow not necessarily assoc. with a load (L1d).
- ➤ Good qualit. agreement between the (c) jump in the integ. EyJy seen by CODIF and EFW, but a factor of 2 missing: CODIF=400 for tres=24 s, EFW=1200 for tres=4 s (6 times more points).



B Load Event L1: Interpretation B



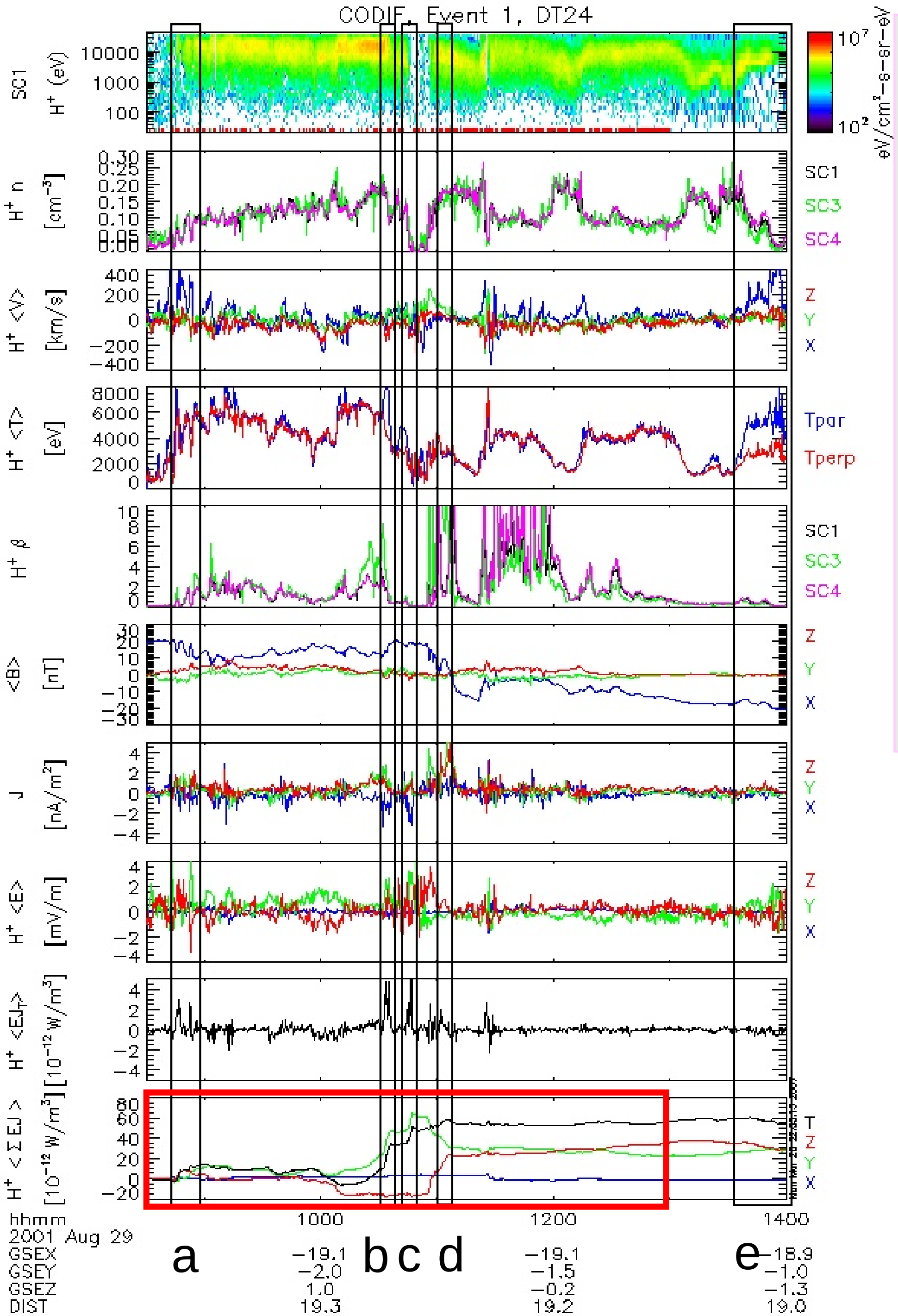




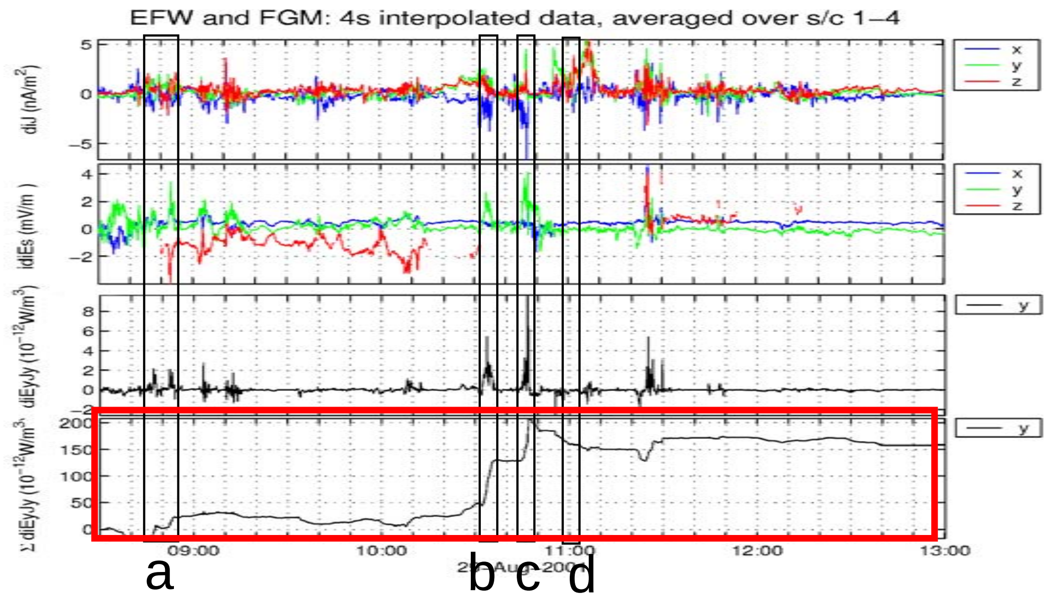
Birn and Hesse, Annales, 2005.

- Substantial change between (b) and (c), possibly related to the substorm development.
- If there is indeed a relation to the substorm, then the motion of the reconnection site to the Earth is surprising for the growth phase. Fast tailward motion after the Cluster pass?

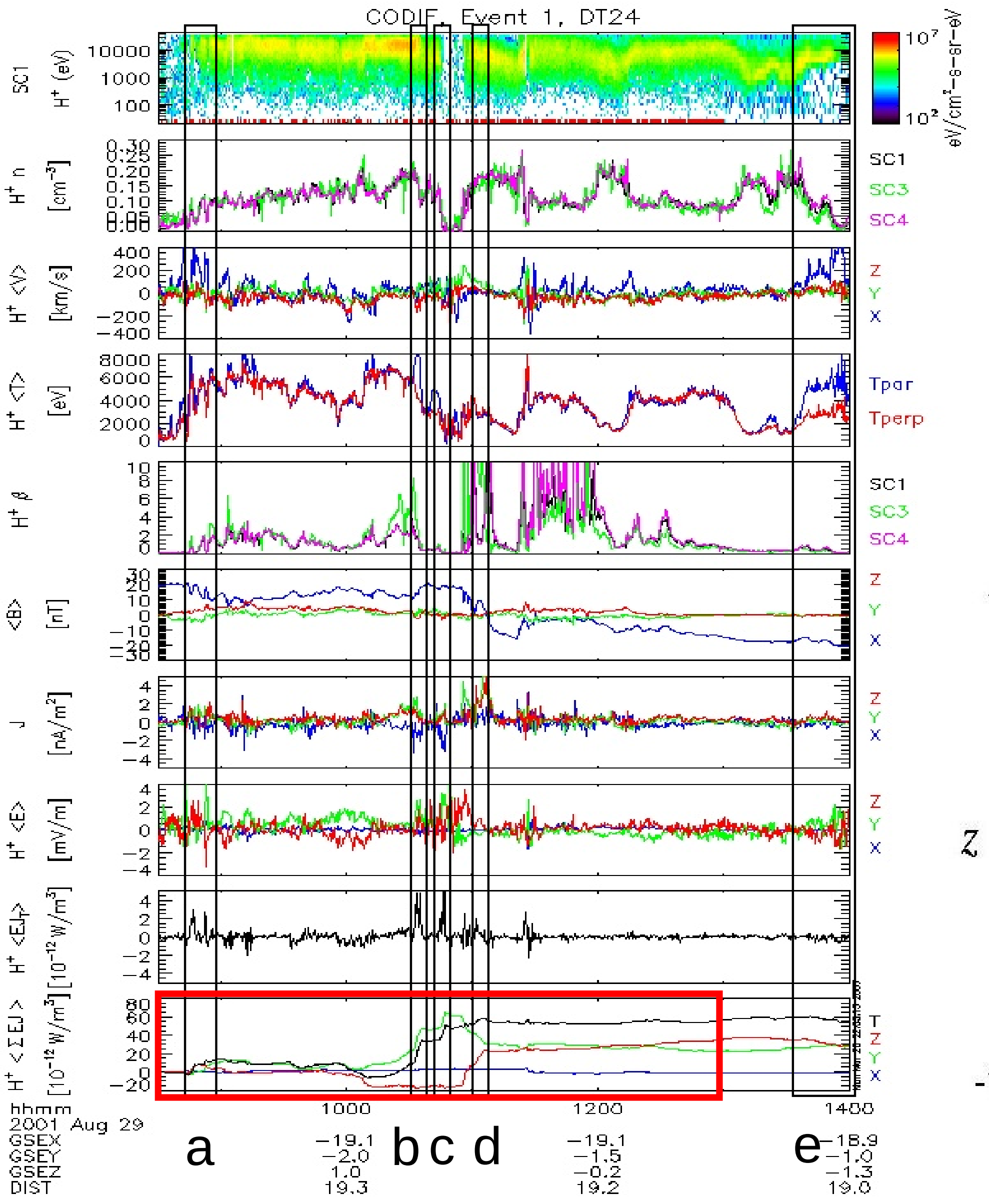
B Load Event L2: Data B

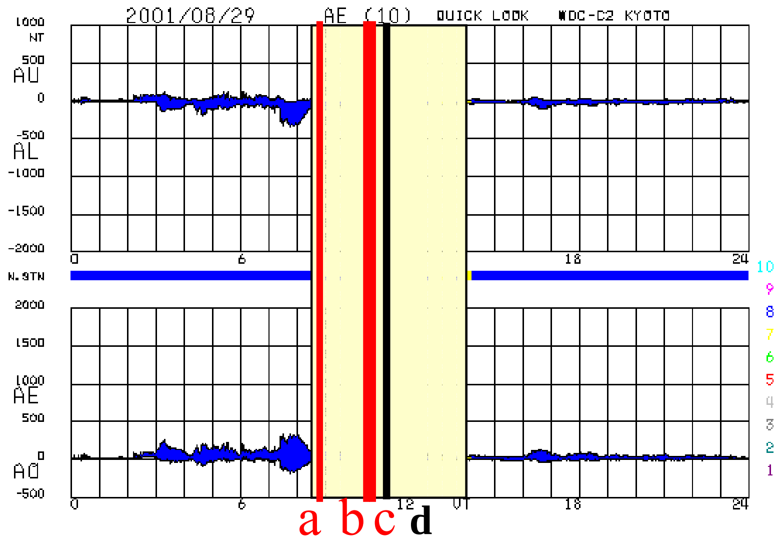


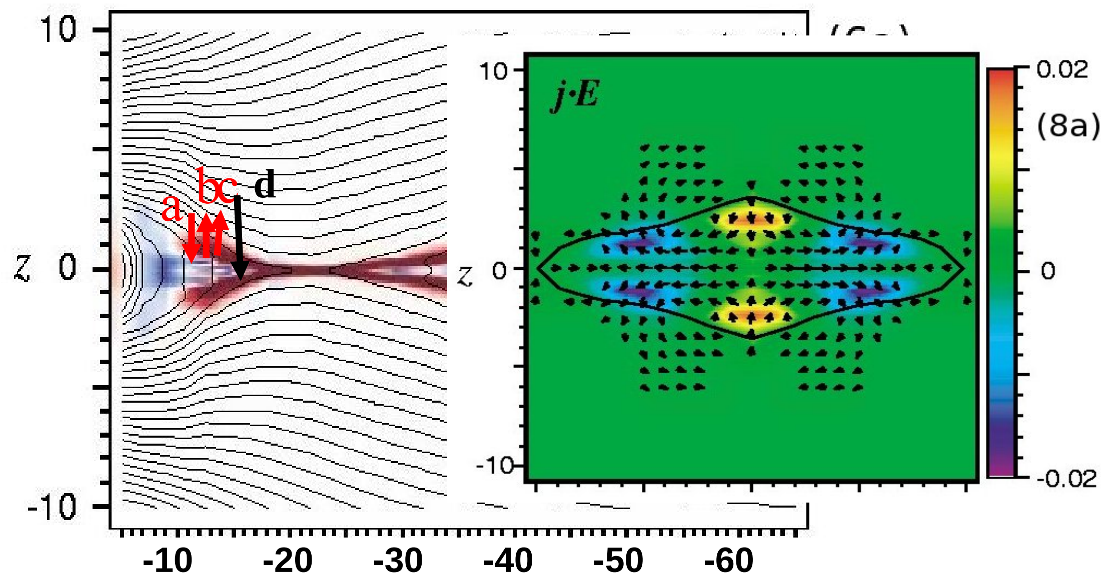
- Small and moderate loads (L2a, L2b, L2c) near the plasma sheet boundary (low/moderate beta).
- L2a assoc. with field aligned flow. L2b assoc. with Z bulk flow (untypical). L2c at the edge of field aligned flow. L2b, L2c assoc. with temp. anis. ($T_{\|} > T_{\perp}$).
- No load when crossing the neutral sheet (L2d).
- Neither bulk flow nor temperature anisotropy are necessarily associated with a load (L2e).
- Qualitative agreement again good, but we miss a factor of 2.5: L2b+L2c ~60 (CODIF) vs ~150 (EFW).



Load Event L2: Interpretation



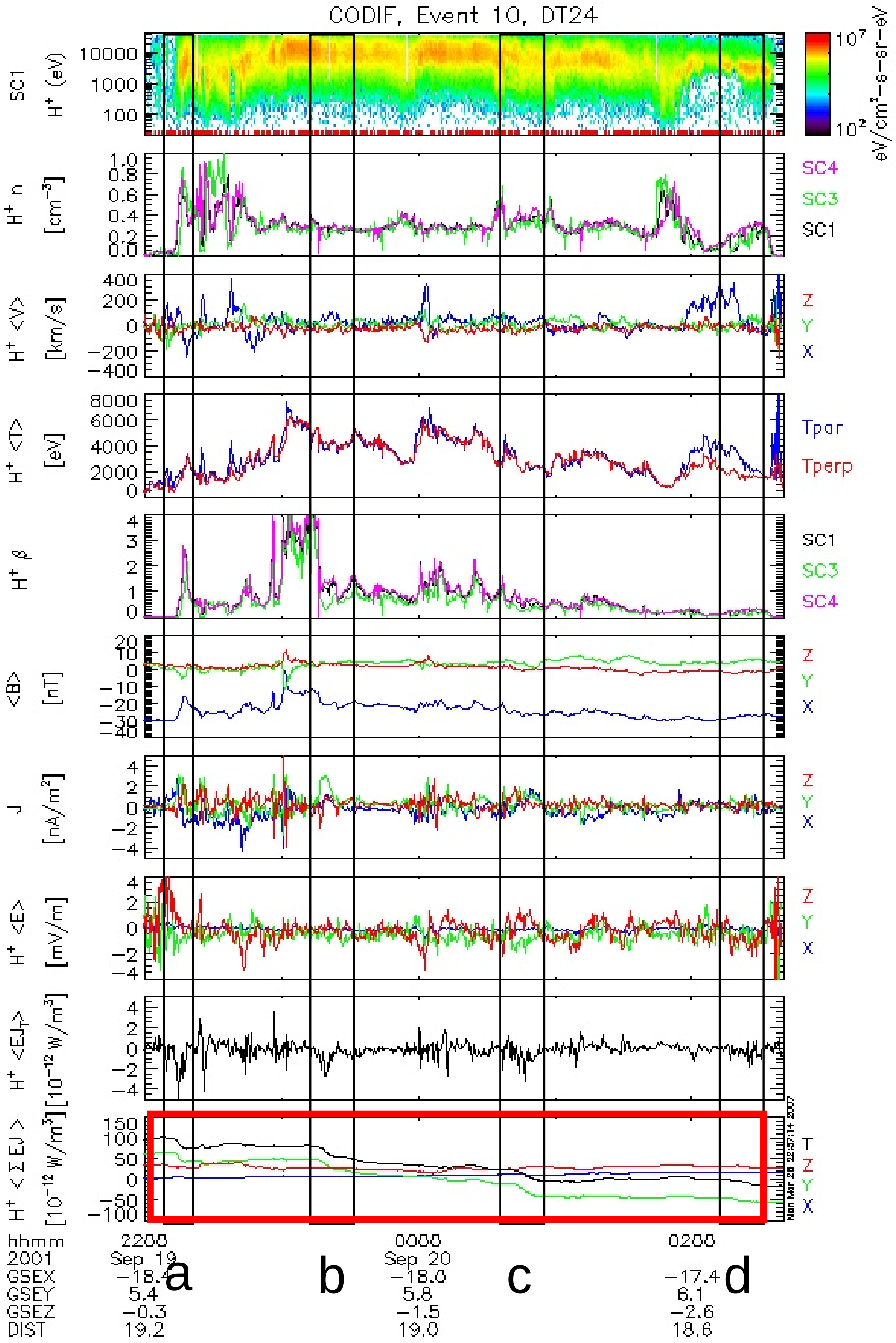




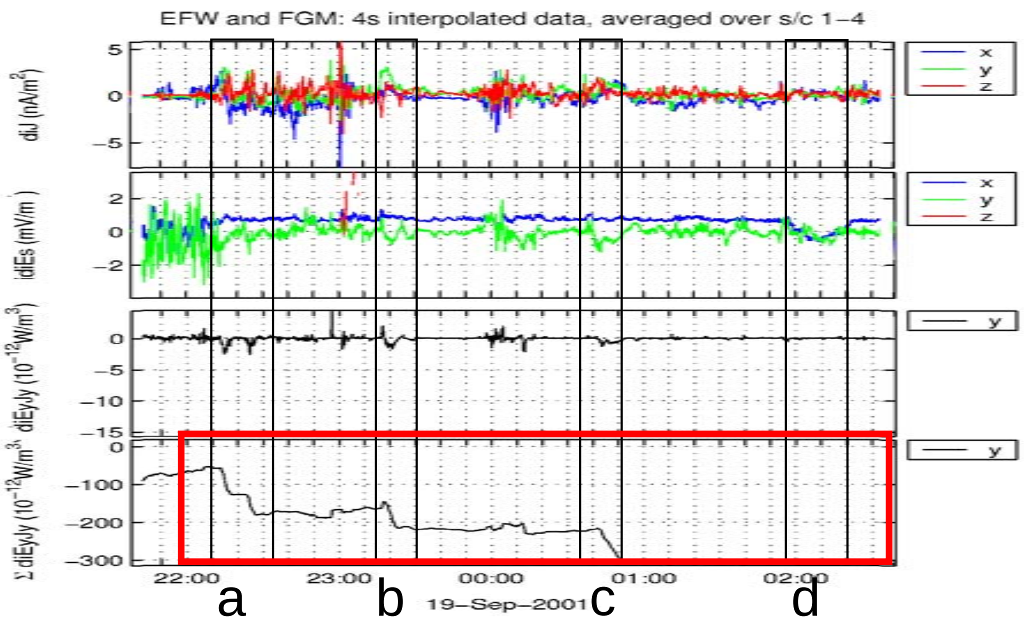
➢ Possibly the reconnection site comes closer to the Earth during the substorm expansion phase, but not close enough, so that eventually Cluster crosses the neutral sheet without encountering a load.

➢ E.J in the [x, z] panel is integrated along y. Even if on average E.J>0, locally one can have E.J=0 (L2d), or even E.J<0 (next slide).

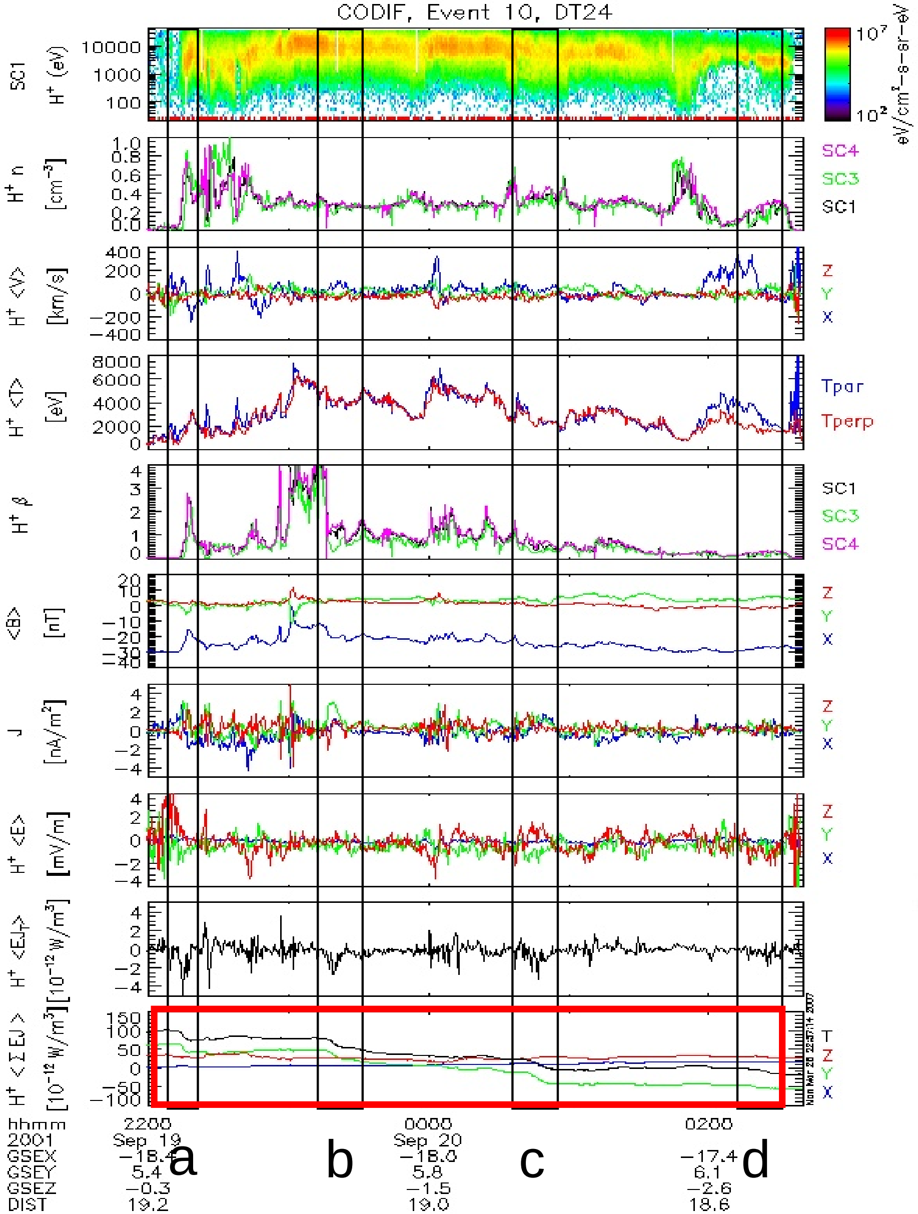
C Generator Event G1: Data C

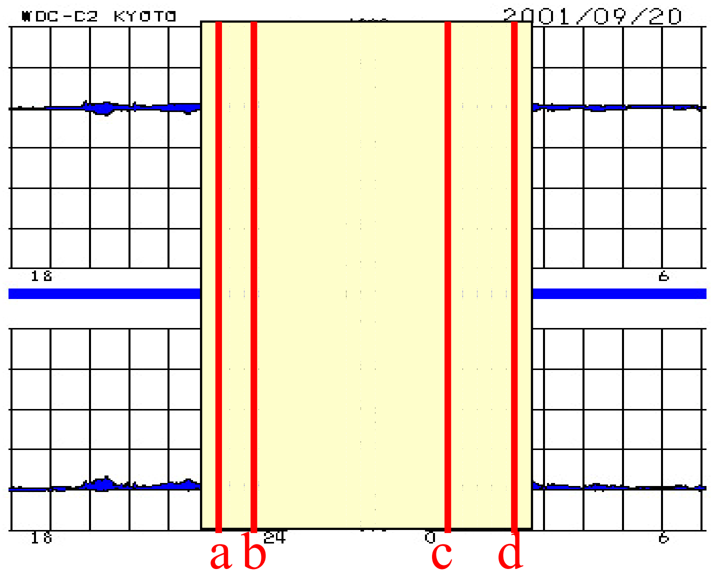


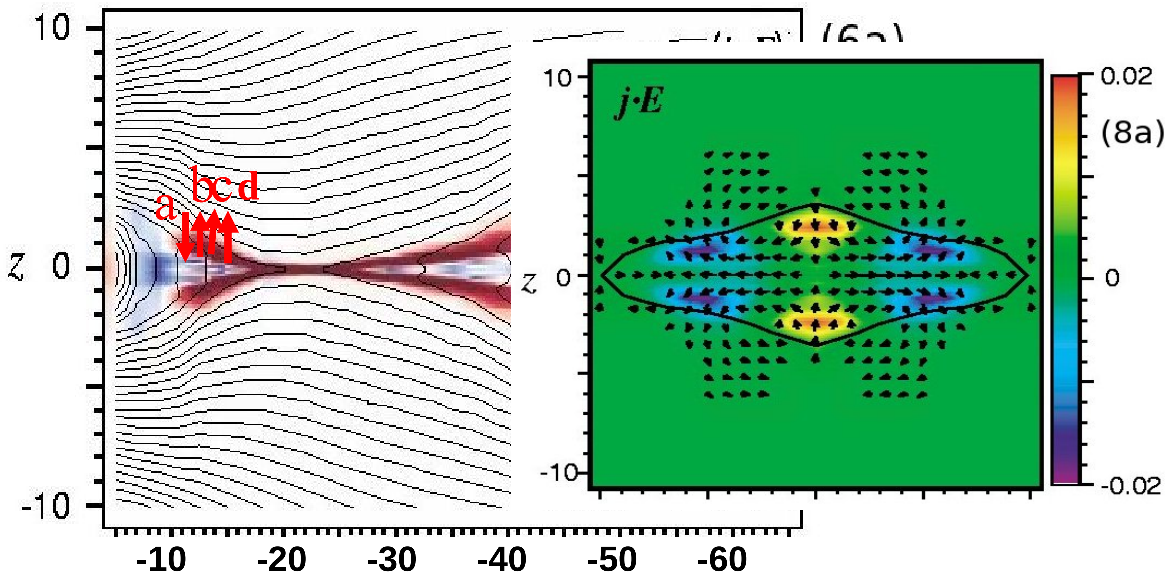
- ➢ Concentrated Generator Regions (CGRs) in the PSBL, discussed by Marghitu et al. (2006) and Hamrin et al. (2006), Ann. Geophys.
- ➢ Four CGRs of moderate (G1a, G1b, G1c) or small (G1d) power density.
- ➢ G1, G2, and G4 associated with field aligned flow. No field aligned flow for G3.
- ➢ G4 assoc. with temp. anis. No temp. anis. for G1–3.



Generator Event G1: Interpretation

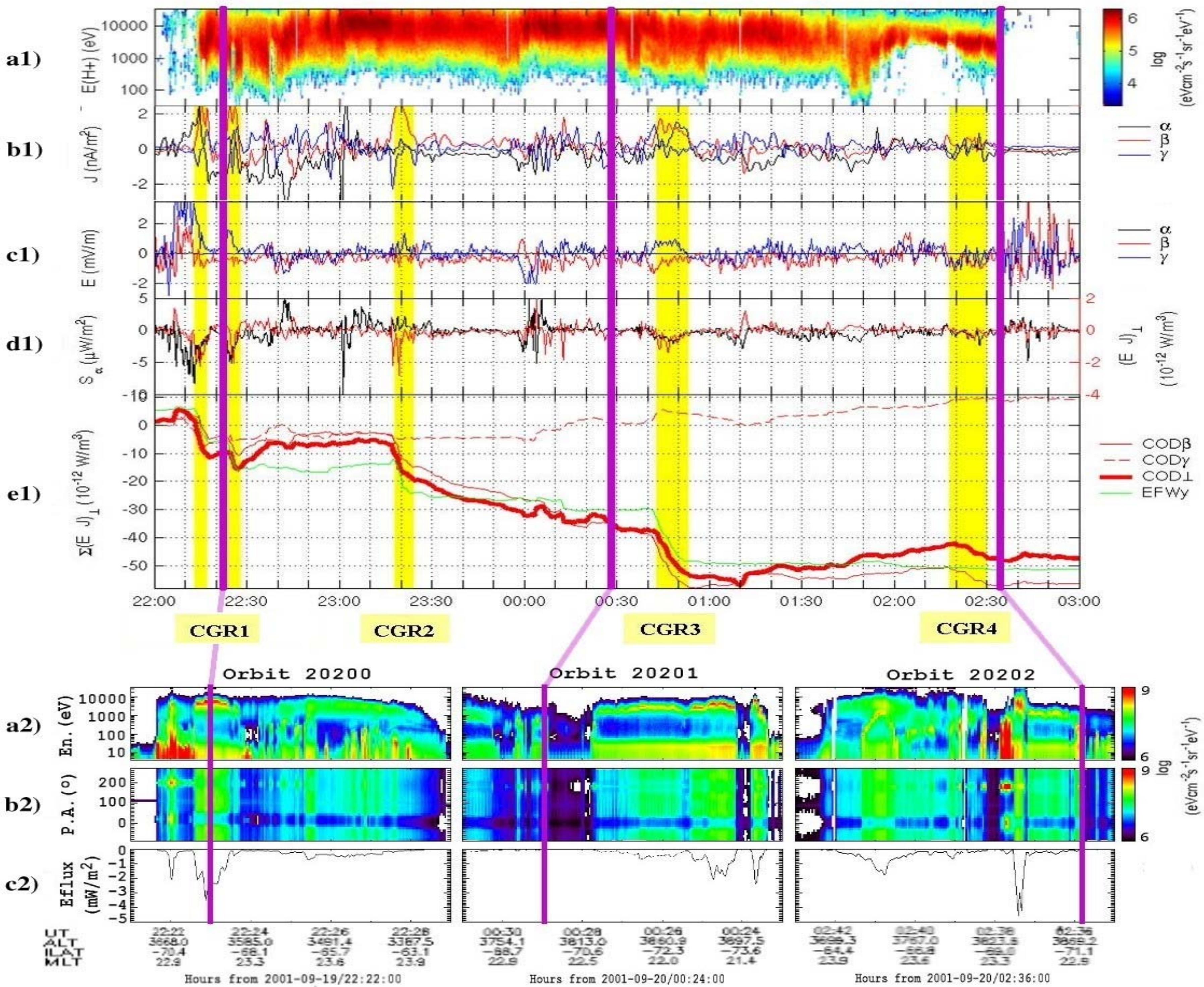






➤ Although the average E.J shows load character [(x, z) panel], the local signature can still indicate a generator [(y, z) panel].

B Generator Regions: Cluster versus FAST data B



$\mathcal{B}$ Generator Regions: Consistency Checks $\mathcal{B}$

$\Sigma E_Y J_Y$

E_Y

J_Y

P_K

P_B

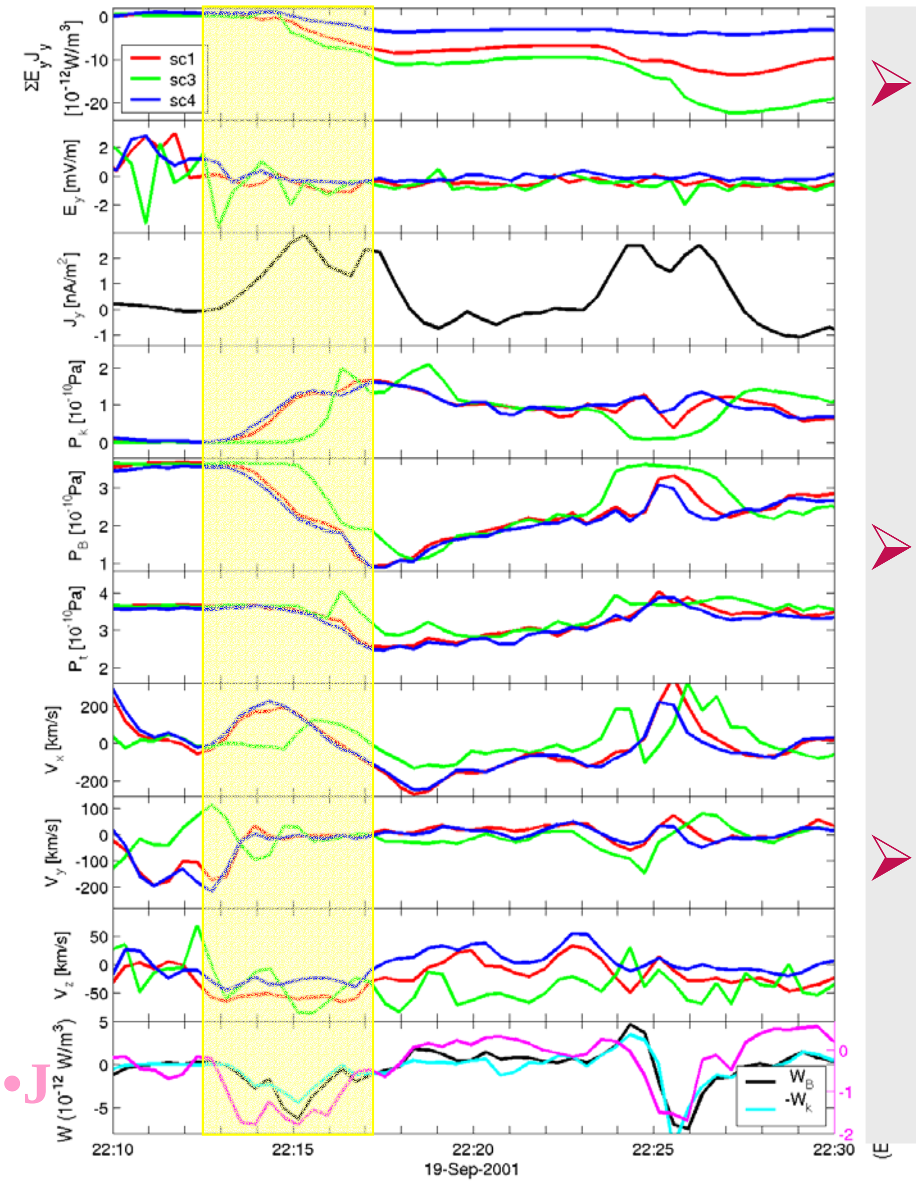
P_T

V_X

V_Y

V_Z

$-W_K, W_B, E \bullet J$



CGR1

- $\partial\mathcal{E}/\partial t = -\nabla \bullet (\mathcal{E}\ \mathbf{V}) + \mathbf{W_K} + \mathbf{W_L}$
  - $n < 1 cm^{-3}$, $V < 100 km/s \Rightarrow \mathcal{E} < 10^{-11} J$
    $W_K + W_L \cong 10^{-13} - 10^{-12}$
  - $\mathcal{E}/T \cong W_K + W_L \Rightarrow T \cong 10 - 100$ s
  - $\mathcal{E}V/L \cong W_K + W_L \Rightarrow L \cong 10^3 - 10^4$ km
- $W_L = W_B + W_T \cong \mathbf{E \bullet J}$
  - $\mathbf{E \bullet J} \cong -2\ 10^{-12}$, $W_B \cong -6\ 10^{-12}$
    $\Rightarrow W_T \cong 4\ 10^{-12}\ W/m^3$
- $W_T = \mathbf{V} \bullet (\nabla \bullet \mathcal{T}_B) \cong VB^2/\mu_0 L$
  - B=30 nT, V=50 km/s
    $\Rightarrow L \cong 10{,}000$ km

B Generator Regions: Consistency Checks B

$\Sigma E_Y J_Y$

E_Y

J_Y

P_K

P_B

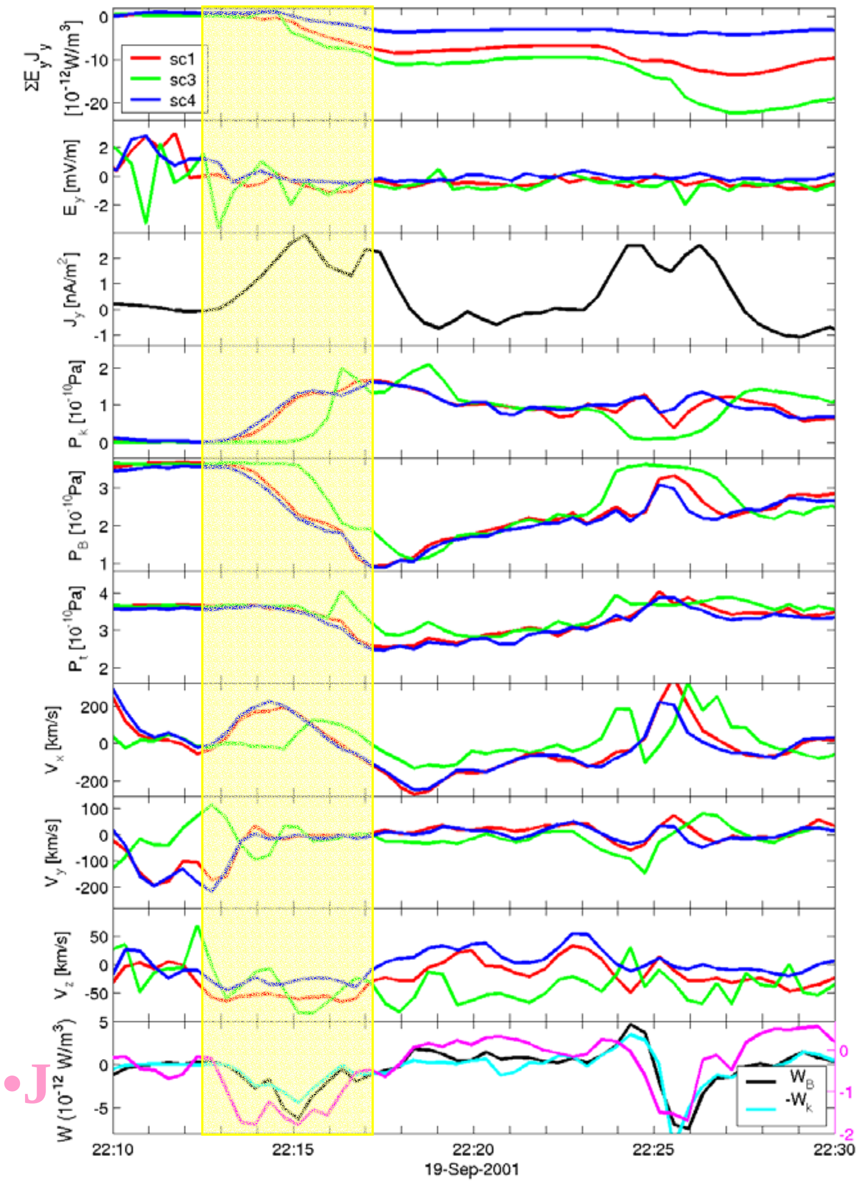
P_T

V_X

V_Y

V_Z

$-W_K, W_B, E \bullet J$



CGR1

- The Poynting theorem (PT):

  $\nabla \bullet \mathbf{S} = -\, \partial W / \partial t - \mathbf{E} \cdot \mathbf{J}$

  with $W \cong W_B = B^2/2\mu_0 \equiv P_B$.
- $\partial / \partial t \simeq d / dt$ in the s/c system, because $V_{sat} << V_{plasma}$. In the P_B panel =>regions where $-dP_B/dt > 0$.
- Both terms on the r.h.s. of PT positive => elmag. energy carried away from the CGR.
- $-\, \partial P_B / \partial t \simeq 0.2 nPa / 200s = 10^{-12} W/m^3$, comparable to $-\mathbf{E} \cdot \mathbf{J}$.
- $\nabla \bullet \mathbf{S} \cong S/L$. $S \approx 4 \cdot 10^{-6}\, W/m^2$, $\nabla \bullet \mathbf{S} \approx 2 \cdot 10^{-12}\, W/m^3 \Rightarrow L \approx 2000\ km$

Summary

- Location of the energy conversion regions (ECRs):
  - High power density loads close to the neutral sheet, in high β plasma.
  - Low/moderate power density loads, as well as generators, near the PSBL, in low β plasma.
- Relation to plasma flow and temperature anisotropy, in particular for loads:
  - EC usually related to plasma flow, dominantly along the magnetic field. The reverse is not true, plasma flow can be observed without EC.
  - Temperature anisotropy often observed, with $T_{\parallel} > T_{\perp}$.
- Possible scenario: Local plasma acceleration (load) naturally associated with bulk flow, which is thermalized faster in parallel direction ($T_{\parallel} > T_{\perp}$). If the satellite path is far from the acceleration site, one observes just the bulk flow and the temperature anisotropy. If the path is very far => just the bulk flow.
- The observations are in decent agreement with simulation results, which can help to understand the context.

Prospects

- Closer look at the micro-physics:
  - Is the plasma flow associated with local acceleration by parallel electric fields, or the Lorentz force is enough?
  - Is the anisotropy indeed related to faster thermalization in parallel direction?
  - Reversible versus irreversible processes – entropy calculation?
- Improvement of the event statistics:
  - Completing the 2001 dawn–dusk survey with Cluster plasma sheet crossings in June – August 2001.
  - Cluster plasma sheet crossings in 2002 – 2004.
- Extension to other regions and missions:
  - Energy conversion at the magnetospheric flanks => better electric field from EFW, as well as EDI.
  - Energy conversion close to the subsolar point (coming soon).
  - Extension to future multi-spacecraft missions, like THEMIS (the current disruption region), MMS (reconnection sites), Cross-Scale (reconnection sites and shocks).