Energy Conversion Regions in the Plasma Sheet as Observed by Cluster

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12th Cluster Workshop, Saariselkä, Finland, September 13, 2006

Session B: Substorms and other Magnetotail Phenomena

Outline

A. Background info

B. Generator regions:

- Signatures
- Consistency checks

C. Load regions: Cluster data and signatures

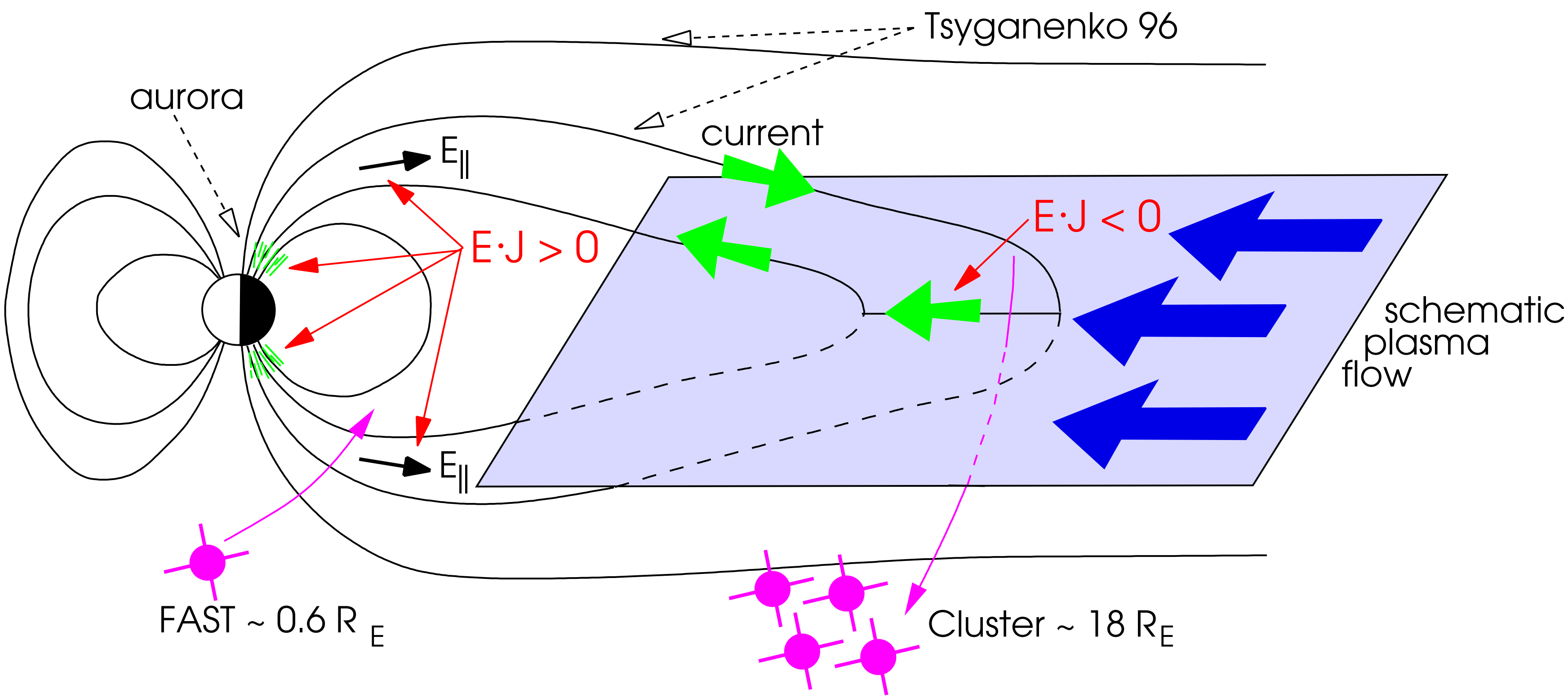
D. Data versus simulations

E. Summary and prospects

Background

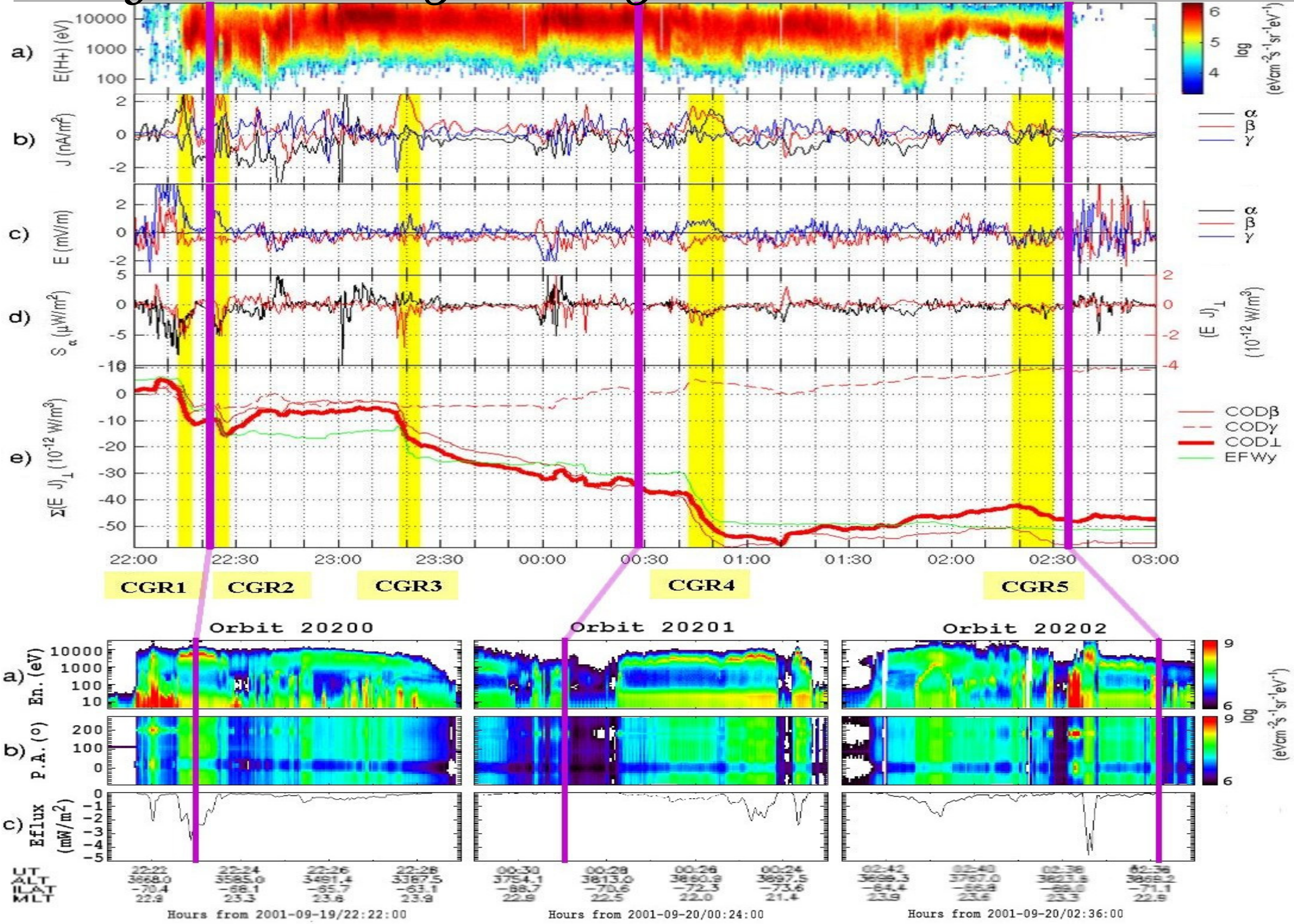
- With Cluster one can investigate local energy conversion, by computation of **E·J**
- **E·J** < 0 => Generator => conversion mechanical → electromagnetic energy
- **E·J** > 0 => Load => conversion electromagnetic → mechanical energy
- In the plasma sheet:
  - **E** can be inferred from two different 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, which are used to cross-check CIS
- **J** can be computed by the Curlometer method from the magnetic field measured on the four satellites
- The reference system is GSE.

B Generator Regions: Sketch *B*



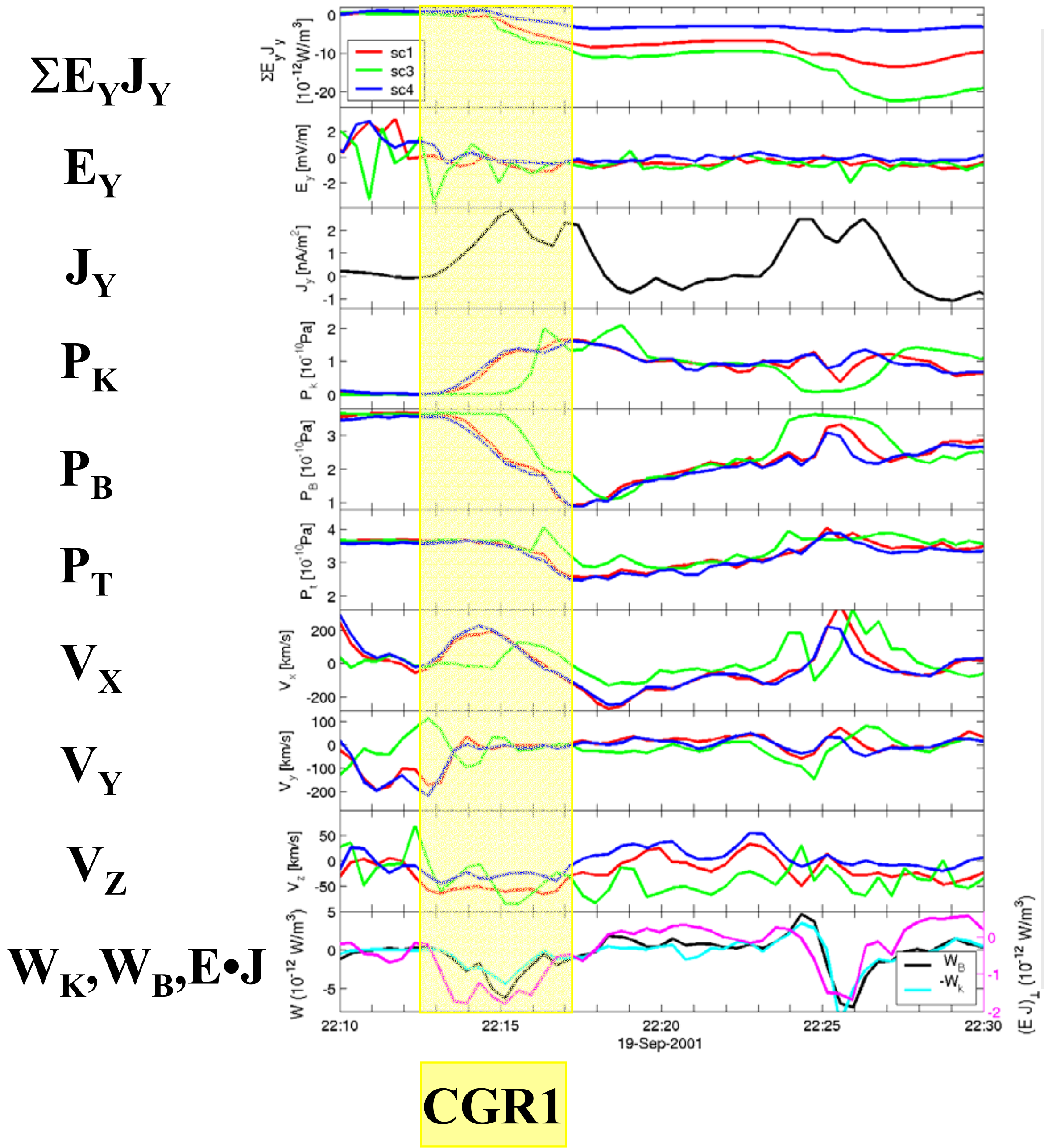
- A magnetospheric generator (**E·J**<0) powers loads (**E·J**>0) in the auroral acceleration region and ionosphere.
- The energy flux of a moderate aurora, ~10^{-2} W/m^2, maps to ~10^{-5} W/m^2 in the tail (mapping factor ~1000). If the generator region extends 10^7–10^8m (1.5–15R_E) along the field line, the power density is ~10^{-13}–10^{-12} W/m^3.

ℬ Generator Regions: Signatures ℬ



Concentrated Generator Regions (CGRs) in the PSBL, discussed by Marghitu et al. (2006) and Hamrin et al. (2006), Ann. Geophys.

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



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

B Generator Regions: Consistency Checks *B*

$\Sigma E_Y J_Y$

E_Y

J_Y

P_K

P_B

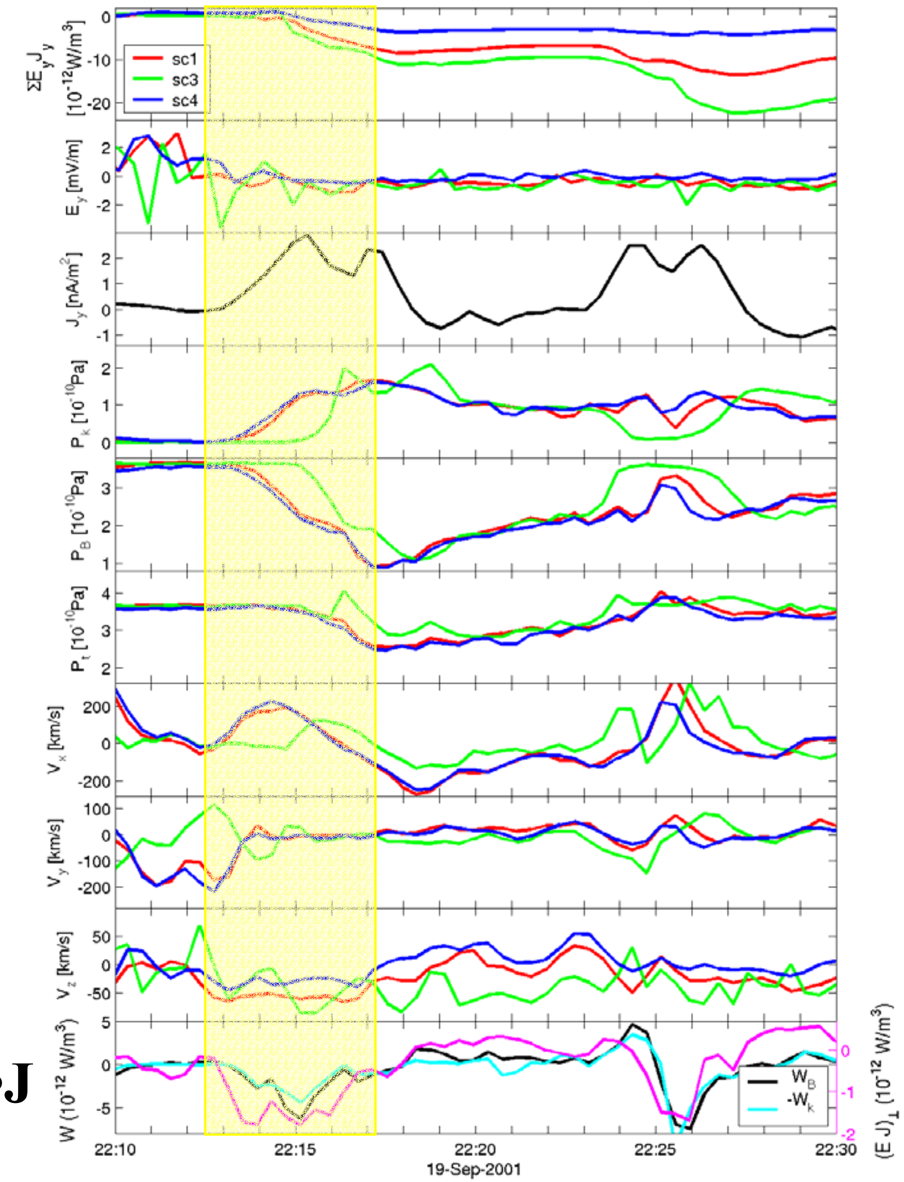
P_T

V_X

V_Y

V_Z

$W_K, W_B, \mathbf{E \bullet J}$



CGR1

- The Poynting theorem (PT):

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

  with $W \cong W_B = B^2/2\mu_0 \equiv P_B$.
  - $\partial / \partial t \cong d / dt$ in the satellite system, because $V_{sat} \ll V_{plasma}$.
  - 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.
- $-\, \partial P_B / \partial t \cong 0.2\text{nPa}/200\text{s} = 10^{-12}\ \text{W/m}^3$, comparable to $-\mathbf{E \bullet J}$ (as in simul.)
- $\nabla \bullet \mathbf{S} \cong S/L$
  - $S \cong 10^{-6}\ \text{W/m}^2$, $\nabla \bullet \mathbf{S} \cong 10^{-12}\ \text{W/m}^3$ => $L \cong 10^3$ km

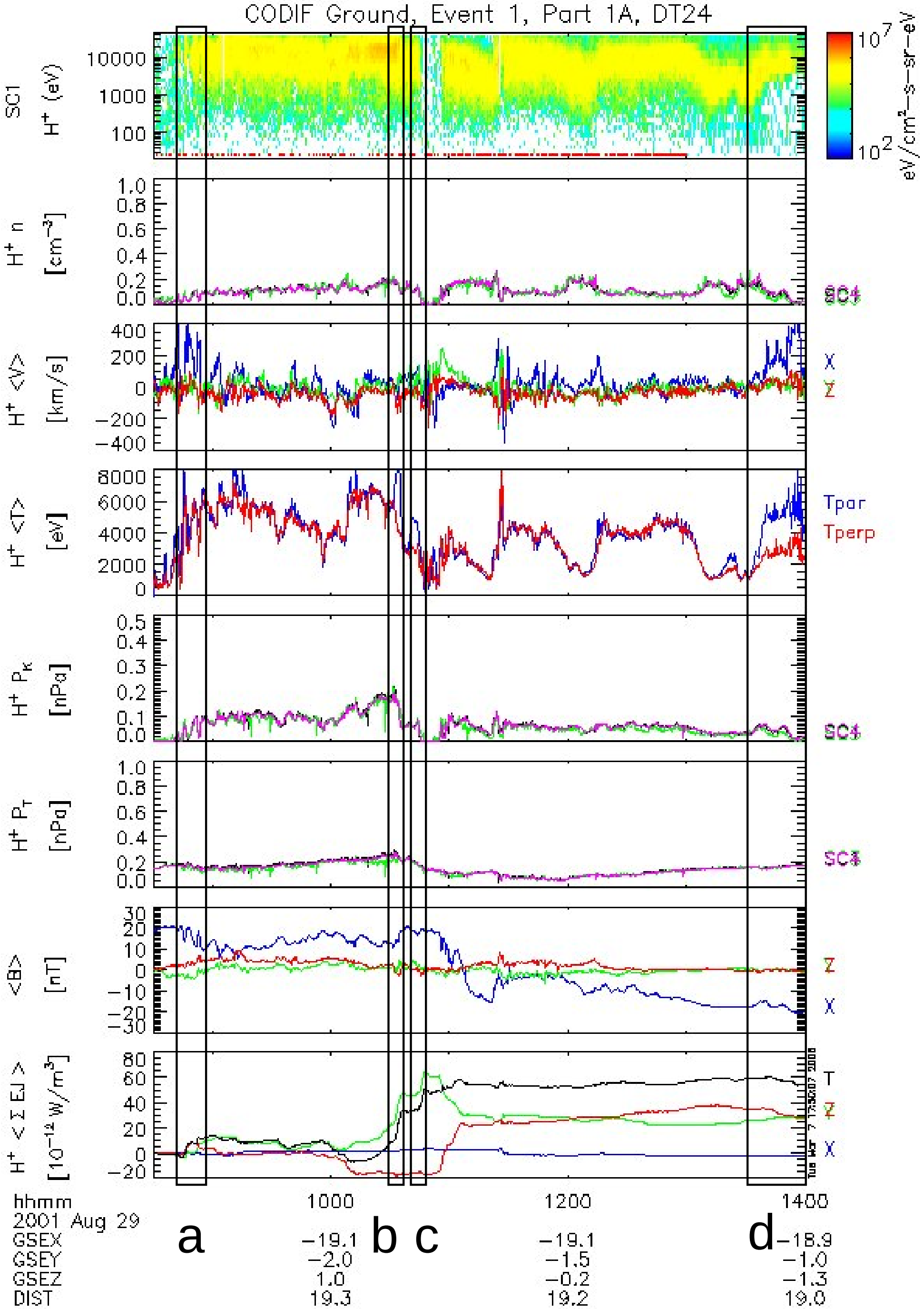
B Generator Regions: Findings *B*

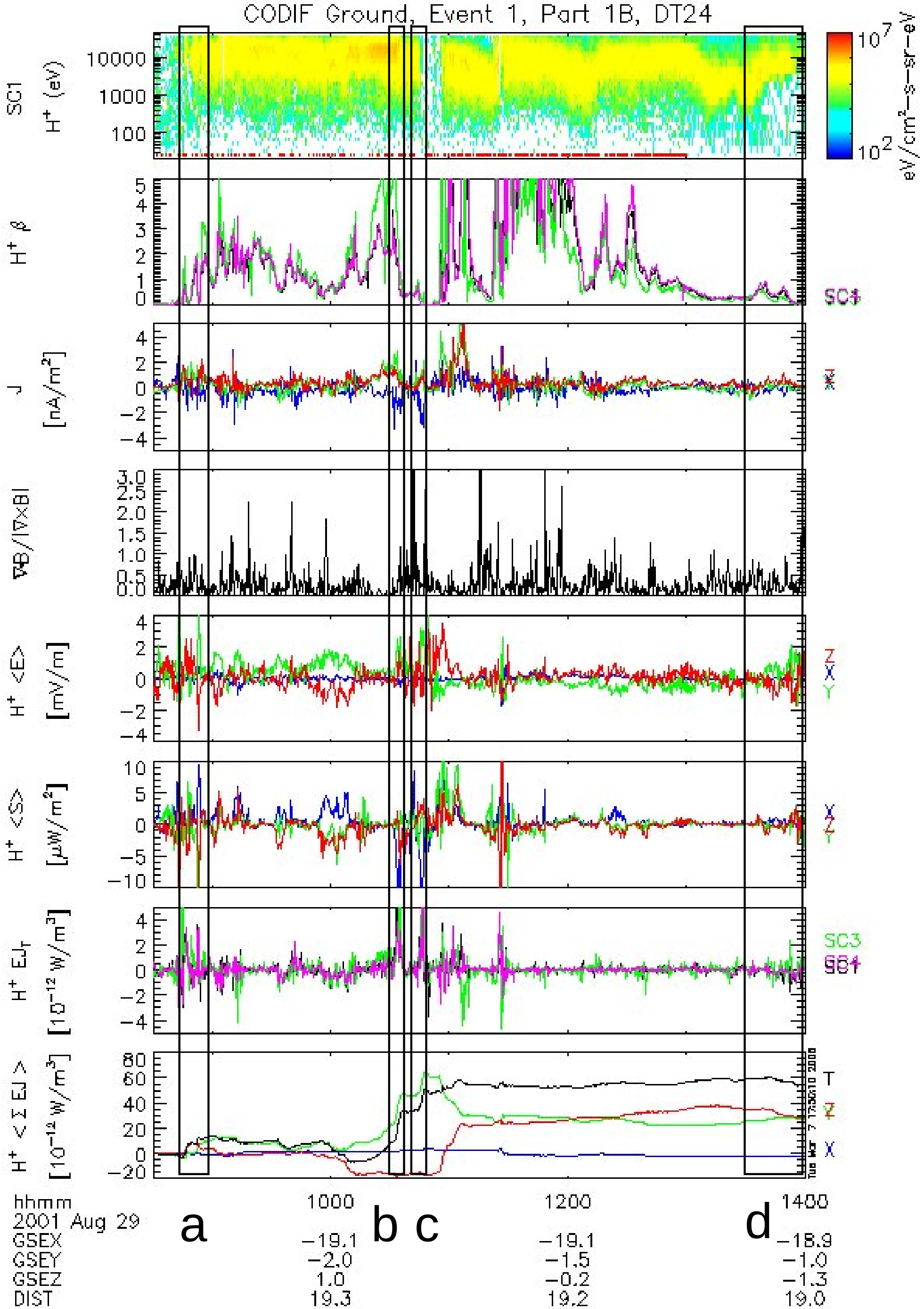
- The CGRs correlate with auroral precipitation observed by FAST.
- CGRs observed close to the plasma sheet boundary (PSB).
- $\nabla P_{kin} \neq 0$ near PSB => $\mathbf{J}_{diamag} = \mathbf{B} \times \nabla P_{kin}/B^2 \approx \mathbf{J}_{Curlometer}$
- Good correlation between $\mathbf{E} \cdot \mathbf{J} < 0$, $W_K > 0$, and $W_B < 0$.
- The thermal pressure forces push the plasma element (PE) against the magnetic pressure, consistent with energy conversion.
- The magnetic tension does work on the PE, $W_T > 0$.
- CGRs have a scale size of a few 1000km, consistent with estimates based on conjunction timing and energy flux mapping.
- In at least one case Poynting flux is leaving the CGR.
- In this case the decrease in the magnetic energy and the conversion term, $\mathbf{E} \cdot \mathbf{J}$, make comparable contributions to $\nabla \cdot \mathbf{S}$.

C Load Regions: Intro C

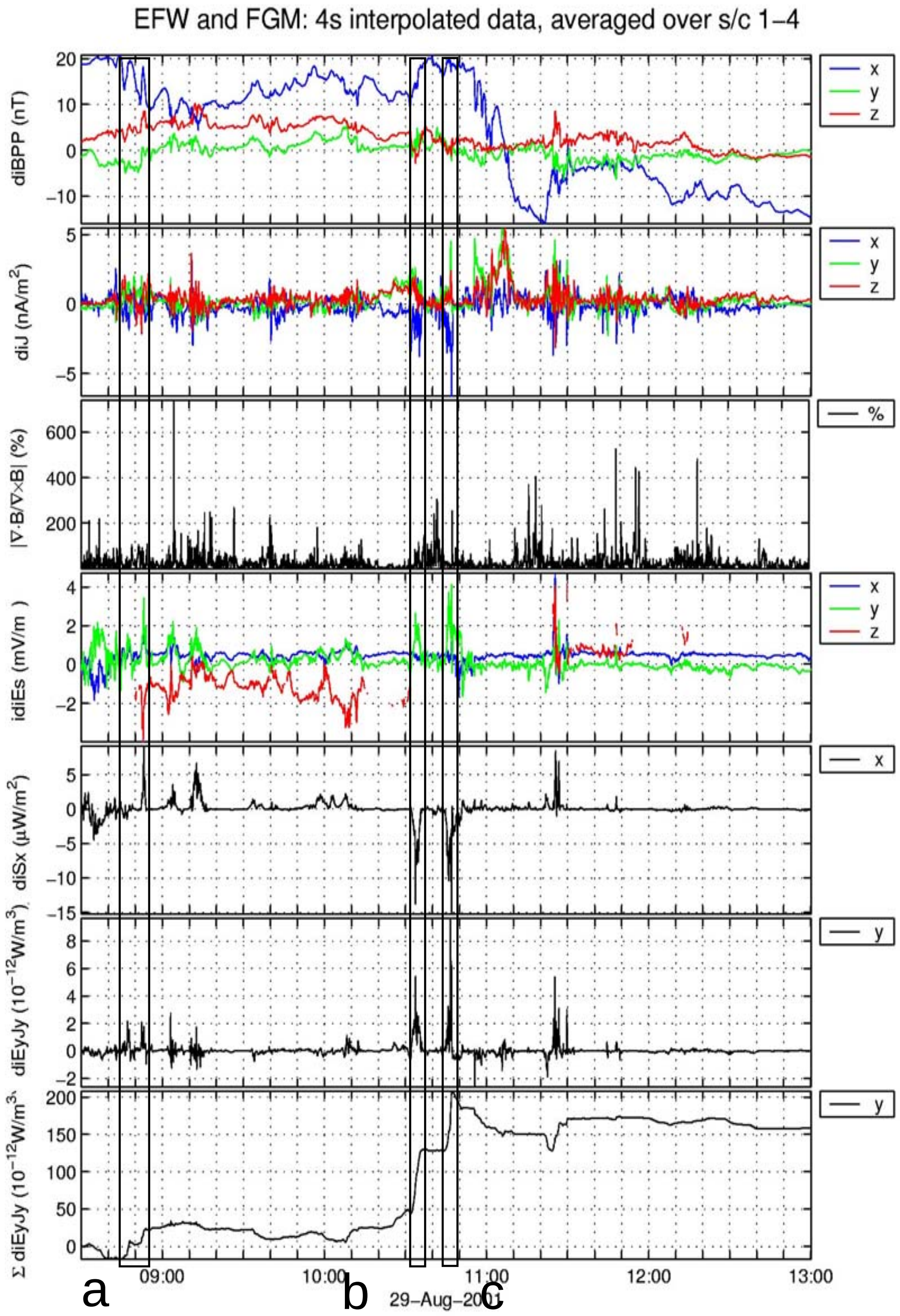
- In order to extend the search for (auroral) generator regions we selected a time interval between the end of August and the beginning of November, 2001, with increased conjunction rate between the two spacecraft. During this time the apogee of Cluster, at 19 R_E, was in the plasma sheet, moving from midnight to the dusk.
- With the progress of the work it became clear that Cluster data can be used for a broader investigation of the energy conversion, not restricted to generator regions. Near the 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.

C Load Regions: CIS Data L1 C

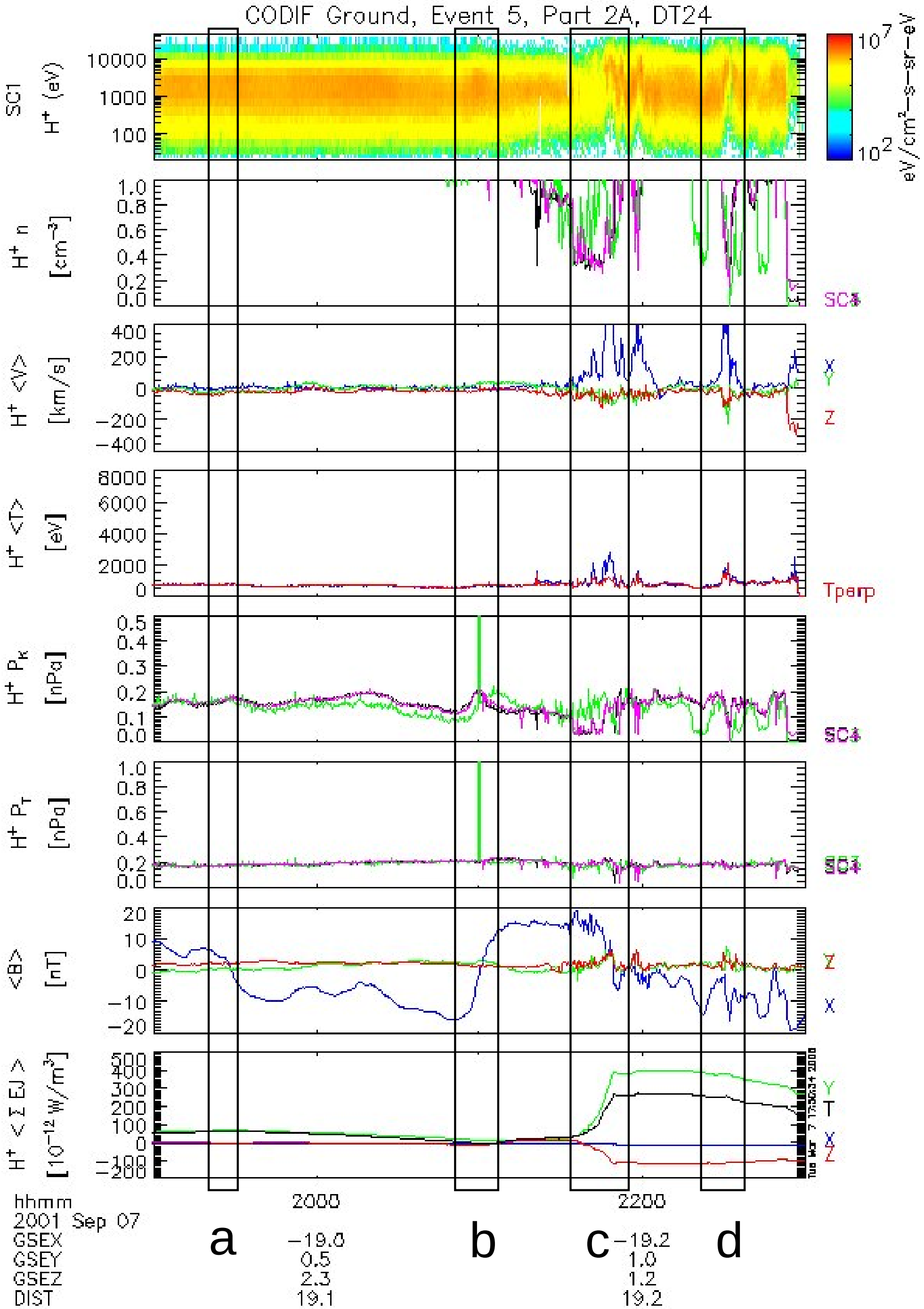


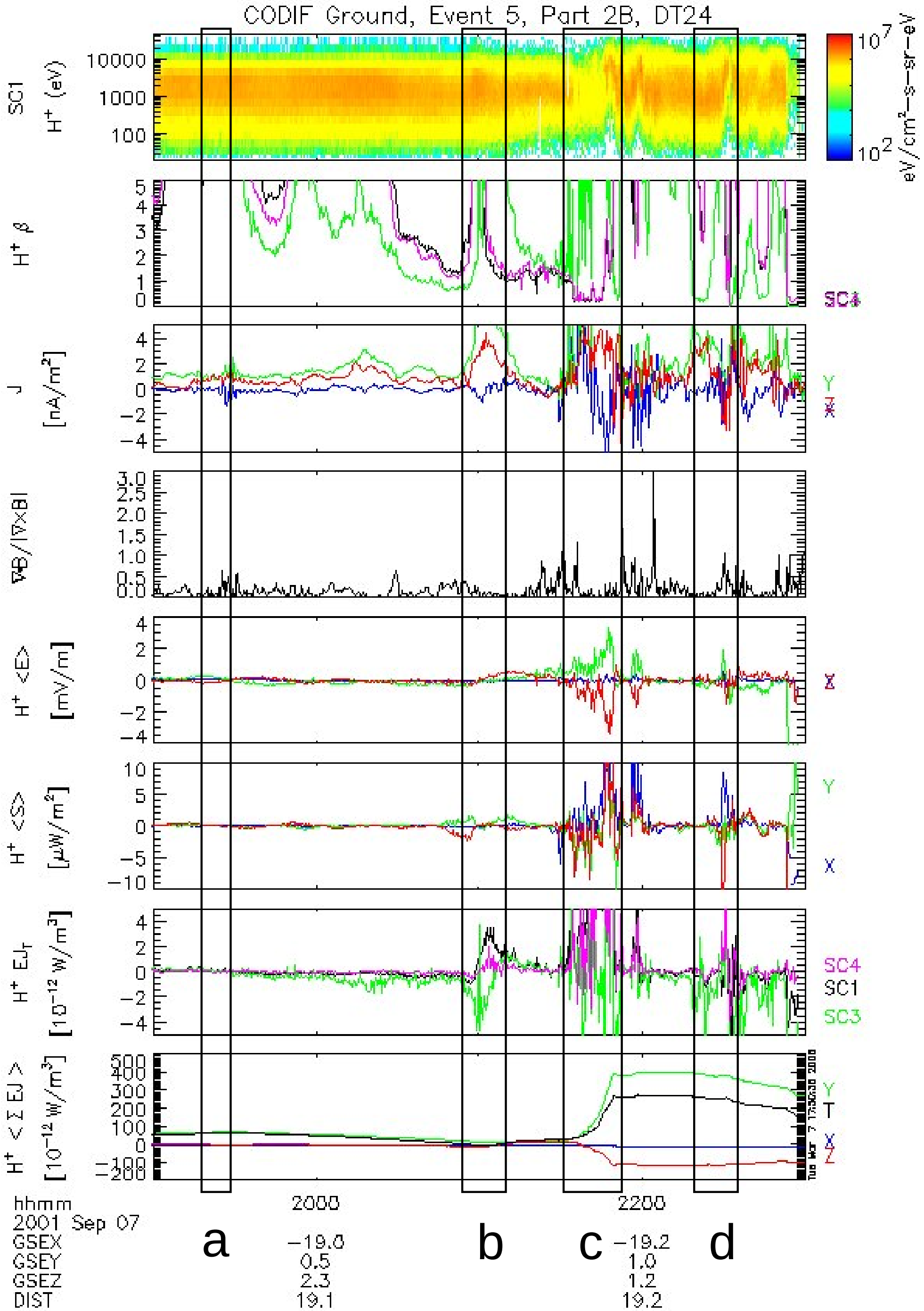


Load Regions: EFW Data L1

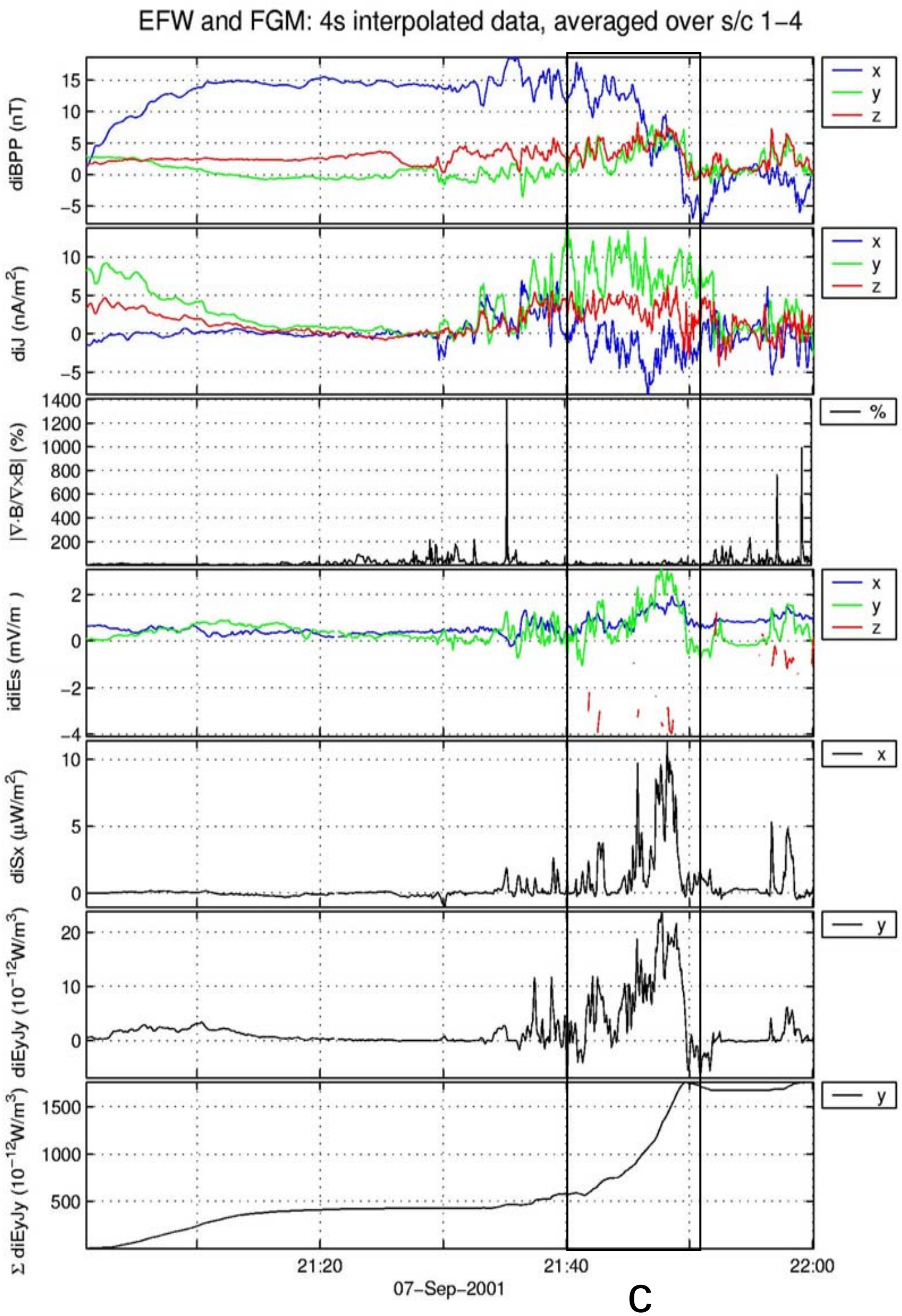


C Load Regions: CIS Data L2 C





C Load Regions: EFW Data L2 C

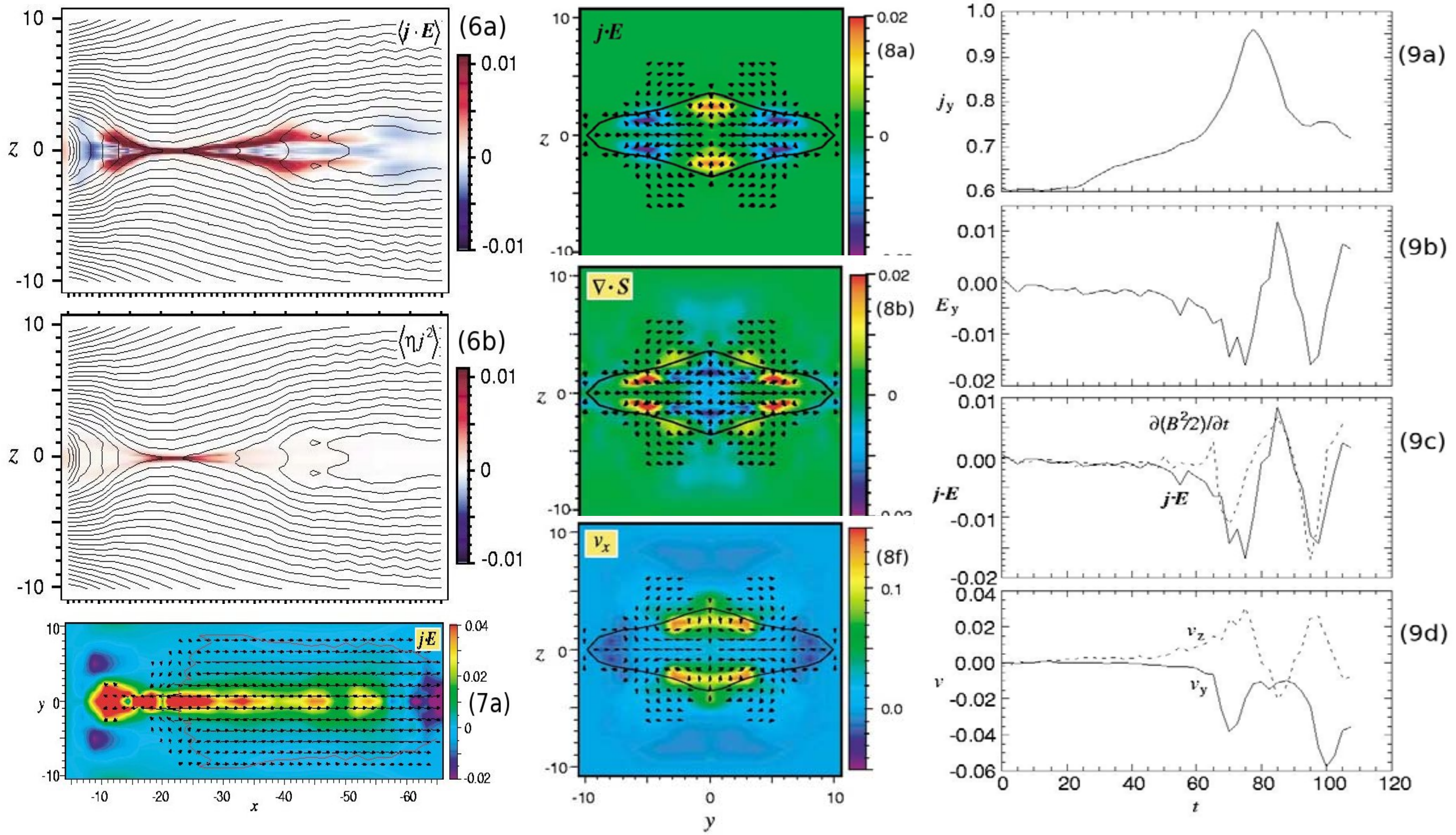


C Loads Regions: Findings C

- Energy conversion is dominated by loads, most of which are associated with bulk flow (mainly field aligned), often also with temperature anisotropy ($T_{\|} > T_{\perp}$).
- Bulk flow, however, is not necessarily associated with loads (L1d, L2d).
- Big loads (L2c) are often seen near midnight, close to the neutral sheet (high β). No significant load is observed, in this region when the bulk flow is missing (L2a, L2b).
- Small and moderate loads (L1b, L1c) are observed near the plasma sheet boundary (low beta).
- Moderate loads observed also close to the neutral sheet, when away from midnight (not shown).
- Some correlation between the load magnitude and AE (not shown).
- Both concentrated and distributed loads (not shown). The distributed loads do not appear to be associated with bulk flow.

D Data versus Simulations: BH05 Results D

Energy conversion and transport in the tail has been also studied by computer simulations, most recently by Birn and Hesse, 2005 (BH05). Multi-satellite missions like Cluster allow for the direct cross-check of the data and simulation results.



Energy conversion features from BH05. Units: L=6–12·10³ km, t=6–12 s, v=1000 km/s, B=40nT.
Left: Energy conversion terms integrated over *y* and over *z*.
Center: Characteristic quantities near the conversion regions, at x=-8.75 and t=100.
Right: Characteristic quantites in the generator region, at x=-8.75, y=-4, z=1.2.

D Data versus Simulations D

Good agreement with data:

- The energy conversion regions (ECRs) have mostly load character.
- Association of the ECRs with bulk flow.
- Integrated load close to midnight.
- Integrated generators on the sides.
- Energy conversion near the plasma sheet boundary.
- Net Poynting flux from the generator regions.
- Few minutes ECR time scale.

E ECRs in the Plasma Sheet : Summary E

- Starting from the examination of generator regions, we developed a method that allows for a systematic investigation of the energy conversion regions (ECRs).
- Cluster North–South crossings of the plasma sheet show, on large scales, mostly load character, with a substantial fraction of the load near the neutral sheet.
- The magnitude of the integrated load seems to decrease from midnight to the dusk. Away from the midnight one can even encounter integrated generator regions, in good agreement with simulation results (Birn and Hesse, 2005).
- The CGRs seem to develop in the PSBL, as inferred from the plasma β – consistent, again, with the simulations. One example was shown, where the CGRs observed by Cluster correlate with electron precipitation observed by FAST.
- High power density CLRs are located not far from the neutral sheet, in high β plasma, while for the low/moderate power density CLRs a clear dependence on β it is not obvious so far.
- The energy conversion seems to be related to bulk plasma flow, dominantly along the magnetic field. Temperature anisotropy is observed as well, with $T_{\parallel} > T_{\perp}$.

E ECRs in the Plasma Sheet : Prospects E

- Further investigation of the generator events presented:
  - Computation of W_T by direct evaluation of $\nabla \bullet \mathcal{T}_B$.
  - Direct evaluation of $\nabla \bullet \mathbf{S}$.
  - CGR geometry – curvature radius, etc.
  - Derivatives by the GALS method (Umeå group) => 3 satellites may suffice!
- Completing the dawn–dusk survey with the Cluster plasma sheet crossings in June – August 2001. Closer look at the local energy budget – work of the pressure forces, Poynting theorem, etc.
- Is the plasma flow associated with local acceleration and parallel electric fields? Is the anisotropy related to thermalization, achieved faster in parallel direction ?
- Reversible versus irreversible processes – entropy calculation?
- Cluster plasma sheet crossings in 2002 – 2004.
- Energy conversion at the magnetospheric flanks => better electric field from EFW, as well as EDI.
- Energy conversion close to the subsolar point (later in the mission).
- Extension to future multi-spacecraft missions, like THEMIS, MMS, Cross Scale.