Local Energy Conversion in the Plasma Sheet as Observed by Cluster

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Preamble

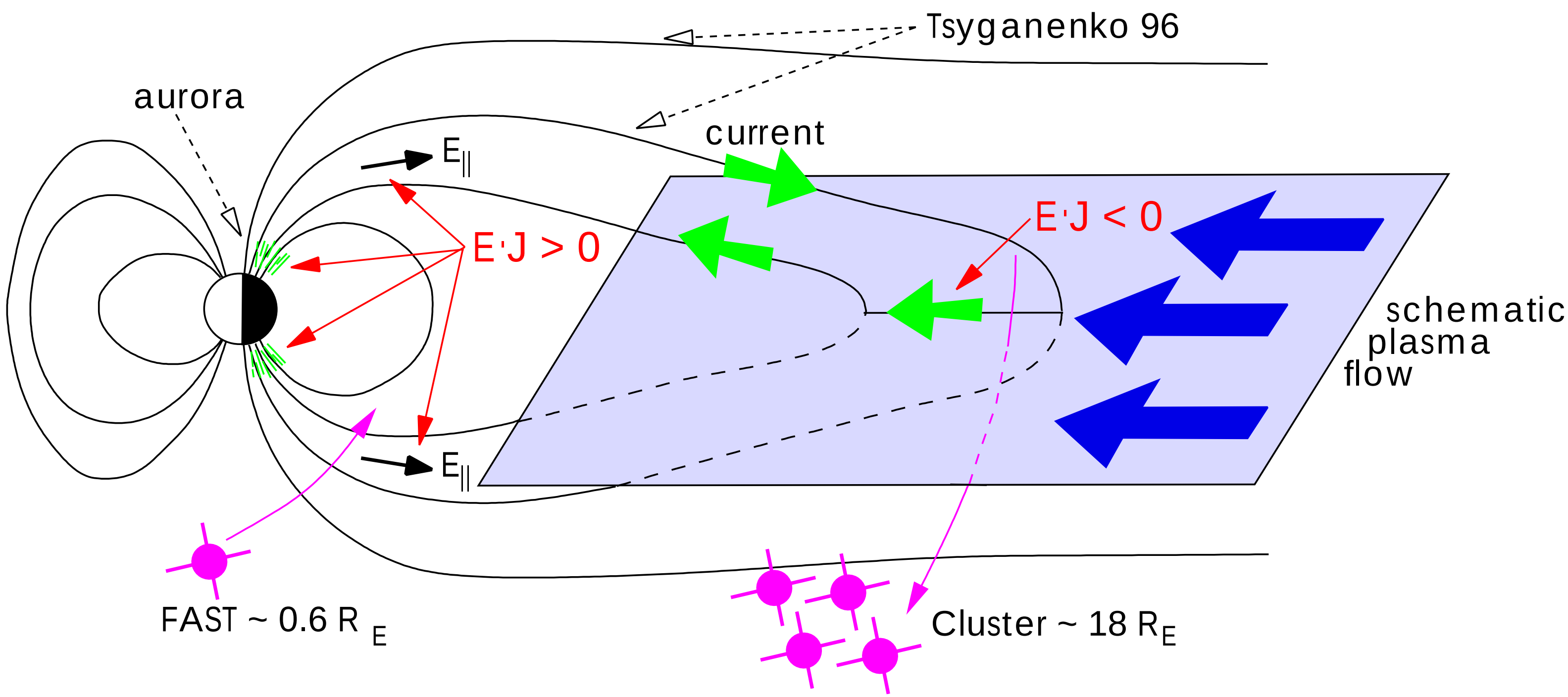
- Since the last CIS meeting => two companion papers on the first *in-situ* observation of generator regions, published in Annales Geophysicae:
  - O. Marghitu, M. Hamrin, B. Klecker, et al., Experimental investigation of auroral generator regions with conjugated Cluster and FAST data
  - M. Hamrin, O. Marghitu, K. Rönnmark, et al., Observations of concentrated generator regions in the nightside magnetosphere by Cluster / FAST conjunctions
- Ongoing work on:

A. CGR Macrostructure: Energy, work, scales, …

B. Energy conversion regions in the plasma sheet

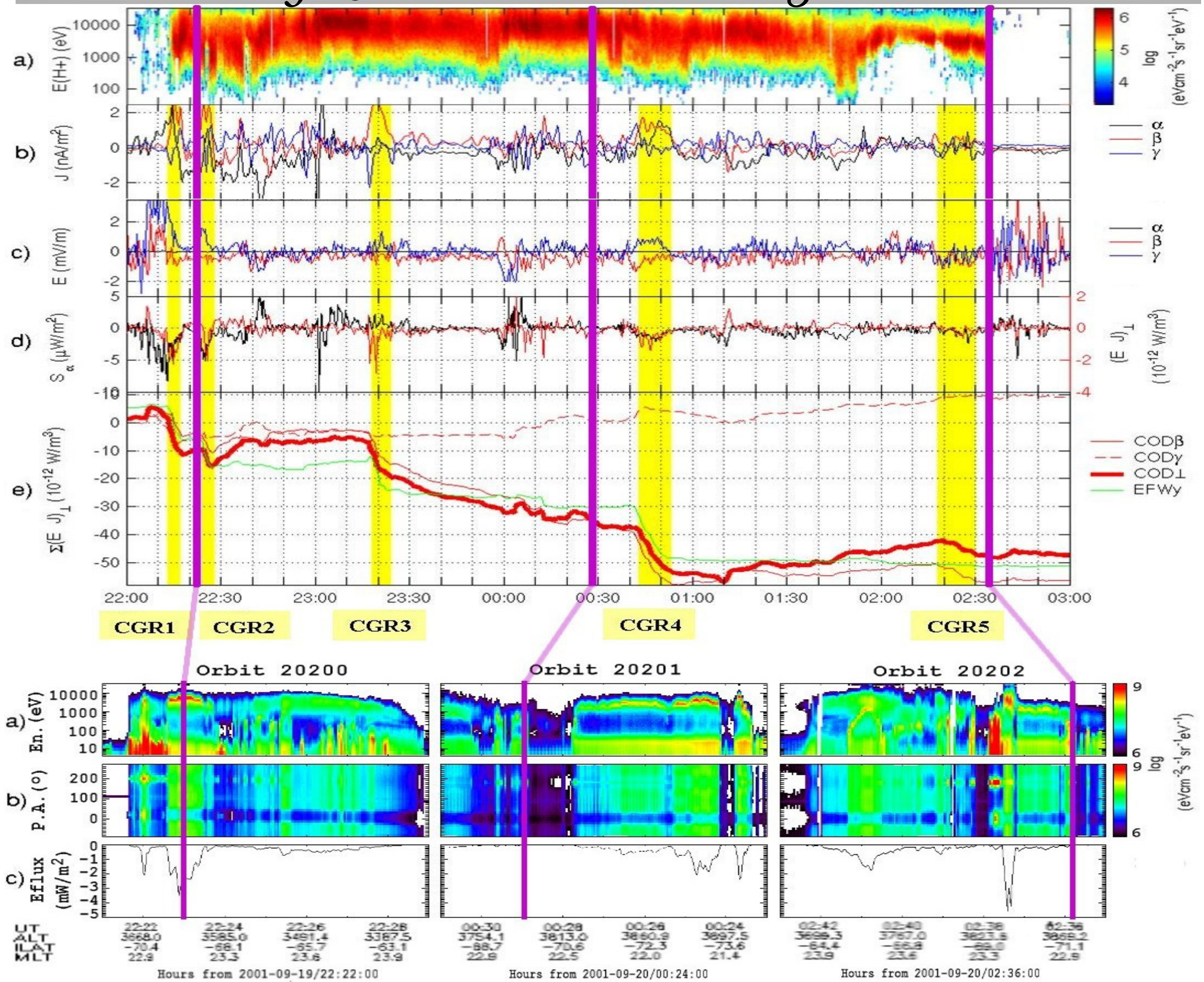
C. CGR Microstructure: Potential structures, waves, …

Background



- 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.

A CGR Macrostructure: Signatures A



𝒜 CGR Macrostructure: Energy, Work, Scales 𝒜

$\Sigma E_Y J_Y$

E_Y

J_Y

P_K

P_B

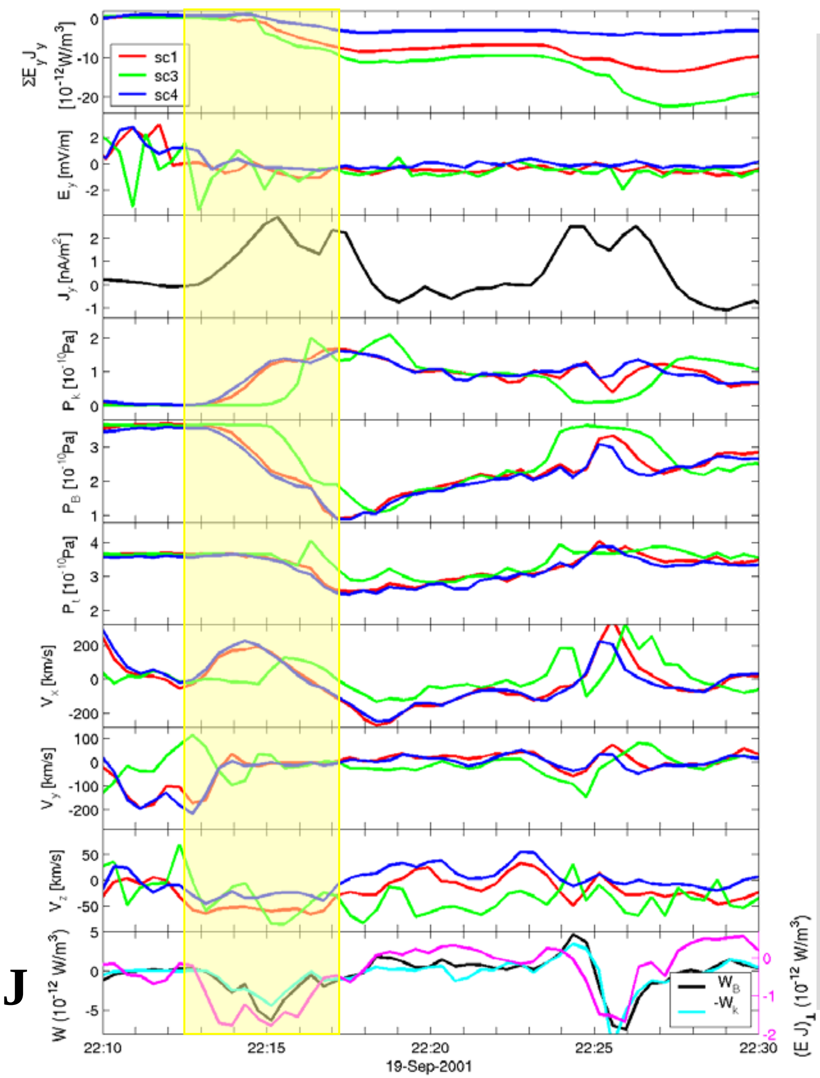
P_T

V_X

V_Y

V_Z

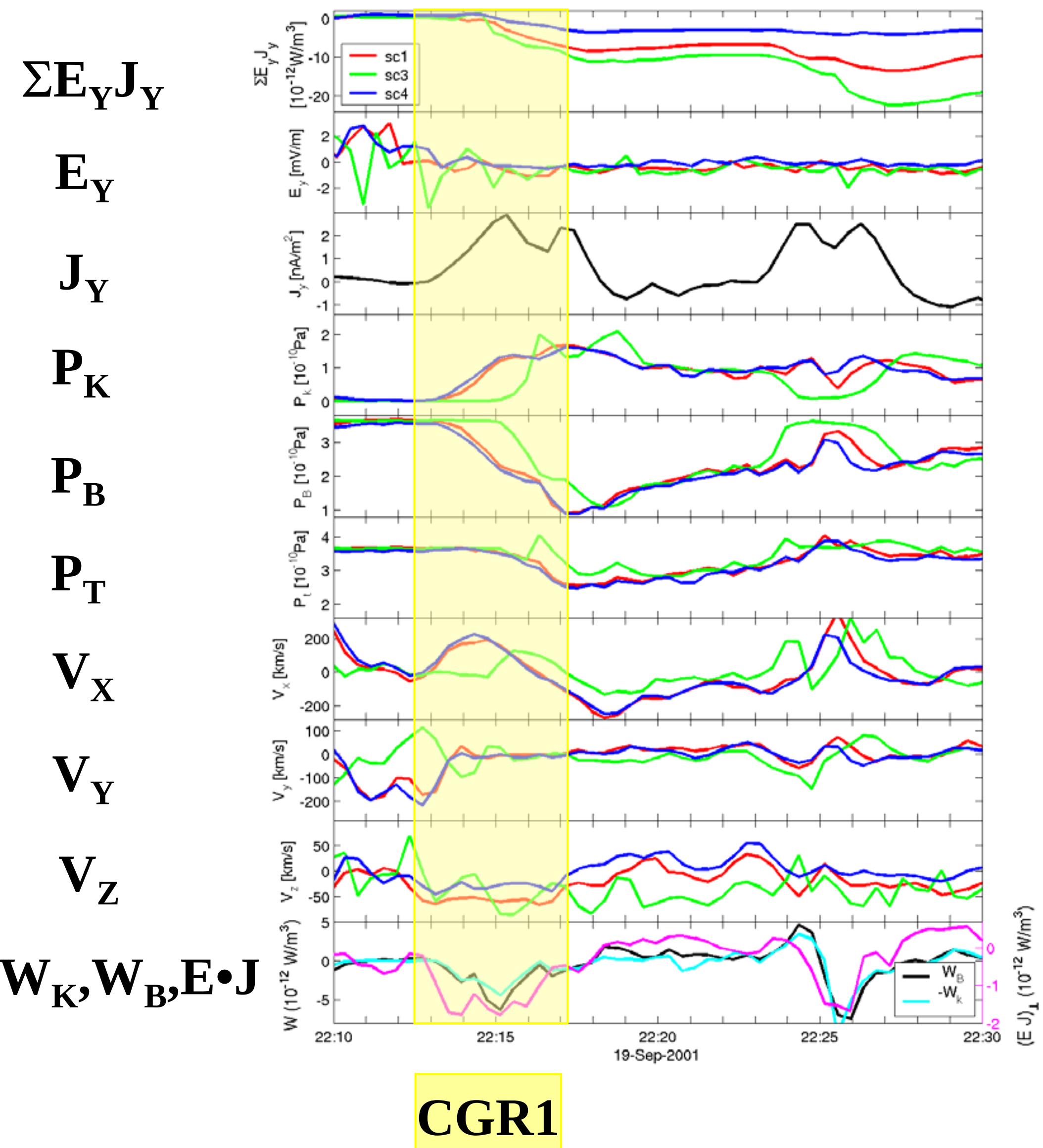
$W_K, W_B, E \bullet J$



CGR1

- $\partial \mathcal{E}/\partial t = -\nabla \bullet (\mathcal{E}\ \mathbf{V}) + \mathbf{W_K} + \mathbf{W_L}$
  - $n < 1 cm^{-3}$, $V < 100 km/s \Rightarrow \mathcal{E} < 10^{-11} J$
    $W_K + W_L \cong 10^{-12}$
  - $\mathcal{E}/T \cong W_K + W_L \Rightarrow T \leq 10s$ (small)
  - $\mathcal{E}V/L \cong W_K + W_L \Rightarrow L \leq 1000km$
- $W_L = W_B + W_T \cong \mathbf{E \bullet J}$
  - $\mathbf{E \bullet J} \cong -2\ 10^{-12}$, $W_B \cong -6\ 10^{-12}$
    $\Rightarrow W_T \cong 4\ 10^{-12}\ W/m^3$
- $W_T = \mathbf{V} \bullet (\nabla \bullet \mathcal{T}_B) \cong VB^2/\mu_0 L$
  - $B = 30\ nT$, $V = 50\ km/s$
    $\Rightarrow L \cong 10{,}000\ km$

CGR Macrostructure: Energy, Work, Scales



- The Poynting theorem:

  $$\nabla \cdot \mathbf{S} = -\partial W / \partial t - \mathbf{E} \cdot \mathbf{J} \quad (7)$$

  with $W \simeq W_B = B^2/2\mu_0 \equiv P_B$.
- $\partial / \partial t \cong d / dt$ in the satellite 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 (7) positive => elmag. energy carried away from the CGR.
- $-\partial P_B / \partial t \cong 0.2$nPa / 200s = 10^{-12}W/m^3, comparable to $-\mathbf{E} \cdot \mathbf{J}$.

A CGR Macrostructures: Findings E

- 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 $\mathbf{E} \bullet \mathbf{J} < 0$, $W_K > 0$, 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, $\mathbf{E} \bullet \mathbf{J}$, make comparable contributions to $\nabla \bullet \mathbf{S}$.

$\mathcal{A}$ CGR Macrostructure: Prospects $\mathcal{A}$

- Better evaluation of ∇P_K, by using P_K+P_B=const. on SC2.
- 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., (cf. Shen et al., 2003)
- Evaluation of the derivatives by the GALS method, developed by the Umeå group => 3 satellites may suffice!

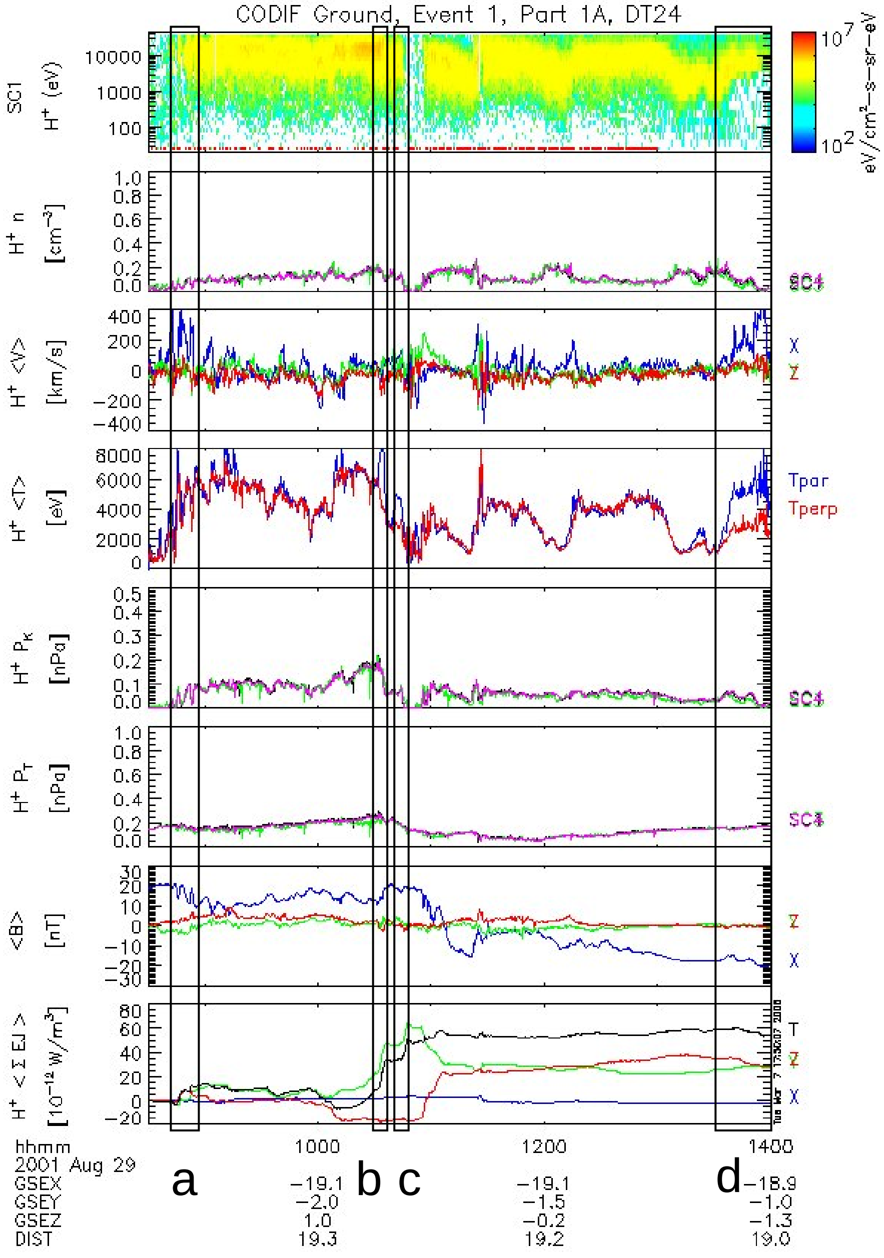
B ECRs in the Plasma Sheet : Intro B

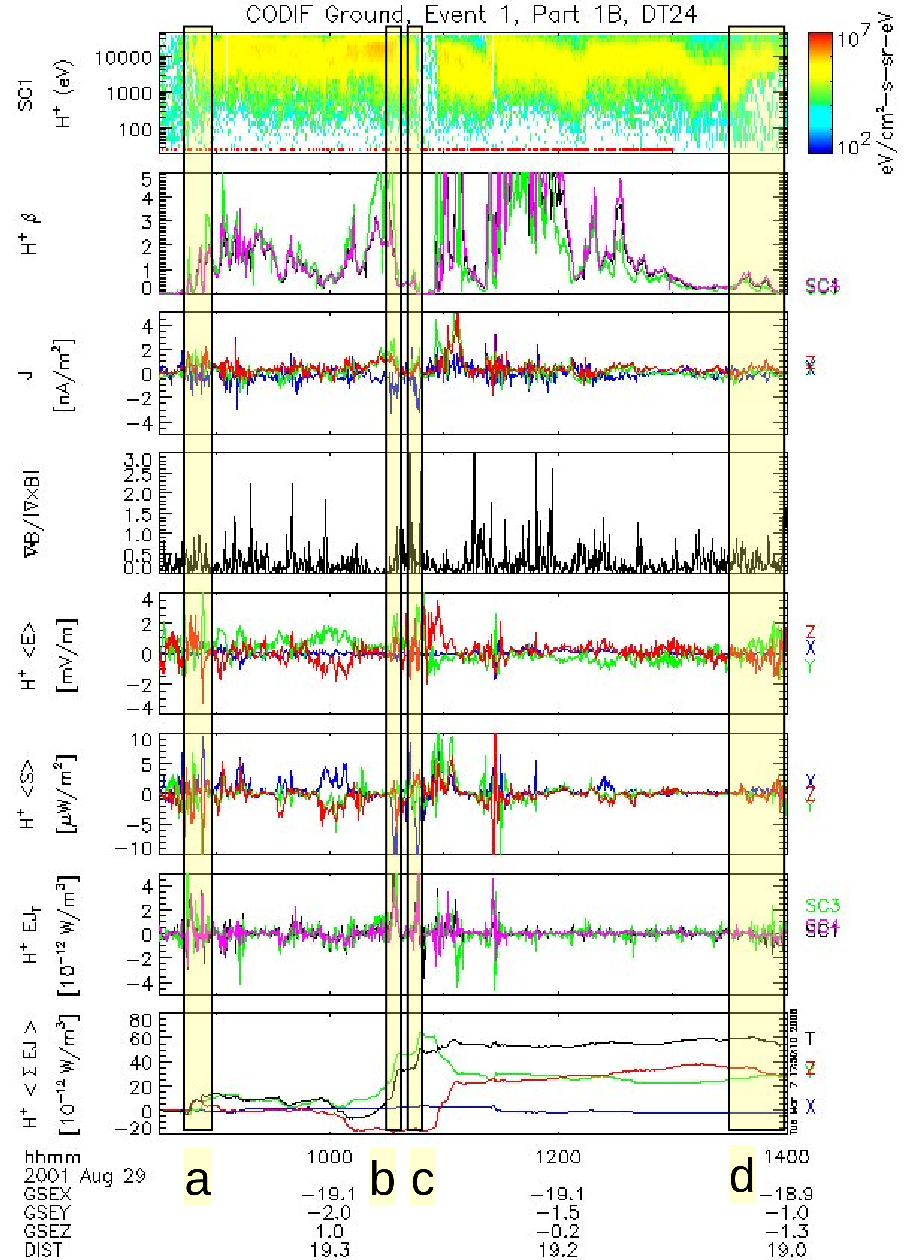
➢ In order to extend the search for (auroral) generator regions we selected a time interval between the end of August and the beginning of November, 2001, with increased conjunction rate between the two spacecraft. During this time the apogee of Cluster, at 19 R_E, was in the plasma sheet, moving from 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.

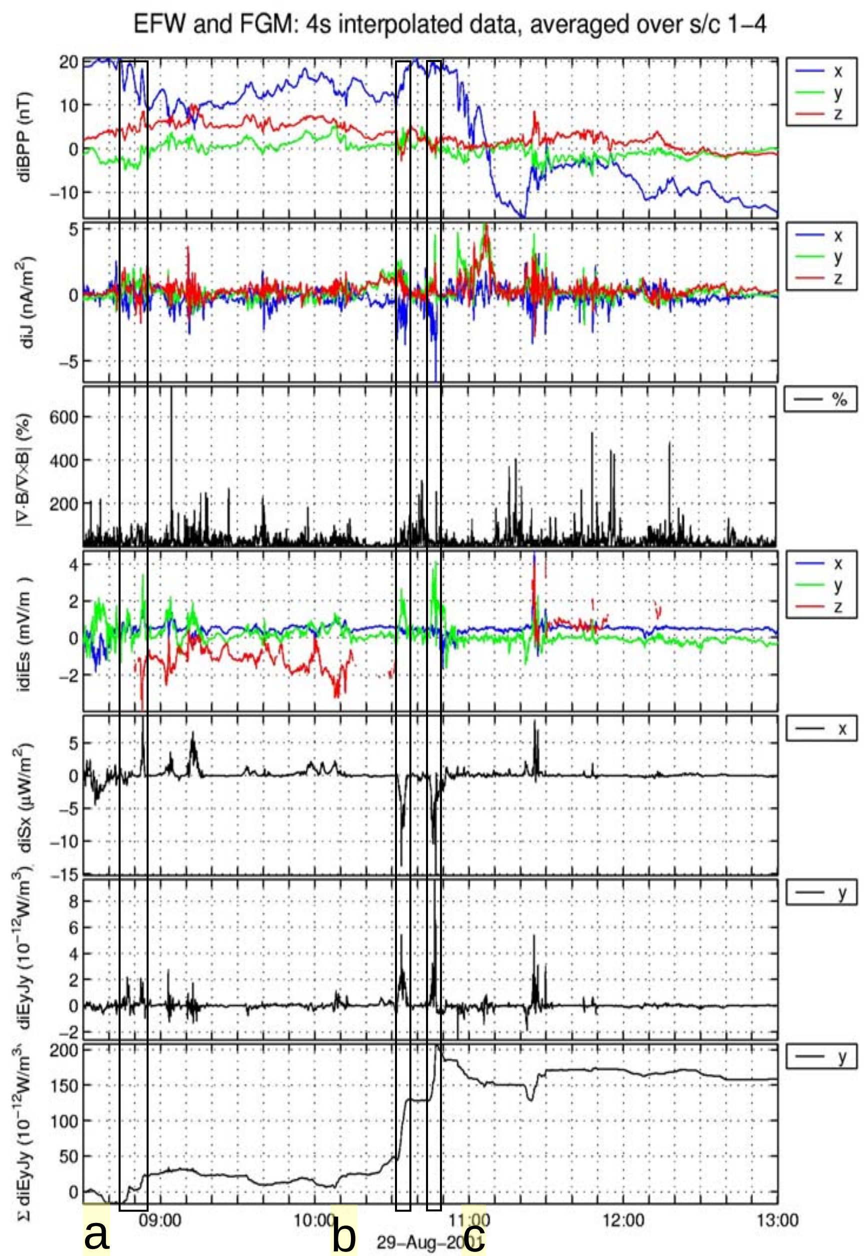
➢ Energy conversion and transport in the tail has been also studied by computer simulations, most recently by Birn and Hesse, 2005. Multi-satellite missions like Cluster allow for the direct cross-check of the data and simulation results.

B Observations: L1 B

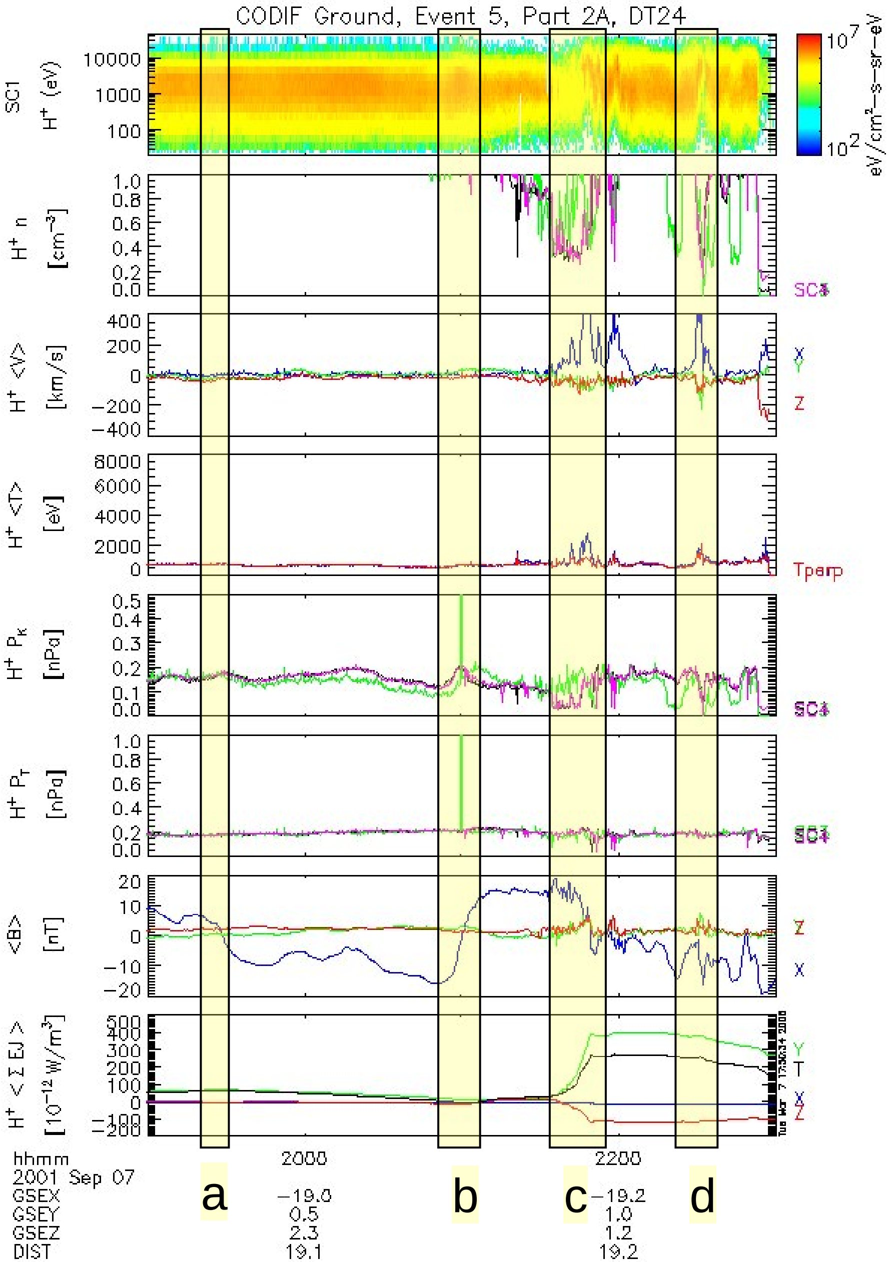


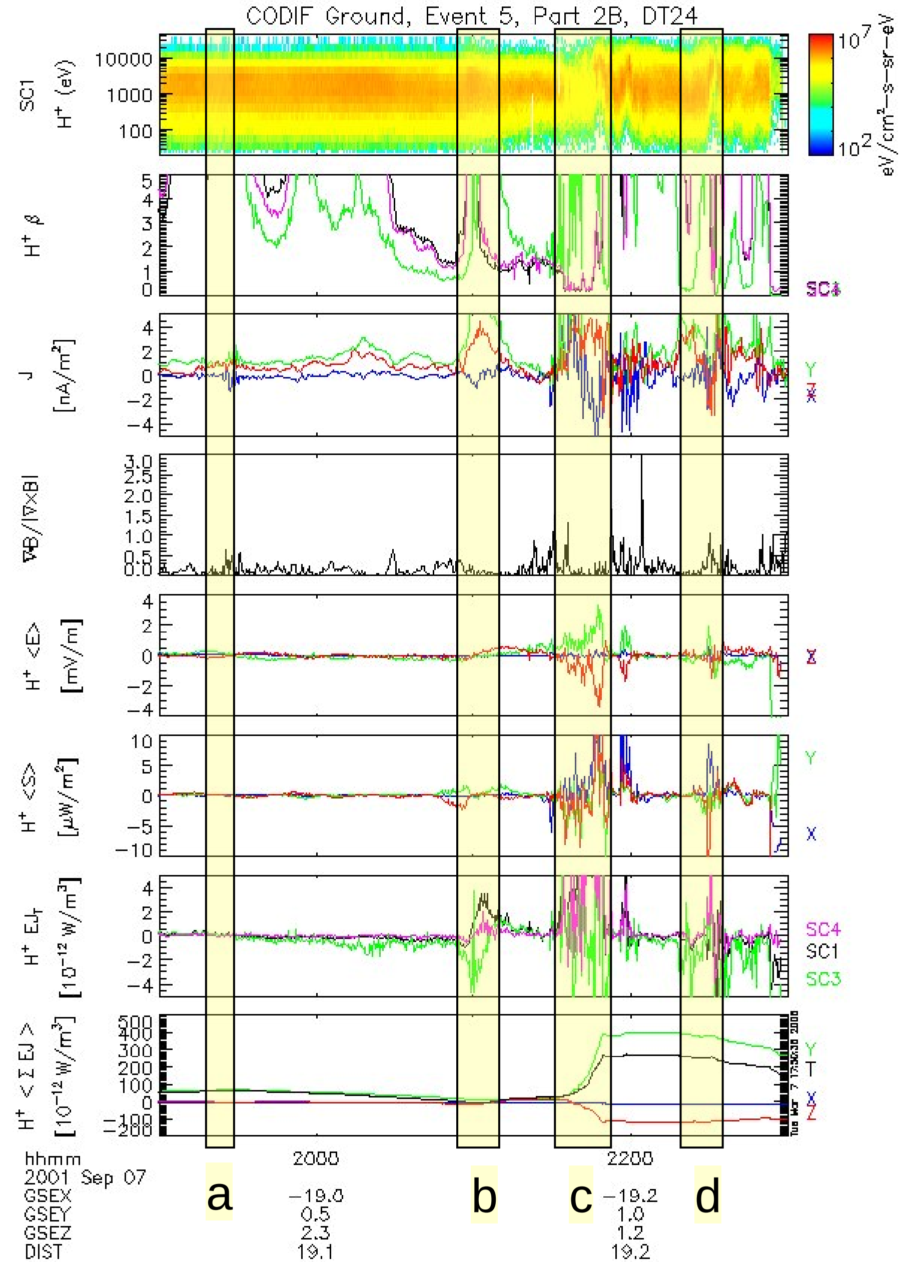


B Observations: L1 B

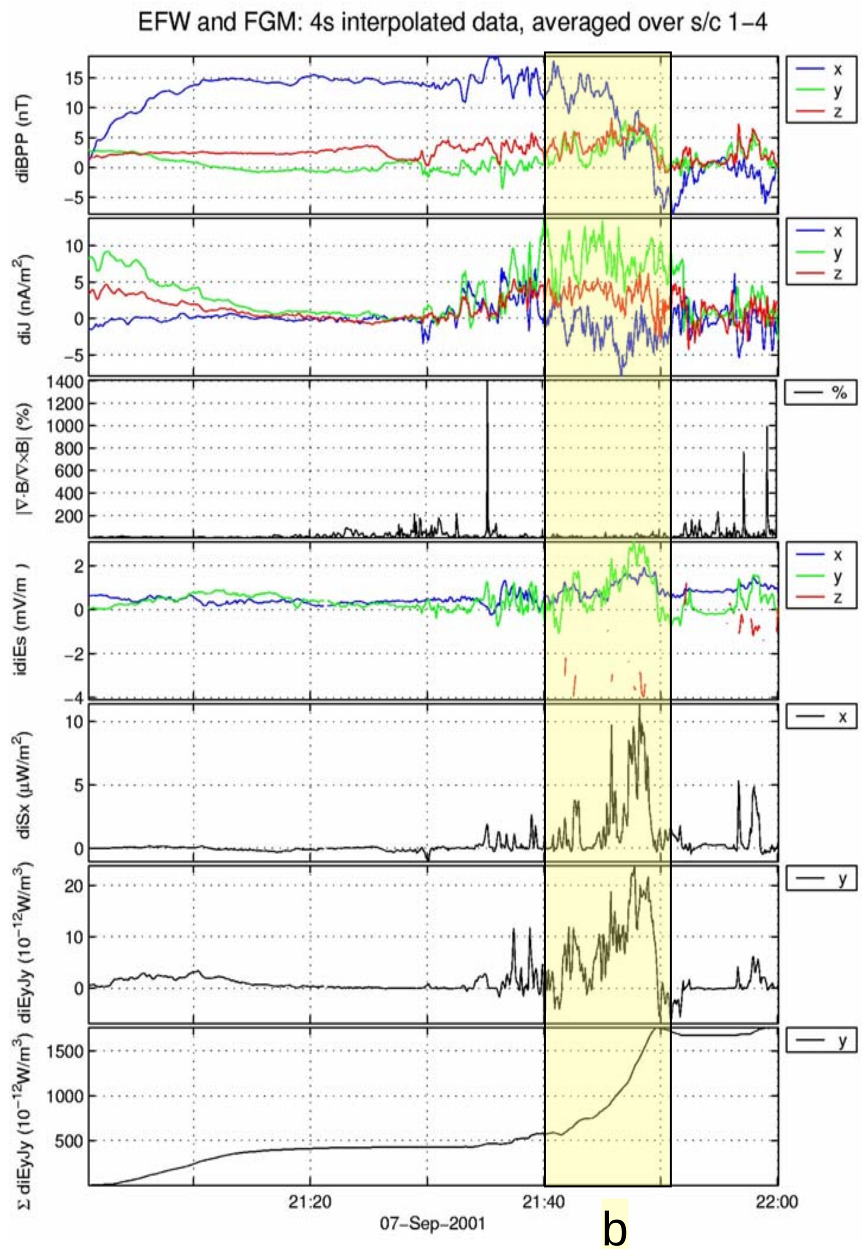


ℬ Observations: L2 ℬ





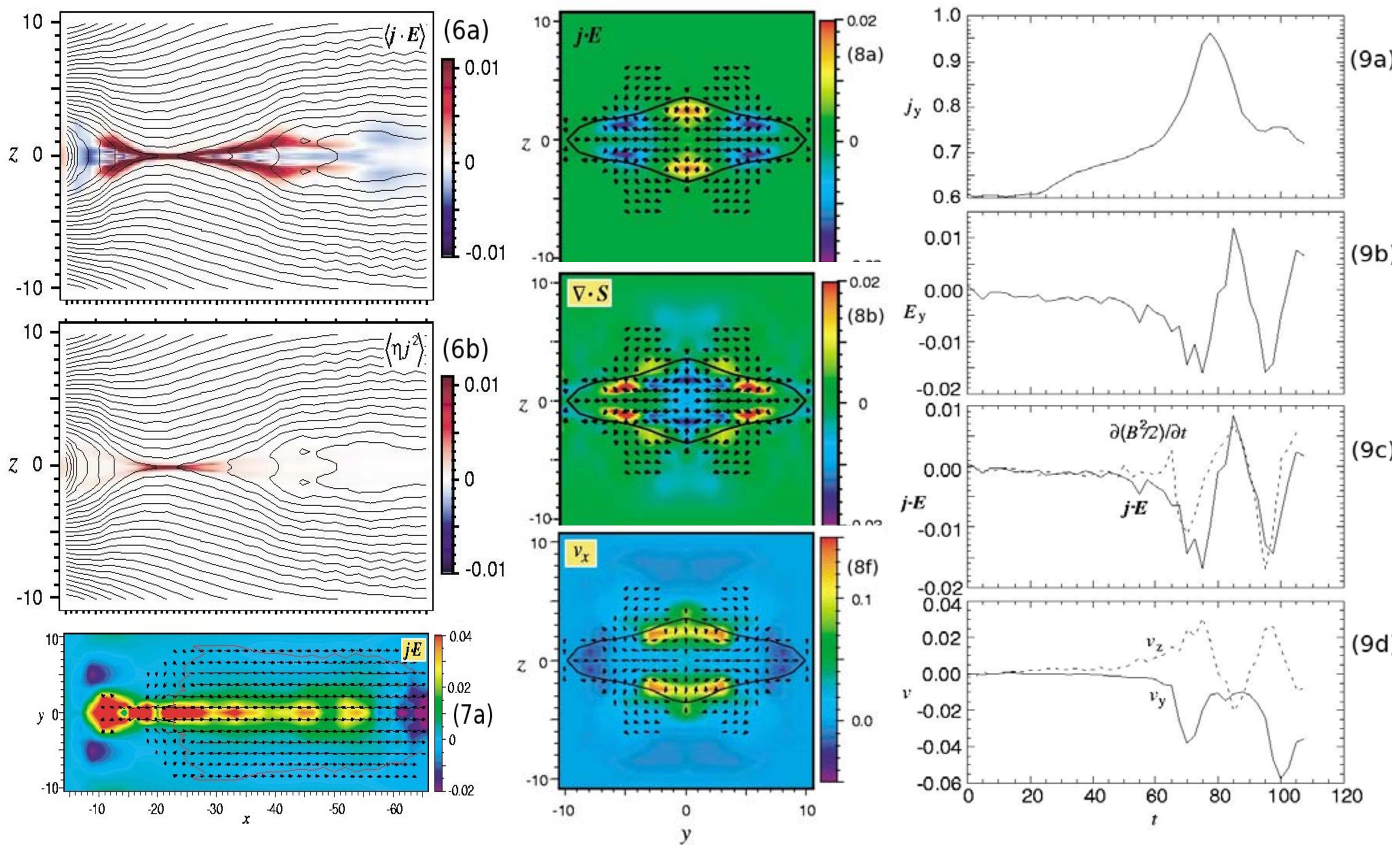
$\mathcal{B}$ Observations: L2 $\mathcal{B}$



Observations: Loads

- 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.

$\mathcal{B}$ Simulation results, Birn and Hesse (BH), 2005 $\mathcal{B}$



Selection of energy conversion features from BH2005. Simulation units: L=6000–12000 km, t=6–12 s, v=1000 km/s, B=40 nT.

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.

Simulation results, Birn and Hesse (BH), 2005

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.

B *ECRs in the Plasma Sheet : Summary* *B*

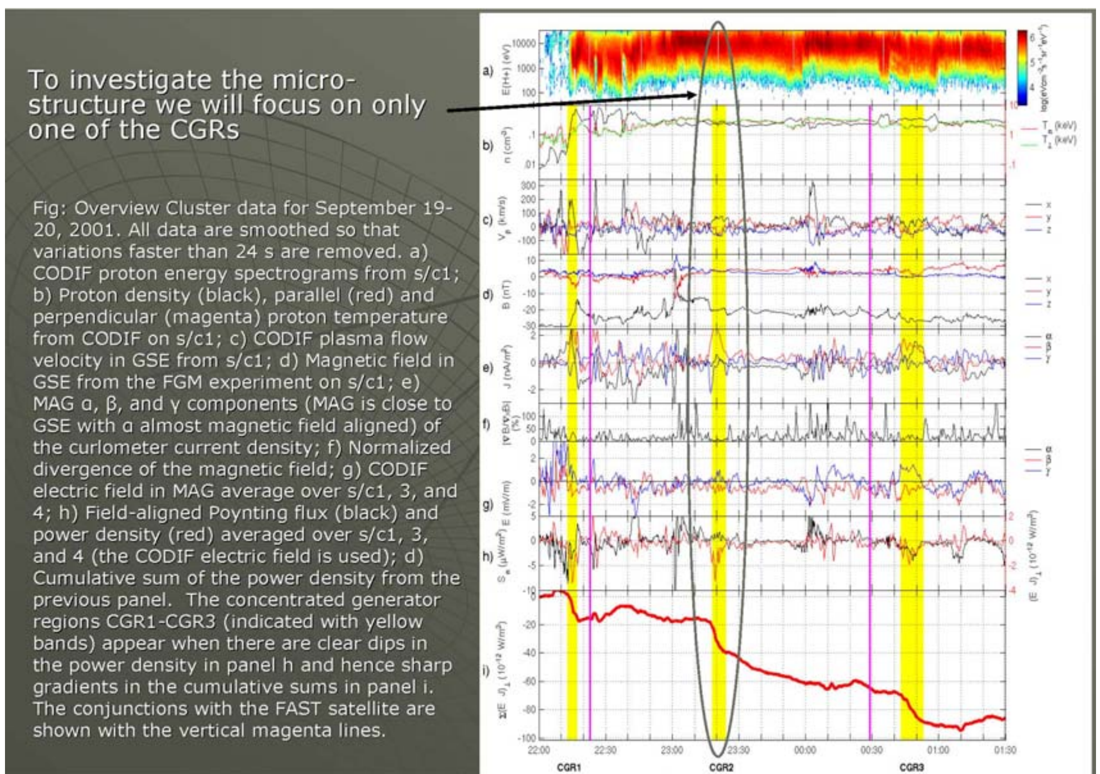
- The investigation method allows for a systematic examination of the local energy conversion in both generator and load regions.
- Cluster North–South crossings of the plasma sheet show, on large scales, mostly load character, with a substantial fraction of the load near the neutral sheet.
- The magnitude of the integrated load seems to decrease from midnight to the dusk. Away from the midnight one can even encounter large scale generator regions, in good agreement with simulation results.
- On small scale, both concentrated load regions (CLRs) and concentrated generator regions (CGRs) are seen. The CGRs seem to develop more often in the PSBL, as inferred from the plasma β – consistent, again, with the simulations. 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.
- The energy conversion is related to bulk plasma flow, dominantly along the magnetic field – also seen in the simulations. Temperature anisotropy is observed as well, with $T_{\parallel} > T_{\perp}$.

B ECRs in the Plasma Sheet : Prospects B

- Closer look at the local energy budget – work of the pressure forces, Poynting theorem, …
- Cross-check of **J** by (rough) comparison with ∇ P.
- Completing the dawn–dusk survey with the Cluster plasma sheet crossings in June – August 2001.
- Integrated load / generator character versus Y_{GSE} (the distance form the midnight), and versus AE.
- 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.
- Also close to the subsolar point, later in the mission?
- Extension to THEMIS and MMS?

C CGR Microstructure C

- Poster by M. Hamrin et al., EGU 2006, Vienna: *The wave environment of plasma sheet generator regions as observed by Cluster and FAST.*
- Event investigation based on a rich collection of Cluster data: CIS, PEACE, EFW, FGM, STAFF, WHISPER.
- Selection of slides follows.



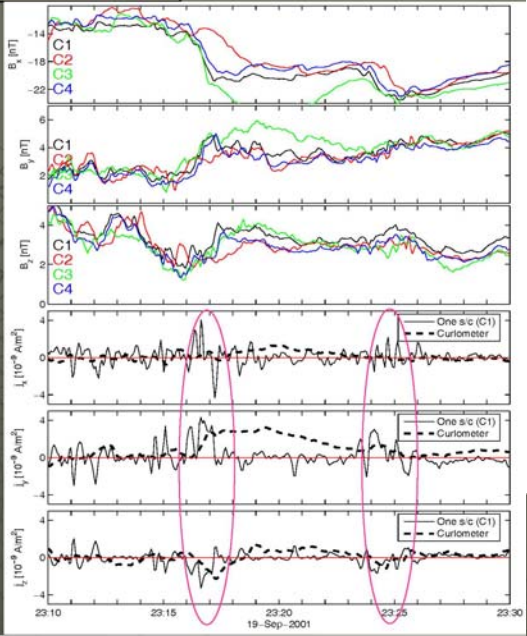
CGR Microstructure

Magnetic field

Zooming in on CGR2, we immediately notice the bifurcated current sheet revealing itself in the magnetic field data. Panel 1 shows the GSE X component and the two current sheets are found at approximately 23:16 UT and 23:24 UT. They are observed by all spacecraft.

Assuming a plane current sheet, the velocity of each sheet can be estimated. We find Vcs≈30*[0.19 0.58 0.79] km/s. Both sheets have the same direction and velocity.

In the bottom three panels we show a comparison between the current obtained from the Curlometer and from the one spacecraft method. We see that both methods give consistent results within the current sheets.

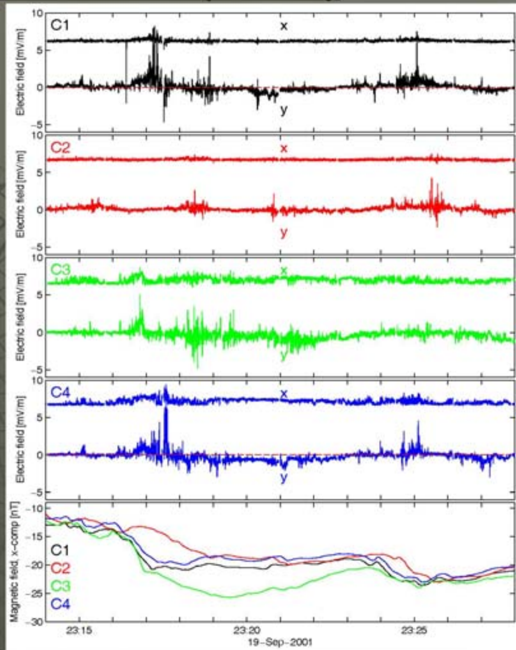


Electric field structures (EFW)

Collocated with the bifurcated current sheets (bottom panel) there are clear potential structures in the EFW electric field in the GSE x (almost magnetic field-aligned) and y directions.

The potential structures are very similar on s/c1 and 4 (which are located on almost the same field-line). This is consistent with the existence of a potential structure along the current sheet.

The scale size of these potential structures are approximately 200 km or about half an proton gyro radii.



CGR Microstructure

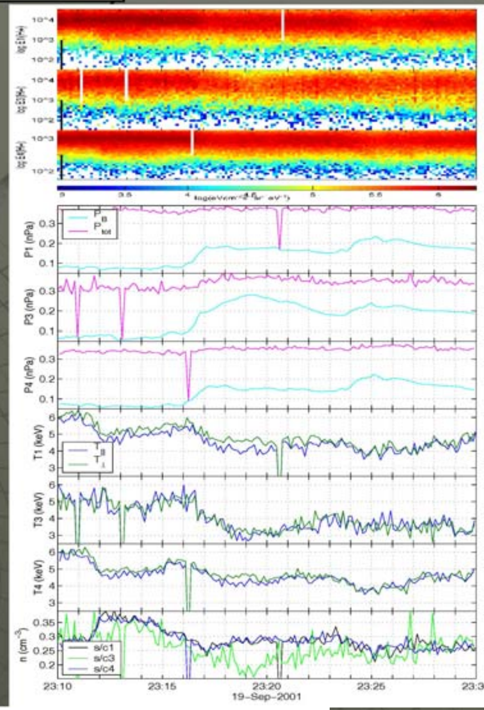
Ions (CIS data)

The magnetic pressure observed by s/c1, 3, and 4 clearly shows the signature of the bifurcated current sheet (panels 4-6).

The total pressure (magnetic plus kinetic pressure) is however constant throughout our event.

We hence note that the variation in the magnetic pressure is balanced by simultaneous changes in the ion temperature (panels 7-9) and density (panel 10).

In the last panel we clearly see a difference in the density, and consequently in the kinetic pressure, between s/c3 and s/c1,4 within the CGR. This is consistent with s/c3 being closest to the plasma sheet boundary (s/c3 is also the most southward satellite) and considerable diamagnetic currents being induced.

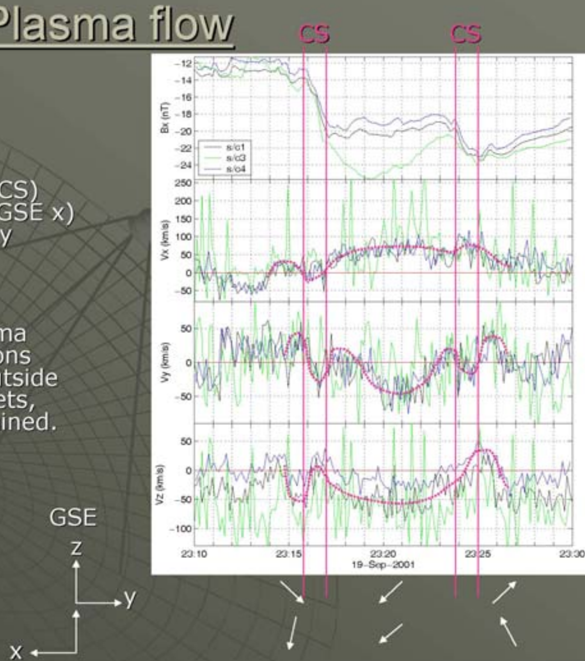


Plasma flow

Between the current sheets (CS) there is a strong Earthward (GSE x) plasma flow (panel 2) possibly originating from a distant reconnection site.

Focusing on the general plasma flows in the yz and xz directions (bottom three panels) just outside and between the current sheets, the bottom sketches are obtained.

Schematic plasma flow:

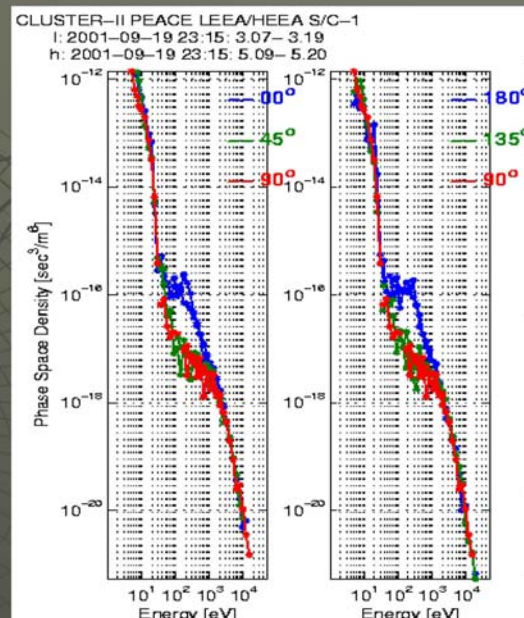


C CGR Microstructure C

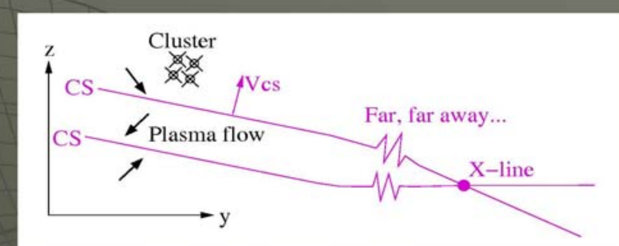
Electrons (PEACE)

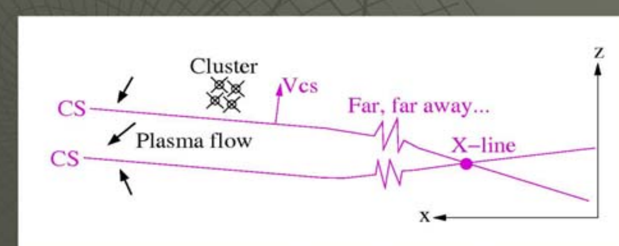
Clear electron beams are seen both parallel and anti-parallel to the ambient magnetic field.

Such electron beams are most likely the source of the high frequency waves observed in the region before encountering the bifurcated current sheet.



Summary and conclusions





C CGR Microstructure C

Our observations are consistent with the Cluster satellites being passed by the separatrices from a distant reconnection site. The current sheets associated with these separatrices are nearly parallel as expected when they are far from the X-line. Moreover, both current sheets are moving with the same speed in the positive GSE ys direction.

As observed in the plasma flow data, north and south of the current sheets the plasma is sucked into the separatrix regions. Between the current sheets there is a strong and almost Earthward plasma flow originating from the distant reconnection site.

The quite large flow velocities in the negative z direction can be explained by the dipolarization of the magnetosphere after a small substorm with onset at 20:39 UT and recovery phase initiated at 22:15 UT (Slavin et al., 2003). The Cluster satellites are in the southern hemisphere and hence probe the plasma flow associated with the consequent broadening of the tail region.

Due to the large distance from the Cluster satellites to the X-line, the separatrices are rather tilted and disrupted. This explains the oblique plasma flows and the less distinct current sheet signatures observed especially on s/c2 and 3.

Framework for Future Work

- The research on energy conversion makes the object of a PECS project proposal.
- PECS = Plan for European Cooperating States => offered by ESA to countries in the Central and Eastern Europe. PECS includes now Hungary, Czech Republic, and Romania (from February this year). Poland is expected to join as well.
- COSPAR Capacity Building Workshop (CBW) & STIMM-2 Workshop, most probably in June 2007.