Cluster results on the magnetotail current sheet structure and dynamics

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....

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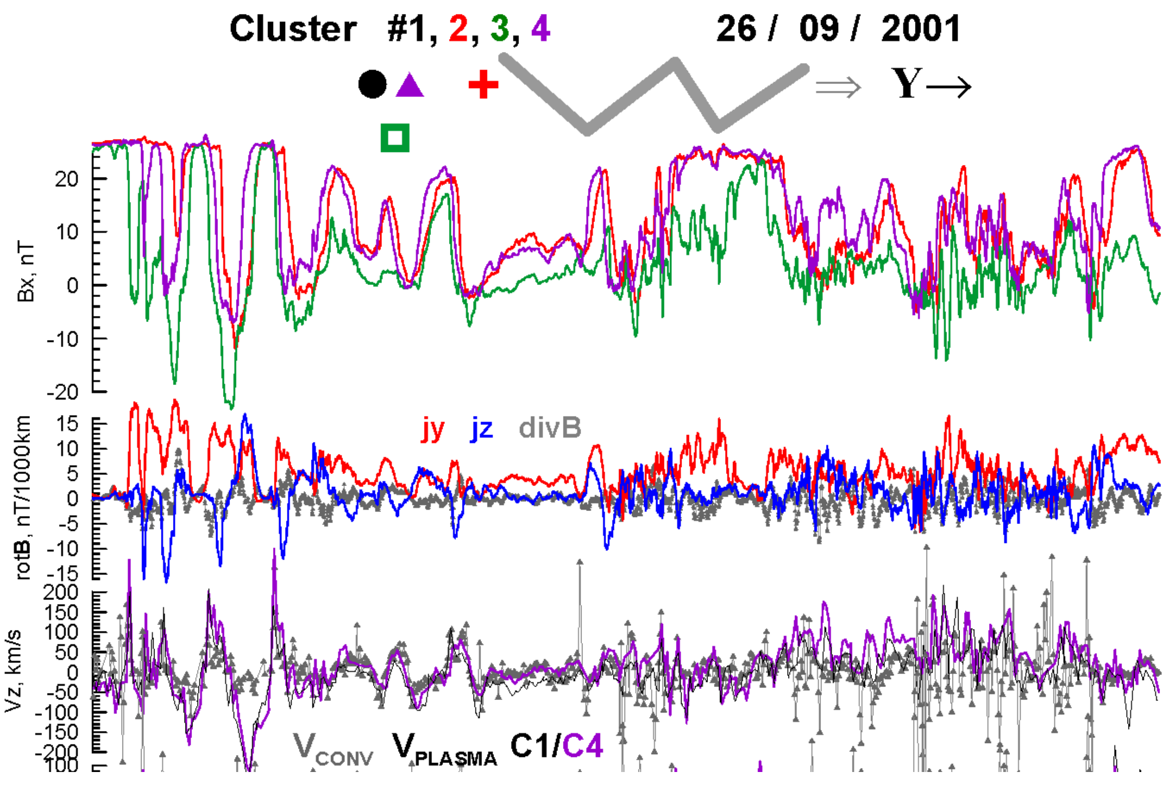
OUTLINE

Example:

Intense **flapping motions** following the onset of small substorm *(Sergeev et al.,GRL 2003)*

- ✓ Dominate over the observed plasma sheet variations in mid- and far tail
- ✓ Well-known since first measurements in the tail (Ness 1965, …)
- ✓ Properties/physics not well-known, mostly due to limitations of single spacecraft data analysis
- ✓ Quick crossings across the current sheet – a **tool to probe/study the CS structure** ‘instantaneously’



O U T L I N E , 2

This talk -

a summary of recent Cluster results concerning:

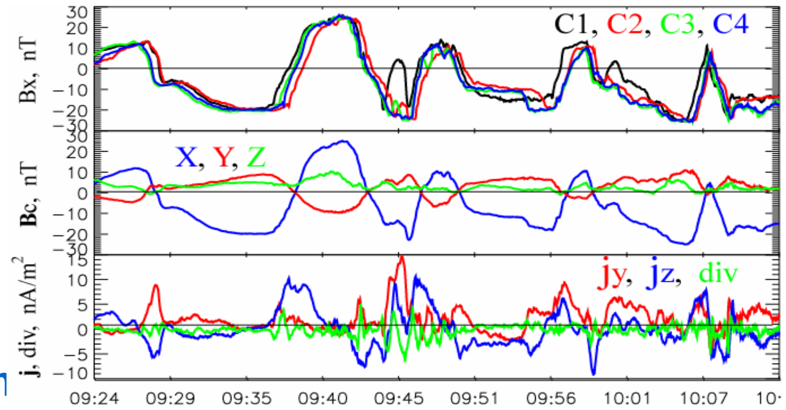
- ✓ Tools to study flapping perturbations (*tilts, propagation,..);*
- ✓ **Properties and origin of flapping motions**;
- ✓ **Structure of flapping current sheet**

Mostly based on systematic study of all rapid CS crossings in 2001
(Sergeev et al. GRL 2004, Runov et al. AnnGeo 2005a,b)

- ➢ Not covered – substorm correlations and reconnection

Data base of rapid CS crossings

FGM + CIS data



Selection criteria , **data set #1** :

- Jump B_x : $|\Delta B_x| > 15$ nT
- Duration: 30s< τ < 300 s
- No special selection of plasma properties.

➔ **186 cases during 2001 tail season (ΔS<~2000km**

http://geo.phys.spbu.ru/~runov/Cluster/2001_xings_survey/

➔ **~250 2004 tail season (ΔS<~1300km);**

➔ **~150 2002 tail season (ΔS<~4000km);**

Additional selection, **data set #2** (→**78** points in 2001) *[Runov et al, AnnGeo, p.1391, 2005]:*

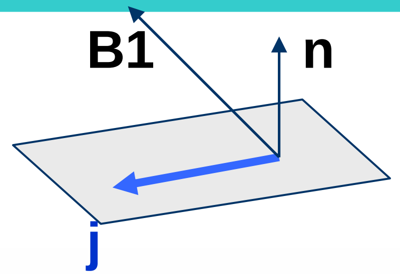
- Baricenter cross the neutral sheet;
- Smooth (minimum small-scale temporal variations) crossings, similar traces at all sc;
- Four point calculations: DivB/Curl B < 0.3 in > 60% of time points;

Additional selection, **data set #3** (→**30** profiles) *[Runov et al, AnnGeo, submitted, 2005]*

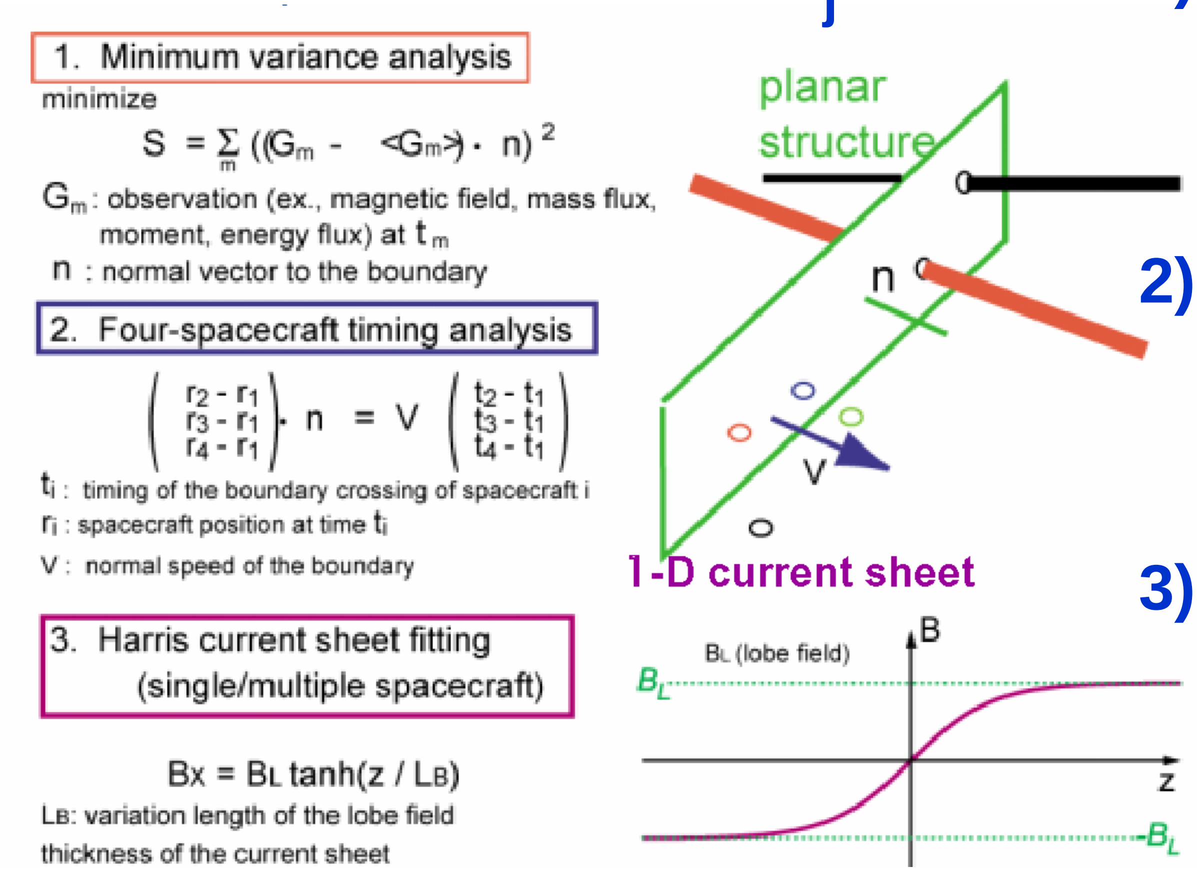
Thin CS (<1000km) might be lost from 2001 DB!

Methods   Data/Assumptions/Output

gradB , rotB=μ_0 j from 4SC
to find CS orientation suggesting
j in the CS plane, or grad $B_1 \perp$ CS plane



1)



2)

3)

$B_{1234} \Rightarrow$ gradB , rotB

Orientation (n)
if j in the CS plane and
no sausage

B(t) time seria , at 1 SC
(others used for control)

Orientation (n) if plane **1D sheet**
(B_n =const)

Δt_{ij} and Δr_{ij}

Orientation (n) , propagation V
if plane **1D sheet**
and **no acceleration**

(B,z) at 3 SC (other for control)

B_L, L_H and z_{NS}
if plane Harris-type sheet

Methods : How well MVA works in tail CS??

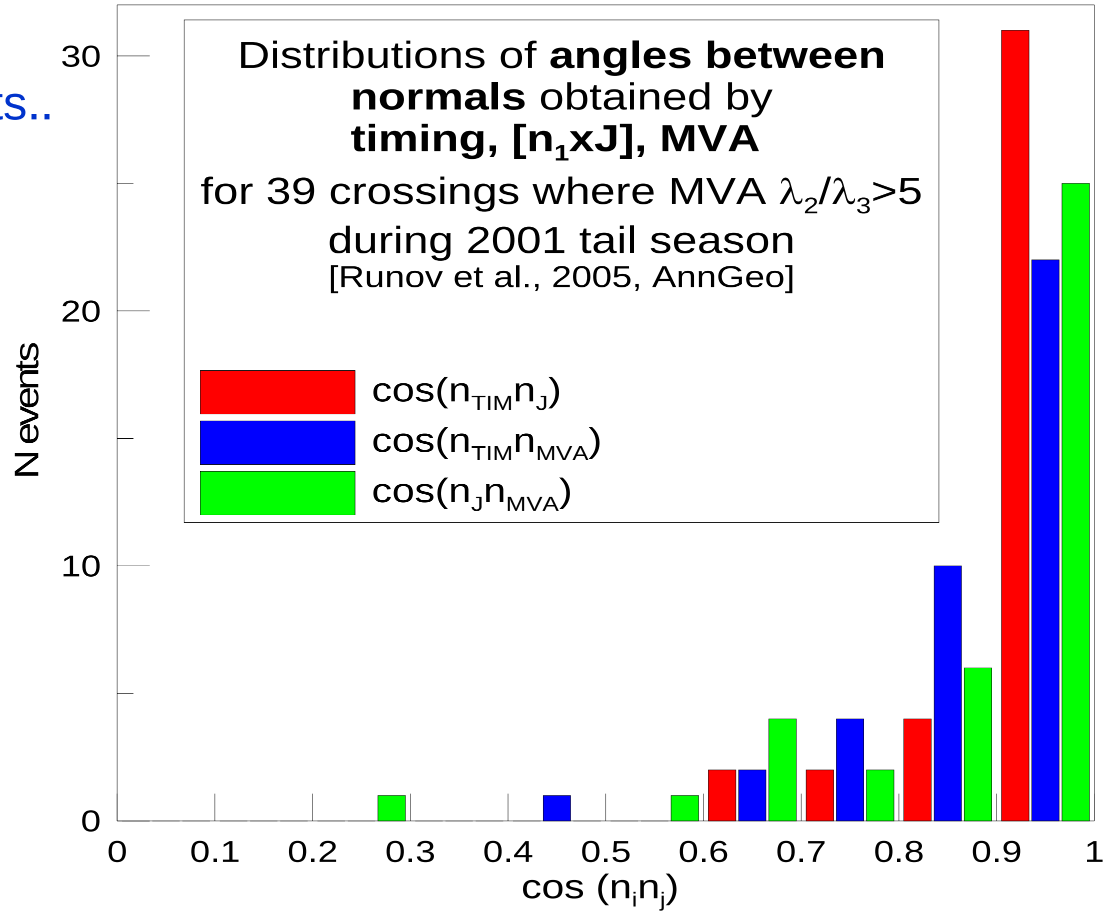
No *a priori* reason why MVA should work in 1D current sheets..

Compazison of CS normal directions determined with

- ✓timing
- ✓current
- ✓ MVA

are in **good agreement**

(n1*n2)>0.9 ⇔ **θ < 18°**



[*Apatenkov et al., paper EGU05-A-00691*]

Methods Data/Assumptions/Output

CLUSTER-specific possibilities :

After estimating linear gradients $\partial B_i / \partial x_j$ from 4 SC

- -

Assuming **time-stationary 1d sheet:**

$$\partial \mathbf{B}/\partial t + \partial \mathbf{B}/\partial z^* \bullet V_{TR} = d\mathbf{B}/dt \sim 0$$

with known orientation (**z***) :

Translational sheet velocity V_{TR} (along **n**) :

$$V_{TR} = -\partial \mathbf{B}/\partial t \; / \; (\partial \mathbf{B}/\partial z^*)$$

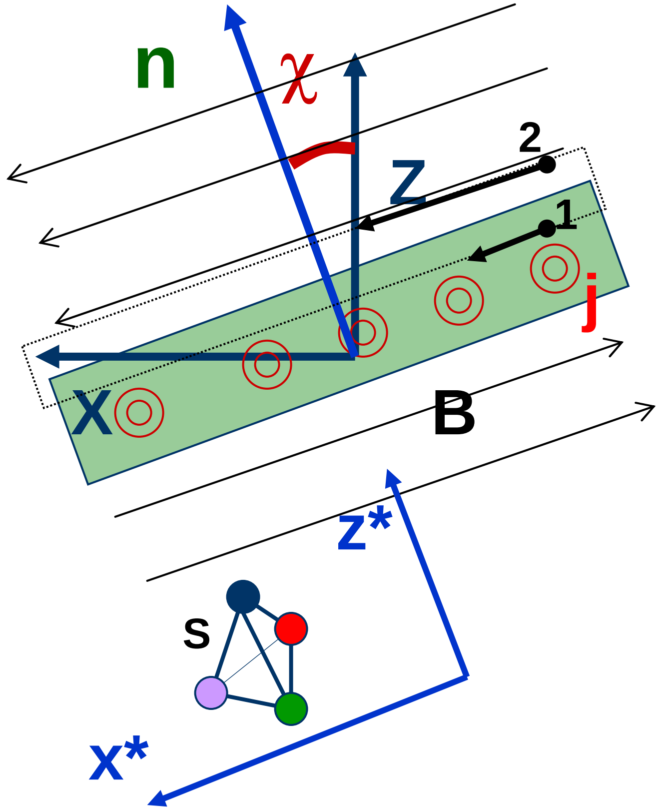
to be used to evaluate sheet displacement

$$z^*(t) \approx -\int dt\, V_{TR} - Z^*(t_{NS})$$

and, then → the sheet structure B(z*)

- -

Alternatively – use **plasma velocity V_P** as proxy of sheet velocity (check $V_P \sim V_{TR}$) in cases with slow convection to get sheet displacement and sheet structure

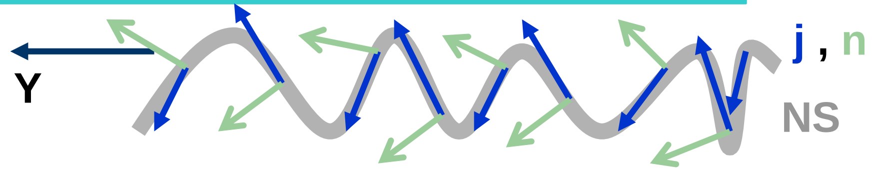


Control $S << L_{CS}$,

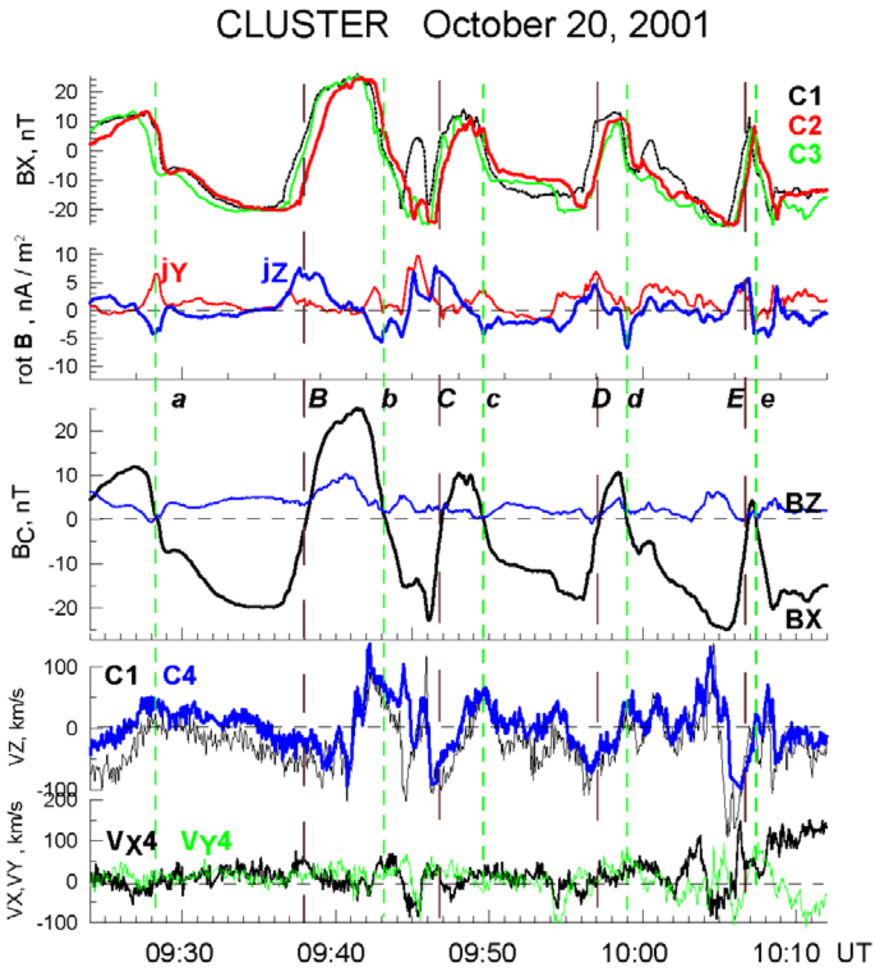
divB<<rotB

Example : October 20, 2001 CL at [-13, 12,-1] Re

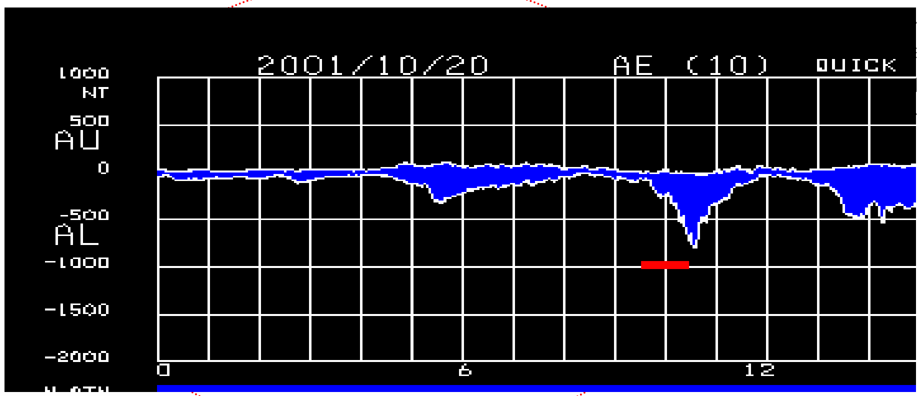
Multiple NS crossings during substorm (onset ~0920UT), slow flow $V_{x,y}$ (passive CS), all time inside PS *(Sergeev et al.,2004 GRL)*



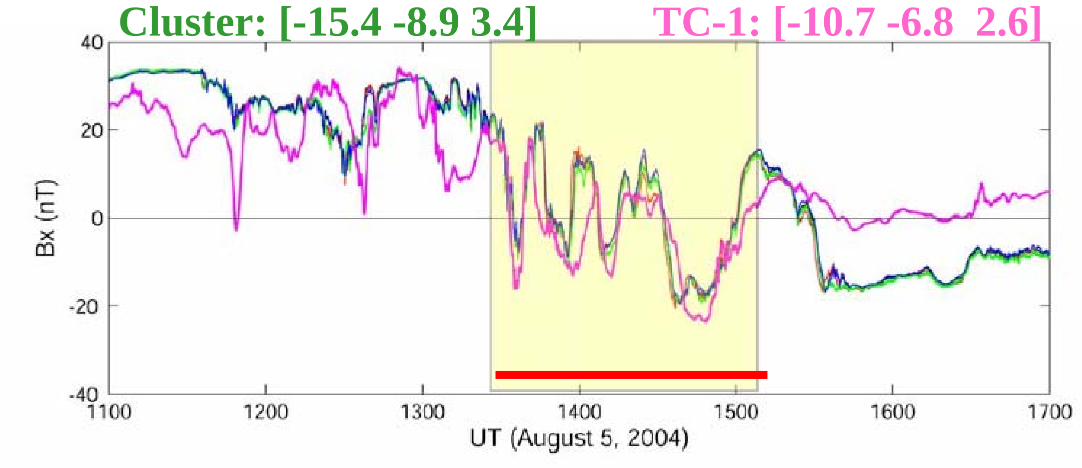
- ✓Consistence of **n** determinations from T and MVA – **very large tilt toward Y !!**
- ✓ Consistent alternating $\mathbf{n_z}$ (see Table)
- ✓ Alternating signs **jz** (+B,-b, etc) and $\mathbf{n_z}$ variations under positive jy; |jz| ≥ |jy| – large tilts
- ✓ Propagate duskward



Kink mode with strong folds confirmed



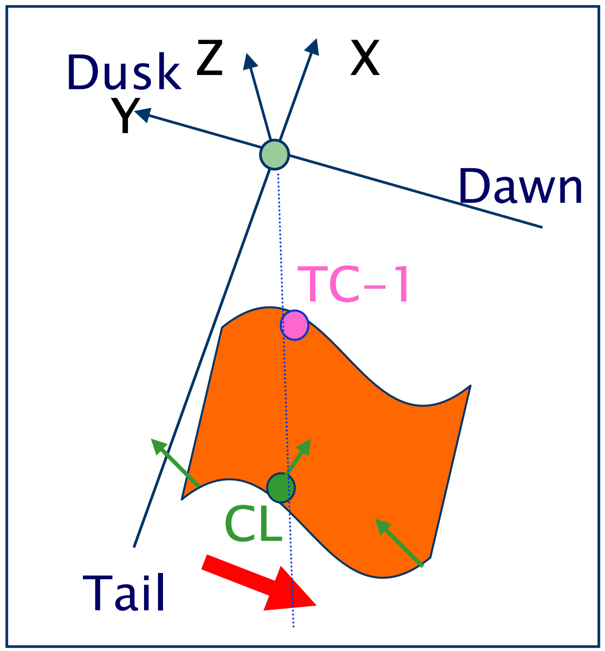
20040805: Cluster & TC-1



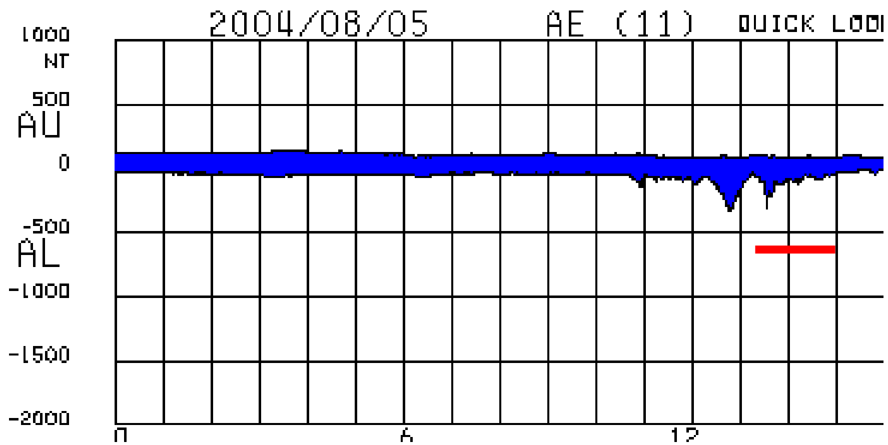
Zhang et al., ***Ann Geo***, *2005 (in press)*

Cluster **Timing & MVA**:

- Normals swinging in YZ plane
- Kinks propagating dawnward at V~30 km/s



- 8 NS crossings, timescale ~150 – 500 s , weak substorms
- Similar ~phased variations of Bx (1320-15 UT)
- Cluster & TC-1 → **kinks with length >5 Re**



Appearance of Flapping Structures

SHAPE (reconstructed from probing small parts !)**:**

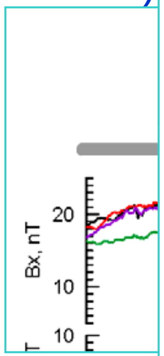
✓ *appear as* parts of **oscillation pattern** o
solitary structures ; parts of plane not unco

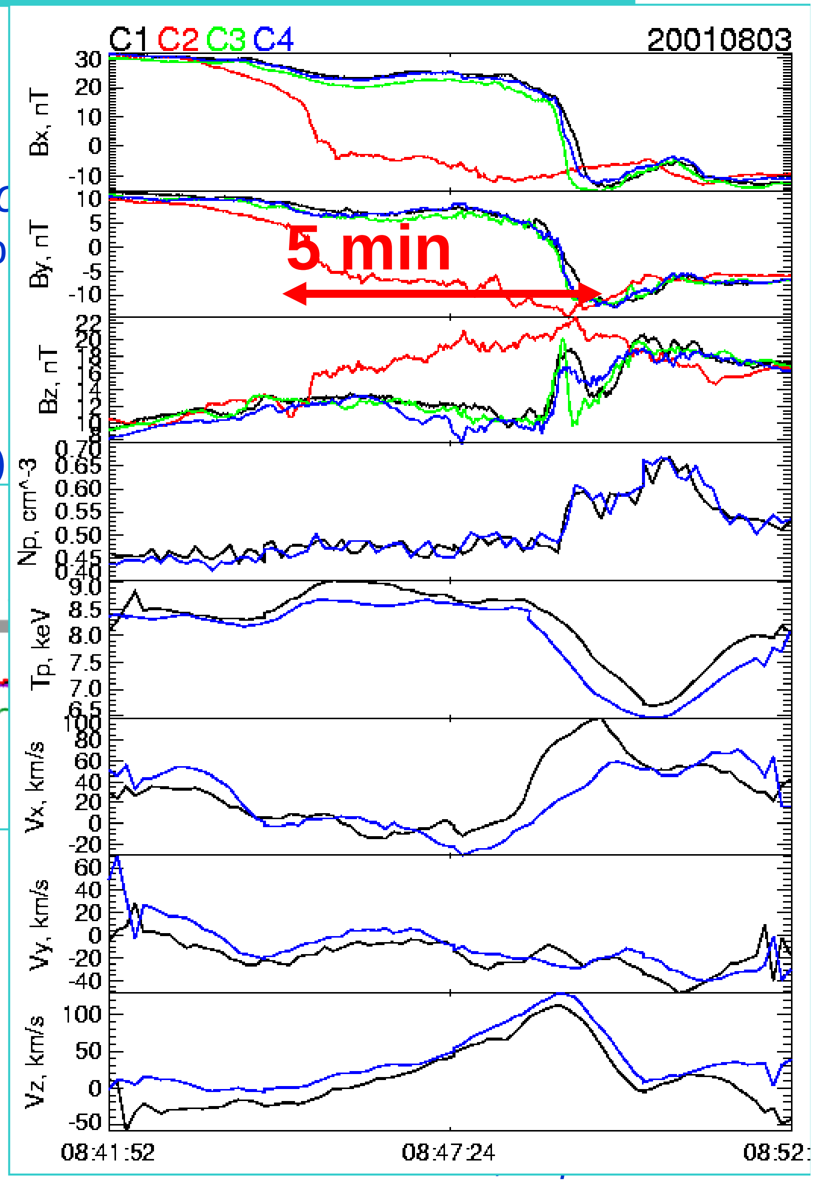
✓ λ_Y ≥ A_Z ≥ h_{CS}

?1-3Re 0.5-2Re 0.2-1Re

✓ Large tilts of CS parts (up to 90º to nominal Z)

> Large-amplitude Nonlinear Structures (Waves)





LIFETIME :

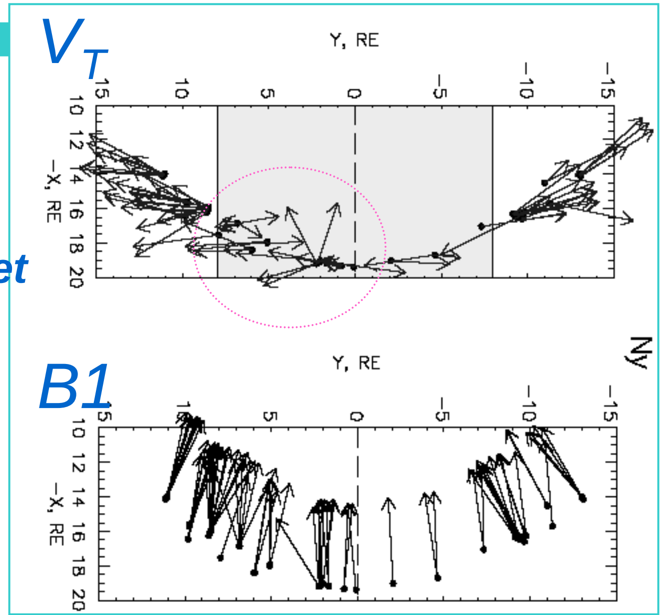
Only lower estimates are possible in examples with slow propagation which give

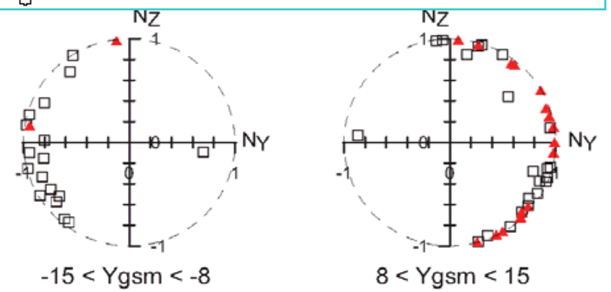
✓ TL can be ≥ 5 min

Timing : normals and propagation velocities

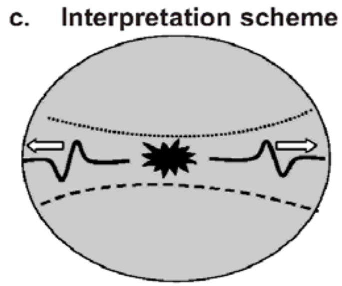
- ✓ **Propagation from center to flanks**, perpendicular to ‘magnetic field plane’;
- ✓ Zone of ‘mixed direction‘ near midnight (*esp. premidnight*) where X-line observations are most frequent at substorm onset (Nagai et 1998);
- ✓ Propagation speeds 20-300 km/s, median ~ 50 km/s;
- ✓ Larger speeds near MReconnection site and in BBFs;
- ✓ Propagation pattern reminds the pattern of cross-tail average flow, could be *<u>structures standing in the flow</u>*???

Runov et al., AG 2005





Sergeev et al., GRL 2004



Propagation and Ion flows

ION FLOWS *(from CIS)* :

Problems: effect of same order of magnitude as possible instrumental Z-offsets and errors; transient effects and changing tilts easily ruin any correlation; only Vn is available from timing

REQUIRE careful selection:

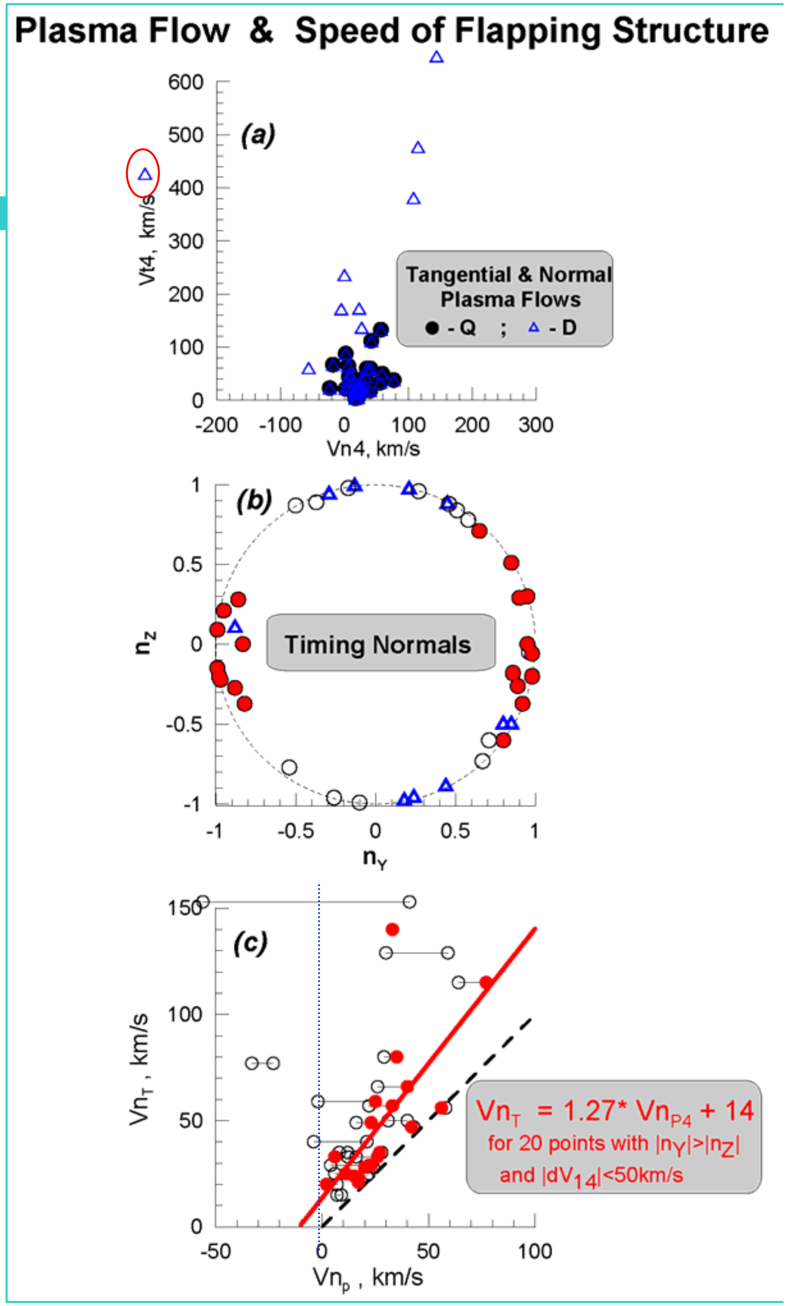
Special subset : 43 events with $\mathbf{n_T \uparrow\uparrow n_J \uparrow\uparrow n_{MVA}}$ within 20º , also compare $\mathbf{V_{C1}}$ and $\mathbf{V_{C4}}$ to control transient effects ; RESULTS :

- Strong flows –mainly along CS ($\mathbf{V_n} << \mathbf{V_t}$) , →large errors in $\mathbf{V_n}$ ***(a);***
- For weak flows - flows along the normal are consistent with $\mathbf{V_T}$, have same sign and similar value; $\mathbf{V_n \leq V_T}$ ***(c);***

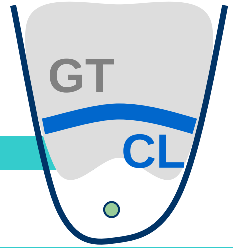
Flapping structures – <u>can be</u> the structures nearly standing in the flow

(?near the accuracy limit)

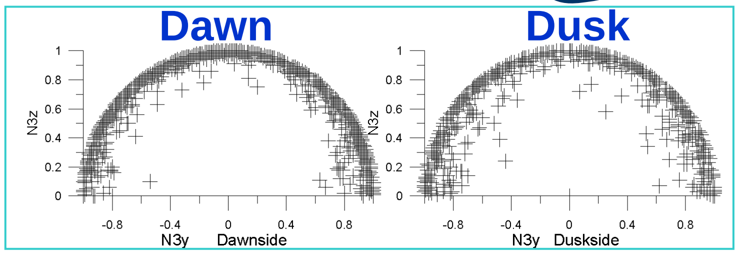
[*Apatenkov et al., paper EGU05-A-00691*]



Occurrence of Fast CS crossings



MVA normals

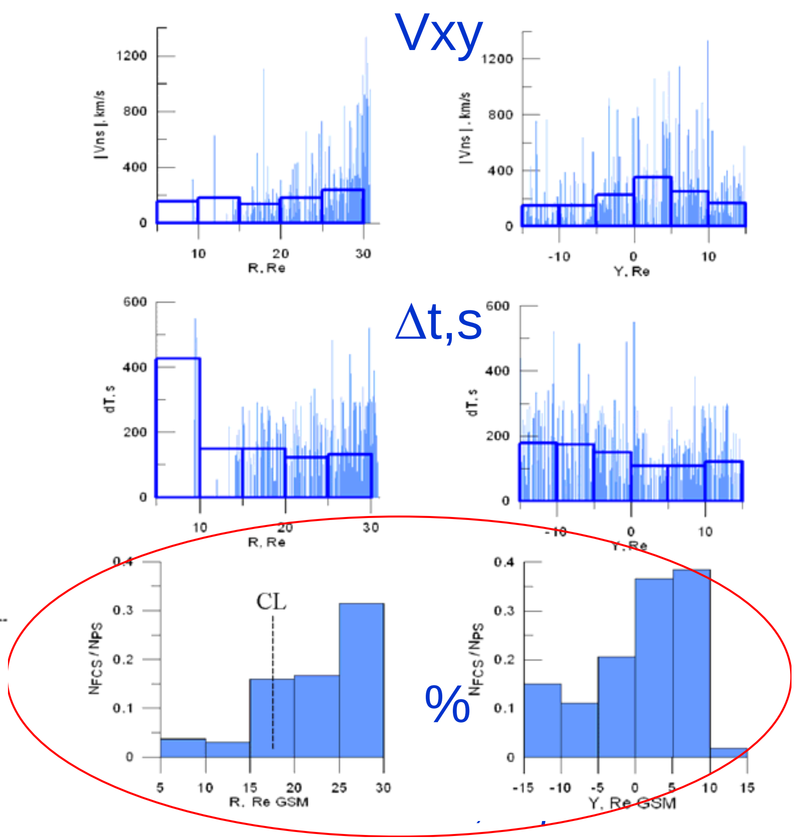


Geotail :

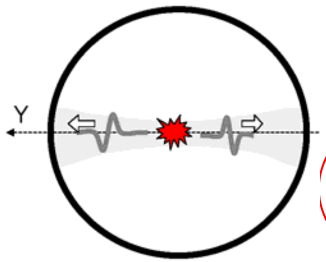
- ✓ 3 years data set, 3s B-field from DARTS;
- ✓ 1100 fast crossings (occurrence);
- ✓ MVA with $\lambda 2/\lambda 3>4$ and N>15 to get normals (480 events, for tilts study);

Results

- ✓ $\mathbf{n_3}$ ≈ [~0, n_Y, n_Z] like at Cluster → confirm **kink mode**
- ✓ occurrence frequency increasing downtail and increased in Y ~ [0..+10] Re,
- ✓ occurrence <u>resemble occurrence of BBFs and MR at substorm onsets</u> (Nagai et al.,1998)
- ✓ consistent with flankward propagation



(Sergeev,Sormakov et al, poster IAGA GAIII-05, 2005)



Activity Dependence

Dependence on AE and auroral activity

❑ Common during substorms, but sometimes met during quiet AE

❑ Usually associated with auroral brightenings or poleward arcs (PC or streamer?), but clear one-to-one relationship occur rarely

❑ flapping propagation direction is outward from brighhtening location in 5 of 6 clear cases

❑ few events with NO auroral brightenings (all – CDPS events).

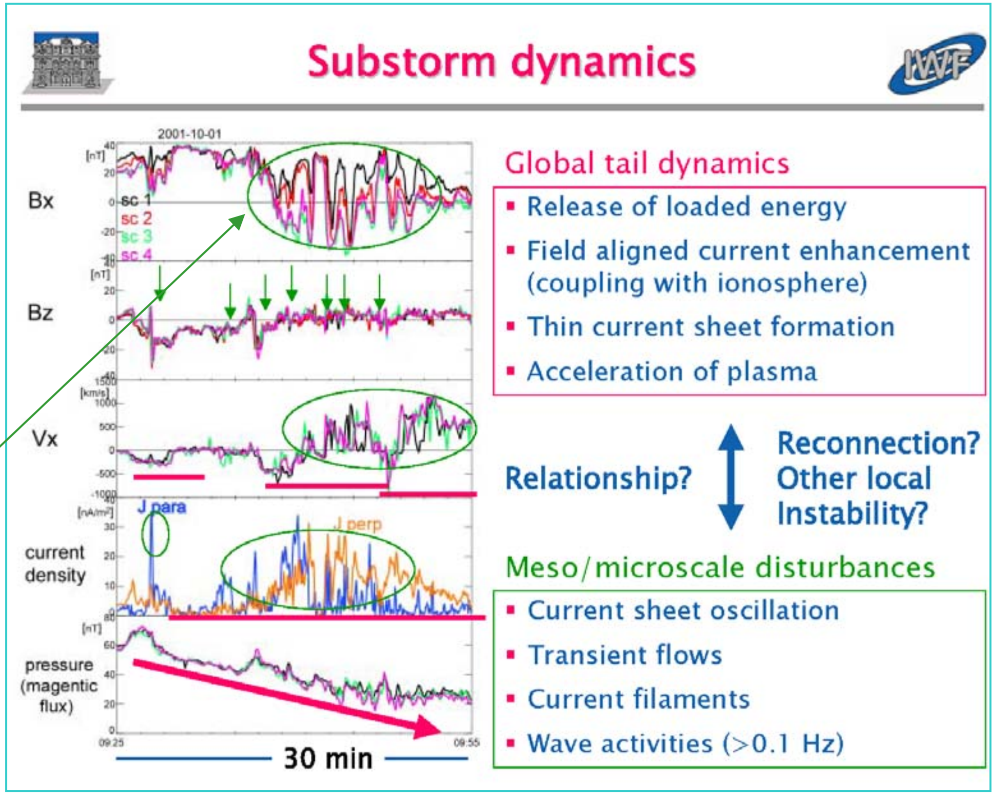
[*Dubyagin et al., paper IAGA2005-A-00302*]

Dependence on Local activity

❑ flapping appear within the whole range of PS parameters

❑ sharp crossings with large tilts and large Vz and V_T are frequently noticed near MR region, and in BBFs (?);

❑ propagation speed is large (>100km/s) only in /near the BBFs, is small (tens km/s) in quiet PS



Needs more (quantitative) study

Parameters of flapping current sheets

- duration 30-300s
- B_{ns} in the neutral sheet: ~4 nT (1..18nT), usually |By*|>Bz*
- curvature –Earthward (closed FL-~90%), remaining- tailward of Xline
- B-curvature radius Rc ~ 5 L_{cp} *(L_{cp} -gyroradius in BL field*)
- halfthickness h~10 L_{cp} (1..20 L_{cp}), weak correlation with Rc
- any density/temperature conditions
- plasma velocity: BBFs only in ~25%, >60% Vp<100km/s
- adiabaticity parameter $\kappa = \{Rc\ BL/\ (Lcp\ Bns)\}^{1/2}$ ~0.6 (0.2..2)

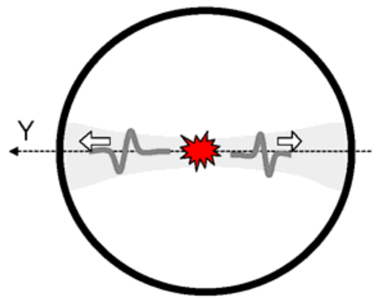
  \- non-adiabatic ions

Runov et al. AnnGeo, 2005, p.1391, also

Shen et al JGR, 2003, p.1168

Summary of Flapping-related structures

- Large-amplitude Nonlinear Structures (Waves or Solitary structures);
- Very large tilts (>45º from Z in ~50% of events)
- Fast CS crossings due to **kink** 'waves' with normals rotated ⊥B (in ~YZ);
- Propagated 'center➔flanks' , ion speeds 20-300 km/s, median ~50km/s;
- Occur 10->30 Re, frequency increases with distance, peaks premidnight
- Associated with auroral brightenings and substorms, exceptions exist
- Ion flow includes :
  - ✓ Vz corresponding to up/down CS motions;
  - ✓ Vpn flow have same sign/magnitude as the propagation velocity for low speed events (?);



WORKING HYPOTHESIS :

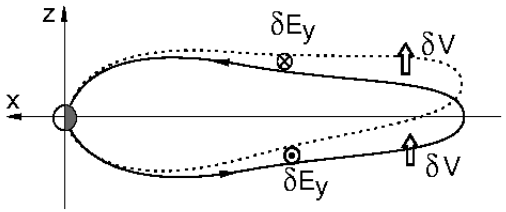
Flapping structures – of inner origin, *most possibly* generated in association with midtail reconnection and BBFs, *can be* the structures ~standing in the plasma flow (or moving slowly against the flow)

Mechanisms of Flapping ?

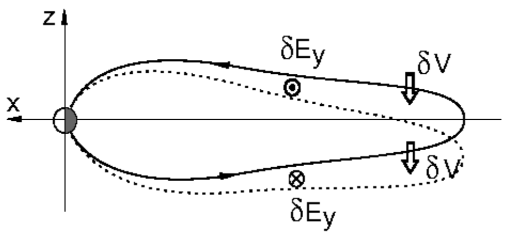
Burst of activity in theory *2002-2005 –10-15 papers

- ❑ Kinetic (KH or drift) instability (Nakagawa-Nishida, 1989, Karimabadi et al., 2003,….)
- ❑ MHD effect of localized reconnection with magnetic shear (Semenov et al.,1994, Shirataki, Fujimoto et al 2005?)
- ❑ Standing modes in (neutral Harris) sheet (Fruit et 2002, Volverk et al., 2003)
- ❑ Eigenmodes in finite Bz current sheet (Golovchanskaya, Maltsev, 2004)
- ❑ PIC simulations of CS instability (e.g. with real h_{cs}, Sitnov et al 2004), association with other instabilities (e.g. LHDI, etc)

Different initial models and parameters, different detailness of predictions - difficult to compare ;
critical issues to answer :



- ➢ MHD or kinetic effects? Instability or generation by reconnection?
- ➢ Propagation velocity (in dHT frame) ?
- ➢ CS parameters/structures favourable for generation?



- ➢Different mechanisms could be involved???

Current sheet structure

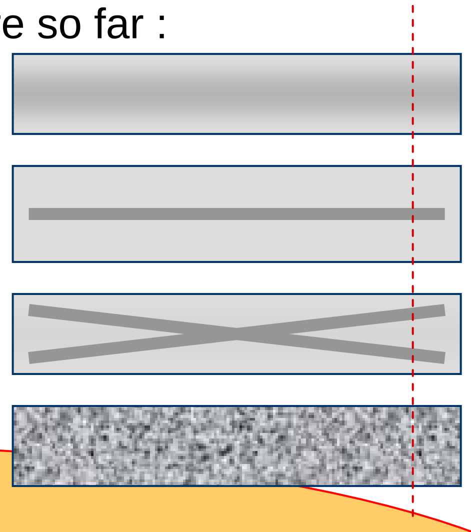
Structure of magnetotail current sheet [**j** (x,y,**z**)]:

Important characteristics, controls distribution of magnetic stresses and CS stability;

Little known observationally → little demands to the theory, mostly based on Harris model;

Types of CS structure discussed in the literature so far :

- Harris kinetic equilibrium;
- embedded (thin) current sheet ;
- bifurcated current sheet (analog of Petchek S shocks, ...;
- turbulent CS ;



Important parameters for CS stability/classification to be determined :

- Ion gyroradius ρ_{i0} / L, λ_i / L, (*$\lambda_i = c/\omega_{pi}$ – ion inertial length, L – CS halfthickness*) ,
- Bn/B_0, guide field By/B_0 (along **j**)
- Current distribution (CS structure)

October 20, 2001: Oscillation amplitude and CS structure

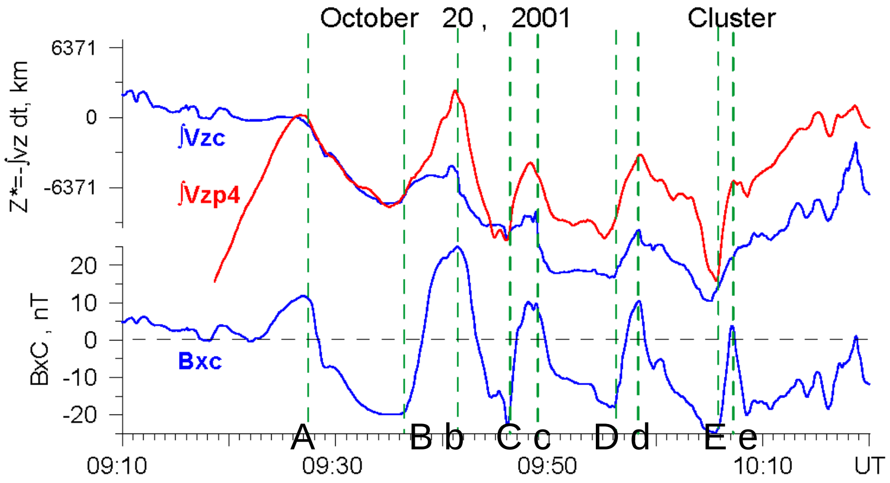
Vz integration – vertical PS/plasma motions:

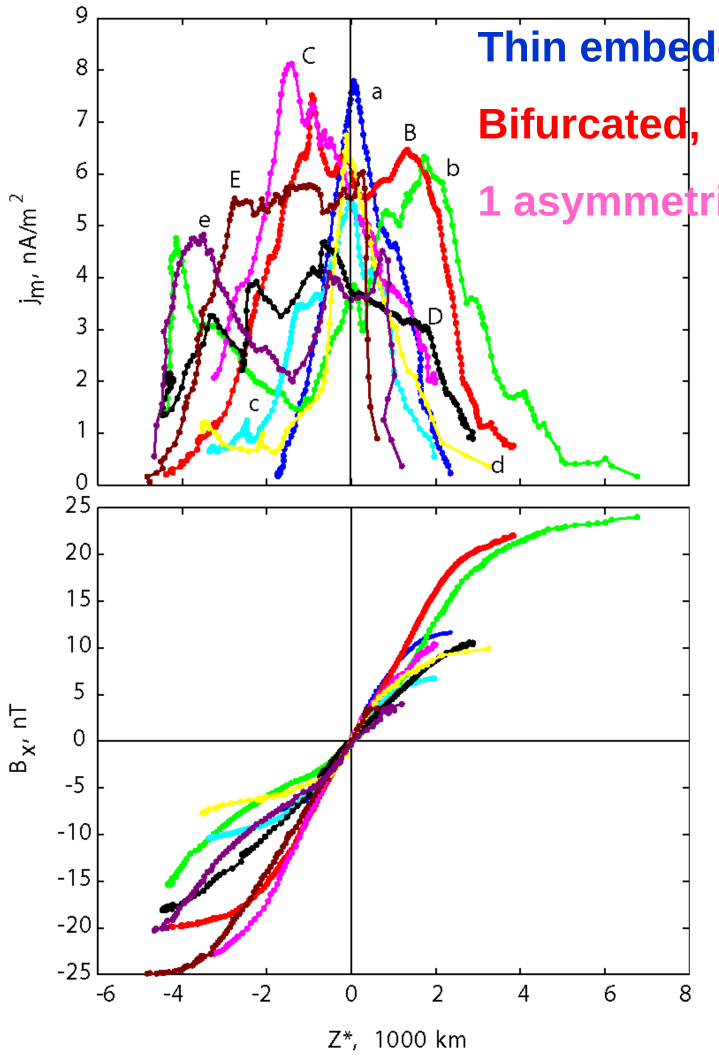
- ✓ consistent variations Vc & Vp ;
- ✓ <u>Δz~1-2 Re</u>

CS structure of individual crossings, from B (z*) (Vc and average tilts used) :

- ✓ different shapes (single peaks, flat, bifurcated, symm/asym, time-dependent?,…) ;
- ✓ CS scale-sizes vary between ~1000 km and ~4000 km;

All crossings <u>are different !</u>





Thin embedded,
Bifurcated,
1 asymmetric, etc

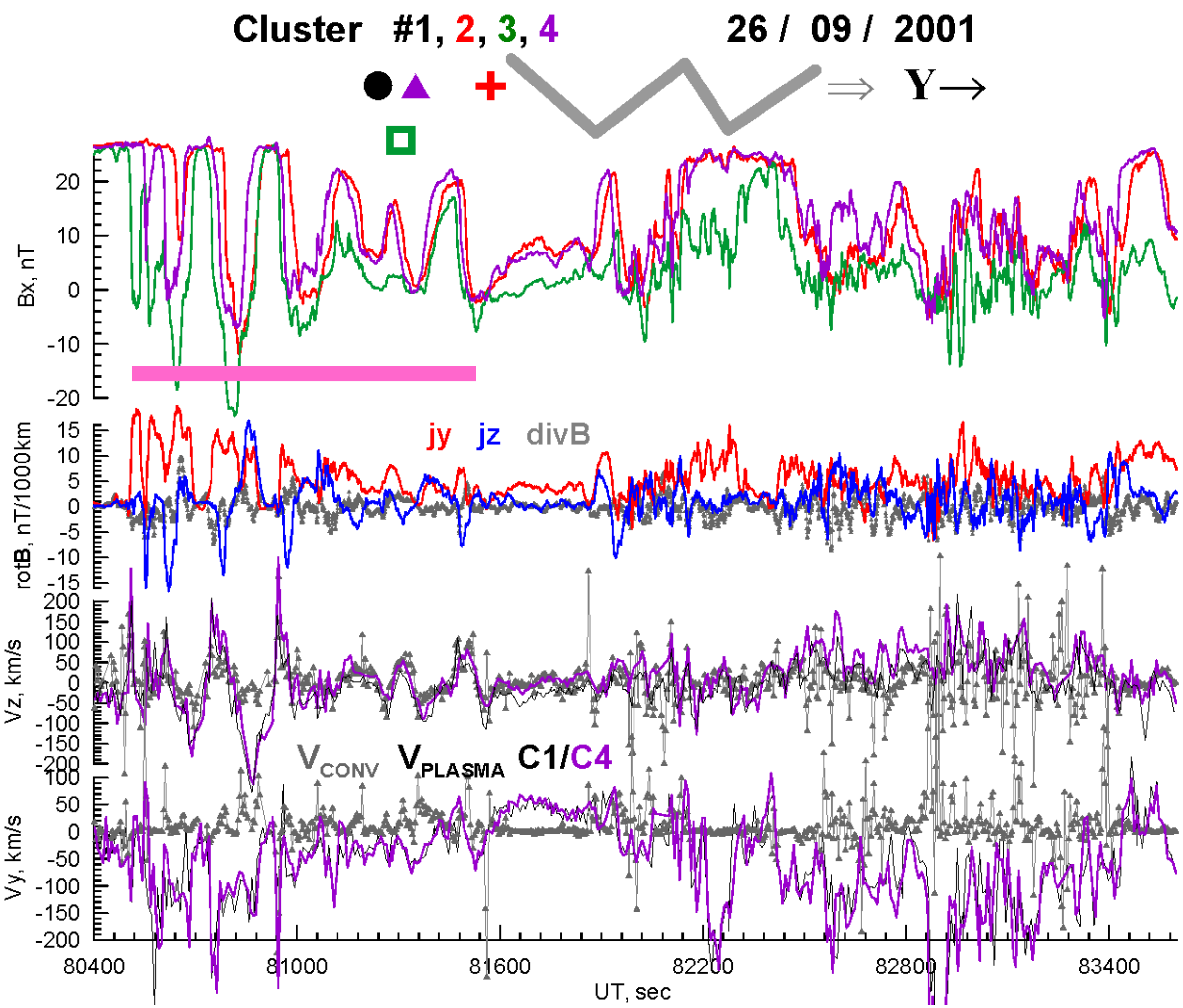
Cluster –5, September 2005

September 26, 2001 CLUSTER: example of intense current sheet flapping at substorm onset

Intense periodic flapping motion induced near the onset of small substorm activation *(Sergeev et al.,GRL 2003)*

Special features :

- ✓Strong |Vz|>100 km/s; ΔZ~1-2 Re
- ✓Stable bifurcated sheet;
- ✓Large tilts (e.g., jz);
- ✓Duskward propagation, λy ~ T ΔY/ Δt ~ **1.5 Re**
- ✓**Good correspondence of Vc and Vp in z-comp;**
- ✓ **No correspondence between y-components – these structures move at large speed with respect to plasma**



September 26, 2001, CLUSTER: stable bifurcated current/plasma sheet

Two methods to probe the current structure give consistent results *(Sergeev et al.,GRL 2003):*

Direct probing of sheet current density J distribution with $\Delta Bx_{13} / \Delta z^*_{13}$:

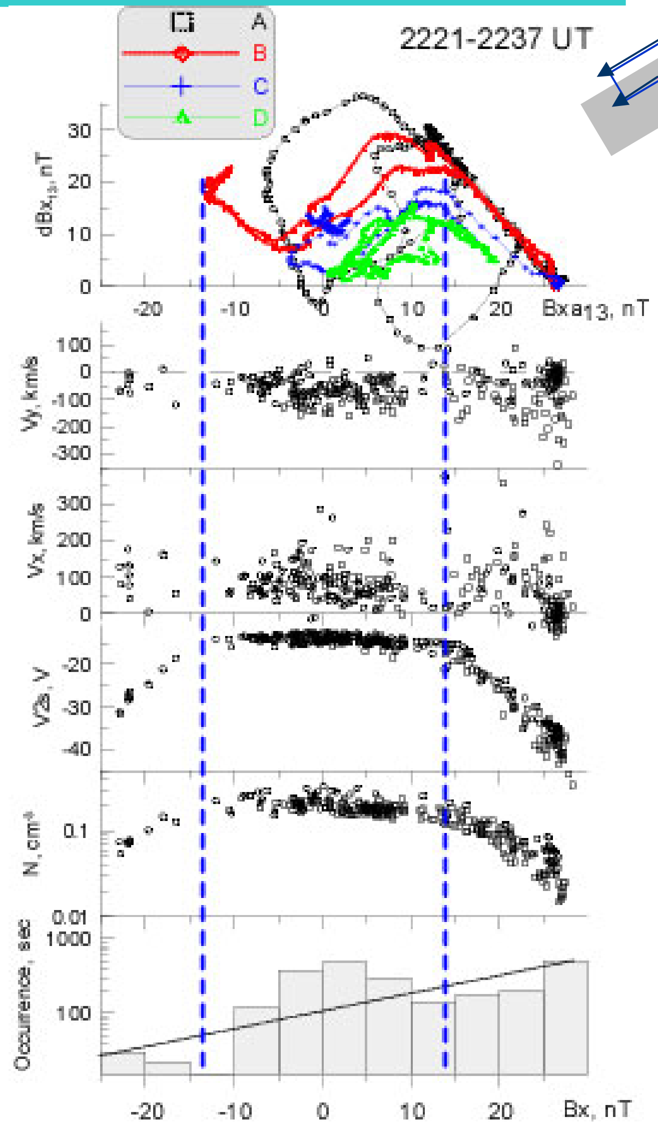
- ✓Repeated on few oscillations– **steady spatial pattern!**
- ✓ **Peak J at |Bx| ~ 0.5 BL**, J ~ 3-4 times smaller in the CS center;

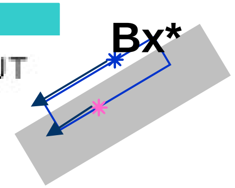
Occurrence frequency of Bx measurements (*Hoshino et al.,1996*):

- ✓ well-defined drops **|Bx| ~ 0.5 BL** as expected in regions of strong gradient (C1 and C3 together)

Plasma structure :

- ✓ Plasma density and spacecraft-plasma potential has plato between two J peaks;
- ✓ <u>Vy velocity is negative</u>, toward tail center and against flapping wave propagation
- ✓ Insufficient coverage in the peak region;
- ✓ Vx is slow , reconnection pattern questionable !





Cluster –5, September 2005

Current sheet structures

~55%: Central peak, main part of the current is concentrated in $|B_x|<0.5BL$, $BL=(B^2+2\mu_0 P_i)^{1/2}$

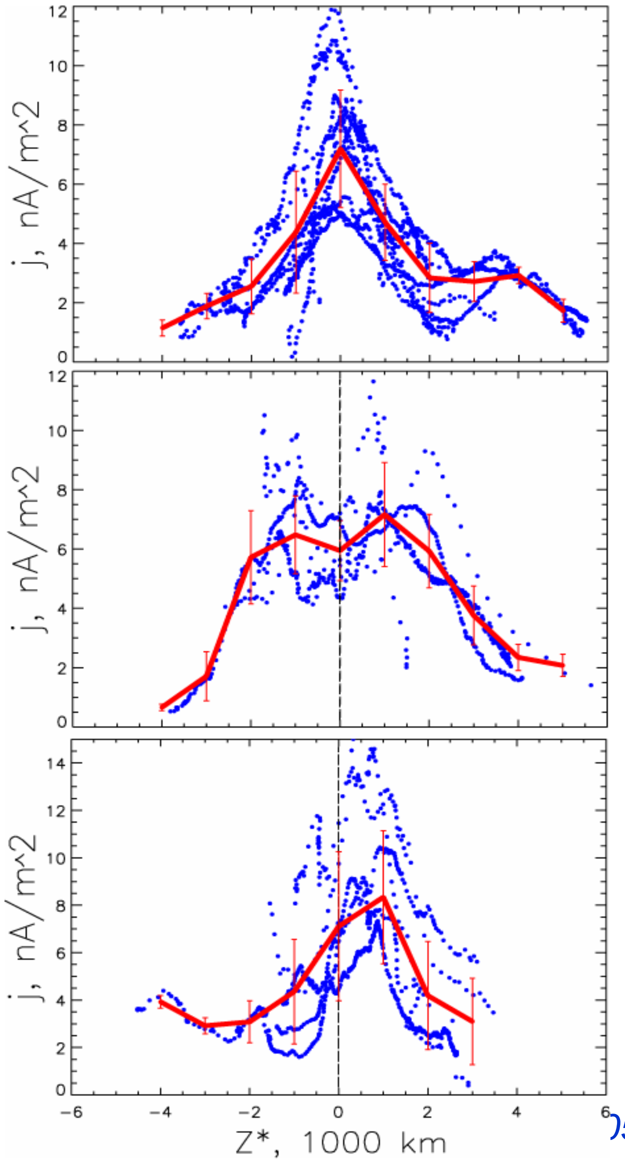
- Typical half-thickness of the central peak ~ 1000 - 2000 km ~ 3 – 7 Lcp,
- "Shoulders"

~10%: Bifurcated: Local minimum of the current density at Z* = 0 (B_x~0)

- Typical half-thickness ~ 3000 km ~ 10 Lcp
- Thicknesses of peaks of 1000 - 2000 km

~35%: Asymmetric: Off-equatorial maximum of the current density

Typical half-thickness ~ 1500 - 3000 km



Current sheet structures

Are non-Harris features special for flapping sheets only (e.g. transient effect??)

Asano et al 2005 (GRL, L03108):

- Other approach and method (no preference to flapping sheets);
- Large tilts excluded;

Results:

- Harris distributions – rare !
- Central embedded sheets - ~40%
- Bifurcated/off-center peaks - ~17%

comparable to % in flapping sheet survey!

- % of bifurcated sheets increases during BBFs

L03108 ASANO ET AL.: HOW TYPICAL A

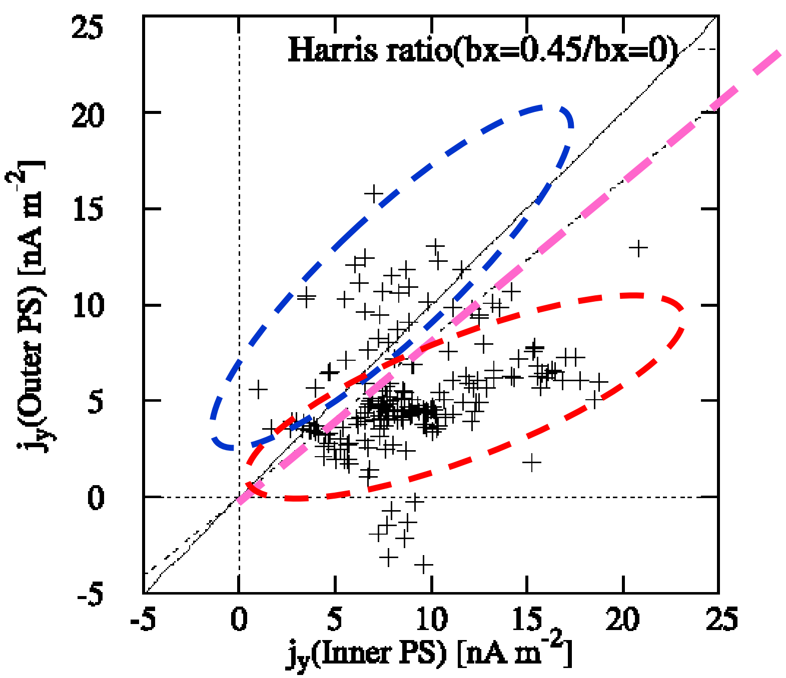


Figure 3. Distribution of j_y in the neutral sheet and in the off-equatorial plasma sheet. Theoretical ratio in the Harris-type current sheet is shown by a dashed line.

Survey of structures , comparison to Harris distributions

Reconstruction of 30 suitable crossings (*tilts, coord.system, Z* scales*);

Identify :

- ✓ central embedded sheets ;
- ✓ bifurcated sheets;
- ✓ asymmetric sheets

Non-Harris distributions !!

- ✓ **j** shape deviate from Harris;
- ✓ Density and **j**- profiles are different, flat density distributions

(Runov et al., AnnGeo 2005, submitted)

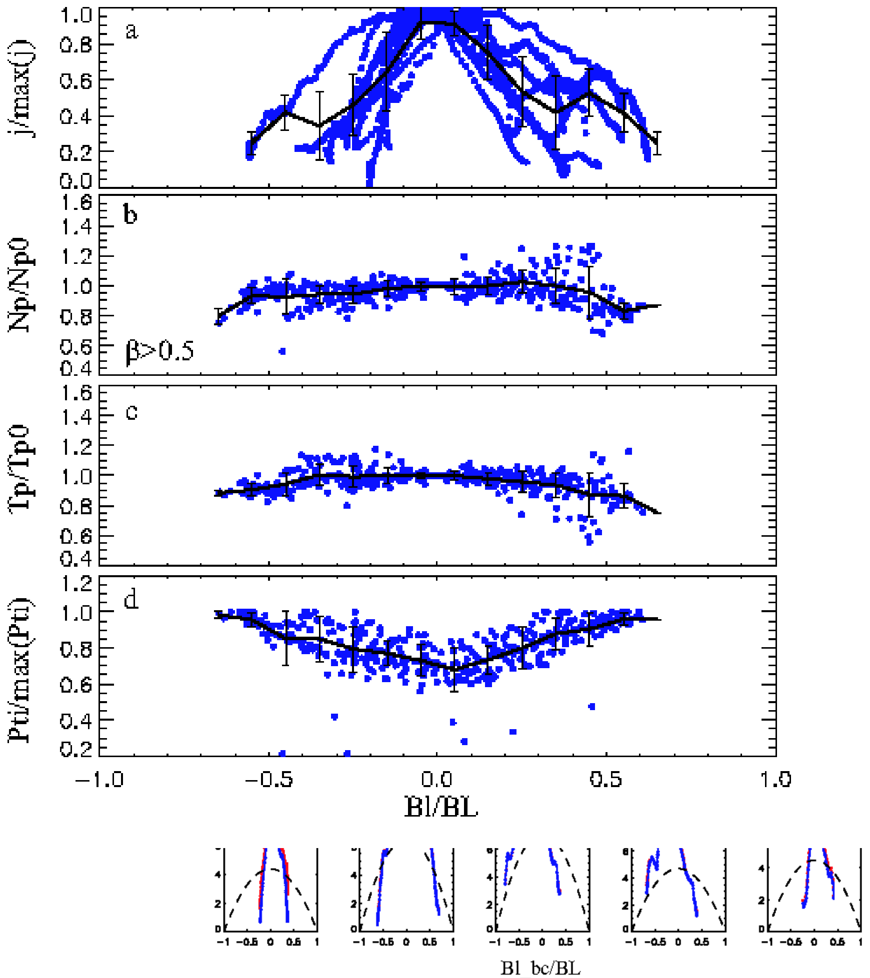


Fig. 2. Hodograms of the current density $\mathbf{j} = \mu_0^{-1}\nabla \times \mathbf{B}$ absolute value (blue) and perpendicular component $j_\perp = \sqrt{j}$ main magnetic field (B_l) for selected 30 cases. Dashed lines show the Harris function (1), with the parameter λ calcu magnetic field gradient.

Curlometer and proton current comparisons

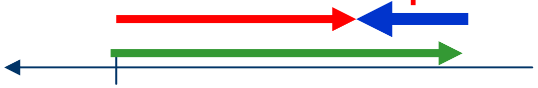
Expected: Ti/Te>>1 → $j_p >> j_e$ *and main contribution from j_p to j_{TOT}*

Observed: large discrepancies for N > 7 for most cases:

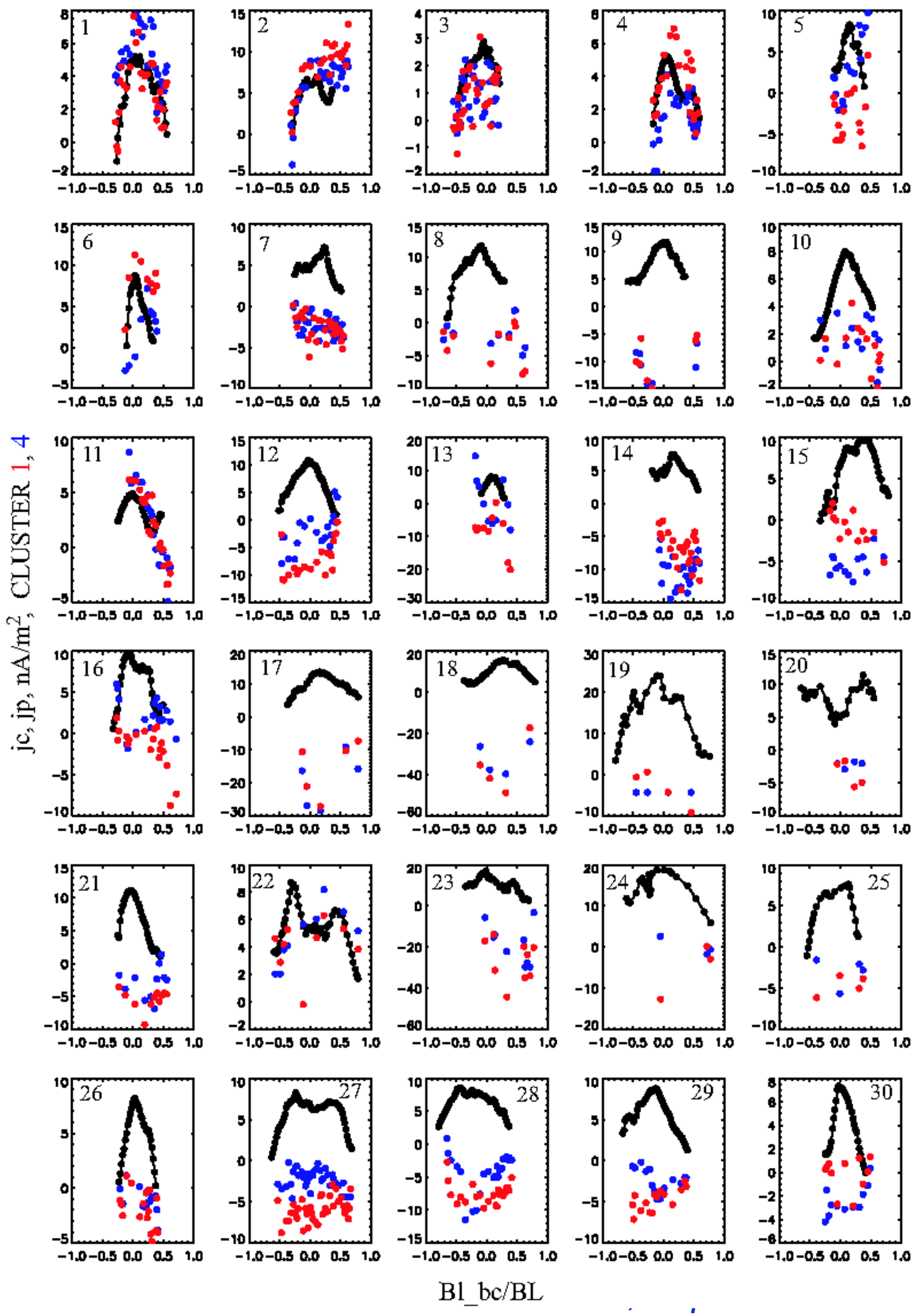
- ✓ different signs j_C and $j_p<0$, $|j_p| > j_C$ implies electrons as main current carriers

Explanation – dawnward convection, implies converging En and negative e-charge in the sheet :

$$j_C = n\,e\,(V_p - V_e)$$



(Runov et al., AnnGeo 2005,submitted)



Curlometer and proton current comparisons

Explanation – requires dawnward convection (~50 km/s),

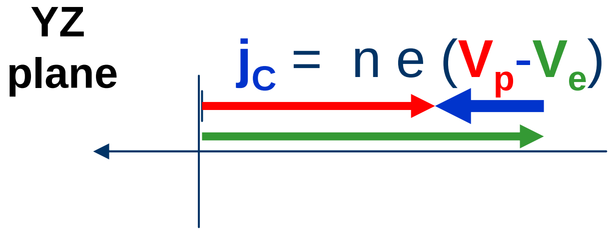
implies converging **En** (+ earthward E in NS) and negative e-charge in the sheet :

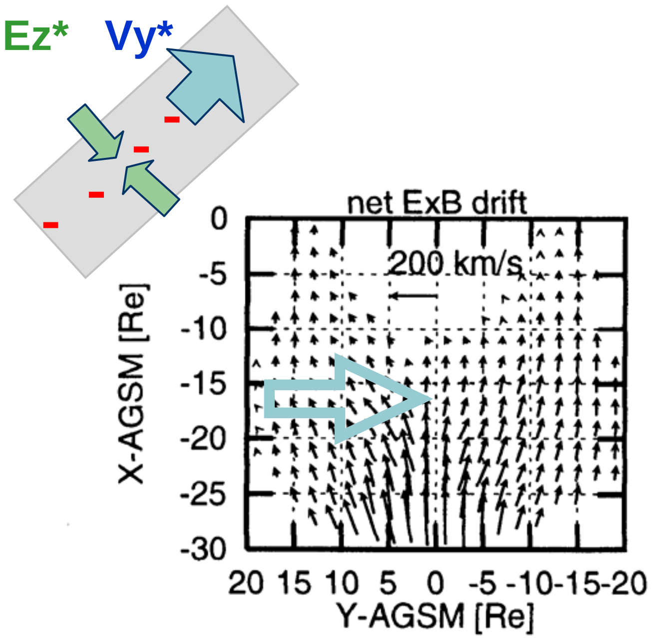
- ✓ origin of dawnward convection on duskside??? – inconsistent with average convection
- ✓ consistent with Wygant et al JGR 2005 Cluster event analyses but obtained in thin electron-scale CS, charge separation near MR as compared to relatively thick (h~few Lcp) events in our survey (?) ;

A challenge:

- to confirm this explanation by studying electron contributions and

- to understand origin/mechanisms of dawnward convection in the sheet;





5. E×B drift vectors in the X-Y plane calculat

Hori et al.,2000, also

Kauffmann et 2001, Asano et 2003 etc

Summary/Future work

<u>Large changes in the basic picture</u>:

- Common picture of ~planar tail current sheet → strongly corrugated plasma sheet including large local tilts (reconnection region is not an exception!)

- Harris sheets → variety of non-Harris distributions;

- both changes inspired a burst of activity in plasma theory