"Dark" electric fields in the Earth magnetotail and their observable manifestations

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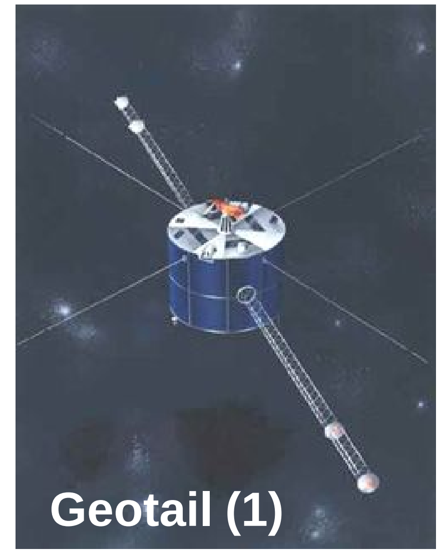
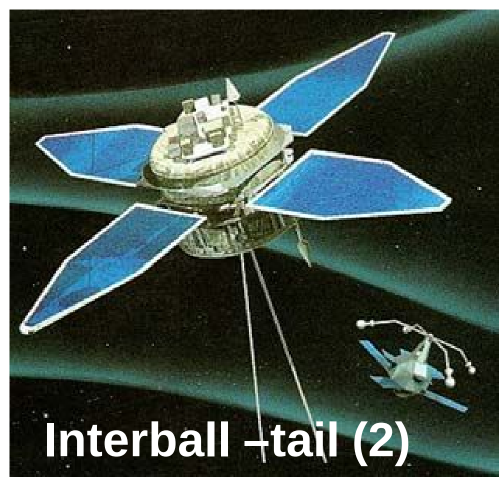
How "in situ" measurements helped to solve headbreaking puzzle



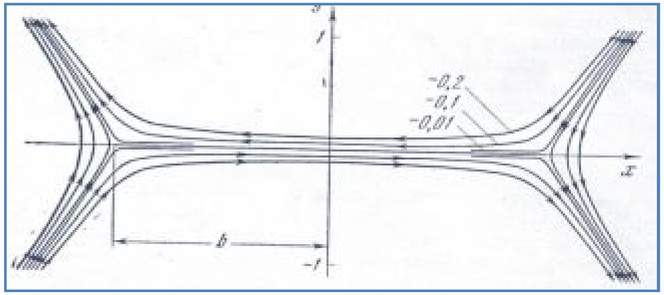


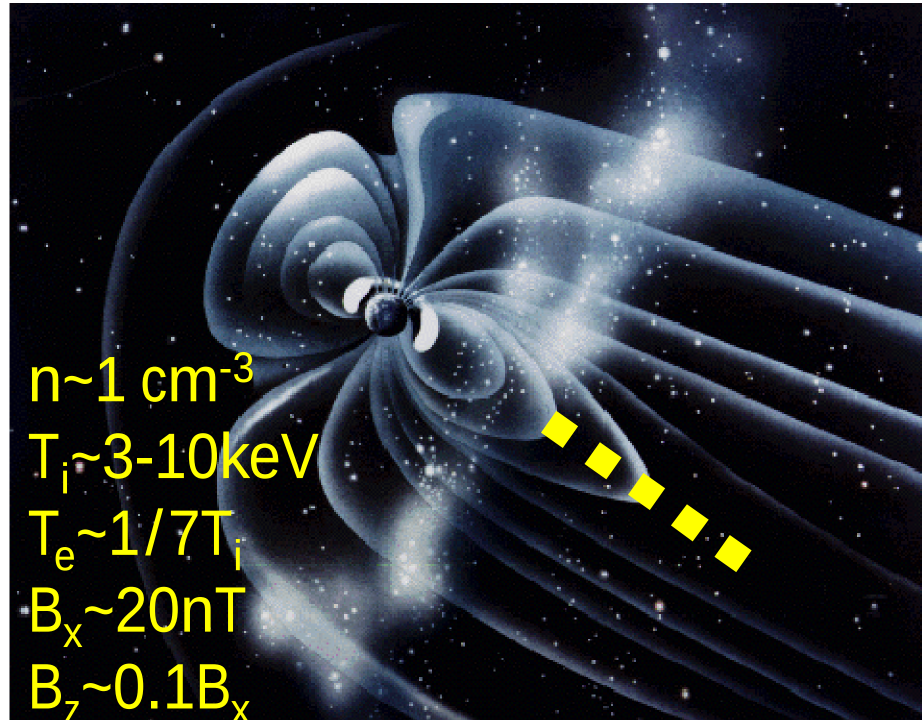
Space Research Institute
Russian Academy of Science

outline

- Current sheet in Earth magnetotail: main conceps
- Thin current sheet (TCS): spacecraft observations
- Effect of TCS embedding
- Current curriers in TCS
- Electrostatic effects: Earthward electric field

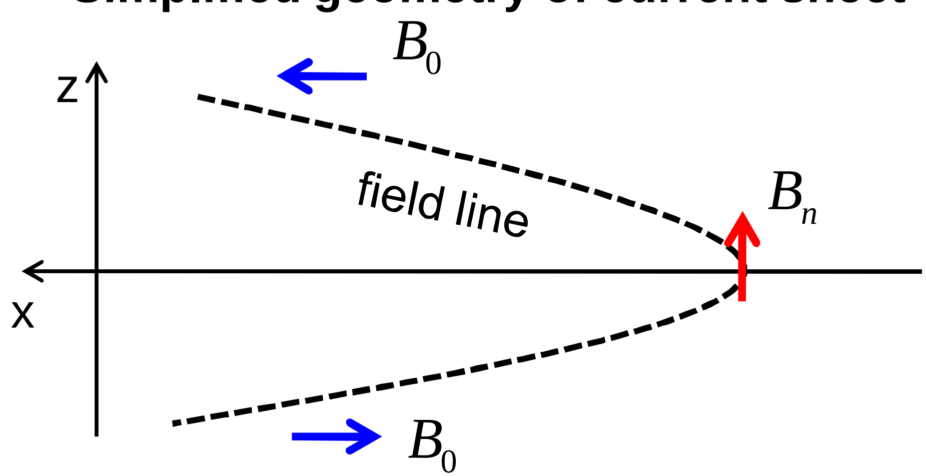
Current sheets in magnetotail





Thin current sheets in the Earth magnetotail – confirmation of the bright early Syrovatsky ideas

Simplified geometry of current sheet



Magnetotail current sheets and Harris model

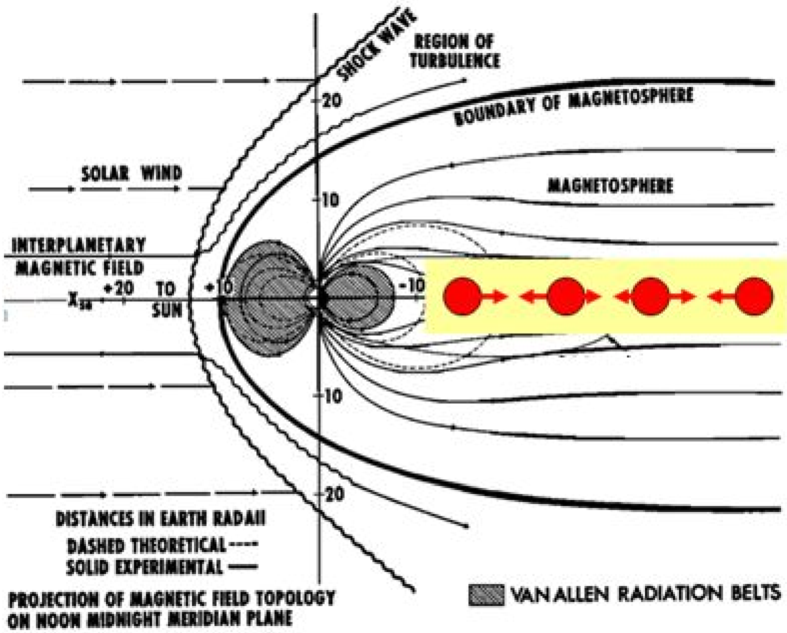
On a plasma sheath separating regions of oppositely directed magnetic fields.
1962

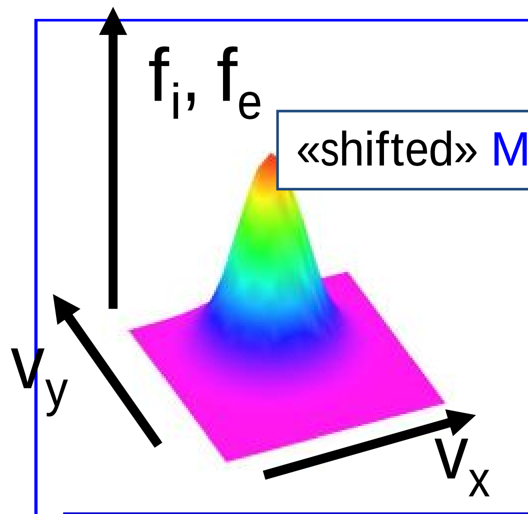
Norman F. Ness

The Earth's Magnetic Tail[1]

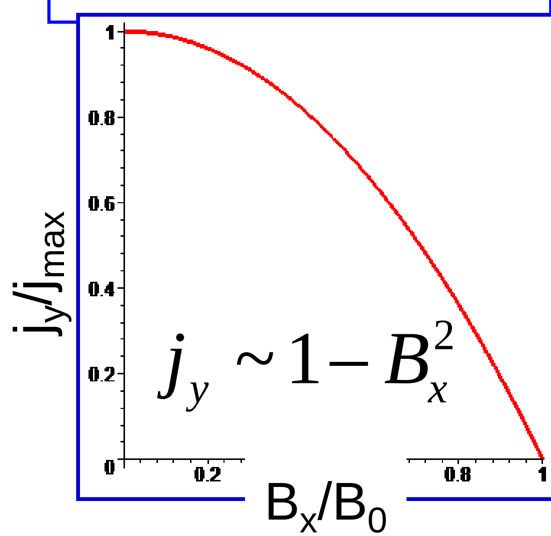
Norman F. Ness

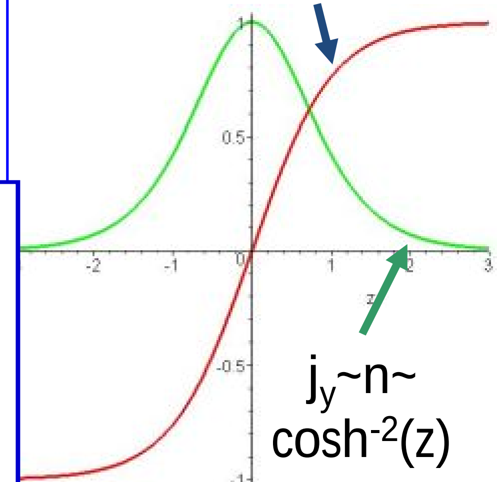
1965



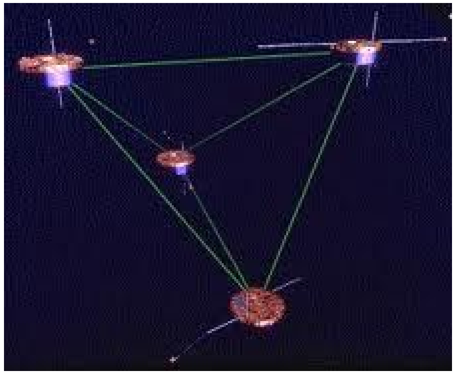


«shifted» Maxwellian distribution





Cluster: first four-spacecraft mission



Double launch on the Soyuz-U/Fregat in 16 July 2000 and 09 August 2000

The first shipment has arrived at Baikonur airport at an Antonov cargo plane

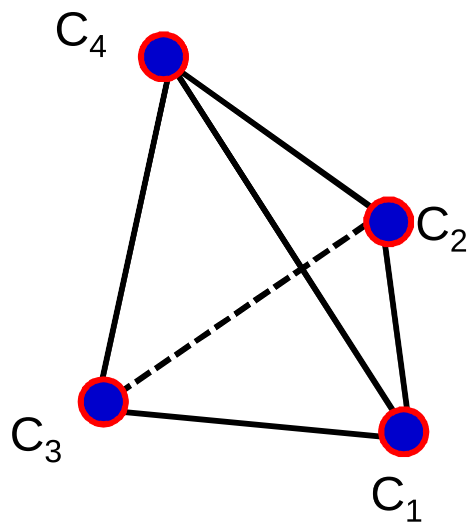
First launch on the Ariane 5 in 4 June 1996

remains of one of the four Cluster spacecraft in the swamps of Kourou

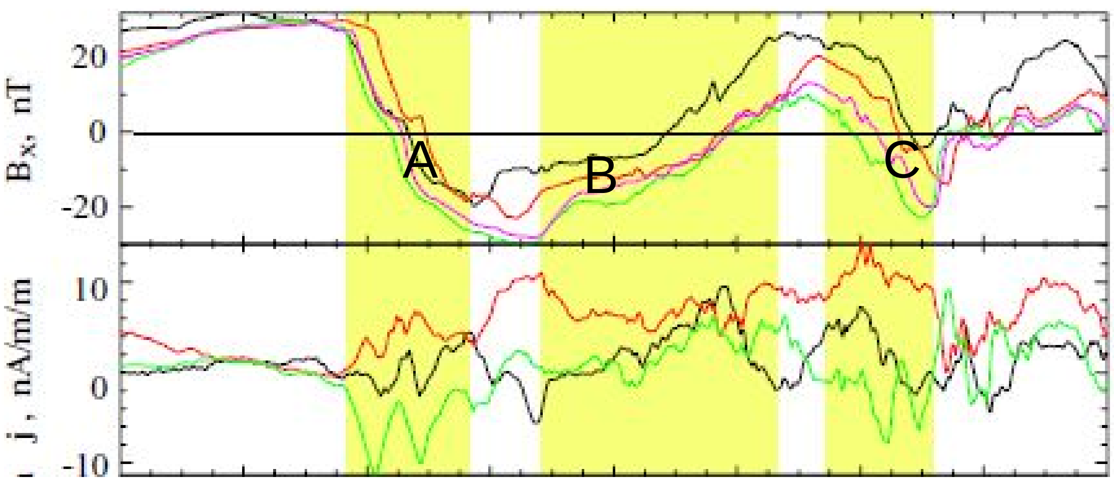
The launch of Cluster from the Baikonur Cosmodrome

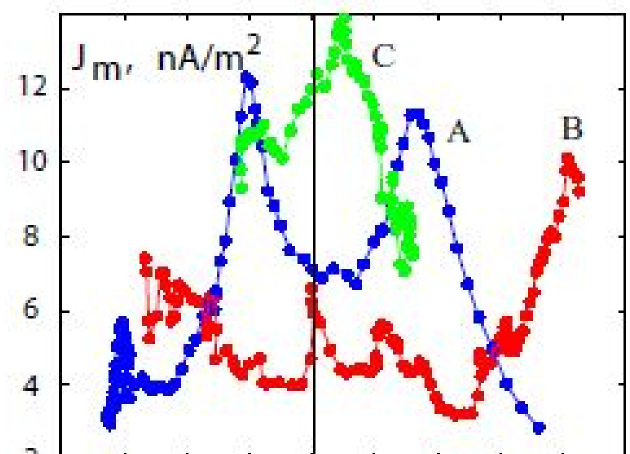
Thin Current Sheet in Earth magnetotail

Cluster mission



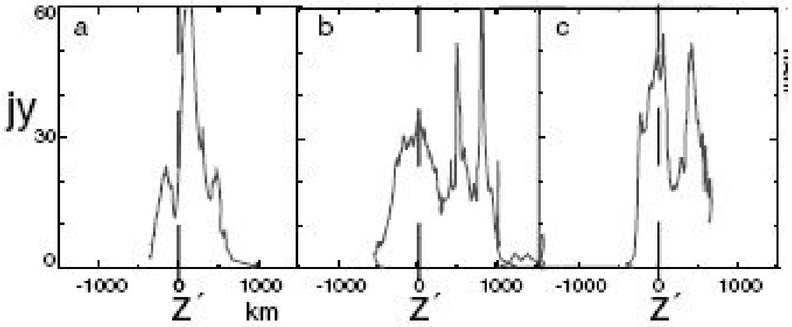
$$\text{rot}B = (4\pi/c)j_{curl}$$



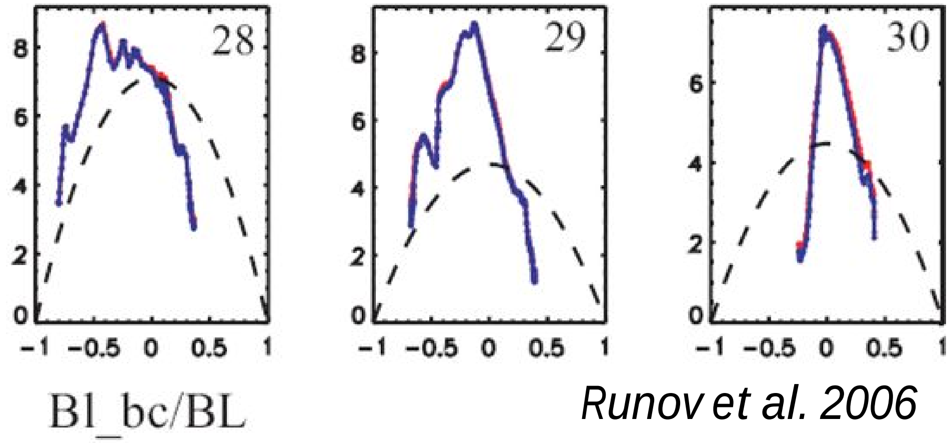


Runov et al. 2006

Currents sheet embedding and bifurcation

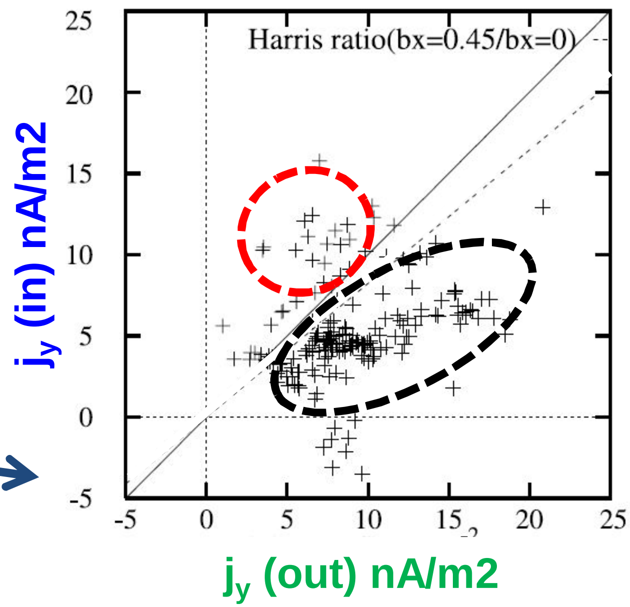


Nakamura et al. 2006

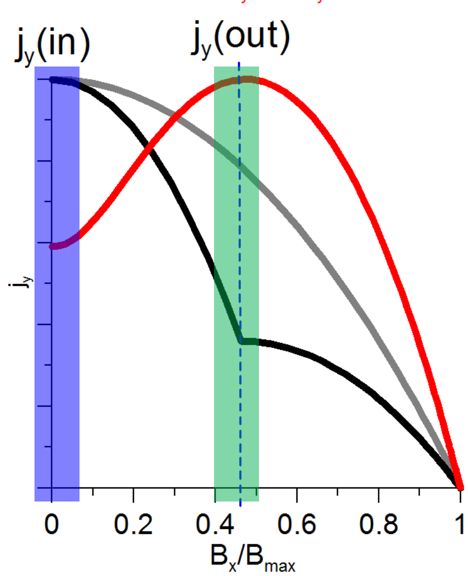


Runov et al. 2006

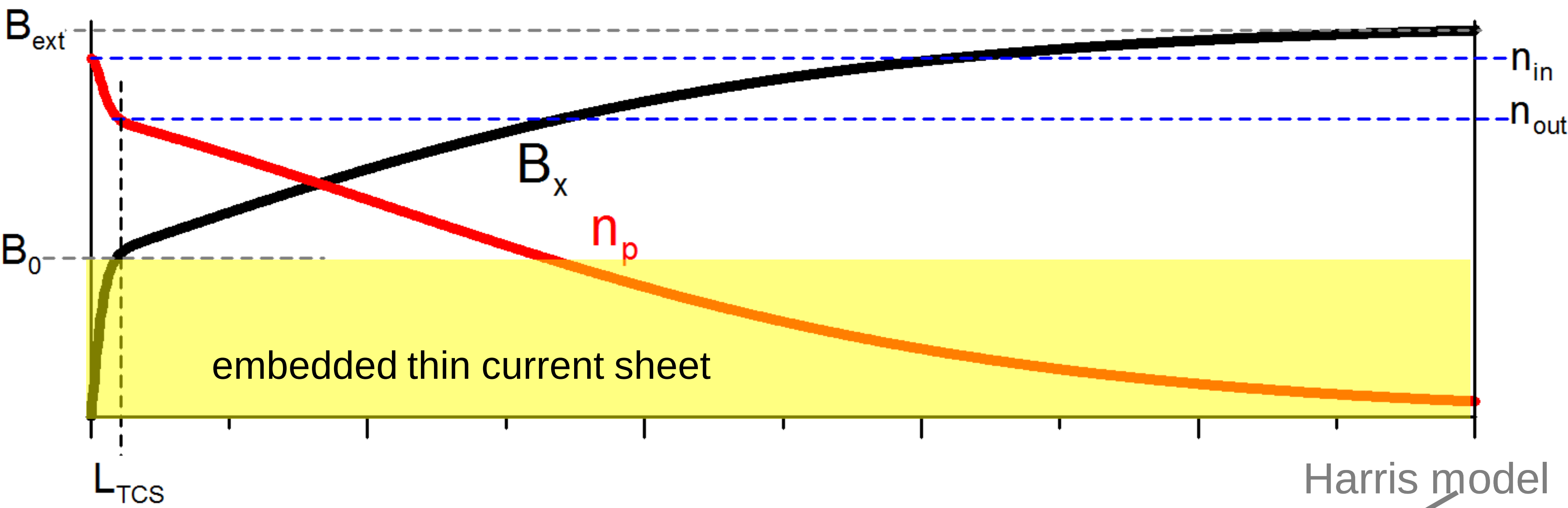
1) TCS thickness~ 1000 km
2) Current density profile can not be approximated by Harris model
3) The majority of TCS is embedded

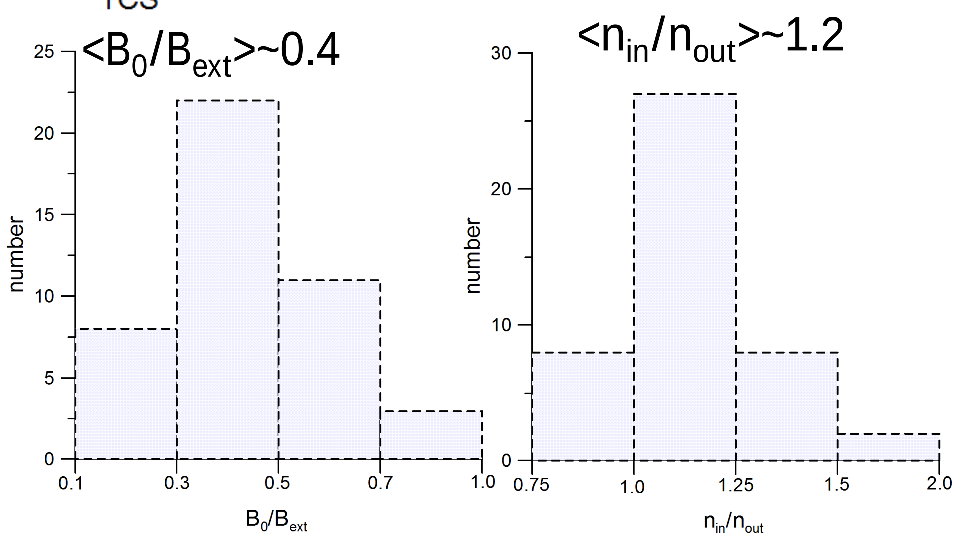


Asano et al. 2005

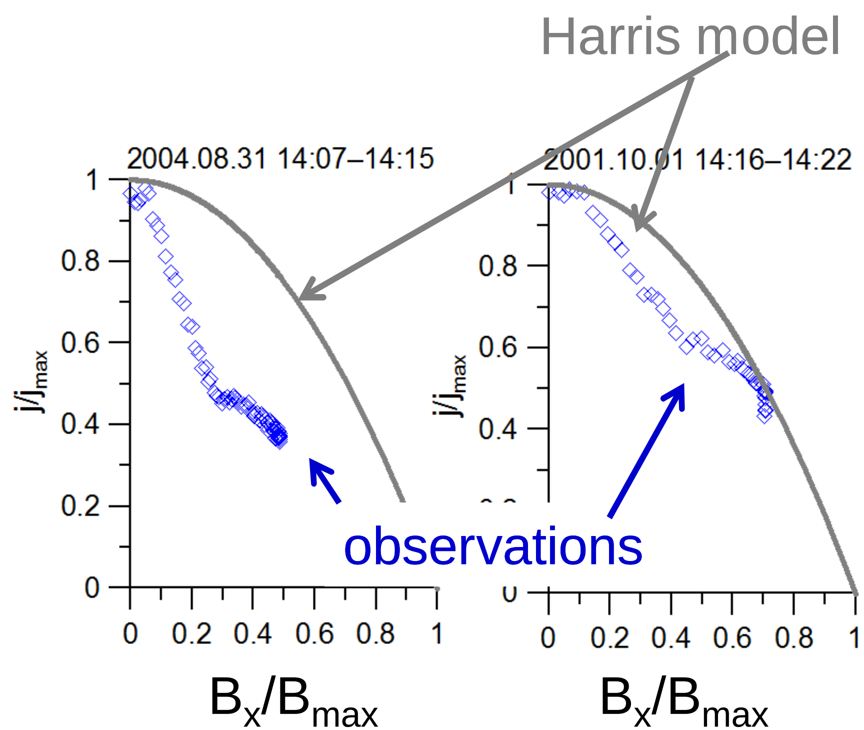


Embedding

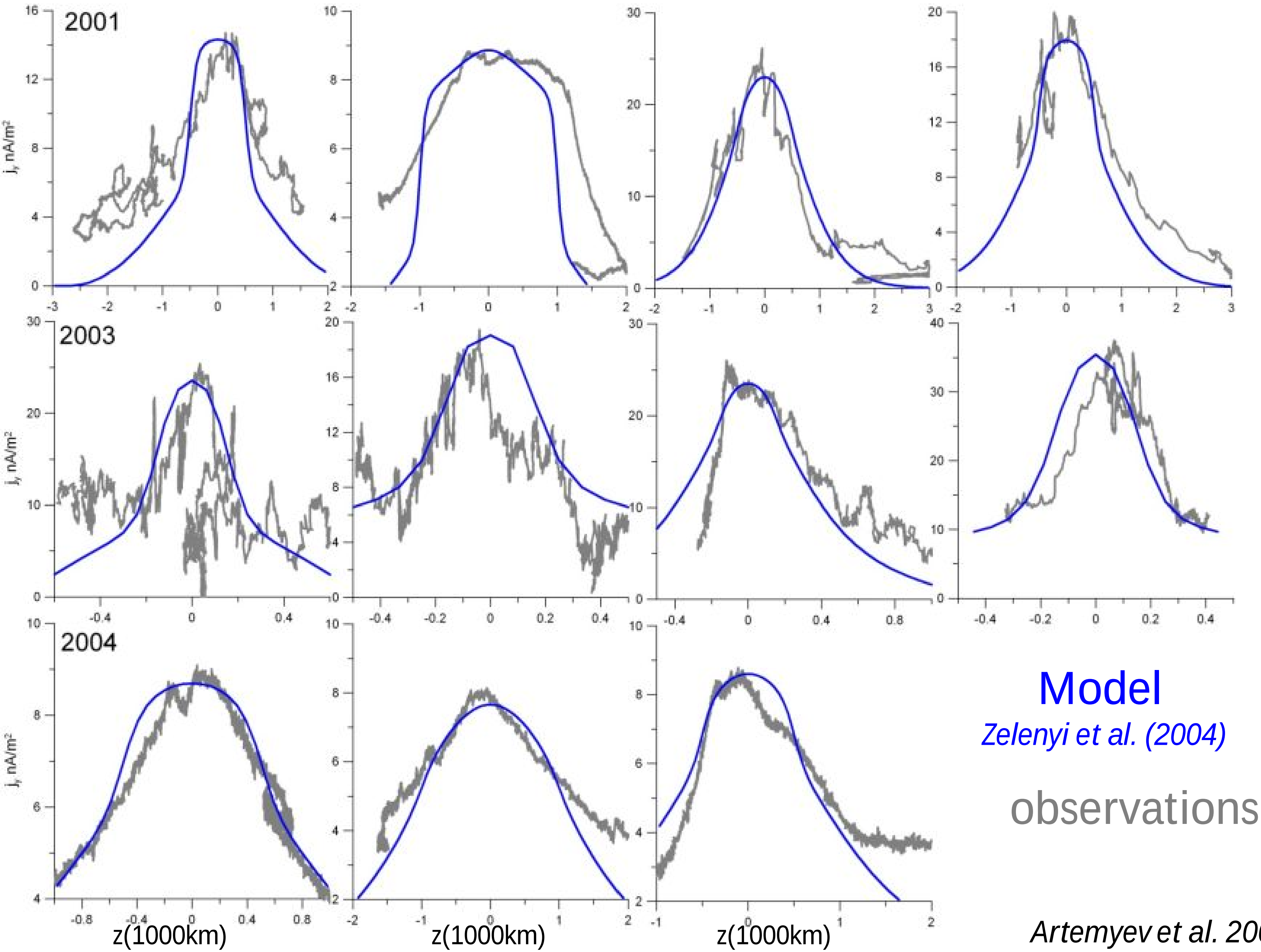




Distribution of ratios B_0/B_{ext} and n_{in}/n_{out}
for Cluster statistics of 43 current sheets



Currents sheet description be model of embedded TCS

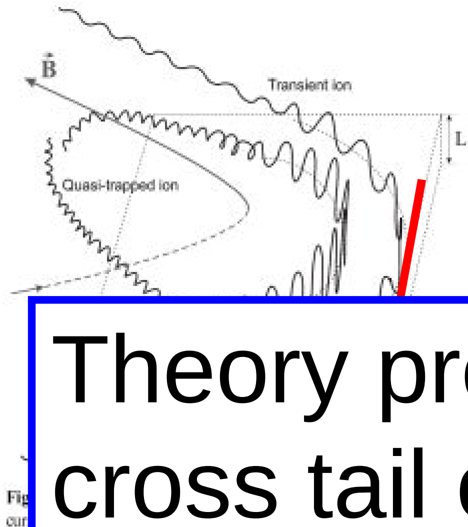


Artemyev et al. 2008

Relation between ion and electron currents: theoretical estimates

Mechanisms of ion current formation

Current of Speiser ions with open orbits: paramagnetic current



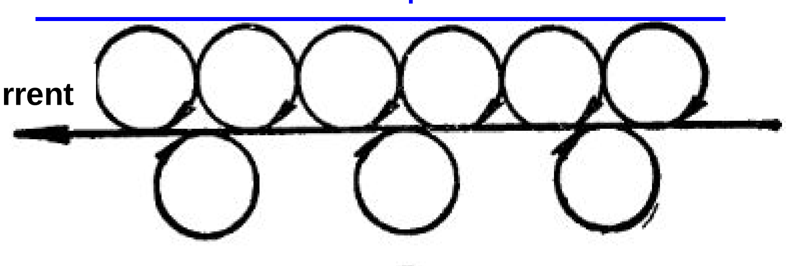
$$j_{sp} = en_{sp}v_{sp} \sim \sqrt{T_i}$$

Diamagnetic current

$$j_{DM} = en_{ion}v_{DMi} = n$$

neutral

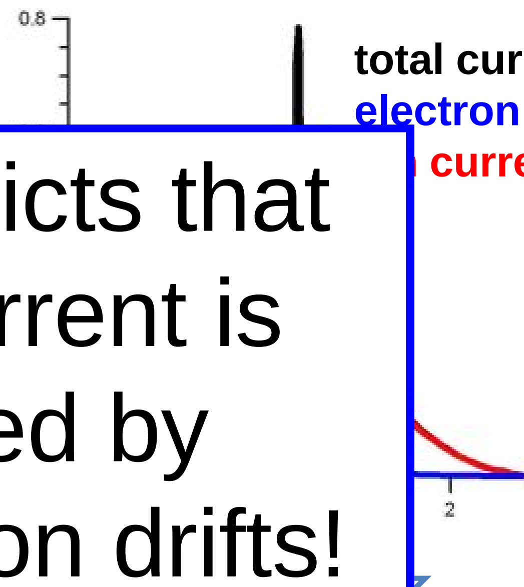
current



Mechanisms of electron current formation

Electrons are magnetized in current sheet

$\rho_e \ll (\nabla B / B)^{-1}$ **and** $T_e / T_i \sim 1/5$



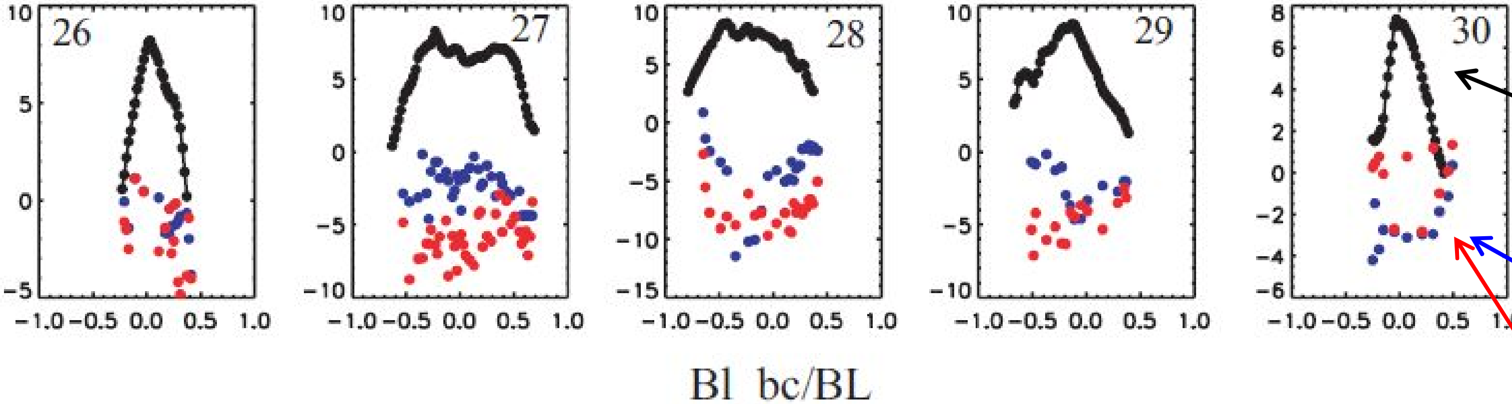
total current density
electron current density
current density

Zelenyi et al. 2004

Theory predicts that cross tail current is mostly carried by transverse ion drifts!

Total electron currents are always smaller than ion current, while the local value of electron curvature drift currents due to temperature anisotropy can strongly LOCALLY exceed ion current.

Current carriers in TCS

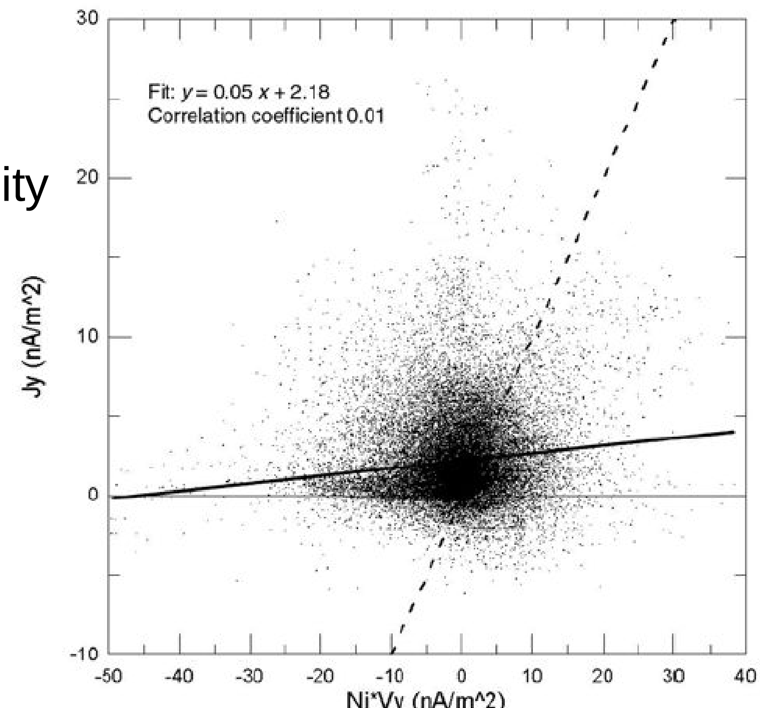


Curlometer current density

Runov et al. 2006

Proton current density from **C1** and **C4**

Curlometer current density



Israelevich *et al. 2008*

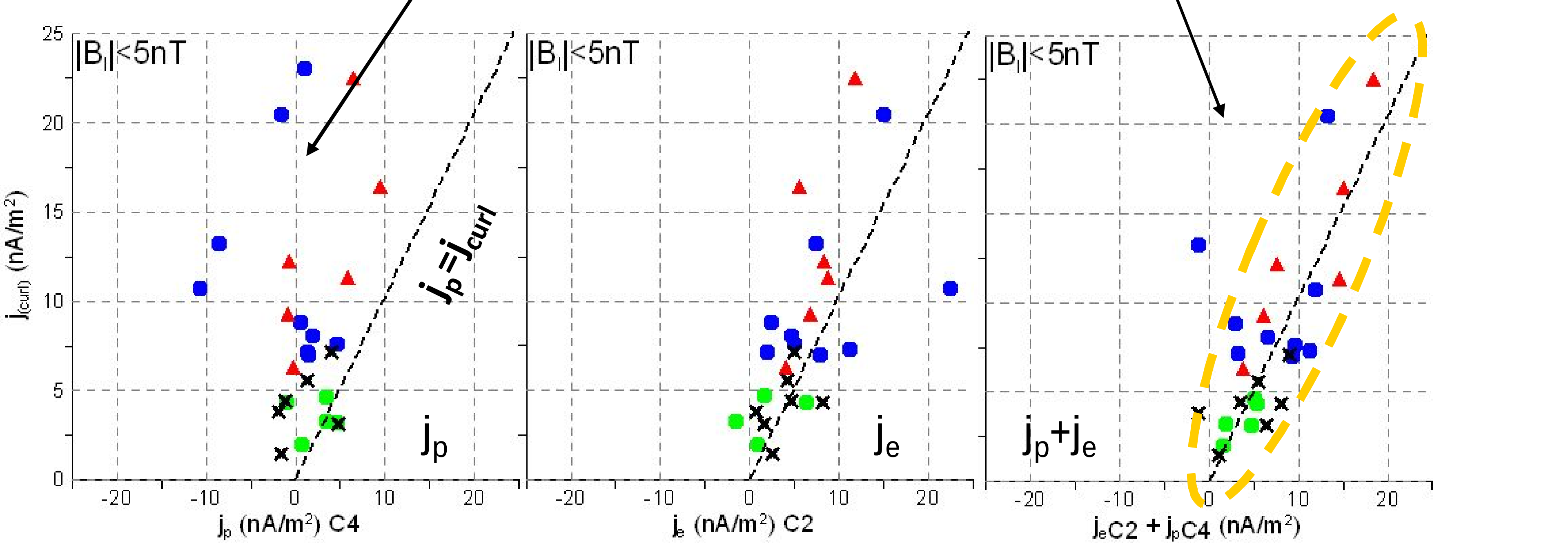
Proton current density

Extremely weak correlation between current density, calculated from variation of magnetic field (curlometer), and proton currents!

Electron currents in TCS

The correlation between ion current density and **rotB** is very poor

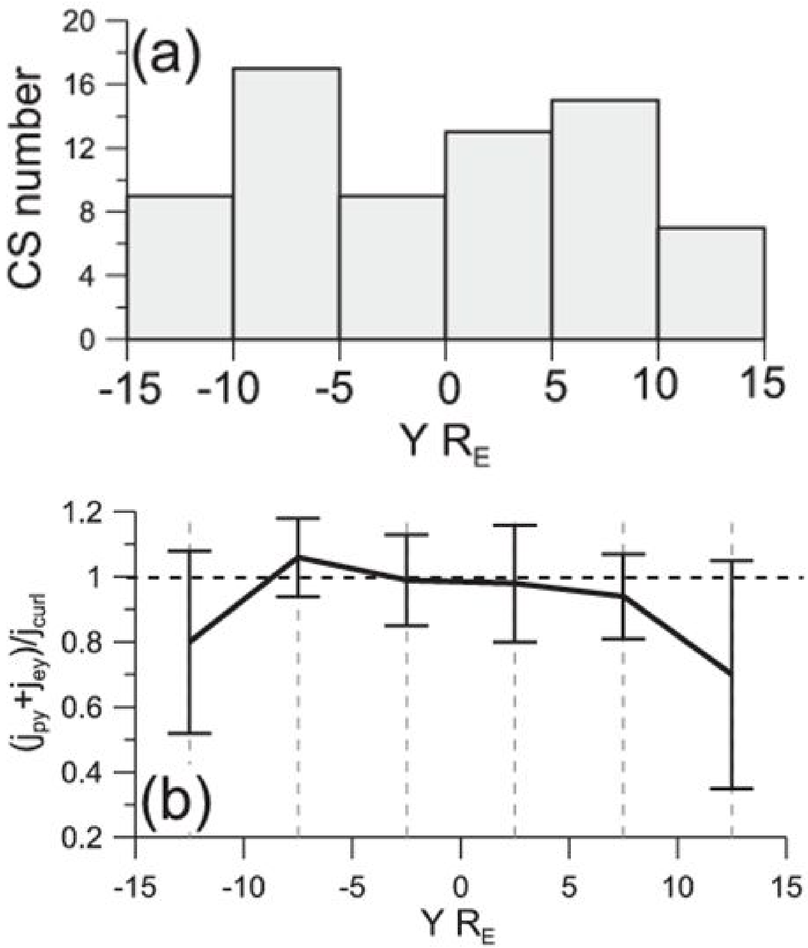
The correlation between total (j_p+j_e) current and **rotB** is sufficiently good



Artemyev et al. 2009

▲, ●, ●, X, - different types of CS (thin, electron CS, thick, ect.)

Statistics of 60 TCS crossings by Cluster



→ $4\pi/c(j_e+j_i) \sim \mathrm{rot}\mathbf{B}$

EXPERIMENT

$j_e >> j_i$ ← *Asano et al. 2005, Runov et al. 2006, Israelevich et al. 2008, Artemyev et al. 2009*

This results contradicts to main theoretical models:

$T_i >> T_e$ → theory → j_i □ j_e, $\int j_i$ □ $\int j_e$

?

Experimental puzzle from Cluster measurements!

Mechanisms driving electron currents

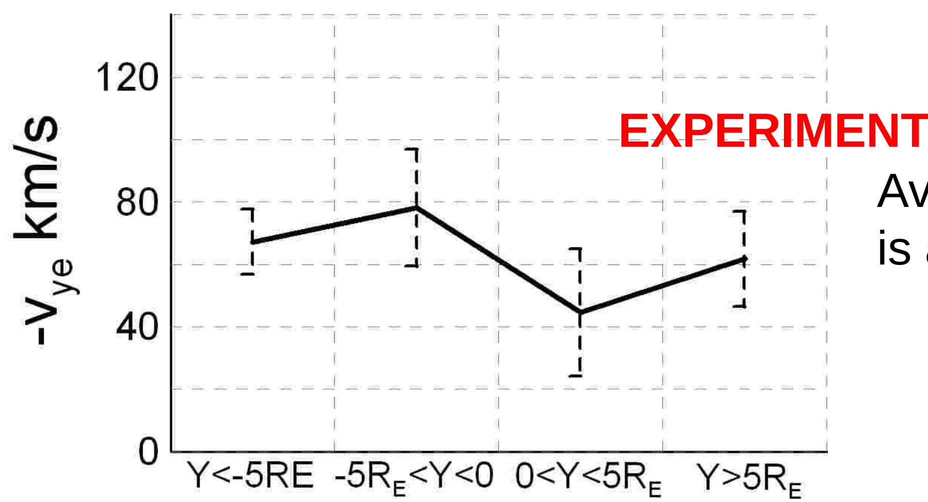
$$j_{e\perp} = -en_e v_{ey} = -en_e\left(V_{\mathbf{E}\times\mathbf{B}} + V_{\mathrm{DM}} + V_{\mathrm{C}}\right)$$

Curvature drift :

$$-en_e V_{\mathrm{C}} = \frac{c}{B^4}\left(p_{\parallel e} - p_{\perp e}\right)\left[\mathbf{B}\times\left(\mathbf{B}\nabla\right)\mathbf{B}\right] = j_y \frac{4\pi\left(p_{\parallel e} - p_{\perp e}\right)B_z^2}{B^4}$$

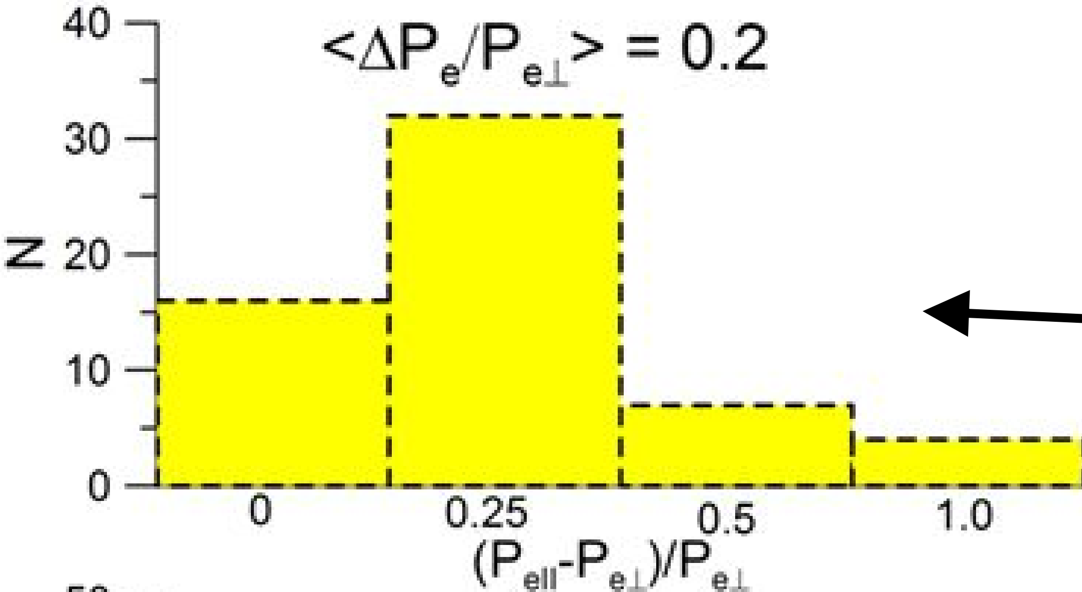
Diamagnetic drift:

$$-en_e V_{\mathrm{DM}} = \frac{c}{B^2}\left[\mathbf{B}\times\nabla_\perp p_{e\perp}\right] = \frac{cB_x}{B^2}\frac{\partial p_{e\perp}}{\partial z} \sim j_y\left(8\pi\frac{\partial p_{e\perp}}{\partial B_l^2}\right)$$

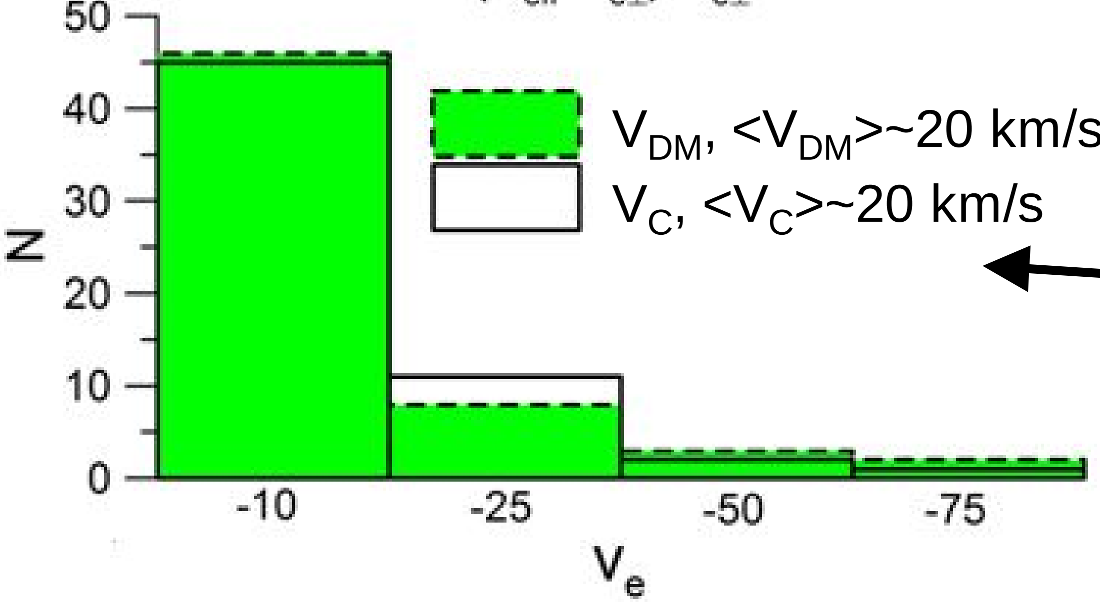


Averaged electron bulk velocity is about 70-80 km/s

The contribution of diamagnetic and curvature drifts



More than 75% of CSs have the electron anisotropy lower 25%!

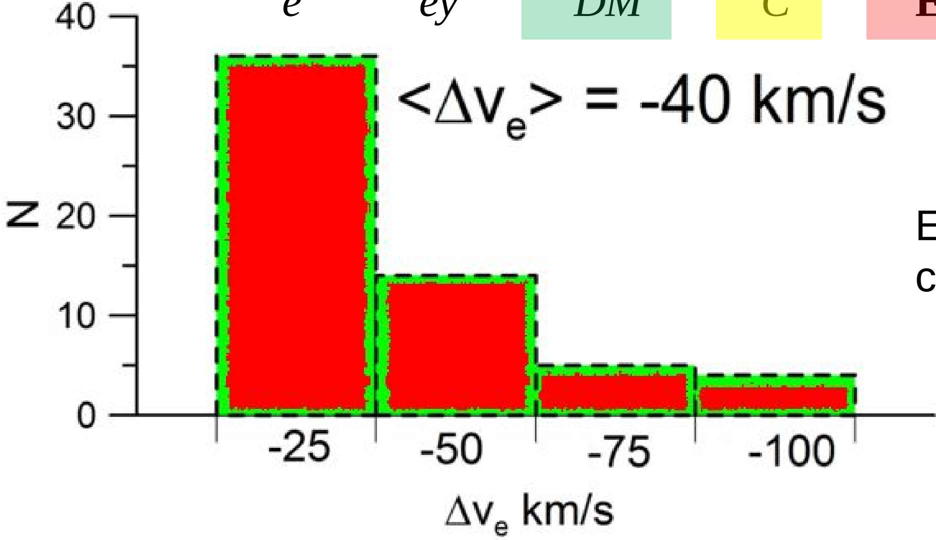


Diamagnetic and curvature drifts can explain less then half of total electron drift!

Data based on statistics of TCS crossings by Cluster.
For details see Zelenyi et al. 2010, GRL

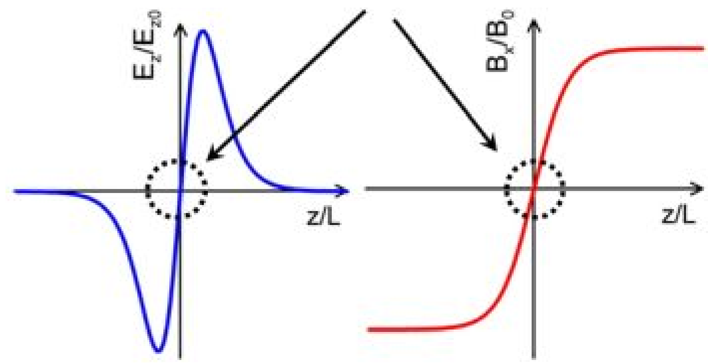
Electron drift without diamagnetic and curvature effect!

$$\Delta v_e = v_{ey} - V_{DM} - V_C \approx V_{\mathbf{E}\times\mathbf{B}}$$



Therefore we need to describe Δv_e = -40 km/s by **E**x**B** drift!

E_z and B_x has zero value in the vicinity of CS centre: $E_z B_x$~0 and cannot support required drift!

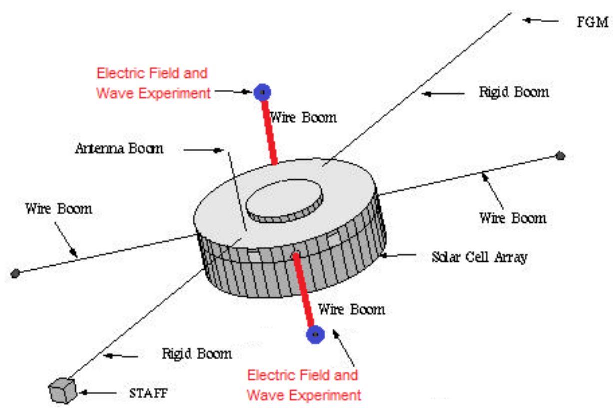


$$v_{\mathbf{E}\times\mathbf{B}} = \frac{E_z B_x - E_x B_z}{B^2}$$

To support such electron drift is required electric field $E_x > 0$

E_x ~ **0.15 mV/m**

So small electrostatic fields cannot be measured directly in the Earth magnetotail



Mechanism of E formation: estimates

$d\phi/ds = F(s)$

For example (Boltzman distribution)

$$qn\frac{\partial\varphi}{\partial s} = \frac{\partial p_{\parallel e}}{\partial s} - \frac{p_{\parallel e} - p_{\perp e}}{B}\frac{\partial B}{\partial s}$$

Electrostatic fields appear due to principally different motion of magnetized electrons and unmagnetized ions in the vicinity of the neutral plane!

Drop of potential across the TCS is about electron temperature

$\Delta\varphi \sim 0.5 T_e/e$

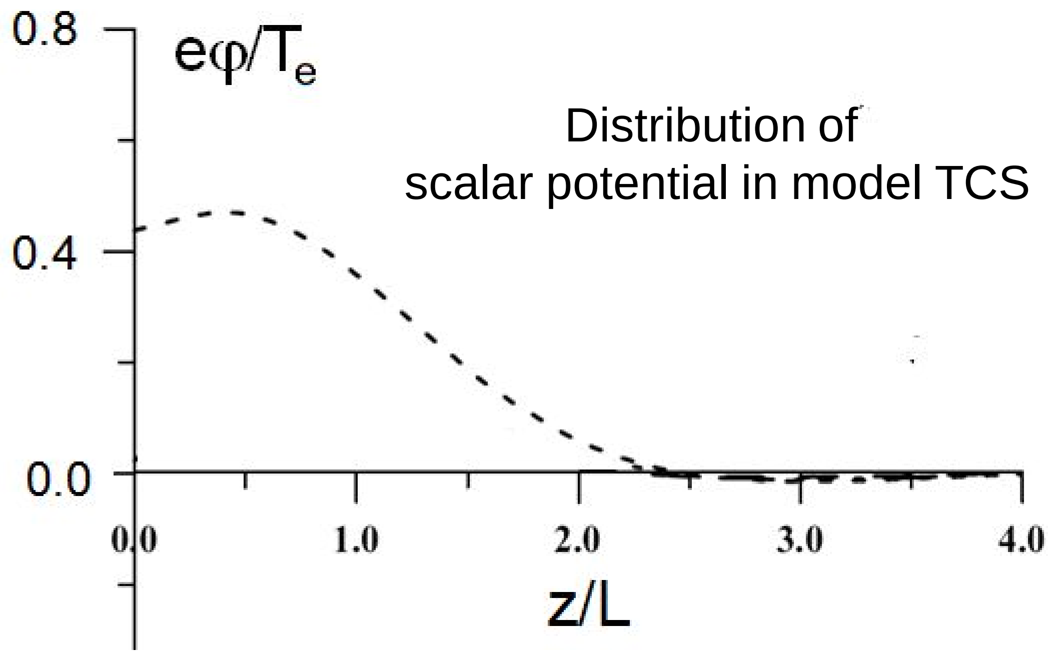
$$E_z \sim \frac{\Delta\varphi}{L_z} = 0.5\frac{T_e}{eL_z} \sim 1.0\ \mathrm{mV/m}$$

$$E_x \sim 0.5\frac{T_e}{eL_x}$$

If T_e=1keV and L_x=10R_E

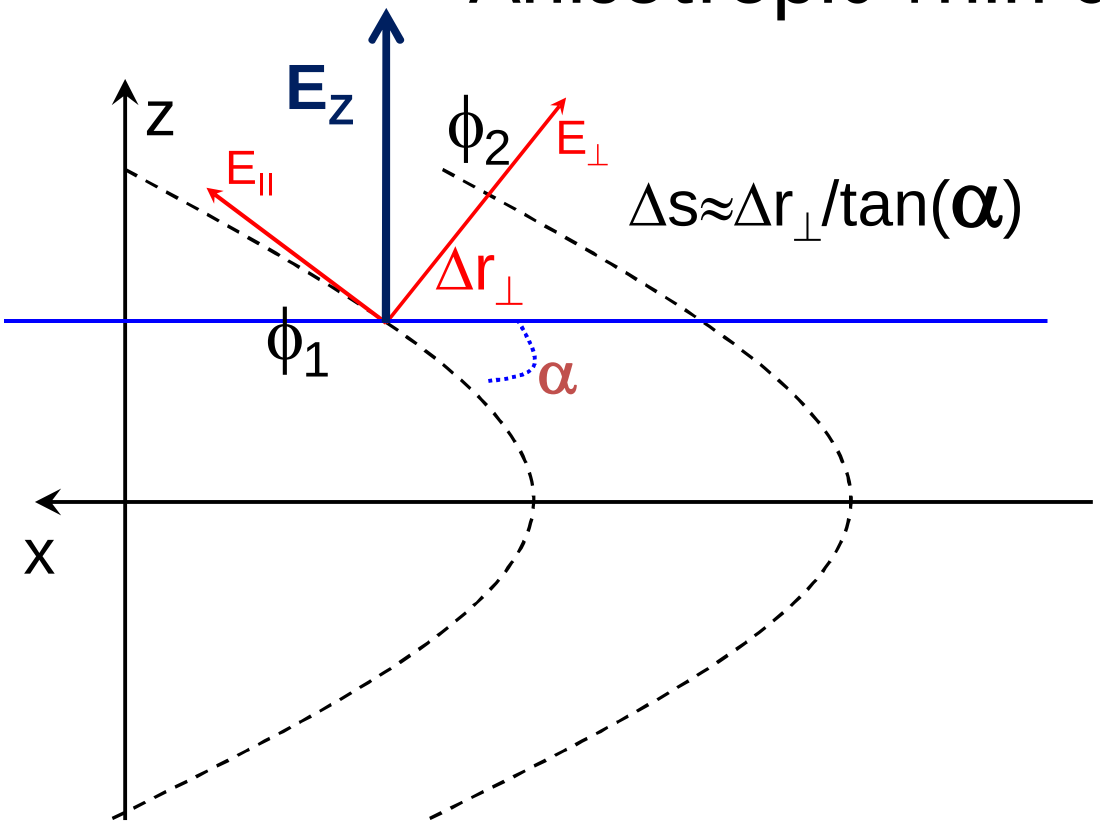
$$E_x \sim 0.1\ \mathrm{mV/m}$$

L_x and L_z are characteristic scales of spatial gradients



Ambipolar electric field required To support charge neutrality in CS

Anisotropic Thin CS: 1D



$$d\phi/ds = F(s)$$

$$\phi_2 = \phi_1 + F(s)\Delta s$$

$$E_\perp = -(\phi_2 - \phi_1)/\Delta r_\perp$$
$$E_\perp = -F(s)\Delta s / \Delta r_\perp$$
$$E_\perp = -F(s)/\tan(\alpha)$$

and

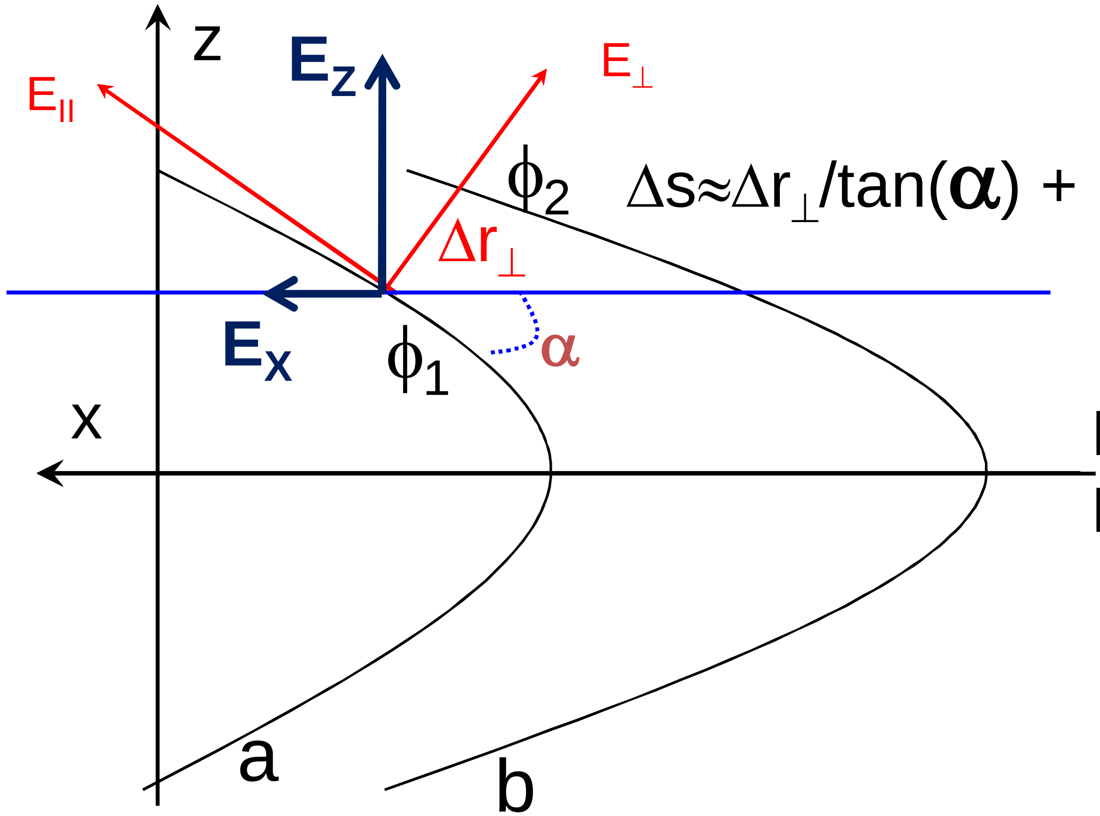
$$E_{II} = -F(s)$$

$$E_z = E_{II}\sin(\alpha) + E_\perp \cos(\alpha)$$
$$E_x = -E_{II}\cos(\alpha) + E_\perp \sin(\alpha)$$

→

$$E_z = -F(s)/\sin(\alpha)$$
$$E_x = 0$$

Anisotropic Thin CS: 2D



$\partial B_z/\partial x>0$

$\Delta s \approx \Delta r_{\perp}/\tan(\alpha) + (\partial B_z/\partial x)\ldots$

$E_z=E_{\parallel}\sin(\alpha)+E_{\perp}\cos(\alpha)$

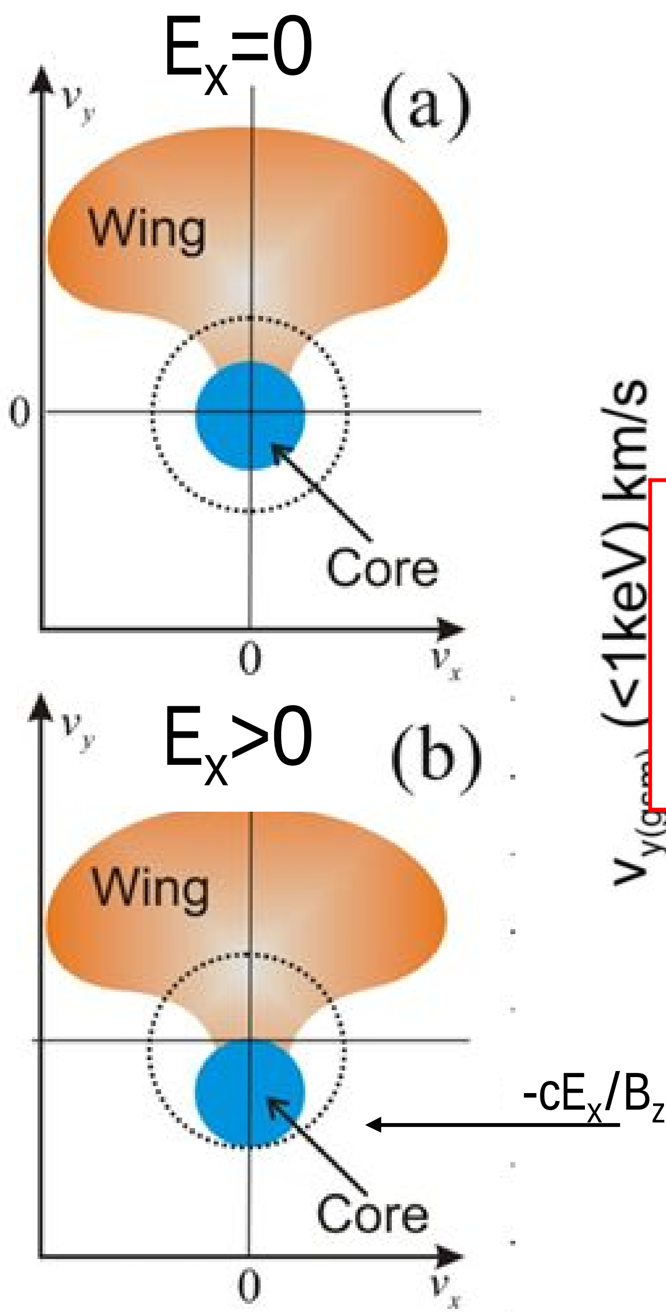
$E_x=-E_{\parallel}\cos(\alpha)+E_{\perp}\sin(\alpha)$

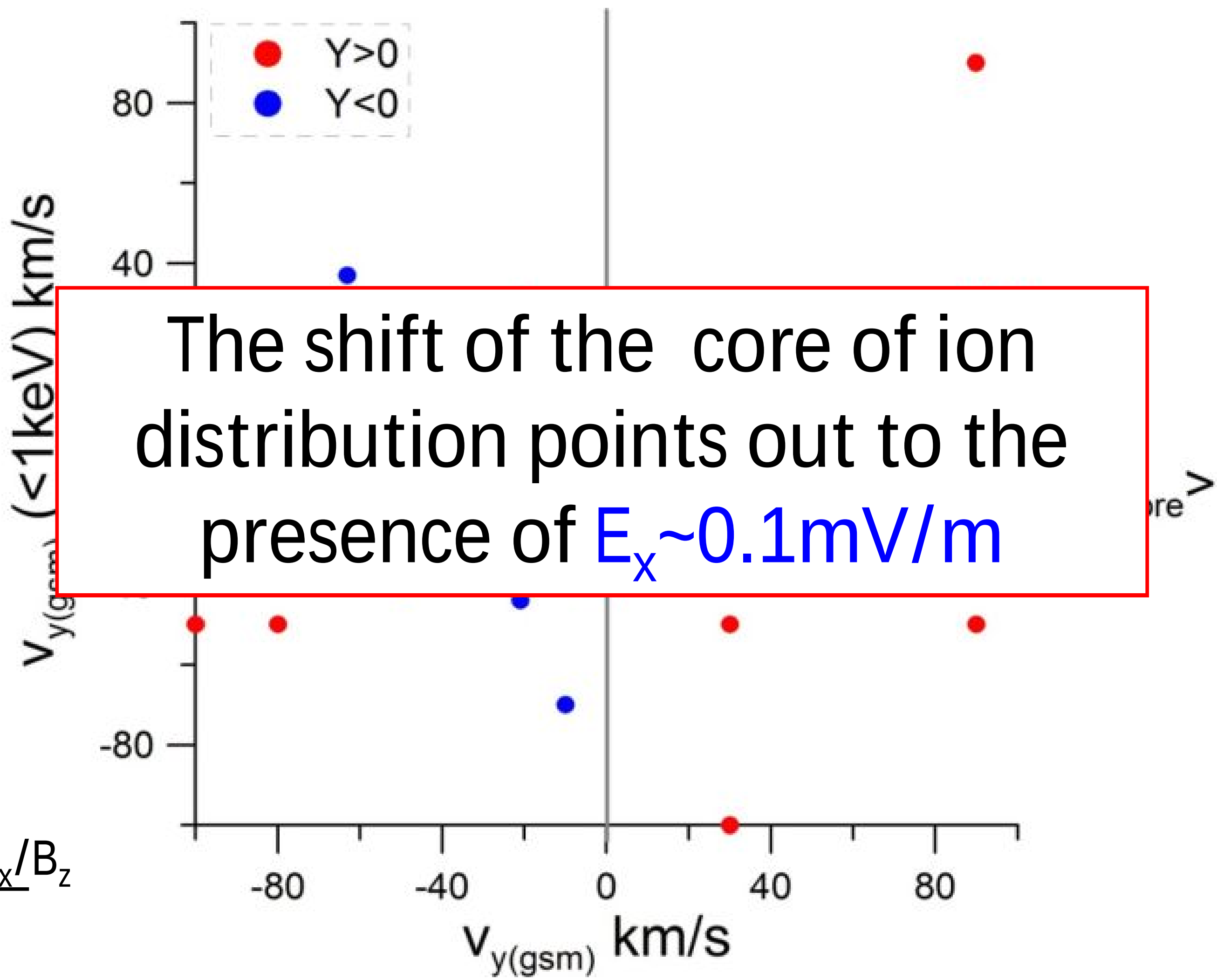
$E_x=(\partial B_z/\partial x)^{*}\ldots.$

$$E_x(z)=\frac{\partial \ln B_z}{\partial x}\int_z^{L_z} E_z(z')\frac{B_x^2(z')}{B_z^2+B_x^2(z')}dz'$$

Earthward electric field influence on ions

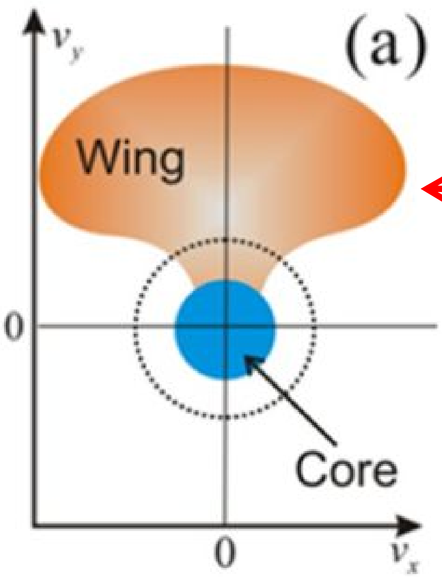
Most ion distribution has negative velocity of central part (ε< 1kev)





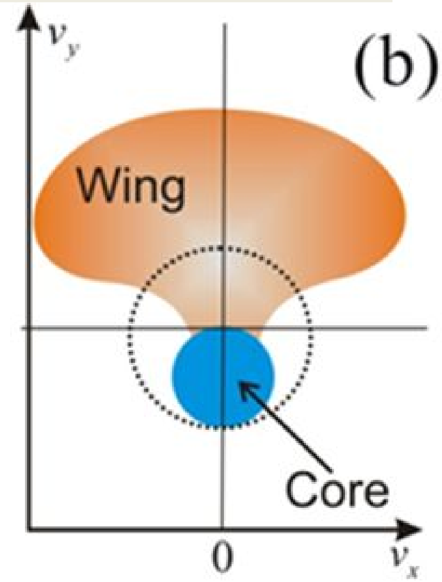
The shift of the core of ion distribution points out to the presence of E_x~0.1mV/m

Role of E_x for ion currents



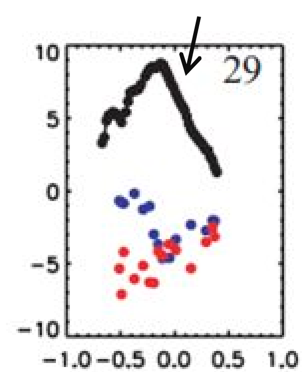
$$j_{0i} = n_{sp} v_{sp}$$

$$n_p = n_{sp} + n_{bg}$$



$$j_i = n_{sp}\left(v_{sp} - v_D\right) - n_{bg} v_D$$

$$j_i = j_{0i}\left(1 - \frac{n_p}{n_{sp}}\frac{v_D}{v_{sp}}\right) \approx j_{0i}\left(1 - \frac{n_p}{n_{sp}}\frac{T_e}{T_i}\right)$$



Ion currents from **C1** and **C4**

If n_p/n_{sp}~5 and T_i/T_e~3-6 observable value of ion current j_i appears to be much smaller (even negative) than j_{0i}

Conclusions:

- Measurements (carefully analyzed) do not disregard intuitive physics of current sheet formation: $j_{ion} >> j_{ele}$
- Hidden (non measurable directly) large scale ambipolar global electric fields plays remarkable role in “masking” real (de-Hoffman Teller frame) effects.
- E_x~0.15 mV/m do exist in magnetotail