Structure of the magnetopause boundary layers discovered by Cluster multipoint observations

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(Cluster-Double Star symposium, Sep. 19-23, 2005)

Outline

☐ **Detection of Rolled-up Kelvin-Helmholtz Vortices**
Cluster + Realistic three-dimensional (3D) MHD simulations

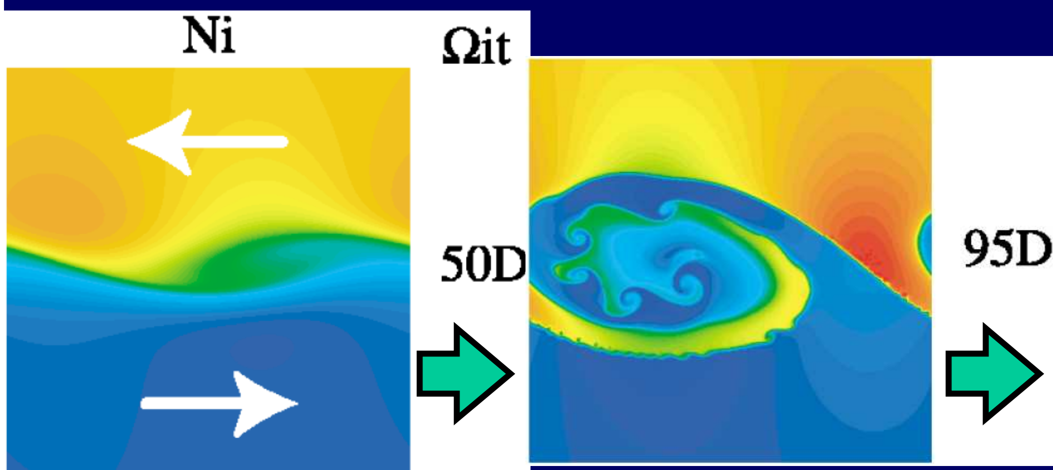
☐ **Two-Dimensional Structure of the Magnetopause and Flux Transfer Event (FTE)**
Cluster + Grad-Shafranov reconstruction technique

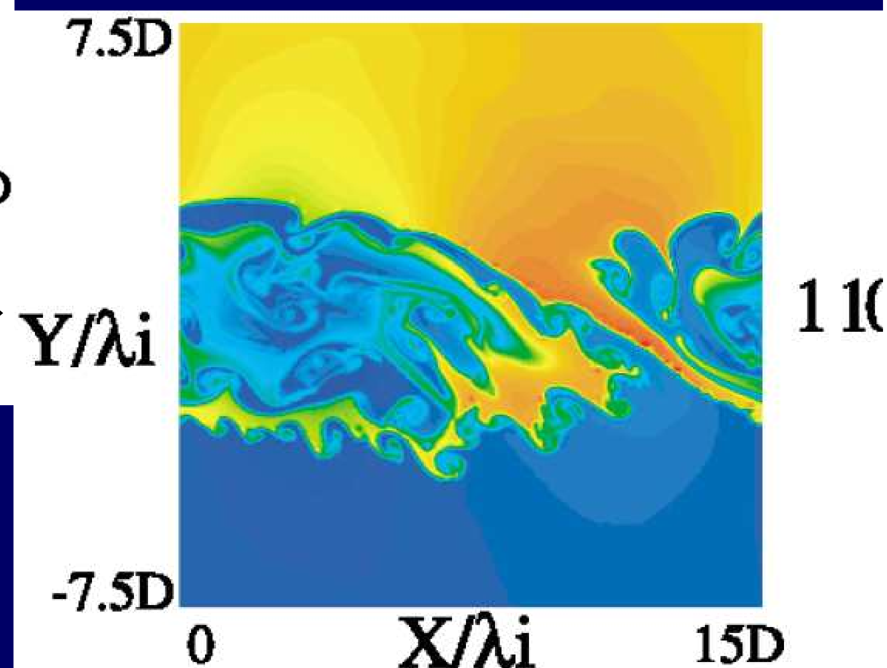
Model-based data analysis helps us a lot to interpret data obtained by the Cluster multi-spacecraft measurements.

Why Kelvin-Helmholtz vortices important?

• Vortices, developed through the nonlinear growth of the Kelvin-Helmholtz instability (KHI) at the flank magnetopause, can be the agent of transport of solar wind plasmas into the magnetosphere under northward IMF conditions, which has been a long-standing problem.

(Nakamura et al., 2004)





2D simulations of KHI using 2-fluid (Hall) MHD equations including finite electron inertia

Plasma transport processes accompanied by the KHI growth

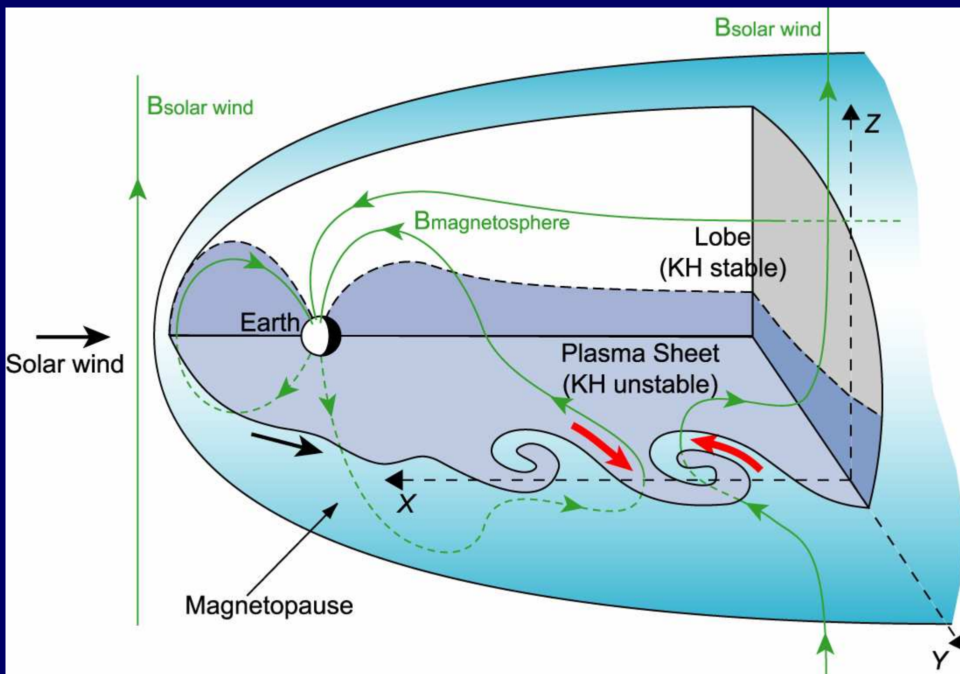
• Magnetic reconnection within a rolled-up KH vortex (e.g., Otto & Fairfield, 2000)

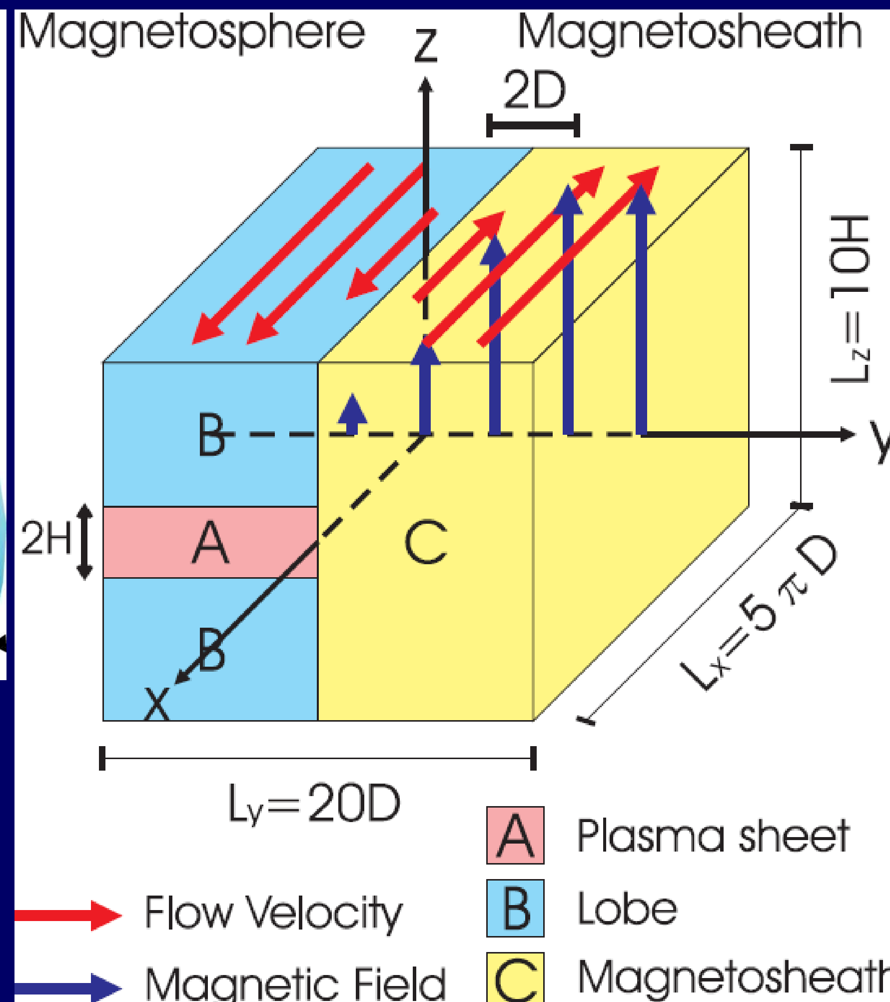
• Collapse of vortices mediated by electron inertia effects (Nakamura et al., 2004)

• Turbulence triggered through Rayleigh-Taylor instability in a rolled-up vortex (Matsumoto & Hoshino, 2004)

Numerical simulations suggest that all these transport mechanisms can occur ONLY when the KHI has grown to form "Rolled-up" vortices.

Can “rolled-up” KH vortices form in a tail flank-like situation?

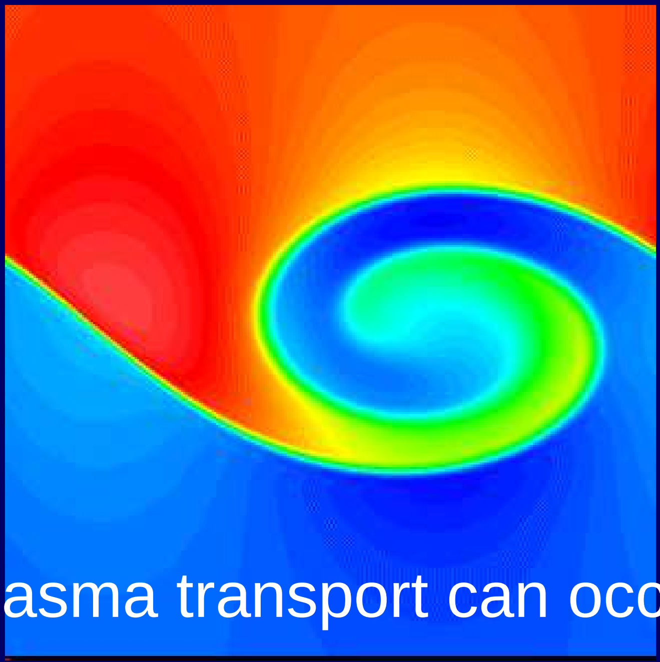




Simulation results suggest that the roll-up of KH waves can be achieved as long as the PS is thick enough (the thickness is comparable to, or larger than, the KHI wave length).

(Takagi et al., 2005)

To what extent does the KHI grow in the actual magnetosphere?



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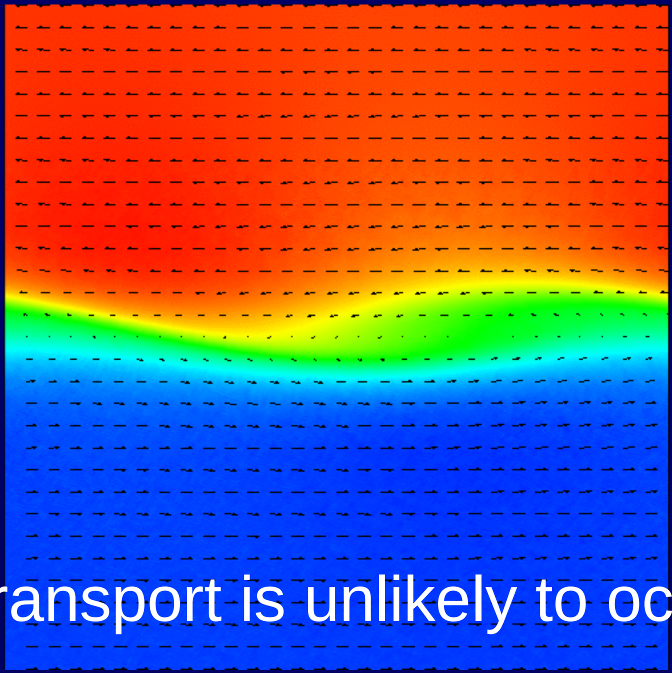


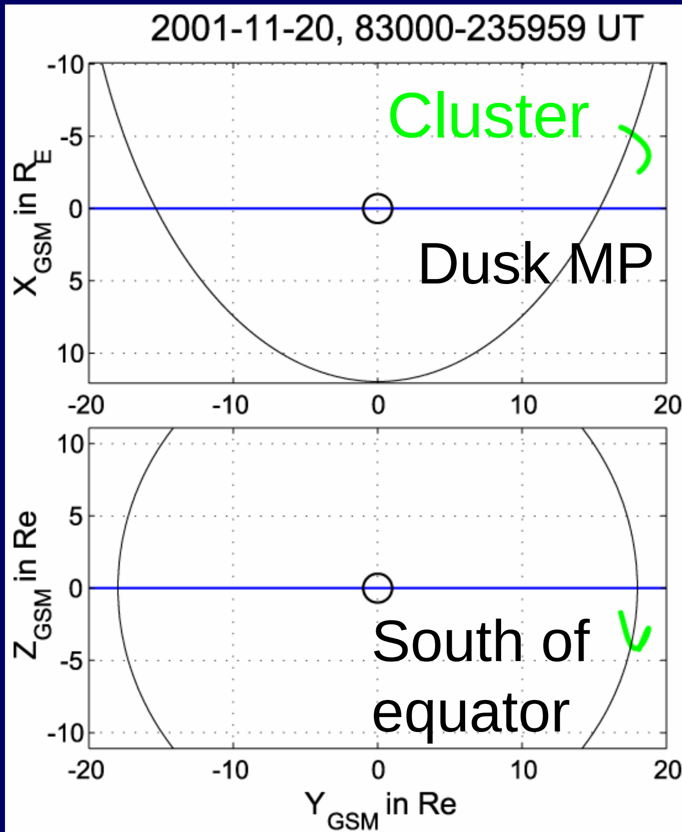
?

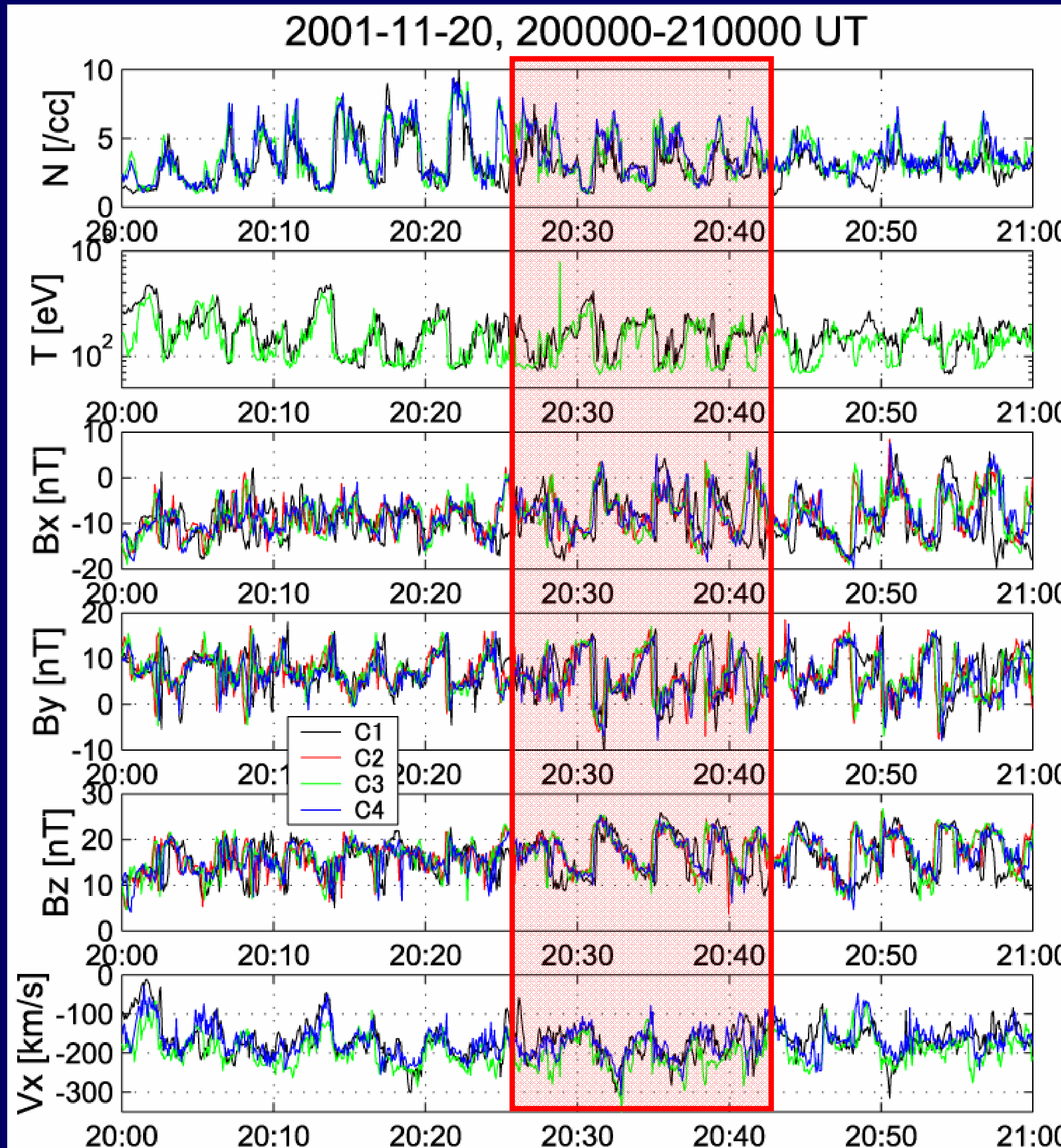
Plasma transport can occur. Transport is unlikely to occur.

Single- (or dual-) spacecraft measurements (e.g., Kivelson & Chen, 1995) could not answer this question.

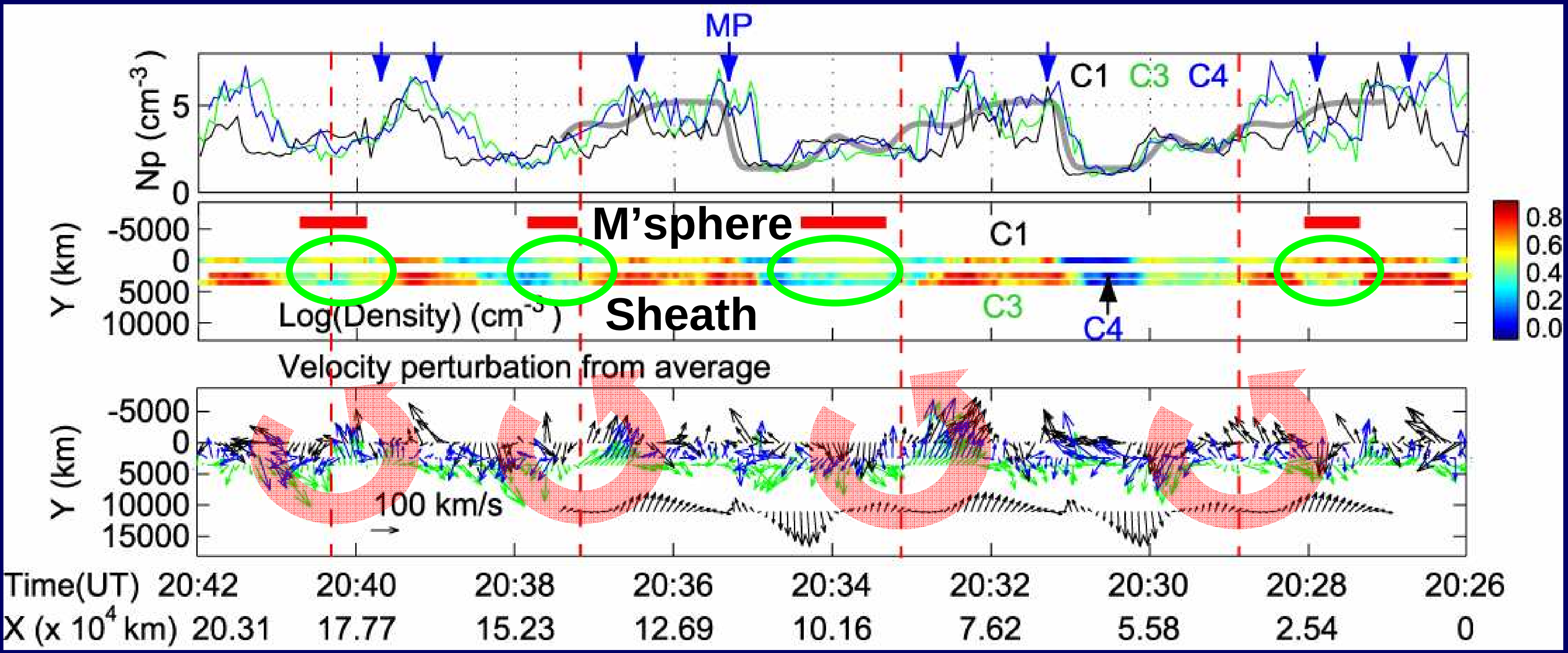
Multipoint measurements by the four Cluster spacecraft can answer.

Cluster detection of "Rolled-up" KH vortices

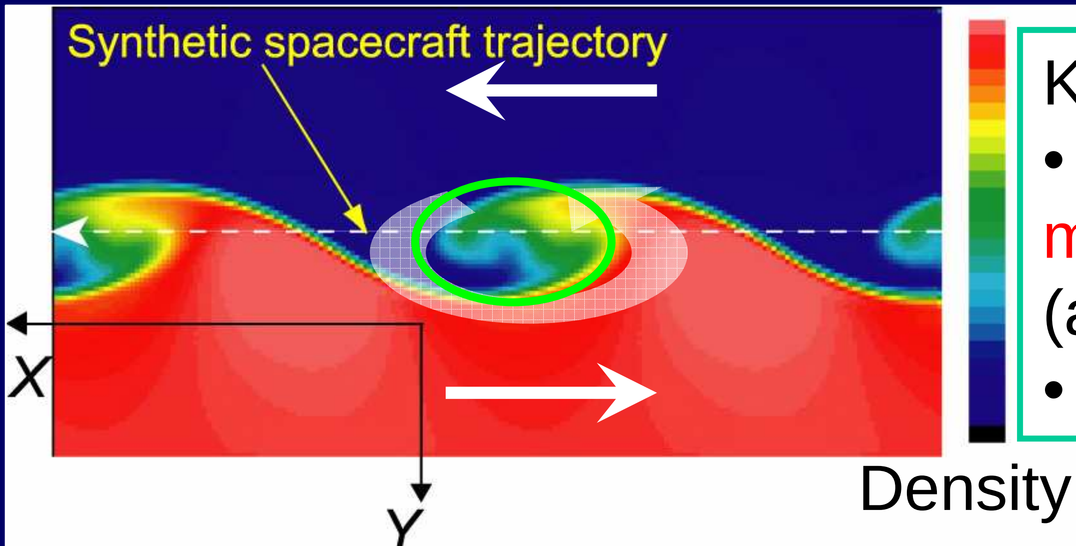




- Northward IMF
- Quasi-periodic plasma & magnetic field perturbations with a period of 2-4 min.



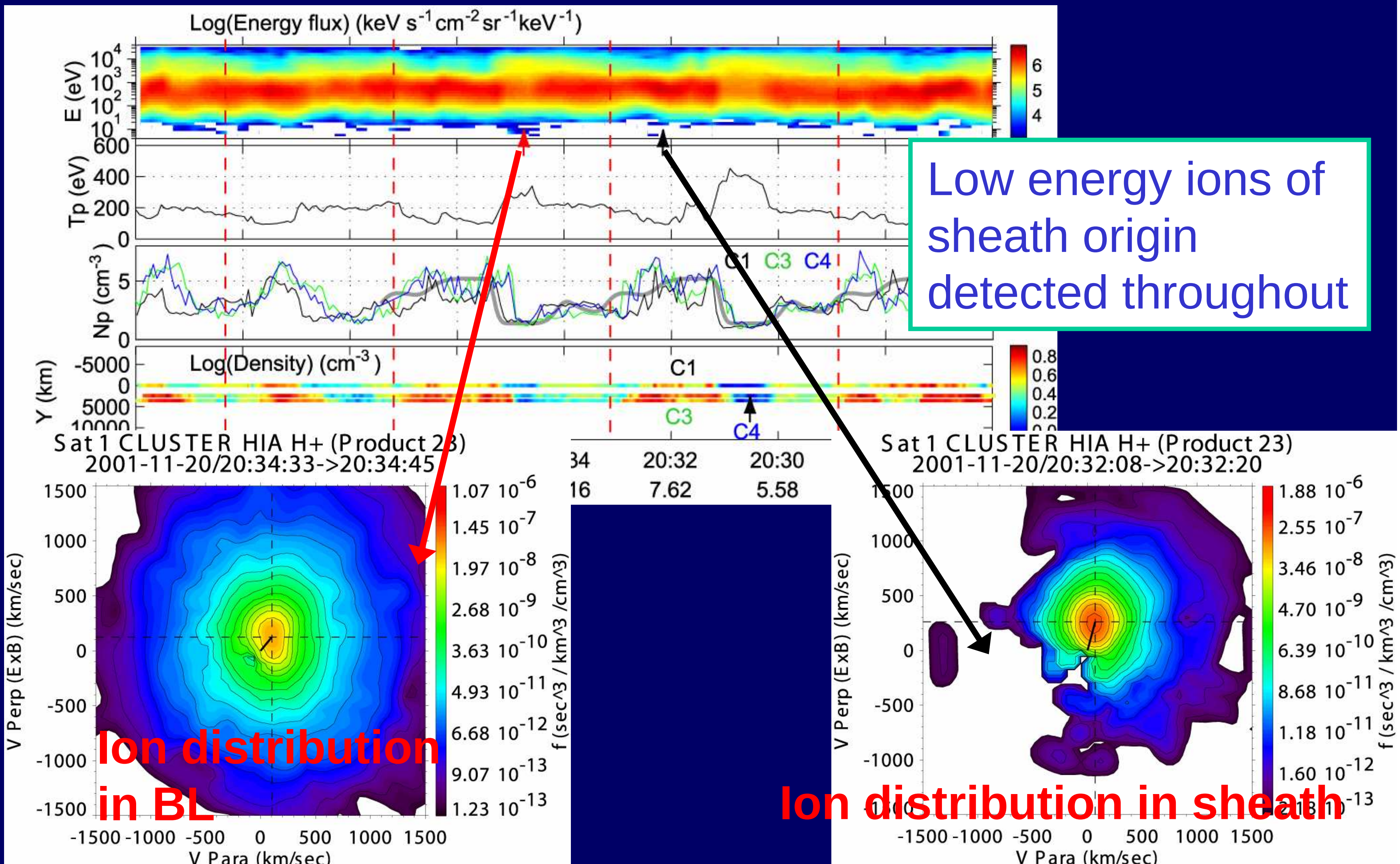
Spacecraft separation ~ 2000 km



Key features:

- Higher density on the most magnetosphere side (at C1)
- Vortical flow pattern

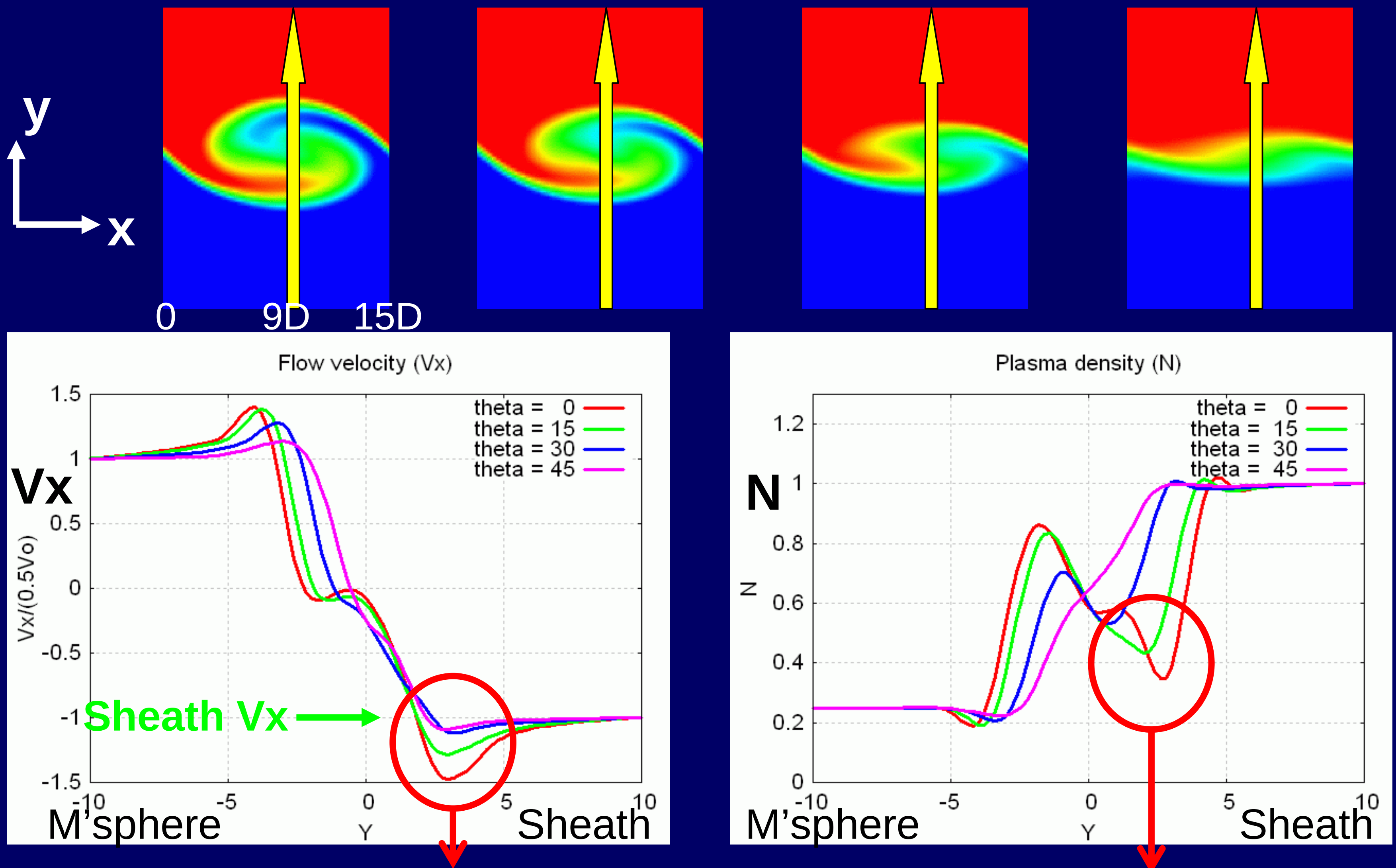
Evidence of plasma transport across the magnetopause



The observation is consistent with transport via KHI!

1-SC detection of "Rolled-up" vortices possible?

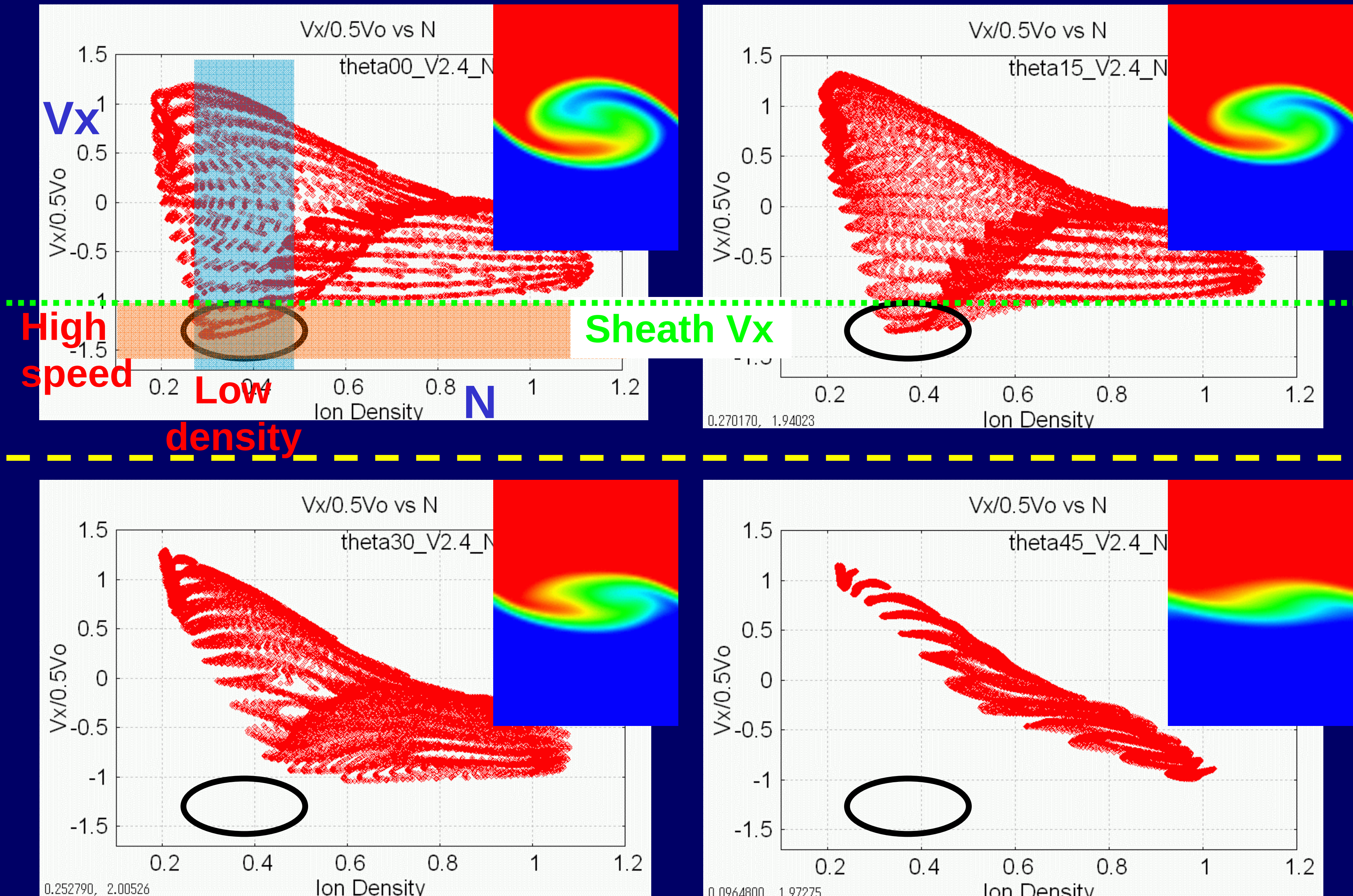
Difference between Rolled-up & Not rolled-up vortices



Flow speed higher than in sheath!

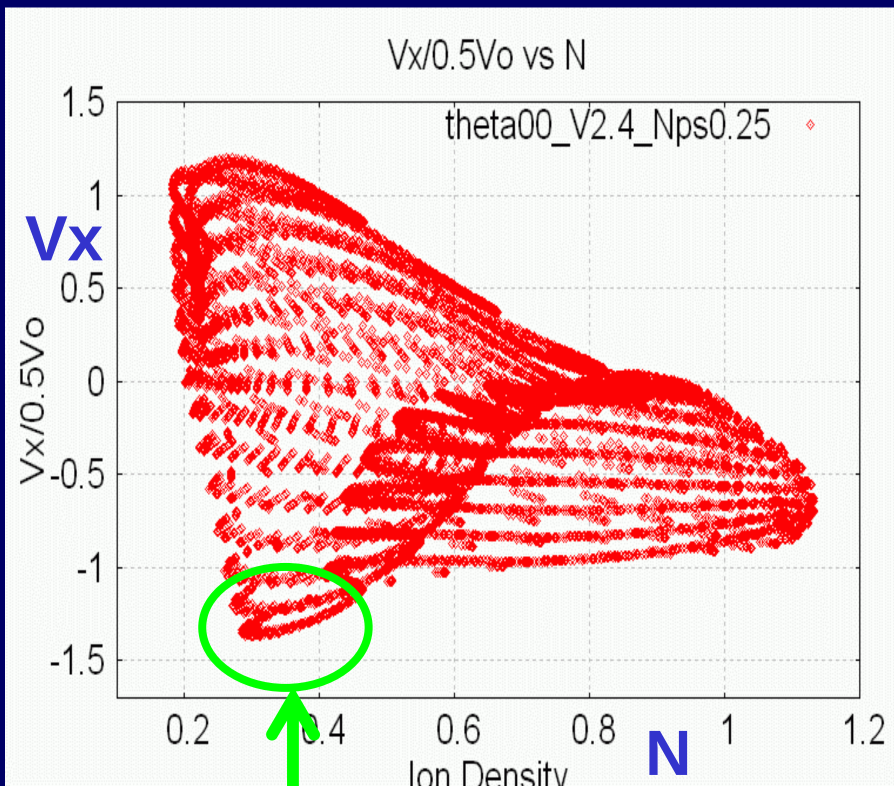
Low density

Vx vs N seen in simulated data

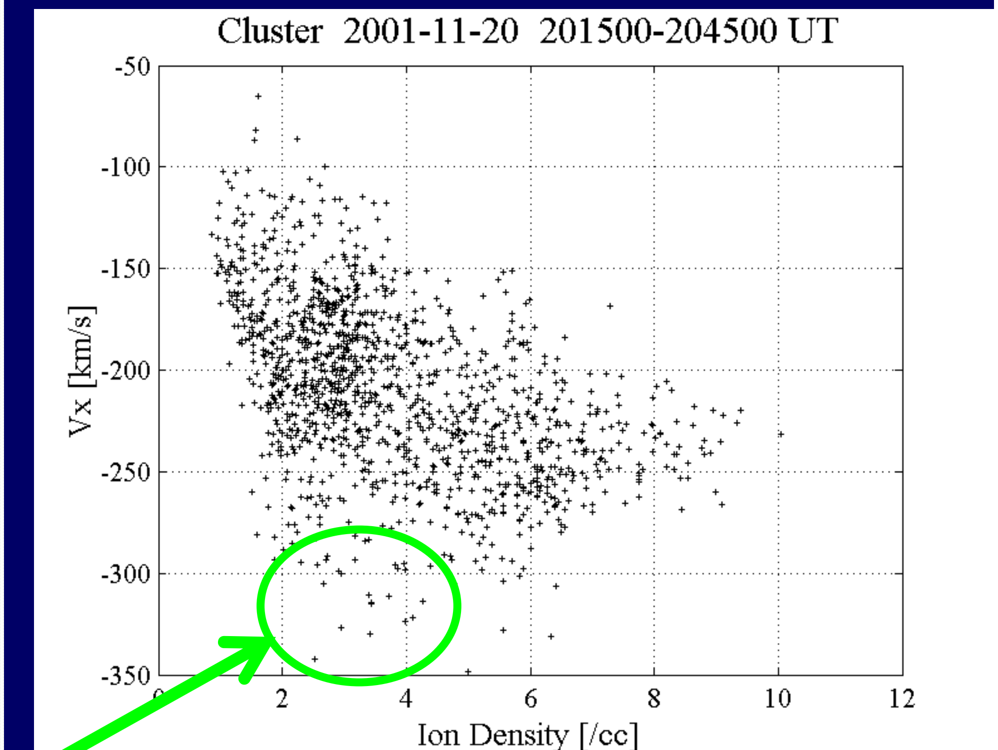


Comparison with vortices observation

MHD simulation



Cluster observations of rolled-up vortices



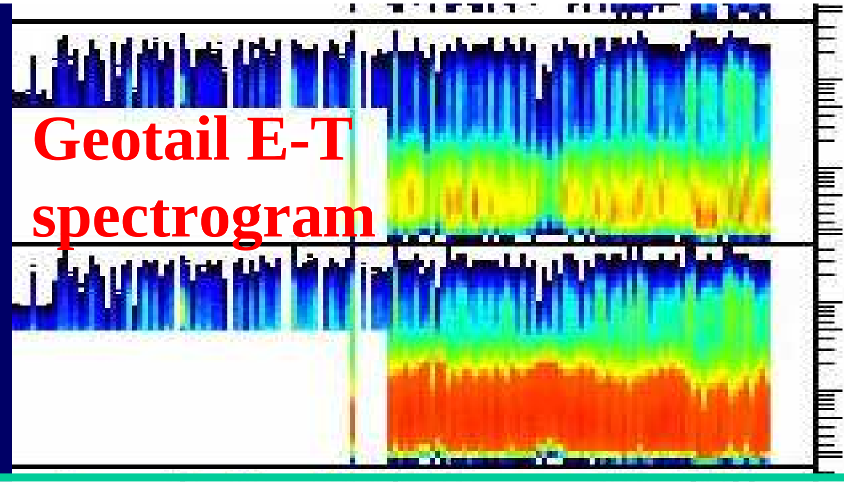
Low-density & High-speed flows are found in real data as well.

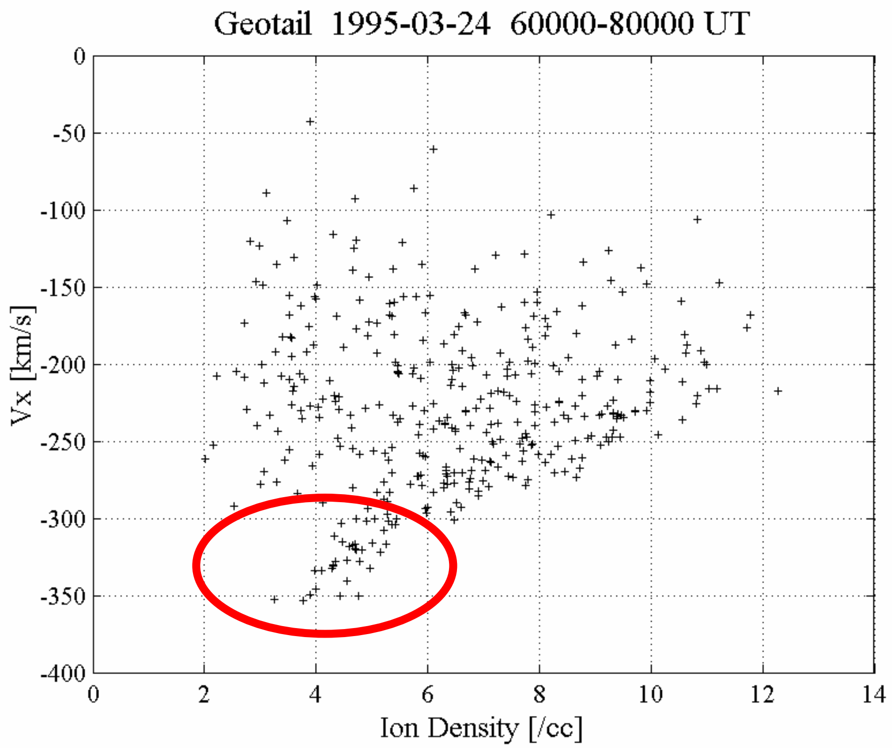
Applicable to single-spacecraft observations!

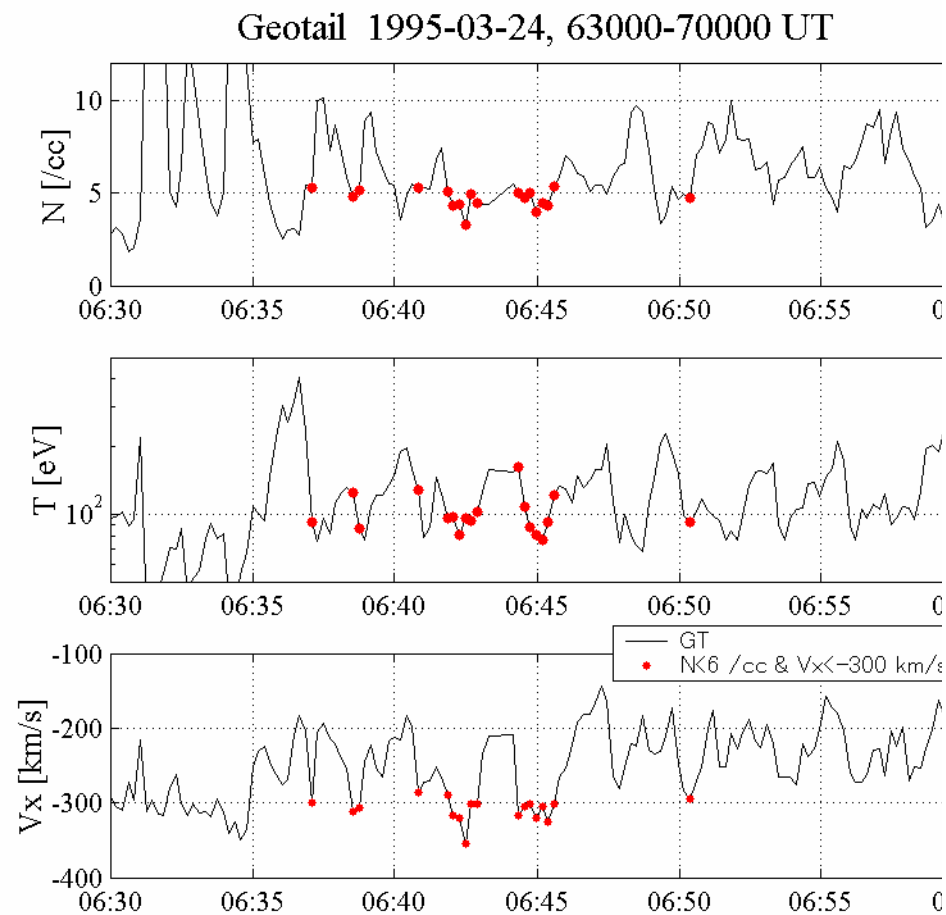
Application to Geotail data

Dusk flank MP event on March 24, 1995 (Fujimoto et al., 1998, Fairfield et al., 2000)

(X, Y, Z)~(-14, 20, 4) Re (GSM)







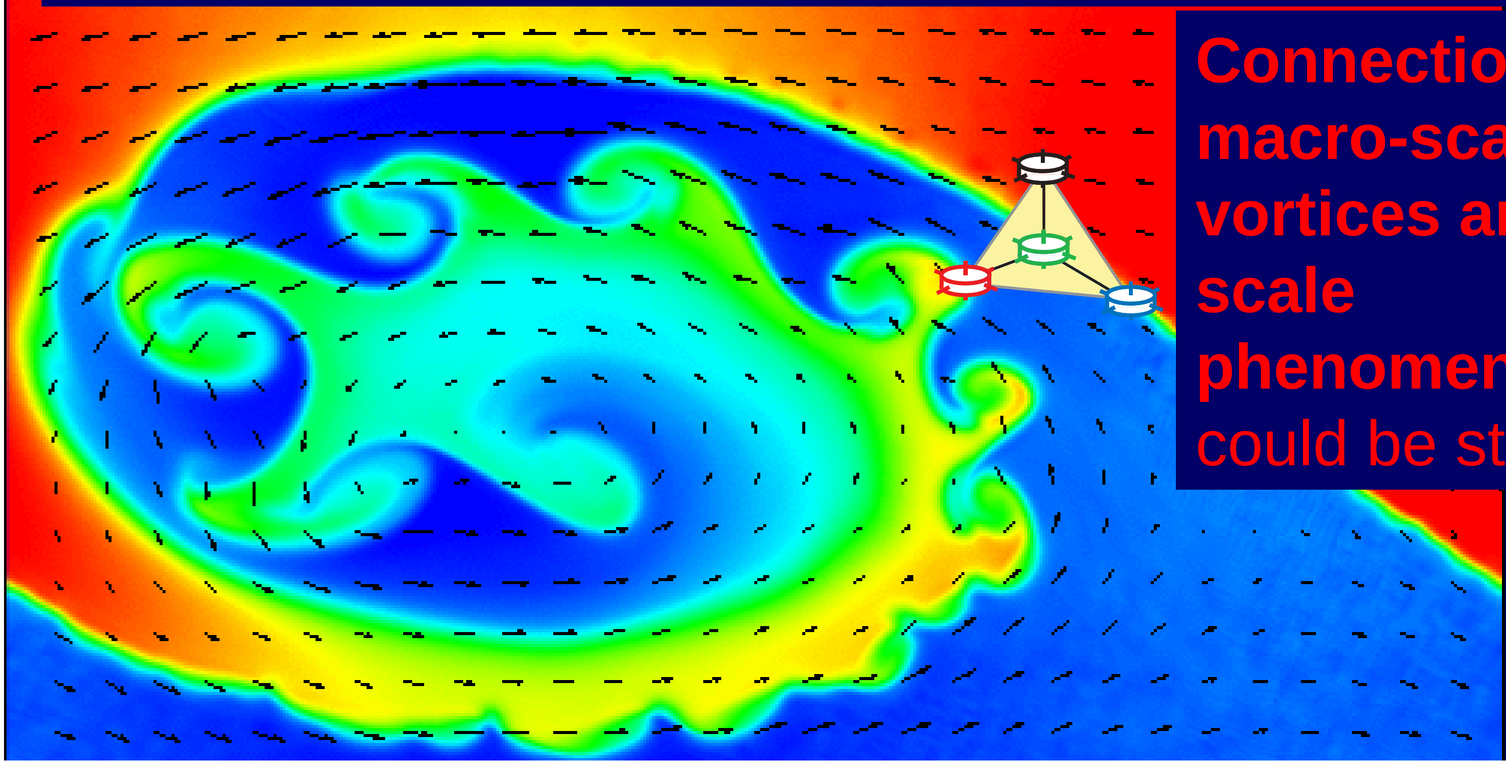
Indicator of “Rolled-up” vortices found in 1-SC data

When SC separation of Cluster is small,

• Detection of a parent rolled-up vortex can be made by either of the four spacecraft, by identifying Low-density & High-speed flows.

Then,

• The nature of small-scale waves excited, or thin current sheets formed, in the vortex can be investigated in detail with the help of the multi-point measurements.



Connections between macro-scale KH vortices and micro-scale phenomena/structures could be studied.

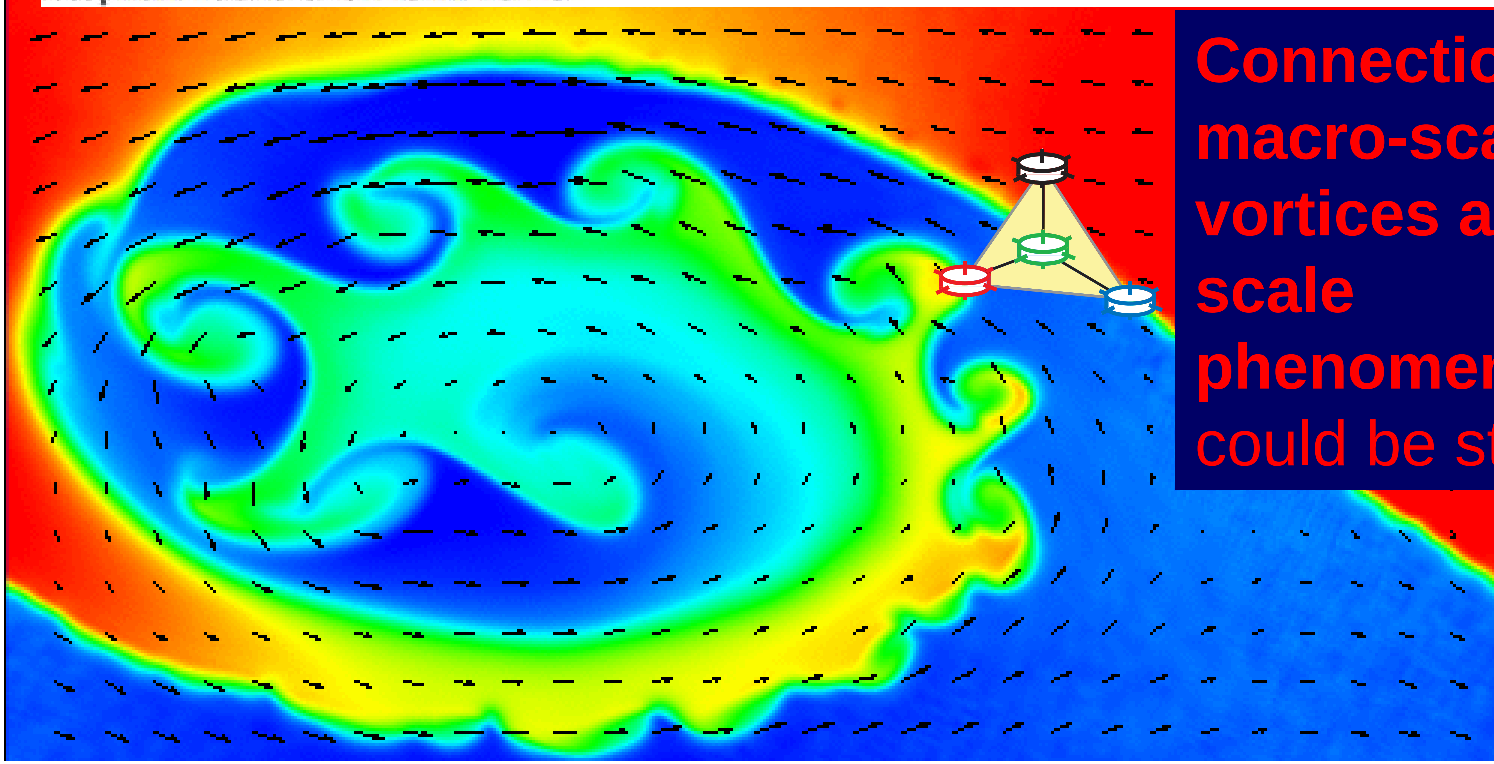
Vol 436|11 August 2005|doi:10.1038/nature03931 nature

Small-scale vortices discovered in the cusp (Sundkvist, et al., 11 Aug. 2005 issue of Nature)

LETTERS

In situ multi-satellite detection of coherent vortices as a manifestation of Alfvénic turbulence

David Sundkvist[1,2], Vladimir Krasnoselskikh[1], Padma K. Shukla[3], Andris Vaivads[2], Mats André[2], Stephan Buchert[2] & Henri Rème[4]



Connections between macro-scale KH vortices and micro-scale phenomena/structures could be studied.

2D structure of the magnetopause and FTE

Grad-Shafranov reconstruction technique

(e.g., Hau & Sonnerup, 1999)

A spatial initial value problem

$$\cancel{\rho\frac{\partial\vec{V}}{\partial t}} + \rho(\cancel{\vec{V}\cdot\nabla})\vec{V} = \vec{J}\times\vec{B} - \nabla\cdot P$$

$$\boxed{\vec{j}\times\vec{B} = \nabla p}$$

Assumptions

The plasma structure is:

- in a magnetohydrostatic equilibrium (time-independent).
- 2-D (invariant along some direction, *z*)

Grad-Shafranov (GS) equation (e.g., Sturrock, 1994)

$$\boxed{\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0\frac{dP_t}{dA} = -\mu_0\, j_z(A)}$$

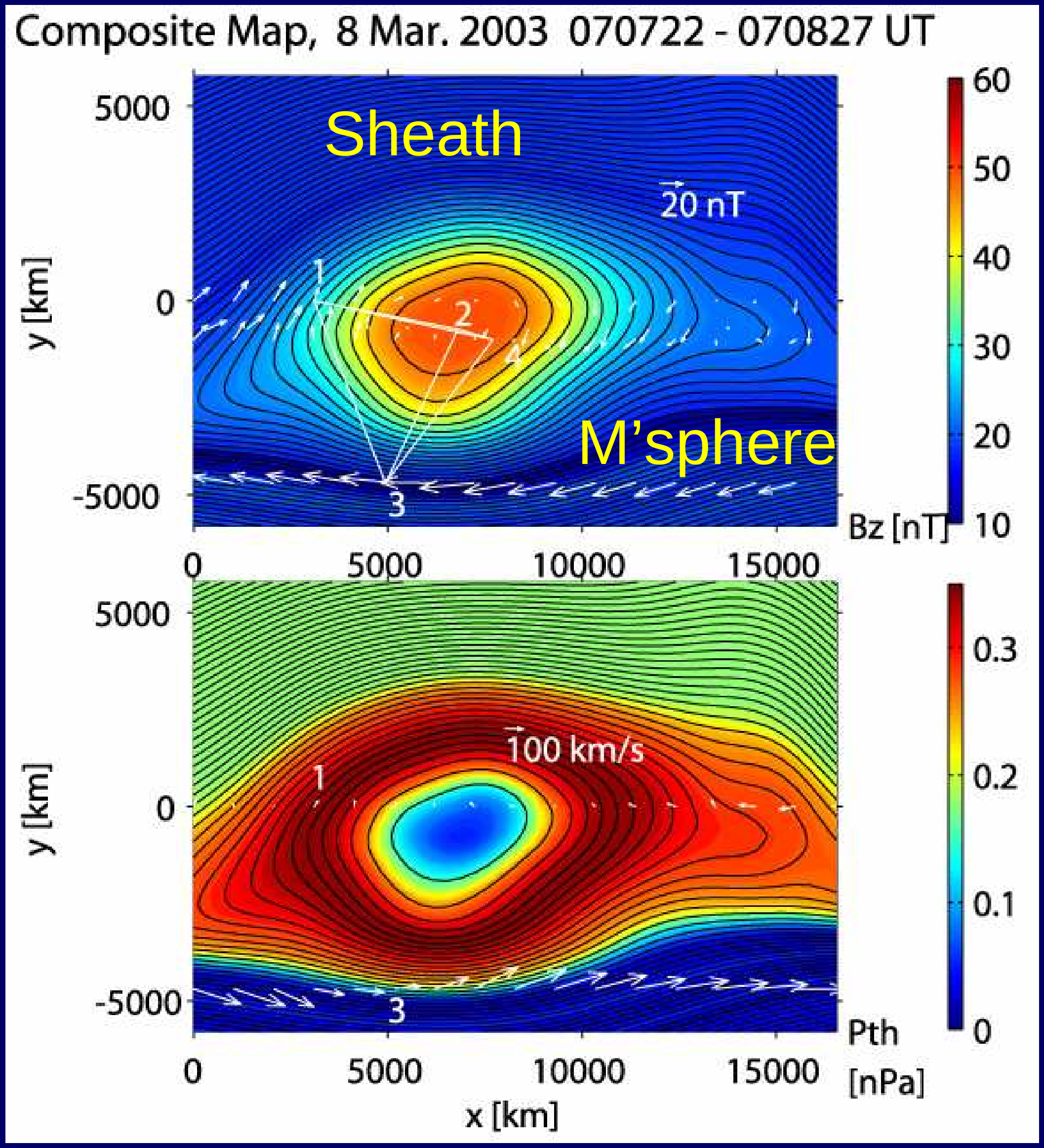
$$\boxed{(A = A_z)}$$

$$\vec{B} = (\partial A/\partial y\,, -\partial A/\partial x\,, B_z(A)\,),$$

$$P_t = (p + B_z{}^2/2\mu_0)$$

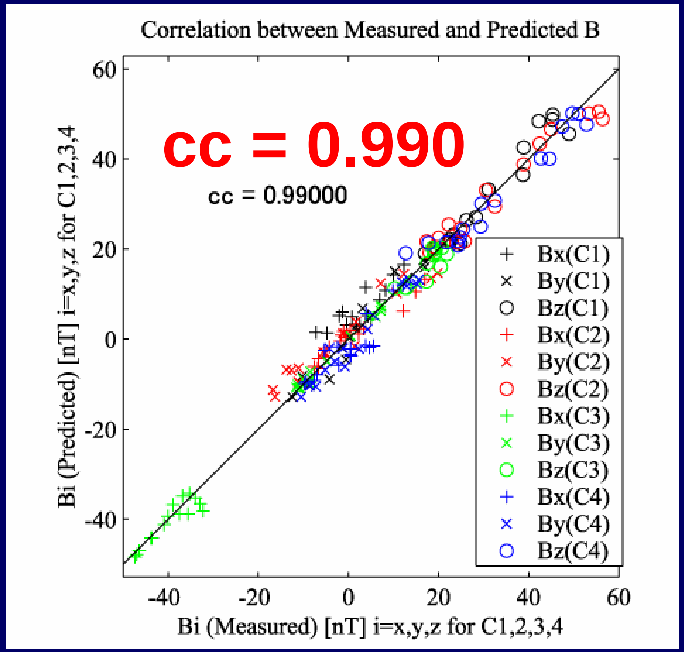
A magnetic field map, $A(x,y)$, is constructed from explicit integration of the GS equation, using measured magnetic fields as spatial initial values.

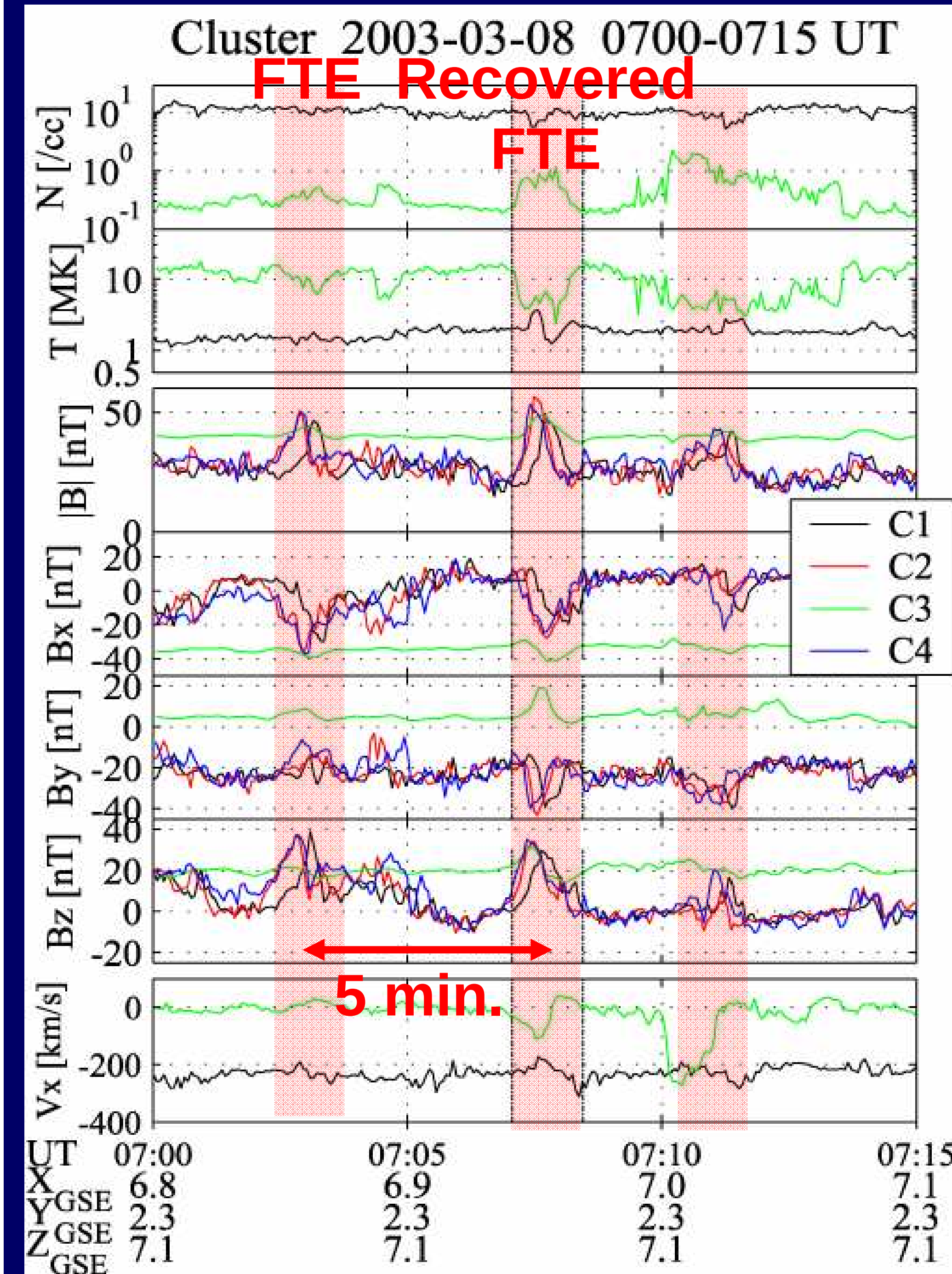
FTE reconstruction → Verification of flux rope models

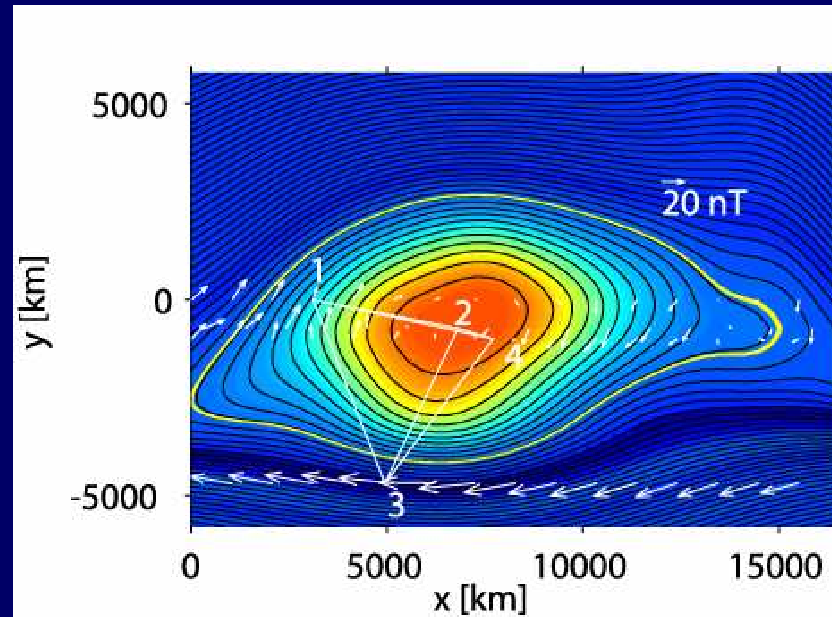


(Sonnerup et al., 2004)

- Flux rope size ~ 1 Re
- Strong core field
→ Evidence of "component" merging
- No reconnection activity any more
- Moving poleward



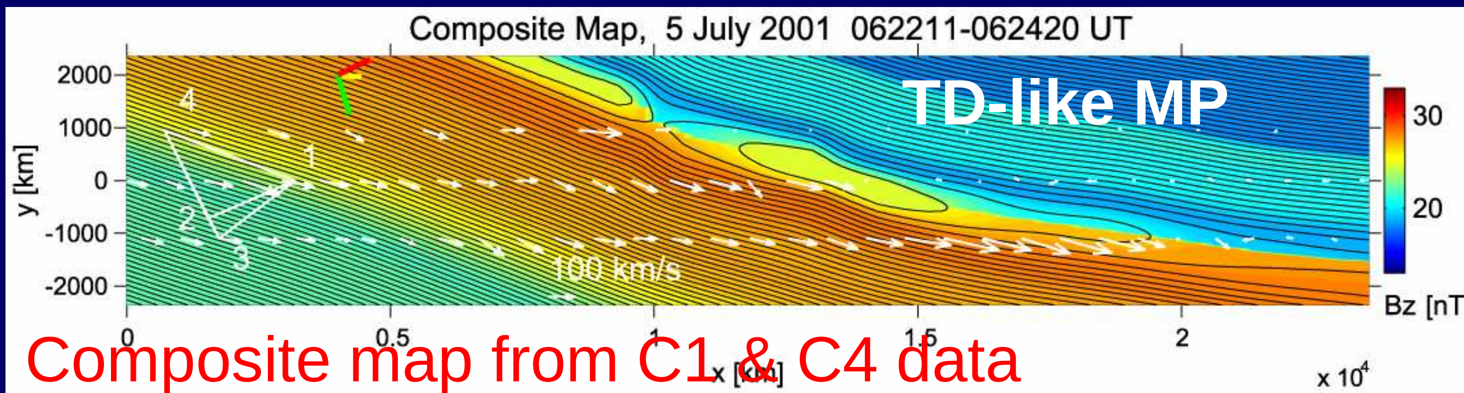




Total transverse magnetic flux within the flux rope = 0.0549 T·m

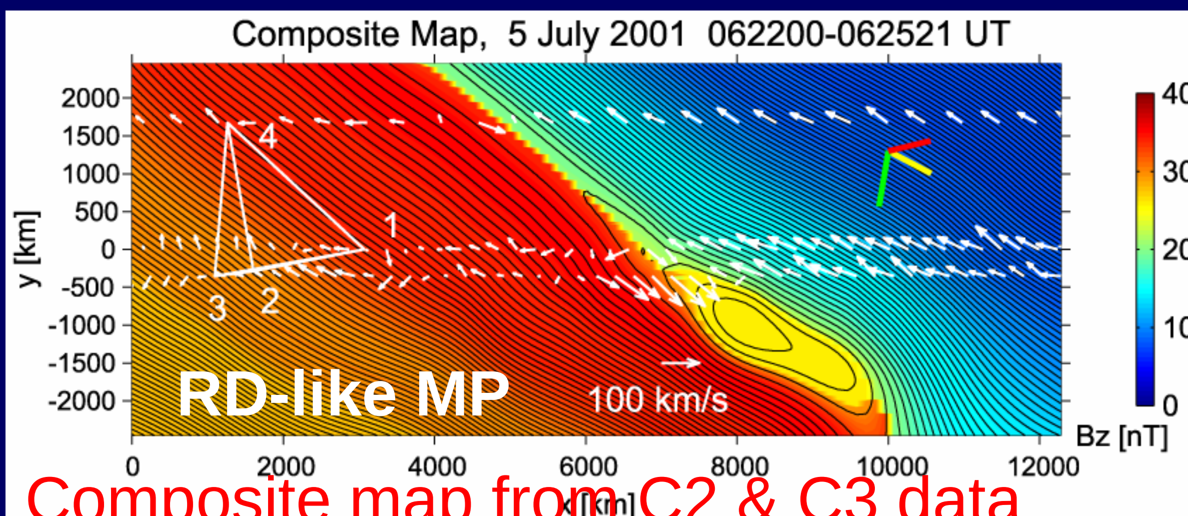
Reconnection *E* field
≥ (total magnetic flux) / (FTE occurrence period)
= 0.0549 (T·m) / 5 (min.)
= 0.183 (mV/m)
~ reconnection rate = 0.04

Reconstruction of a magnetopause on 5 July, 2001

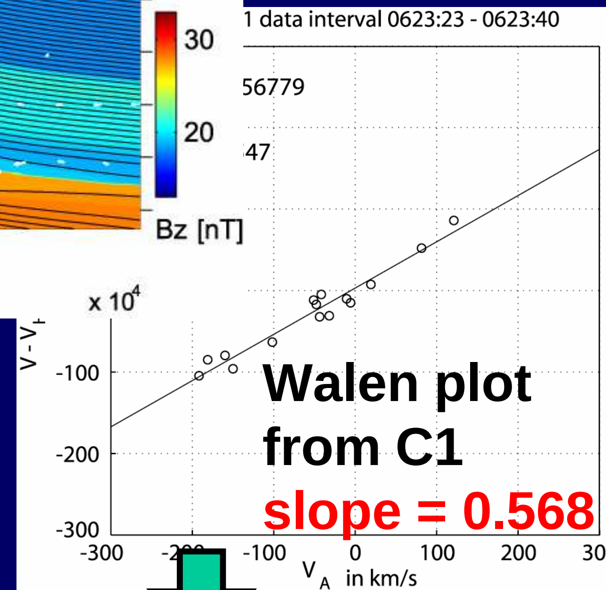


Composite map from C1 & C4 data

~30 sec

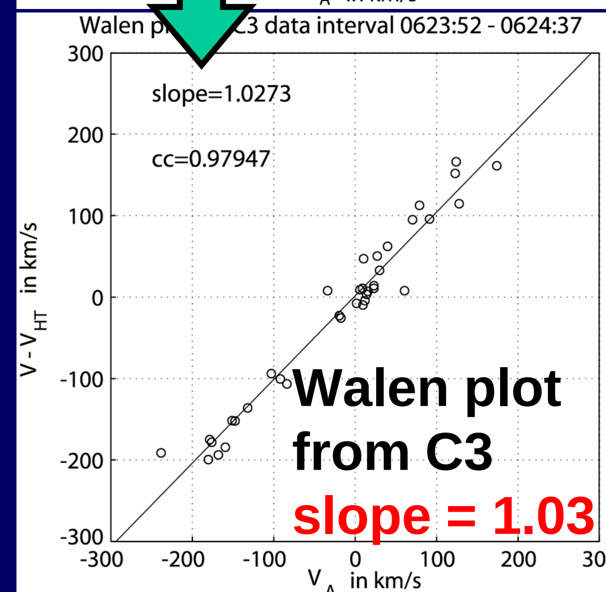


Composite map from C2 & C3 data



Walen plot from C1

slope = 0.568



Walen plot from C3

slope = 1.03

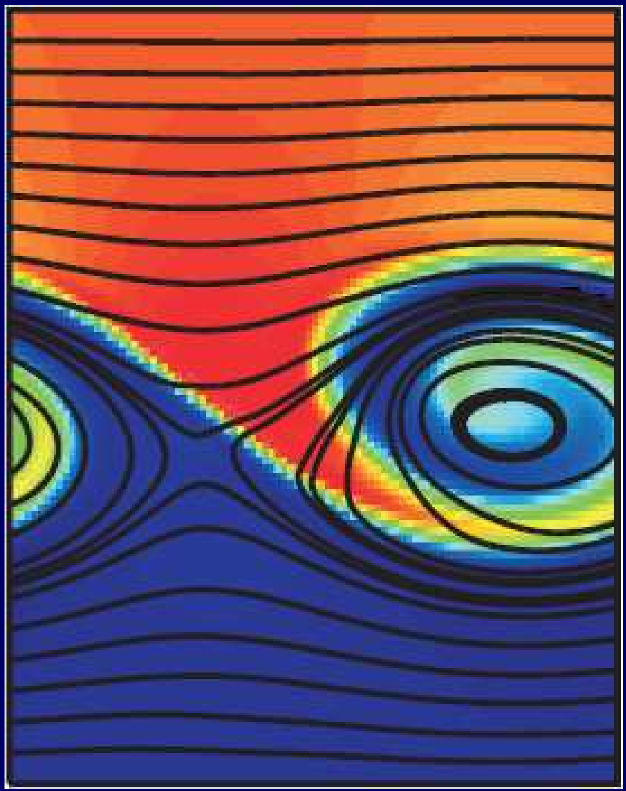
Temporal evolution (development of reconnection)

(Hasegawa et al., 2004)

A future possibility

• There is a Grad-Shafranov-type equation to describe stream lines.

Hopefully, it might become possible to reconstruct a 2D map of the flow velocity field, for example in KH vortices, from SC measurements.

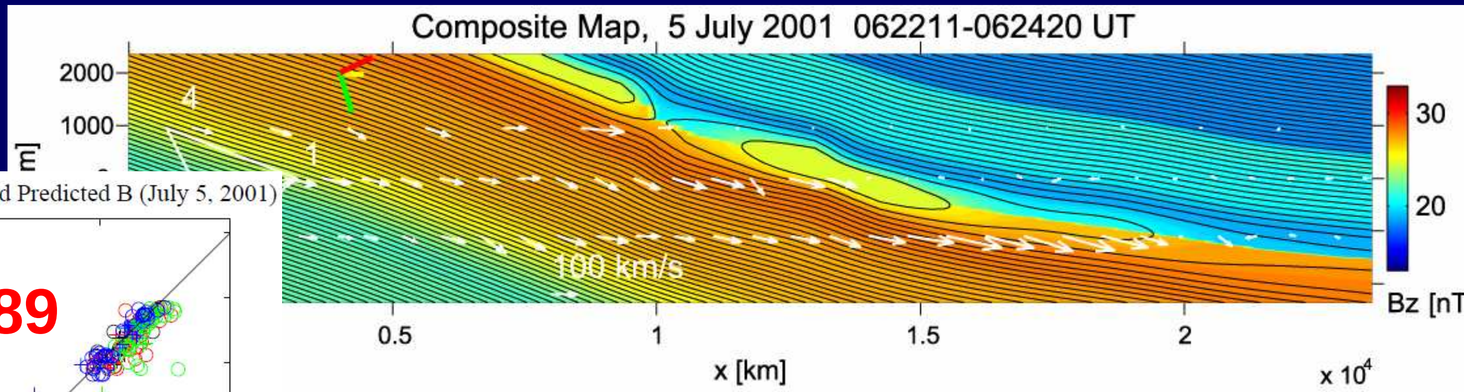


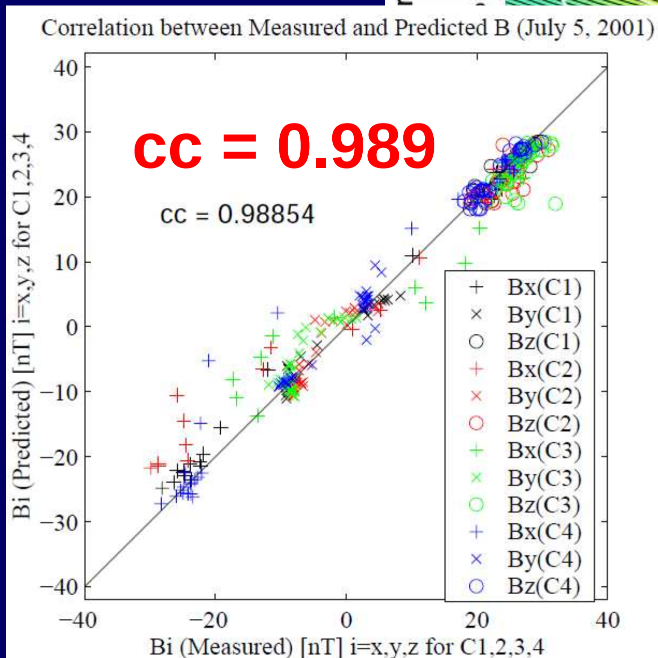
Summary

- A combination of the Cluster multipoint observations and numerical simulations has enabled us to unambiguously detect "rolled-up" KH vortices at the flank magnetopause.

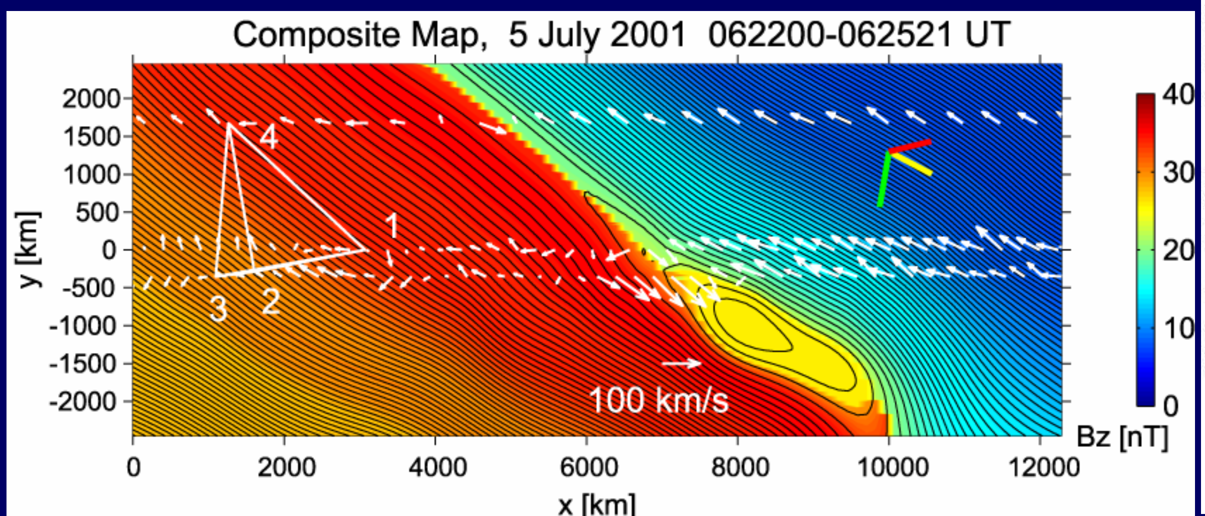
- The detection of the rolled-up vortices is now possible with a 1-SC data, providing a possibility of studying coupling between the vortices and small-scale processes with the Cluster data.

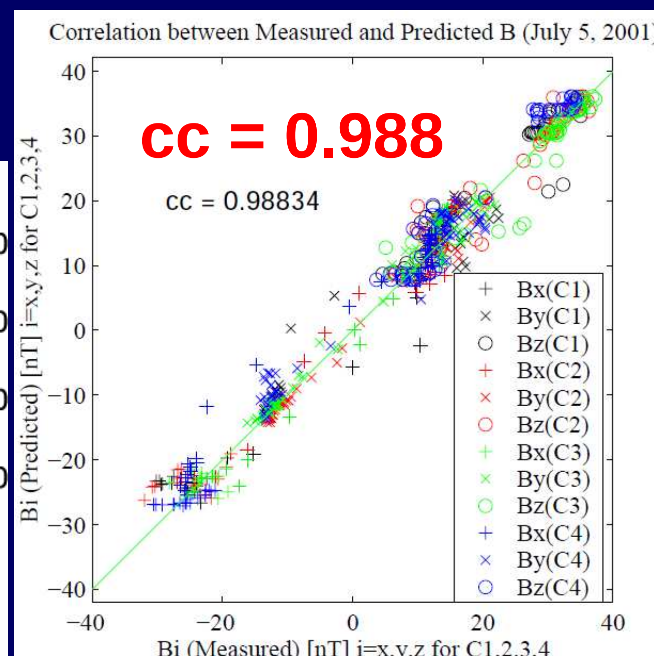
- Grad-Shafranov reconstruction of magnetopause and FTE structures using the Cluster data demonstrates time evolution of the magnetopause structure, and provides information on the appropriate FTE models, and on the nature of magnetopause reconnection (the reconnection rate, orientation of X-line, component merging, etc.).


Composite Map, 5 July 2001 062211-062420 UT
2000
1000
4
1
100 km/s
0.5
1
1.5
2
x [km]
x 10^4
30
20
Bz [nT]


Correlation between Measured and Predicted B (July 5, 2001)
cc = 0.989
cc = 0.98854
Bi (Predicted) [nT] i=x,y,z for C1,2,3,4
Bi (Measured) [nT] i=x,y,z for C1,2,3,4
Bx(C1)
By(C1)
Bz(C1)
Bx(C2)
By(C2)
Bz(C2)
Bx(C3)
By(C3)
Bz(C3)
Bx(C4)
By(C4)
Bz(C4)

~30 sec


Composite Map, 5 July 2001 062200-062521 UT
y [km]
x [km]
4
1
3
2
100 km/s
Bz [nT]

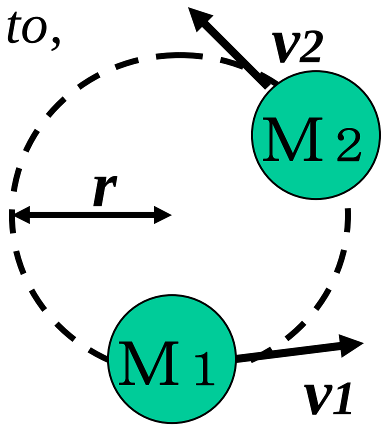

Correlation between Measured and Predicted B (July 5, 2001)
cc = 0.988
cc = 0.98834
Bi (Predicted) [nT] i=x,y,z for C1,2,3,4
Bi (Measured) [nT] i=x,y,z for C1,2,3,4
Bx(C1)
By(C1)
Bz(C1)
Bx(C2)
By(C2)
Bz(C2)
Bx(C3)
By(C3)
Bz(C3)
Bx(C4)
By(C4)
Bz(C4)

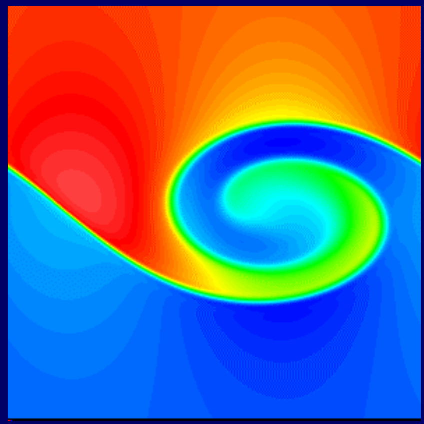
How can the secondary velocity shear be produced?

$$\frac{M_1 v_1^2}{r} = \frac{M_2 v_2^2}{r} = a \quad \textit{leads to,}$$

$$\begin{cases} v_1 = \dfrac{a\sqrt{r}}{\sqrt{M_1}} \\ v_2 = \dfrac{a\sqrt{r}}{\sqrt{M_2}} \end{cases}$$

$$\therefore \left|v_1 - v_2\right| = a\sqrt{r}\left|\frac{1}{\sqrt{M_1}} - \frac{1}{\sqrt{M_2}}\right| = \frac{a\sqrt{r}}{\sqrt{M_1}}\left|1 - \sqrt{\frac{M_1}{M_2}}\right|$$





$$\Delta V_{SEC} \propto \sqrt{r_{SEC}}\left(1 - \sqrt{1/N_{RATIO}}\right)$$

r_{SEC} = curvature radius of the 2nd velocity shear layer

At a certain radial distance from the vortex center, the centrifugal force exerting on the low-density and dense fluids must be equal.

↓

Then, the shear velocity depends on the mass ratio and on the curvature radius of the interface between the two fluids.

Hall (two-fluid) MHD equations including electron inertia effects

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{V}_i) = 0$$

Continuity equation for mass

$$n\frac{d\vec{V}_i}{dt} = -\nabla P + \vec{J} \times \vec{B}$$

Momentum equation

$$\frac{d}{dt}\left(\frac{P}{n^\gamma}\right) = 0$$

Equation of state

$$\frac{\partial}{\partial t}\left(1 - \frac{1}{M}\Delta\right)\vec{B} = \nabla \times \left[\vec{V}_e \times \left(1 - \frac{1}{M}\Delta\right)\vec{B}\right]$$

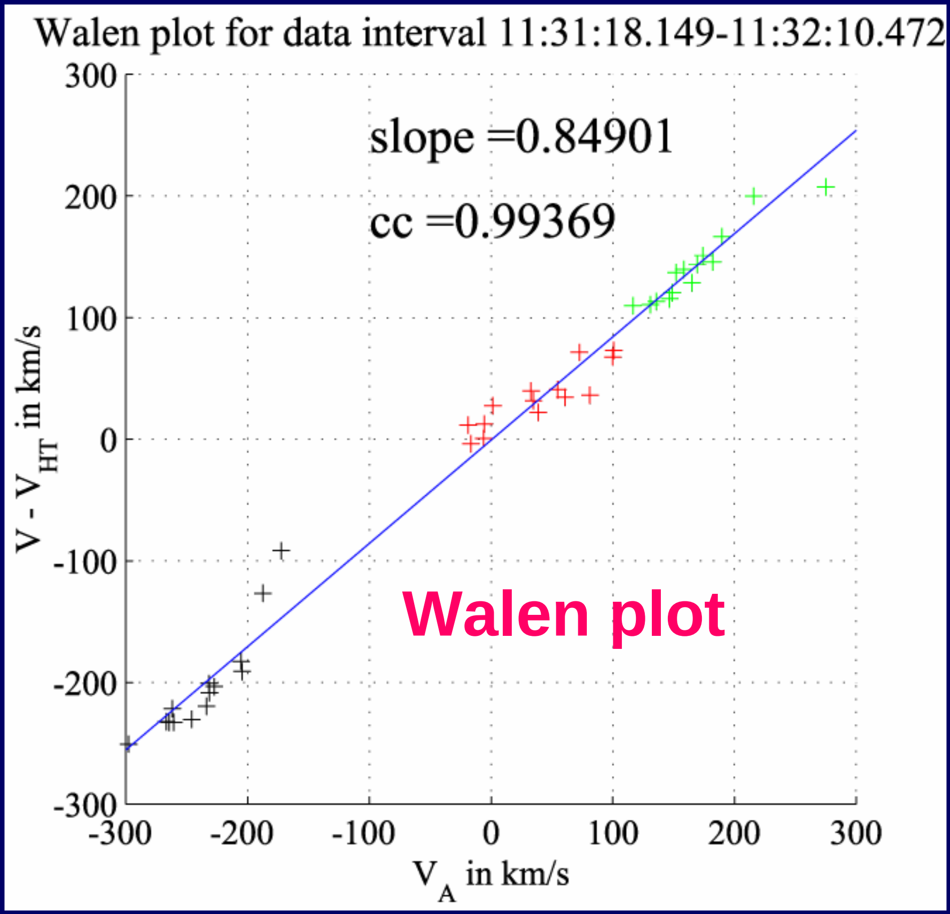
$$\lambda_e = \sqrt{1/M} = \sqrt{m_e/m_i}$$

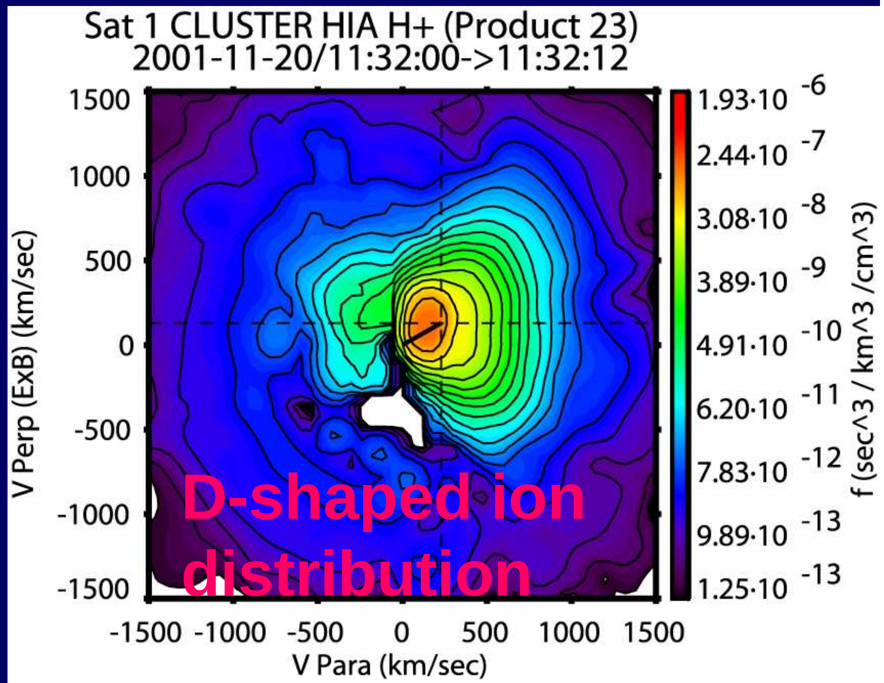
Induction equation including finite electron inertia

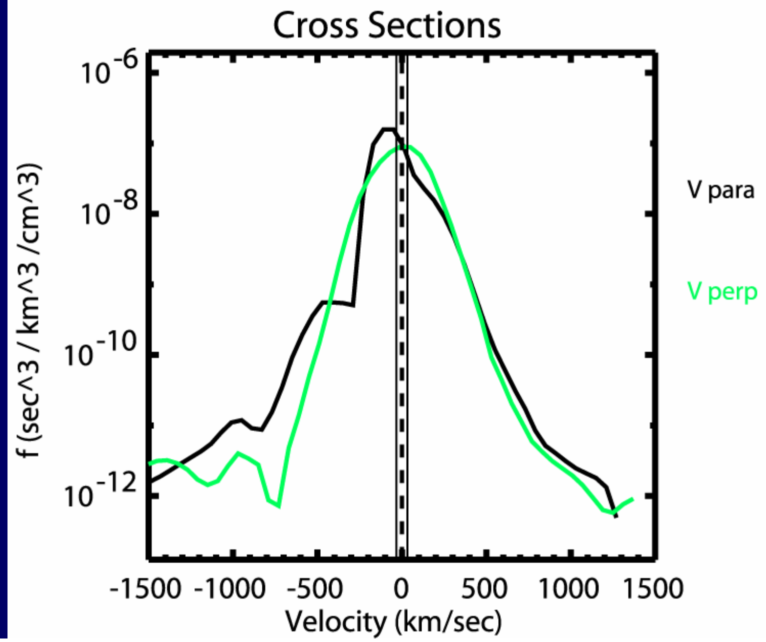
$$\vec{V}_e = \vec{V}_i - \vec{J}/n$$

$$\vec{J} = \nabla \times \vec{B}$$

Measurements for an earlier interval of the day







The result suggests that reconnection occurred near Cluster. This reconnection might have been associated with the KHI growth.