The Ring Current: Cluster Results

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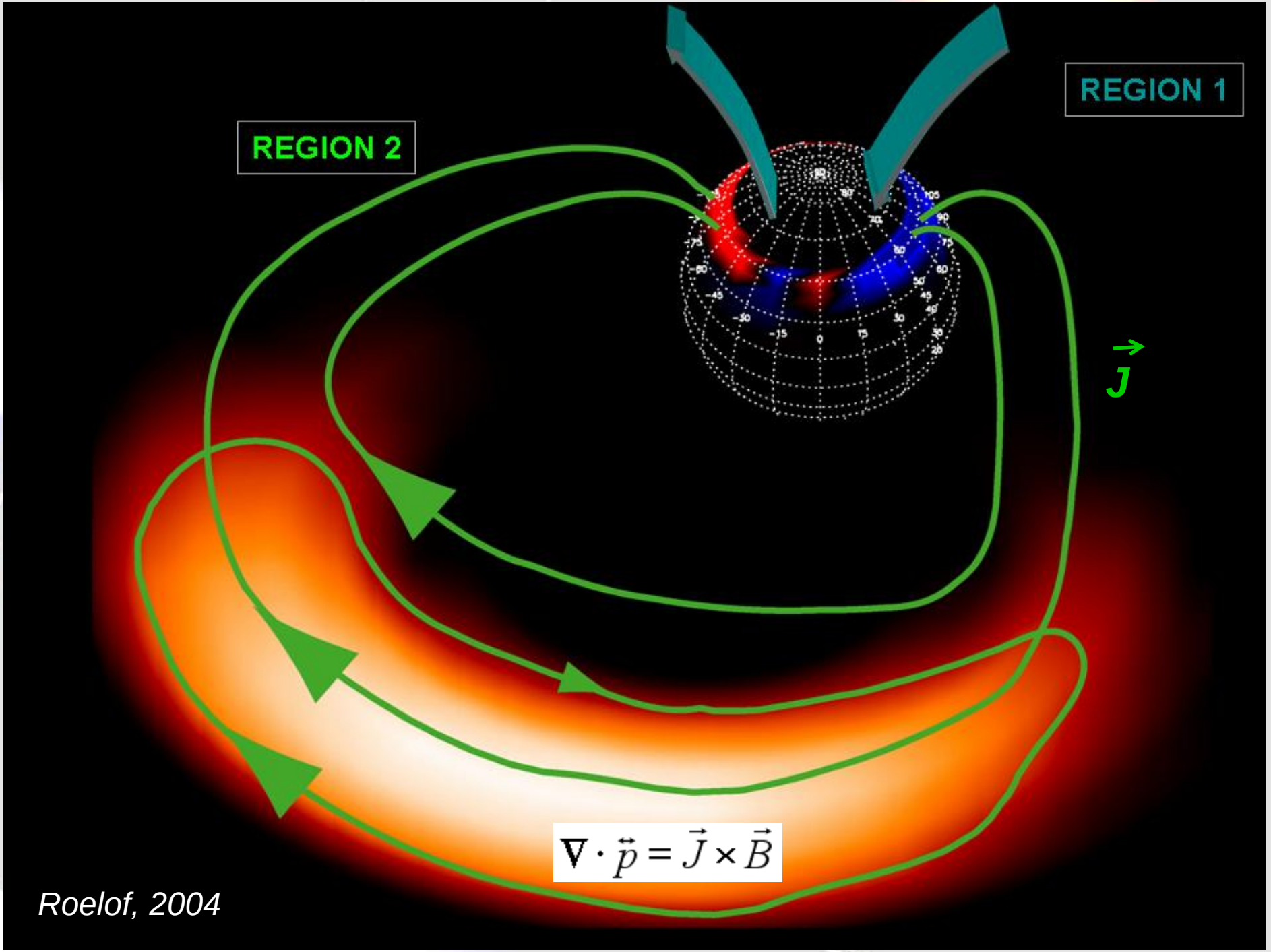
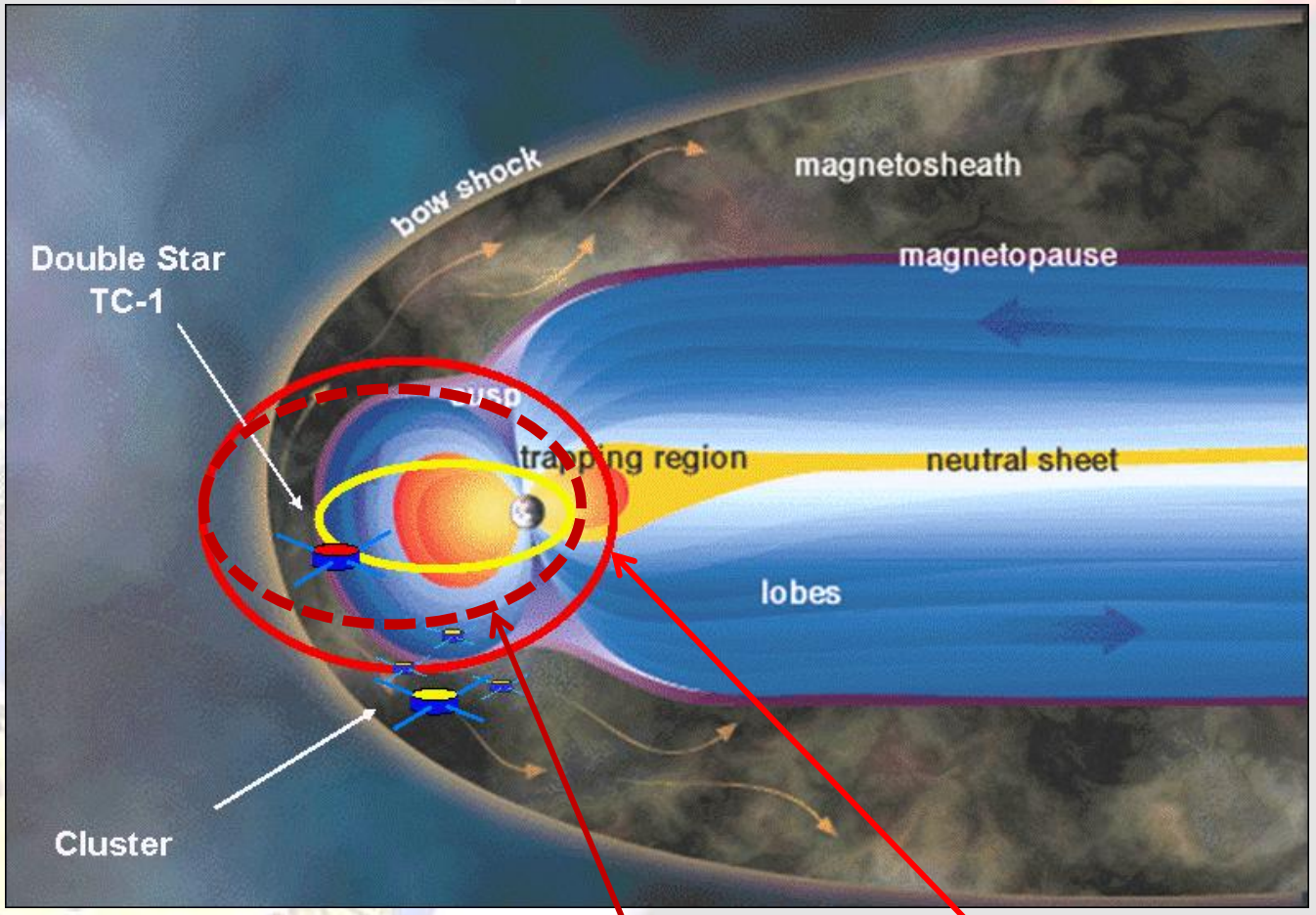


Roelof, 2004

Outline

- The Cluster spacecraft orbit
- The curlometer technique for measuring the current density
- Curlometer technique results in the Ring Current during the early years of Cluster
- Current carriers contribution to the plasma pressure
- Curlometer technique results in the later years of orbit evolution
- Analysis of the applicability of the curlometer technique in the innermost part of the magnetosphere
- The future: Cluster - Swarm Conjunctions

Cluster orbit

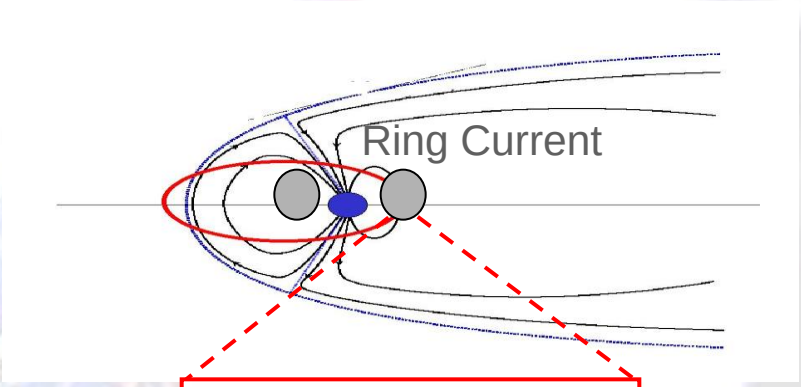


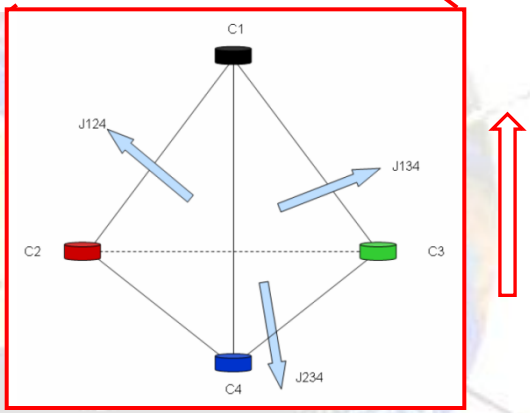
Cluster:
Orbit evolution
since 2007

Cluster:
the “early years”
(2000 – 2006)
4 x 19.6 R_E

Ring Current : *Current Density*
Direct Measurement using the Curlometer Technique

Maxwell-Ampère Law:
Curlometer Method





$$\nabla \times \vec{B} = \mu_0 \cdot \vec{J}$$

$$(\nabla \times B)_x = \frac{\Delta Bz}{\Delta y} - \frac{\Delta By}{\Delta z}$$

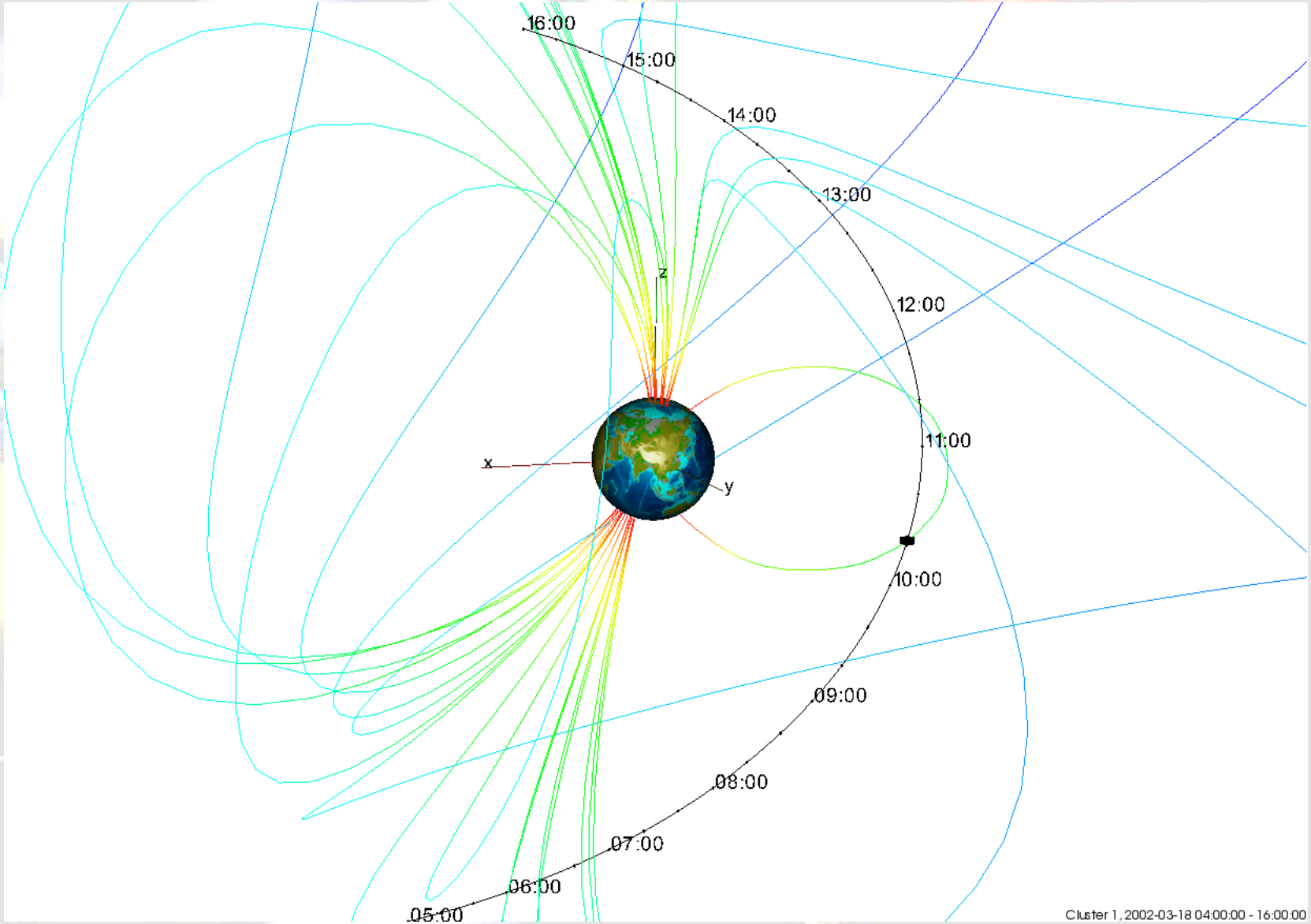
$$(\nabla \times B)y = \frac{\Delta Bx}{\Delta z} - \frac{\Delta Bz}{\Delta x}$$

$$(\nabla \times B)z = \frac{\Delta By}{\Delta x} - \frac{\Delta Bx}{\Delta y}$$

Requires closely-spaced tetrahedron (2002)

⇒ **Curlometer technique**: Local current density measurement (strength and orientation) deduced from the 4 SC magnetic field data.

QUIET EVENT: 18 March 2002 perigee pass



QUIET EVENT: 18 March 2002 perigee pass: Possible errors due to the tetrahedron configuration

1: Size

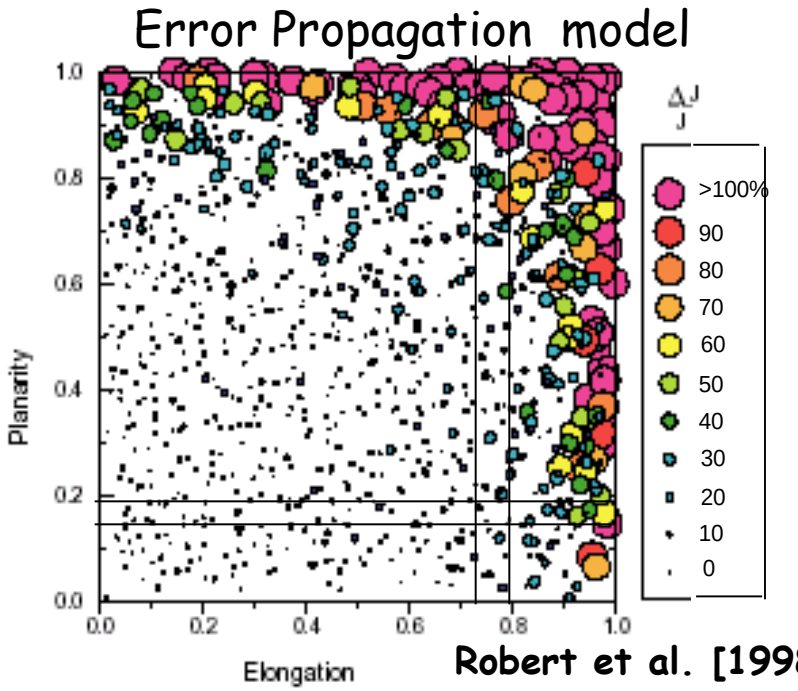
• *Small size:* the 4 Spacecraft must be situated inside the same current sheet (linear gradients).

But:

• *Size sufficient* to reduce the relative error made in the inter-spacecraft distances estimate.

=> The inter-SC distance must be < 500 km at perigee to correctly estimate *J*.

2: Shape



During Cluster perigee passes (and for ΔSC < 500 km):

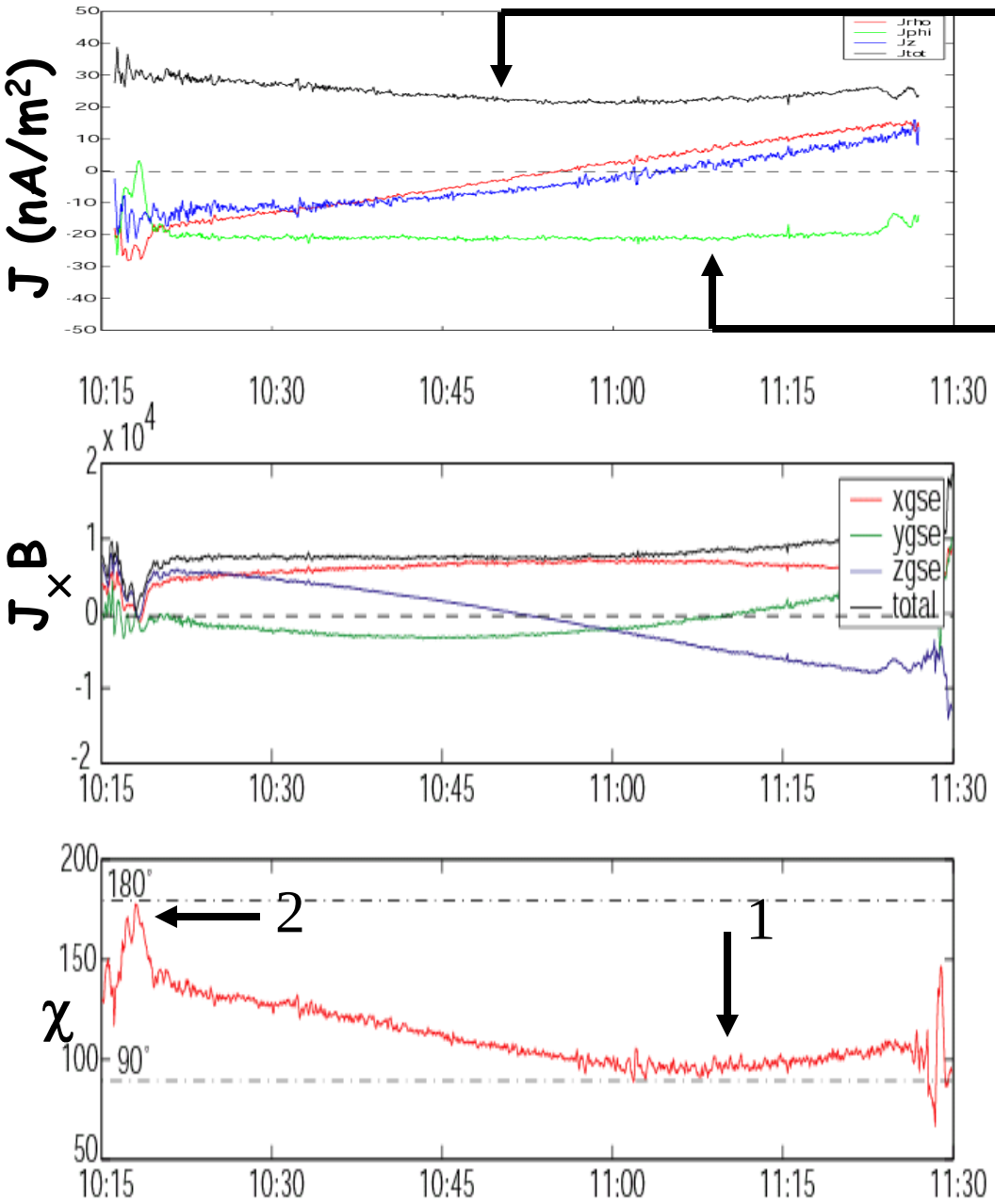
• Tetrahedron elongation along the Z_{sm} axis.

=> Main part of the error carried by Jz_{sm} (component // to *B*).

• $\Delta J / J < 20\%$.

=> Good estimate of the ring current (*J* components $\perp$ *B*).

QUIET EVENT: 18 March 2002 perigee pass



• Ring current density even during quiet events.

• Westward current:

• $\langle J\varphi \rangle \sim -20.6 \pm 20\%$ nA/m^2 (~ constant all along the traversal).

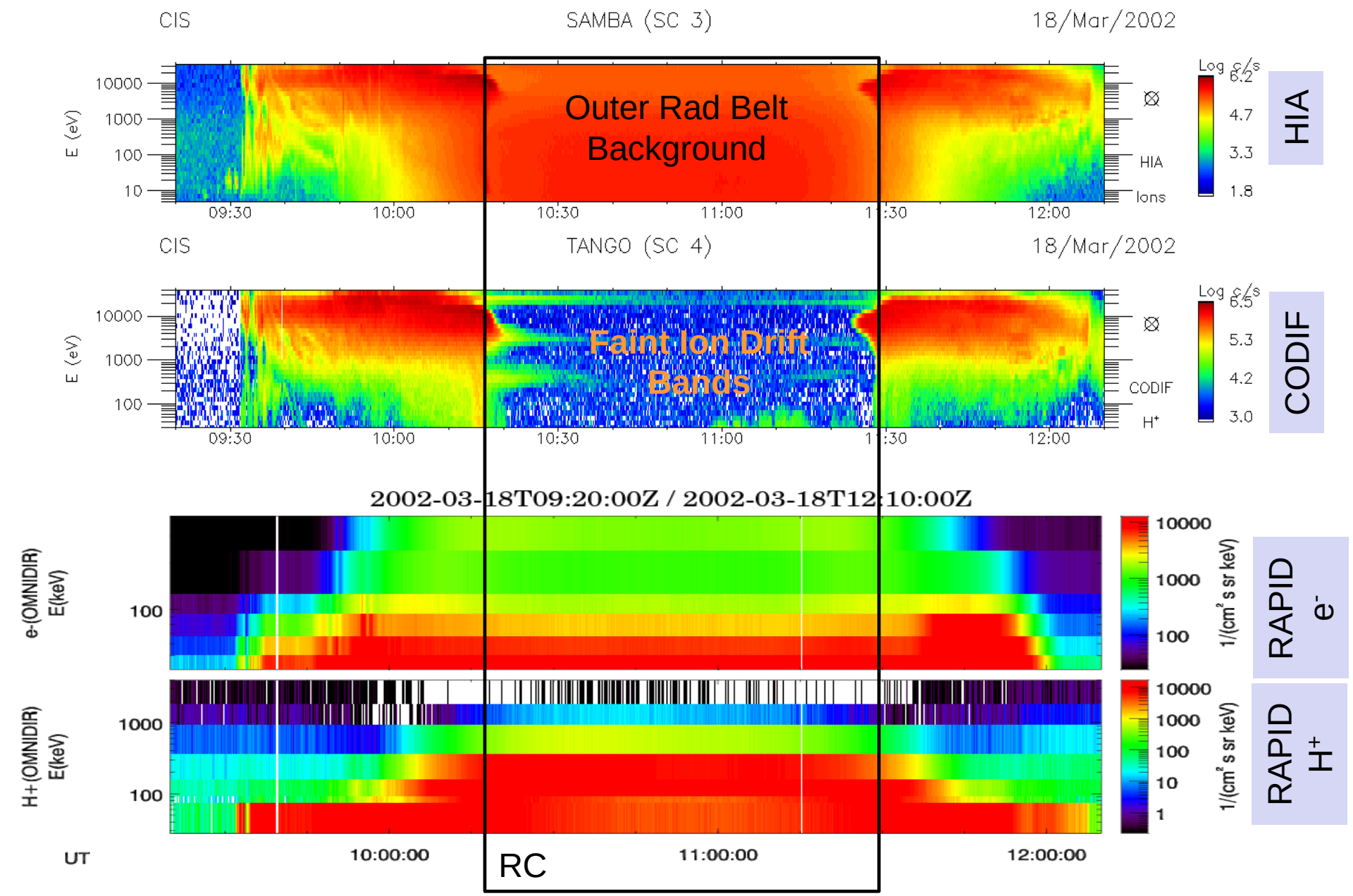
• Large latitudinal extent of the ring current region (between *Ilat*~ -65 and 65).

• $\boldsymbol{J} \times \boldsymbol{B} \propto \nabla P$: gives the position w.r.t the maximum pressure.

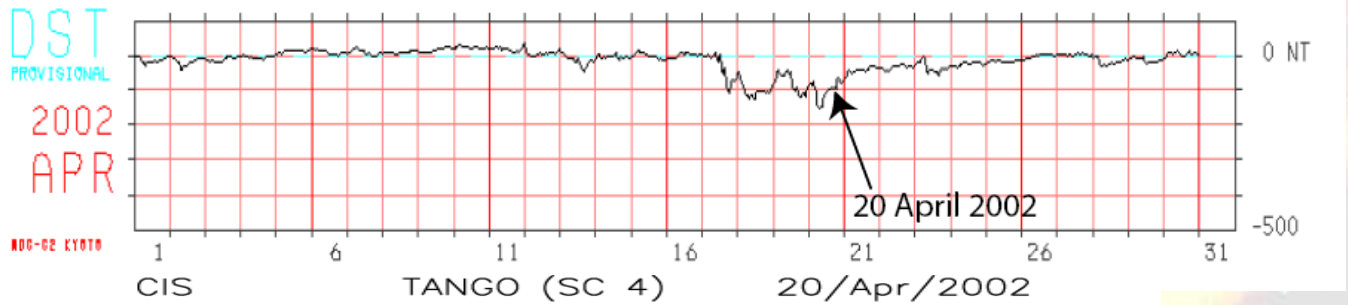
• 1: Current at Equator is almost fully azimuthal (~ 88%).

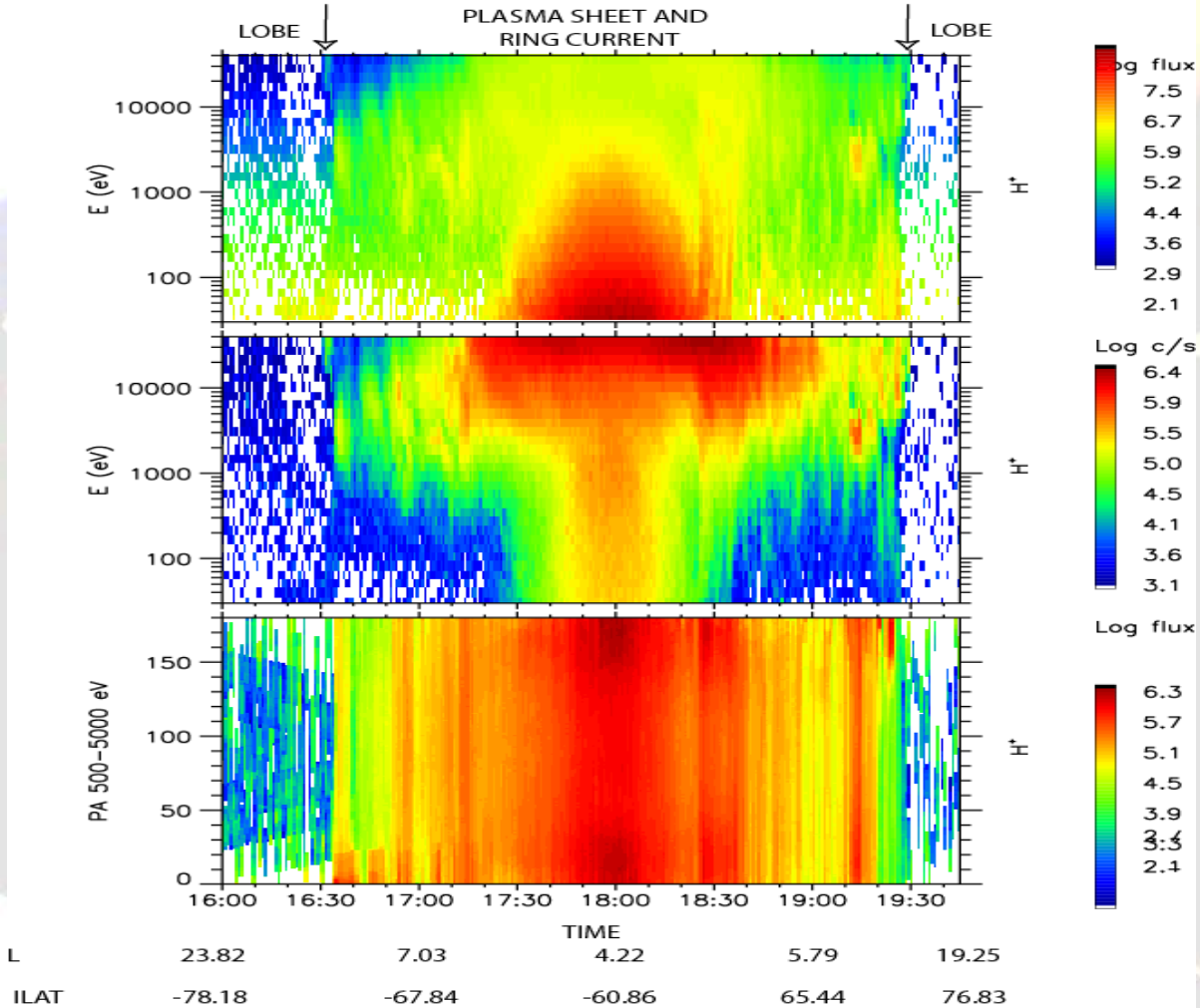
• 2: Field aligned currents at the transition between plasma sheet and ring current.
=> Diamagnetic signature

18 March 2002 perigee pass: What are the current carriers ?



STORM-TIME EVENT: 20 April 2002



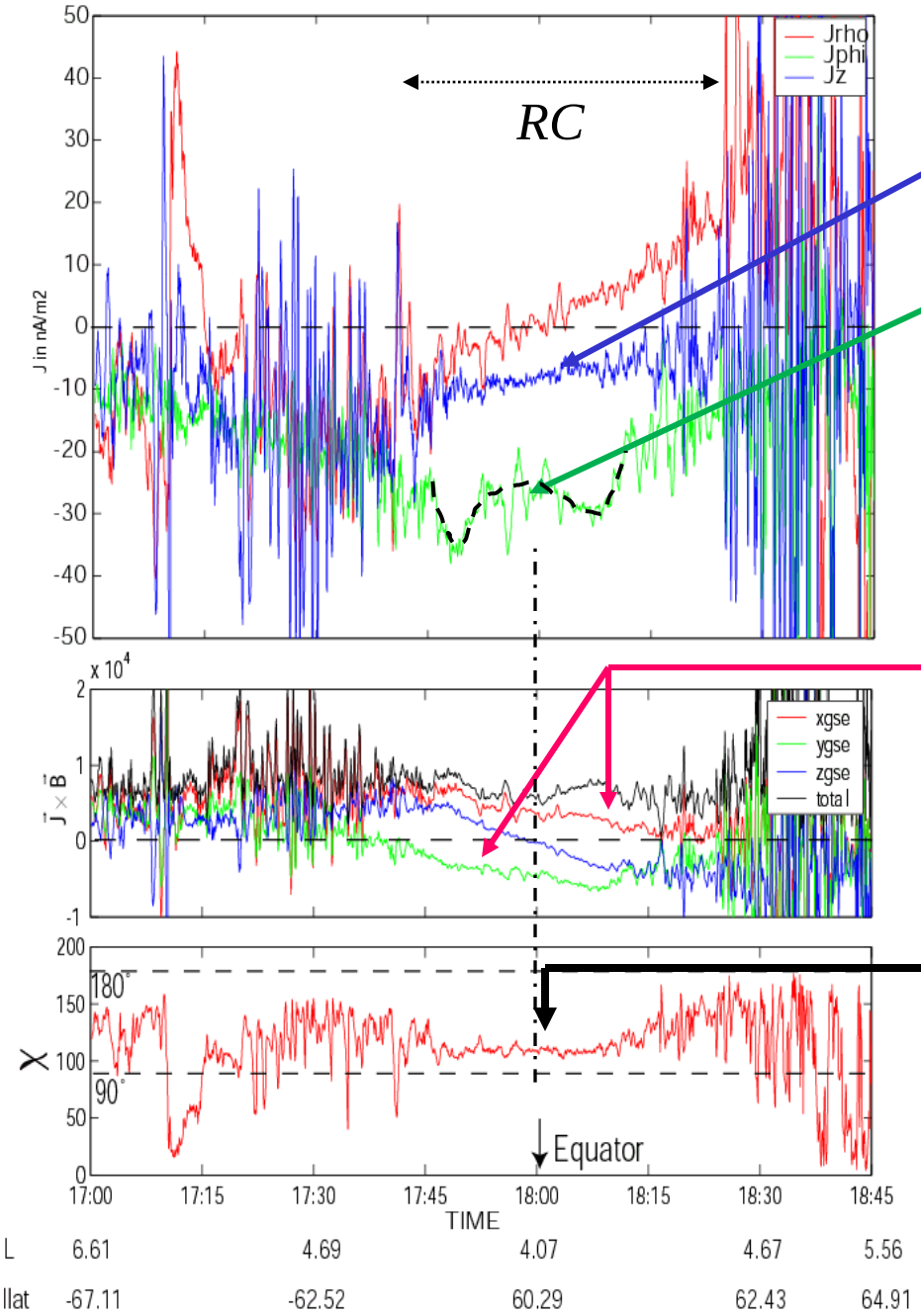


- Storm conditions.
- Dst ~ -100 nT:
  Well-developed ring current.
- Cluster perigee crossing:

  MLT ~ 21
- CIS/Cluster ion data:

Gradual transition between the plasma sheet and the ring current.

STORM-TIME EVENT: 20 April 2002



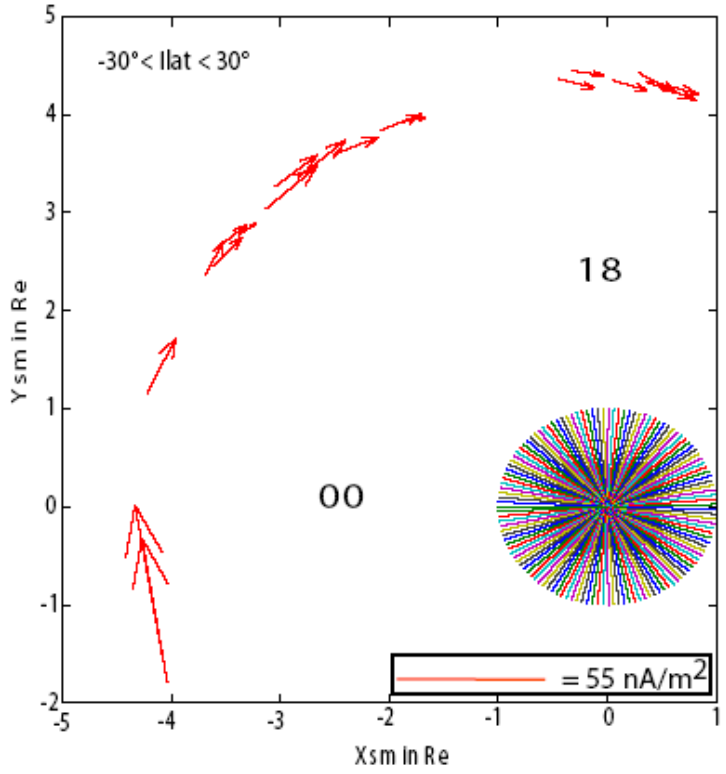
• Negative, stable ***Jz*** component of the current all along the ring current traversal.

• **Dominance** of the **azimuthal component**.
• Local minimum at magnetic equator: **bifurcation**

• ***J B*** values: position of the tetrahedron w.r.t the maximum pressure:
⇒ P_{max} situated dawnward and earthward of the tetrahedron.

• Storm-time equatorial current **not fully azimuthal**:
⇒ Existence also of a **small parallel component near the Equator**. (inter-hemisphere coupling)?

2002 Cluster data: Ring Current density statistical study



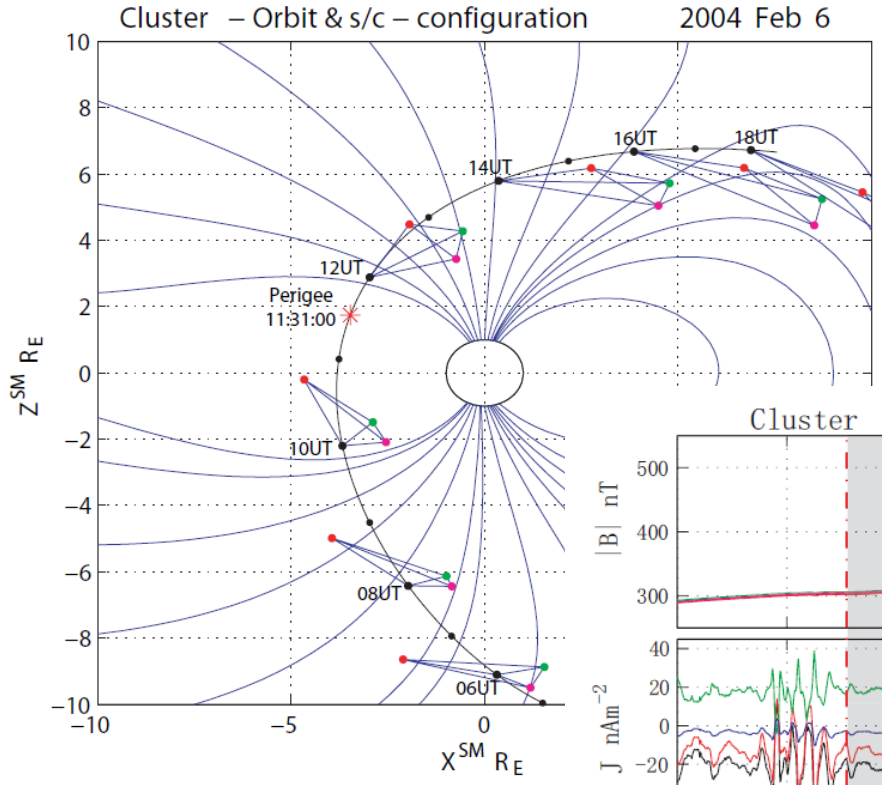
- Only ~ 20 perigee passes:

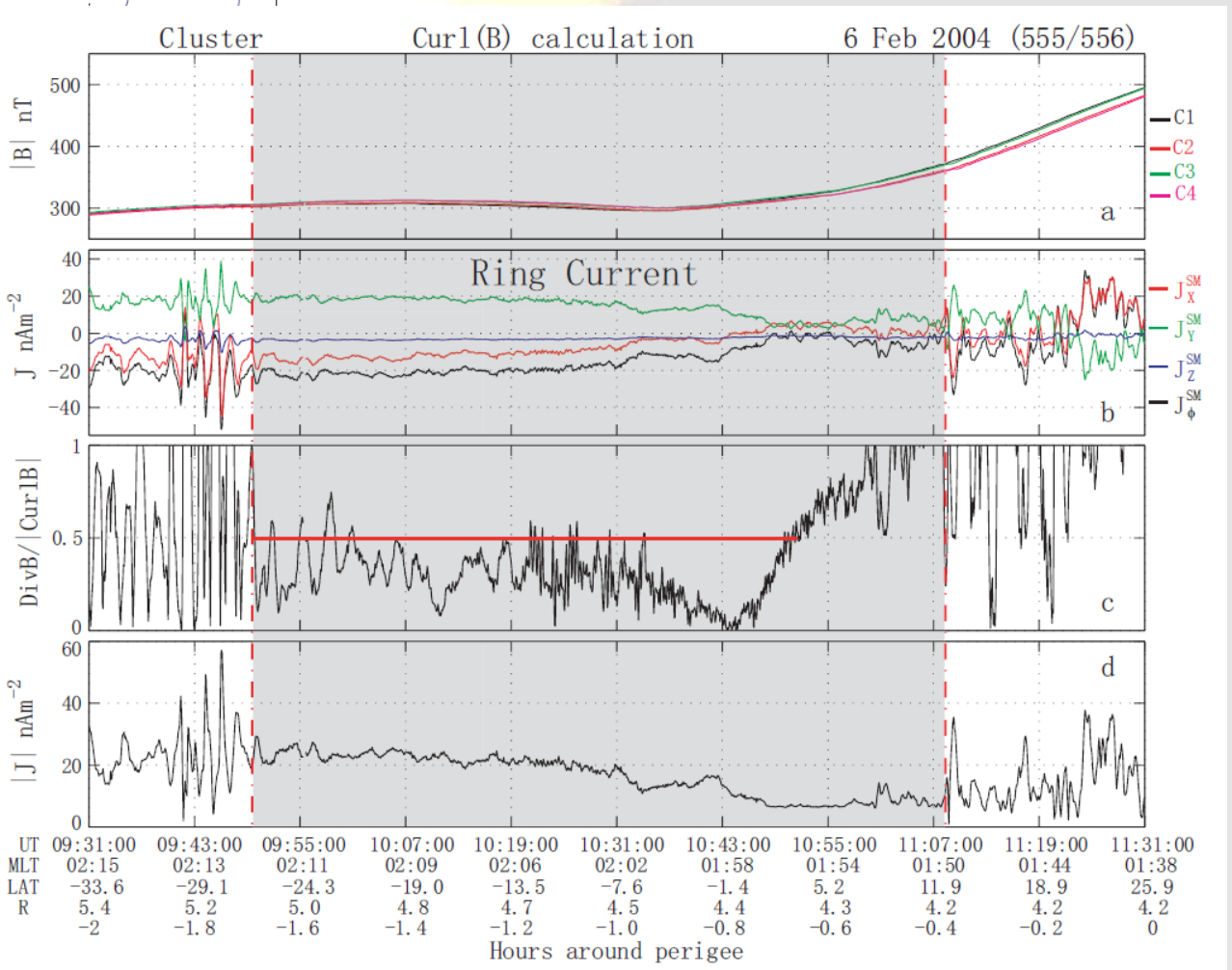
Lack of data in the 01 H to 17 H MLT sector (inappropriate inter-spacecraft separation).

- **No drastic increase of the current density with decreasing Dst (no more than 30%)** in the evening sector.

Vallat, Dandouras, et al., Ann. Geophys., 2005

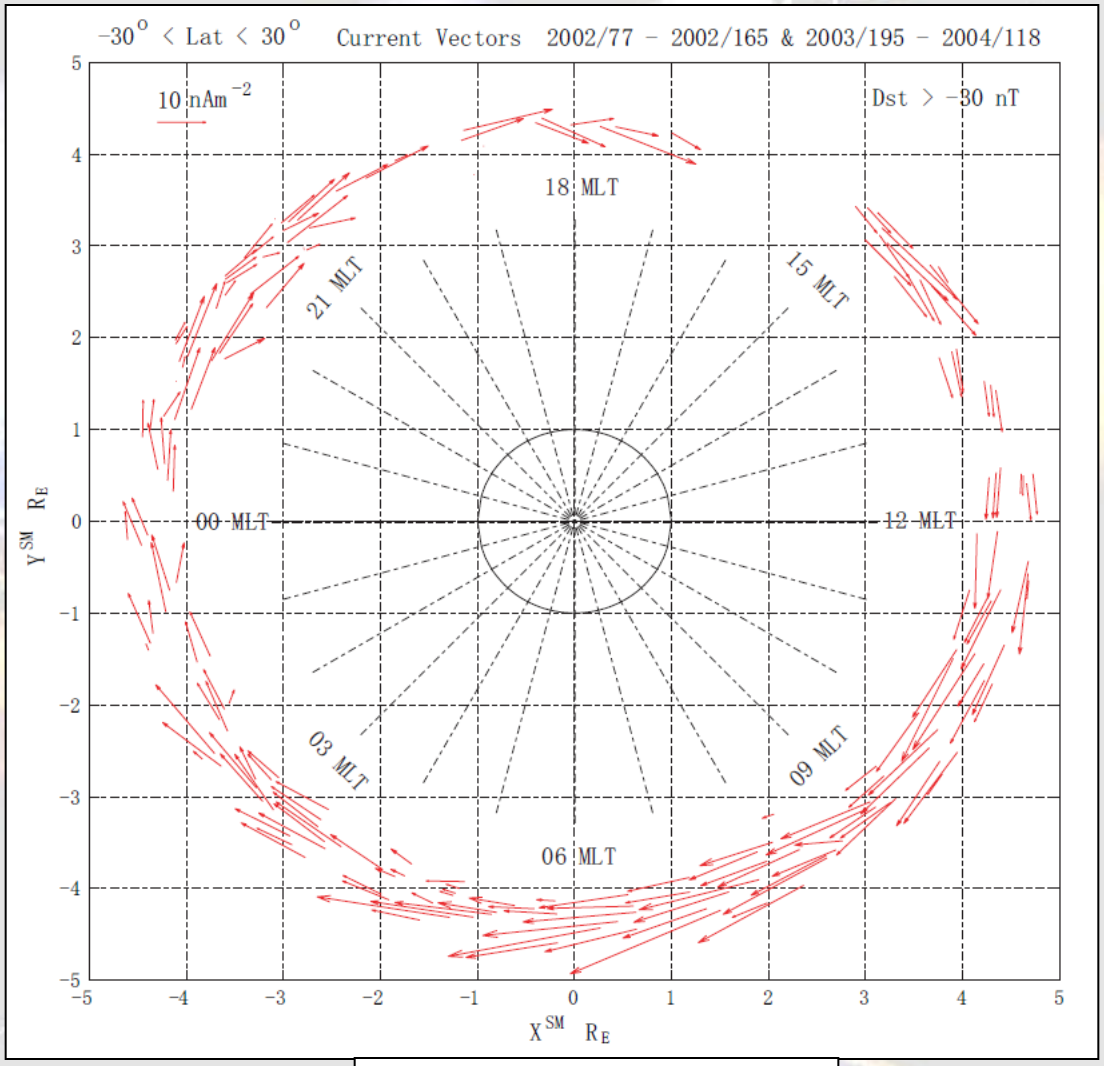
Ring Current density analysis using the Curlometer Technique: Extension to Cluster data acquired up to end 2004





Zhang, Dunlop, et al., Ann. Geophys., 2011

Ring Current density statistical study: Extension to Cluster data acquired up to end 2004



Dst > -30 nT
(non-storm conditions)

- **Well-organised**, westward ring current
- Substantial **non-storm ring current density**: 9 - 27 nA m^{-2}
- **Azimuthal asymmetry**:
  - Enhanced (factor ~2) between 5 and 11 MLT
  - Reduced between 12 and 17 MLT
- Region-2 FAC feeding effect?
- 4 - 4.5 R_E sampling effect?
- AE sampling effect?

Zhang, Dunlop, et al., Ann. Geophys., 2011

Westward Ring Current Density : SUMMARY

- The curlometer technique reproduces very well the ring current flow.

  - Shows the **existence of a quiet time ring current :** $|J\varphi| \sim 20$ nA / m^2

  (the five quietest days of each month are subtracted to estimate the Dst index, making the quiet time ring current estimate impossible by this index).

  ➢ implications for the **respective contributions of the internal/external sources of the geomagnetic field**

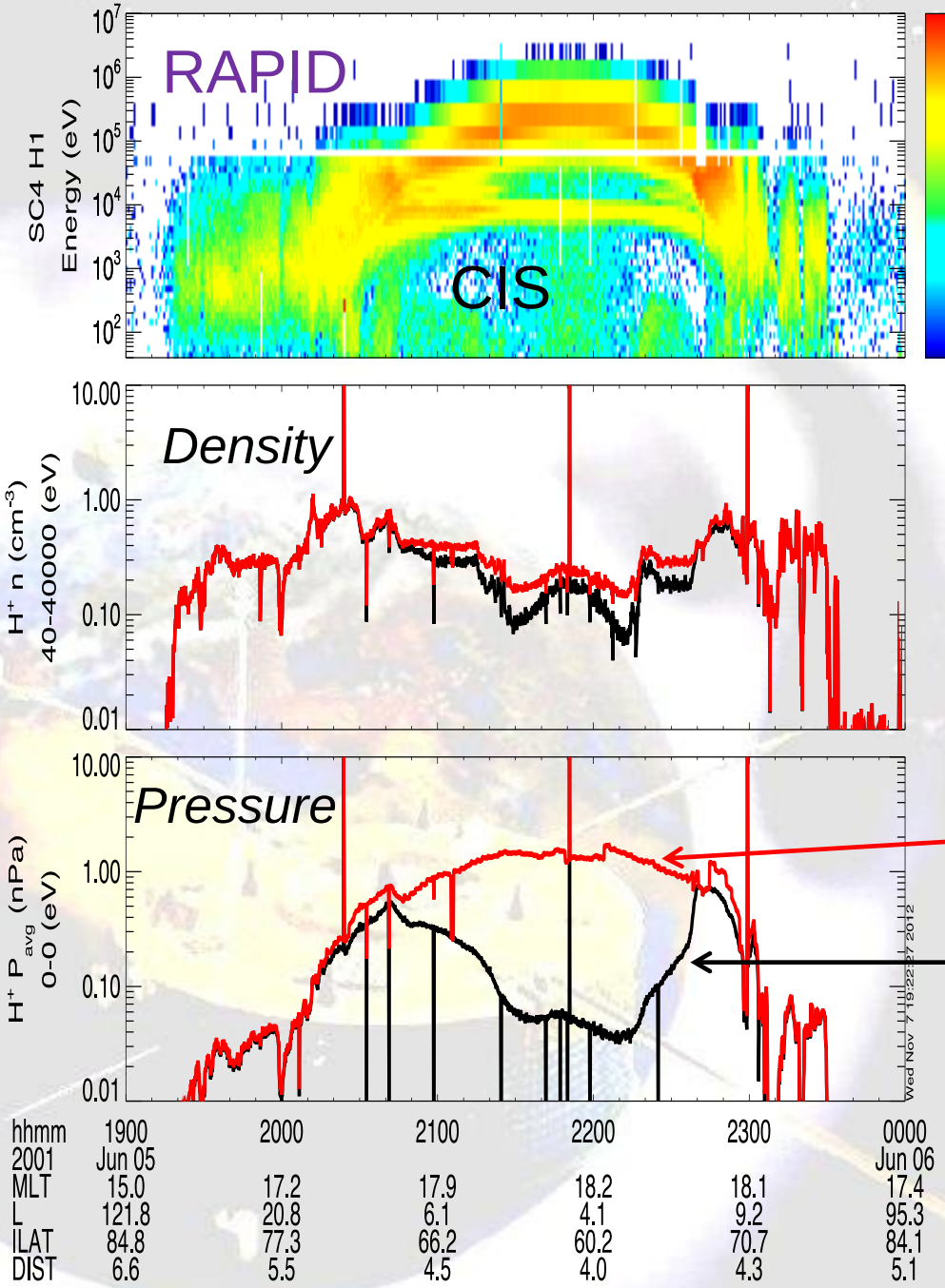
- Permits to study the latitudinal evolution of the *J* orientation :

  - Gradual evolution of the *J* orientation as a function of *llat* in the ring current region.

  - **Discontinuous evolution** of the *J* orientation at the **boundary between the ring current and the plasma sheet**.

  ➢ Brings a **crucial information concerning M-I coupling** (FACs).

Ring Current Carriers: Plasma Pressure



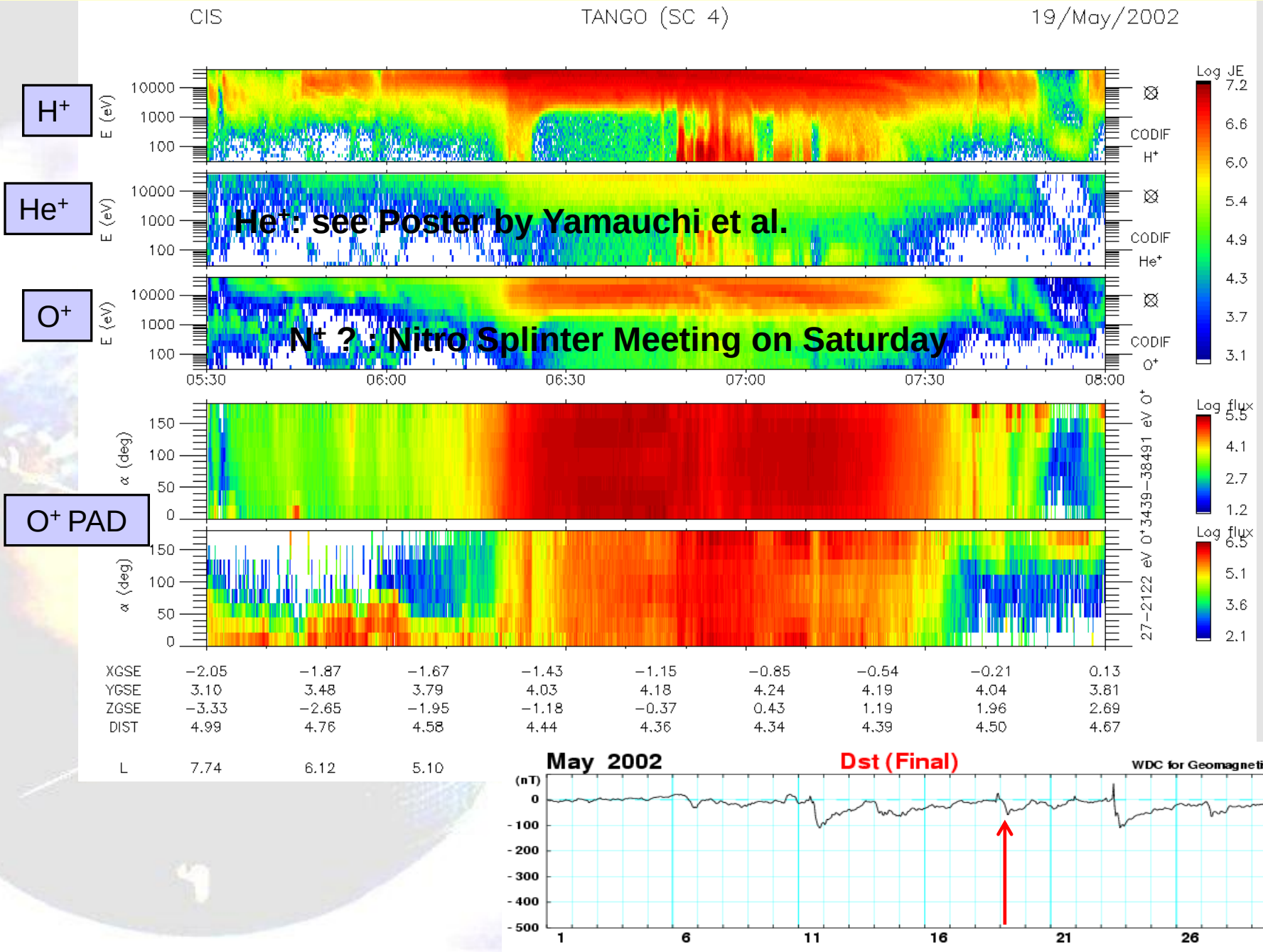
Merging
CIS-CODIF (25 eV - 40 keV)
and
RAPID (28 - 1500 keV) data
in the Ring Current
to Calculate Moments
with Full Energy Range

CIS + RAPID

CIS only

Mouikis and Kistler,
Cluster CAA Workshop, 2012

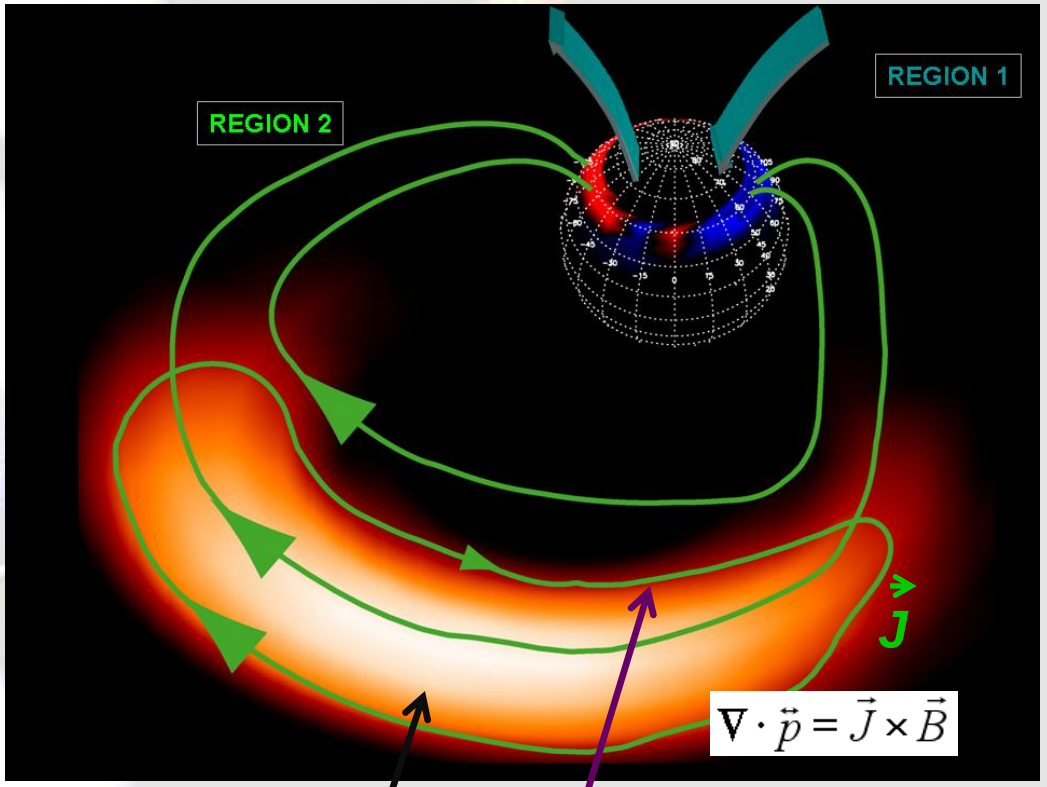
Composition: Moderate Storm time RC event



Cluster orbit evolution since 2007

Eastward Ring Current ?

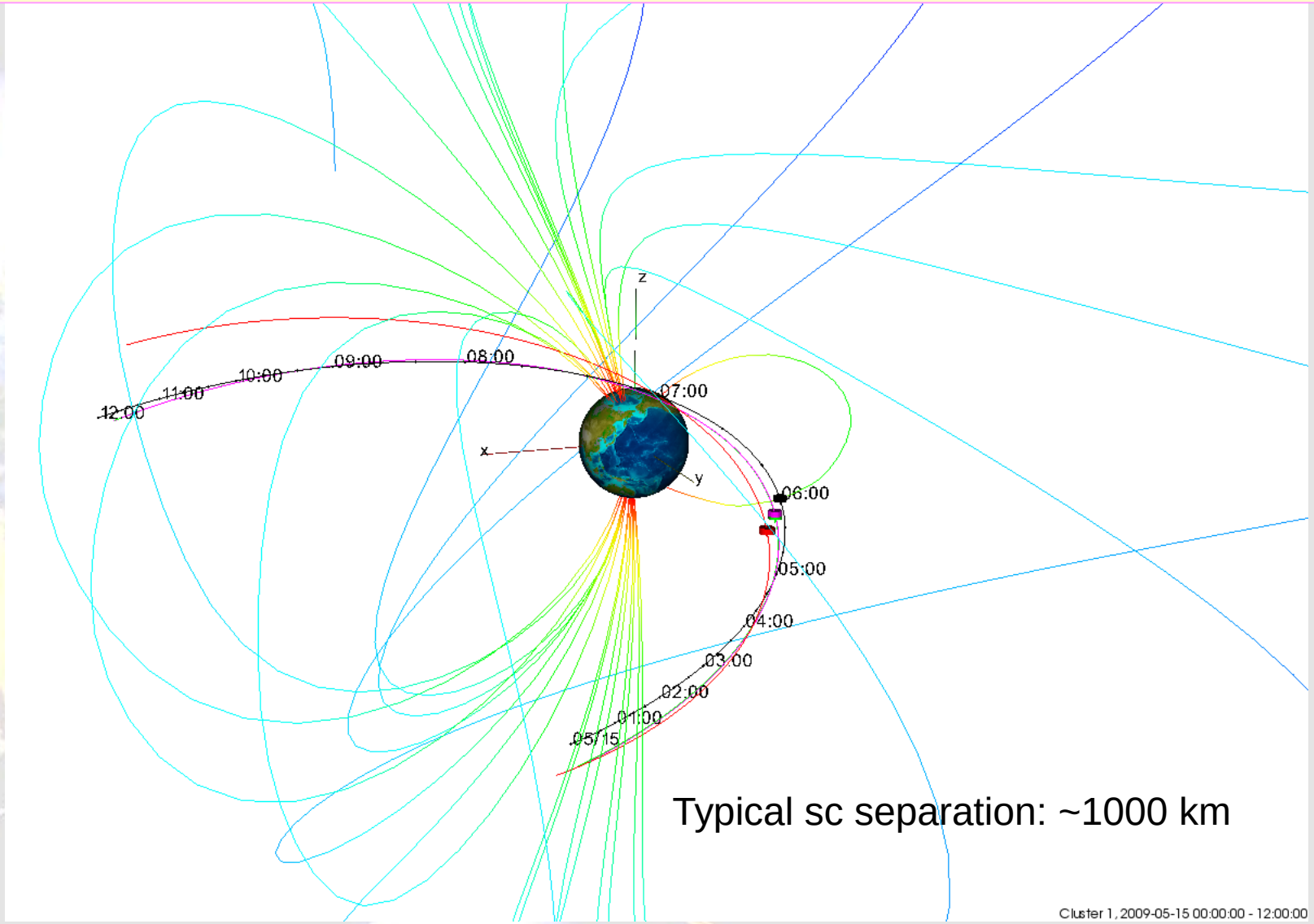
Crucial information on the inner magnetosphere pressure balance and the coupling with the ionosphere



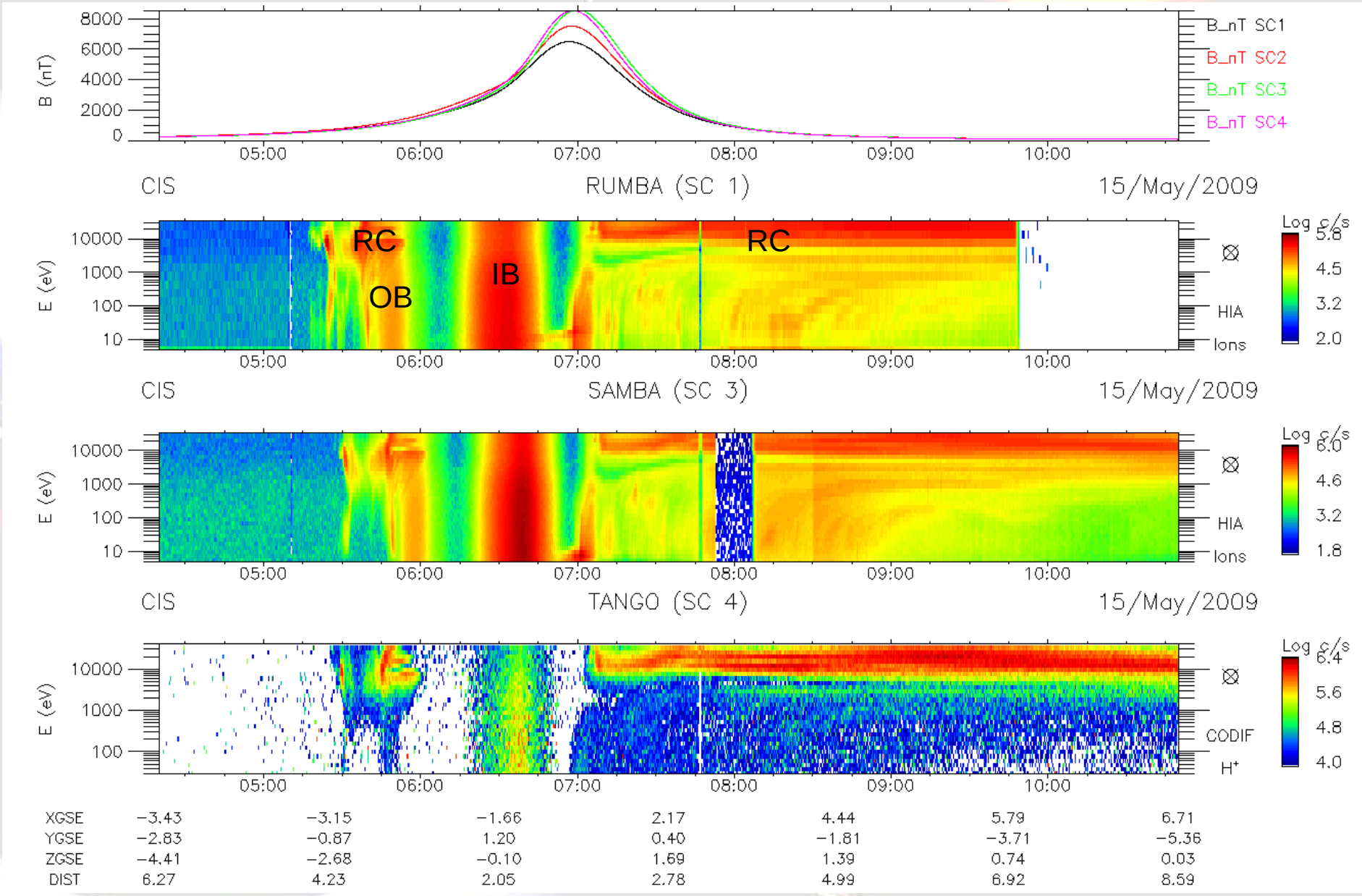
Early years Cluster perigee

New perigee ?

15 May 2009 event:
Low-altitude perigee pass, weak activity

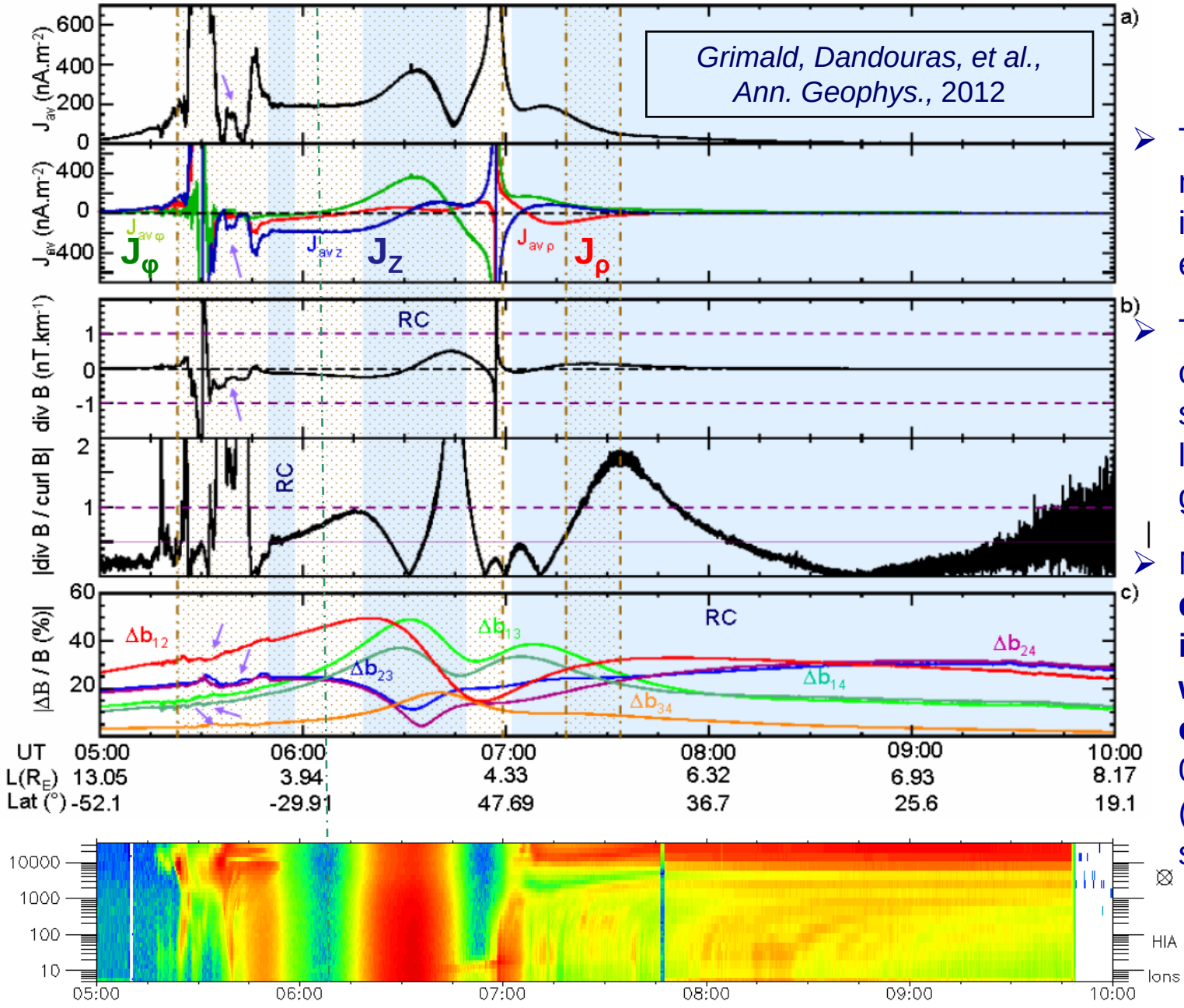


15 May 2009 event: Ion data



XGSE	−3.43	−3.15	−1.66	2.17	4.44	5.79	6.71
YGSE	−2.83	−0.87	1.20	0.40	−1.81	−3.71	−5.36
ZGSE	−4.41	−2.68	−0.10	1.69	1.39	0.74	0.03
DIST	6.27	4.23	2.05	2.78	4.99	6.92	8.59

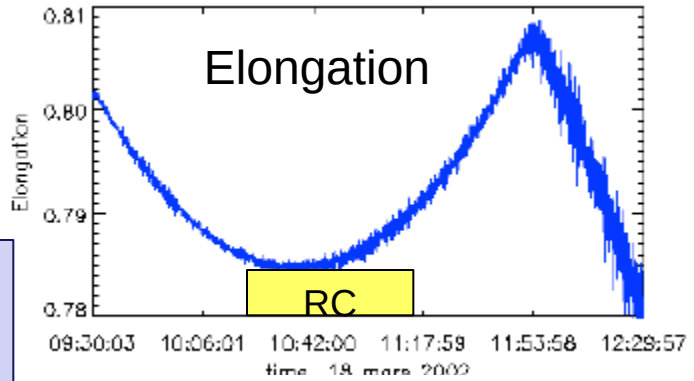
15 May 2009 event: Curlometer calulations

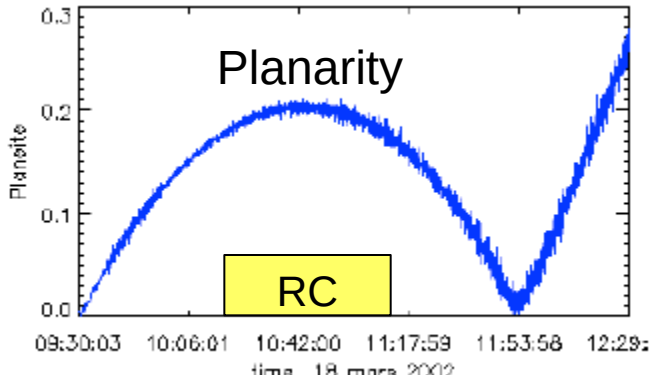


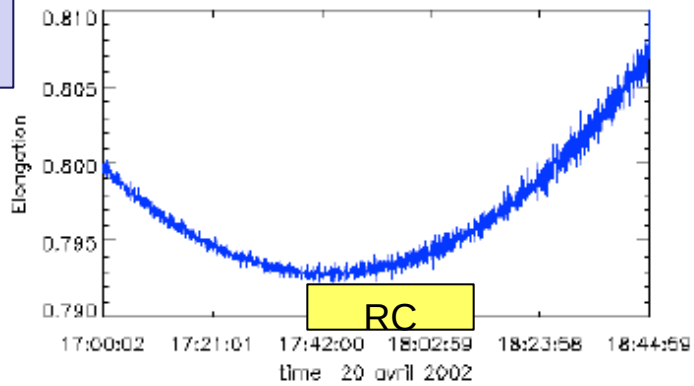
- Too high div***B*** in most of the interval, with two extreme cases
- This limitation comes from strong and non-linear B-field gradients
- Nevertheless: **data suggest inversion from westward to eastward RC** at 06:03 UT (***L*=3.59**), in the slot region

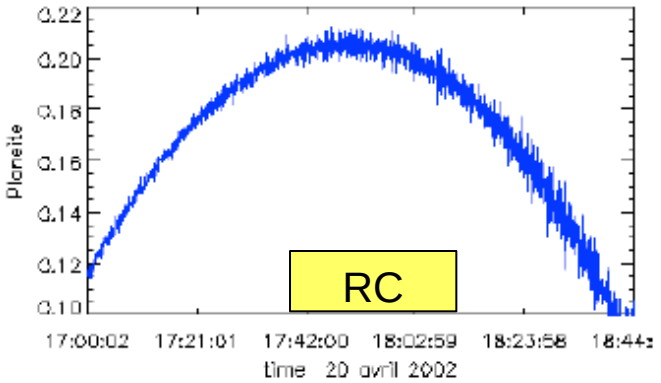
Analysis of the applicability of the curlometer technique: I. Tetrahedron Geometry

2002

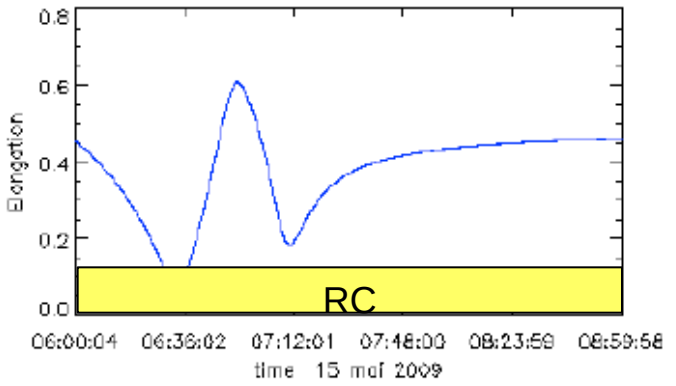


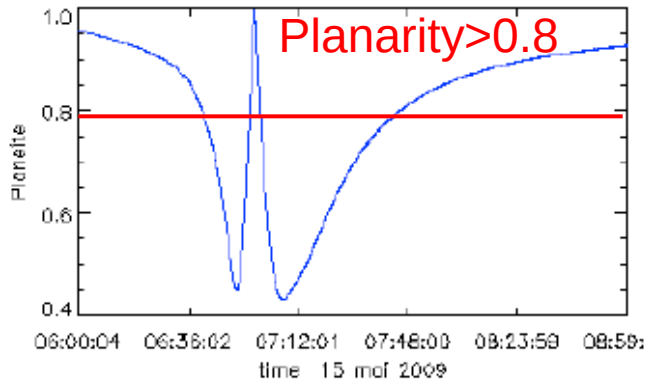






2009

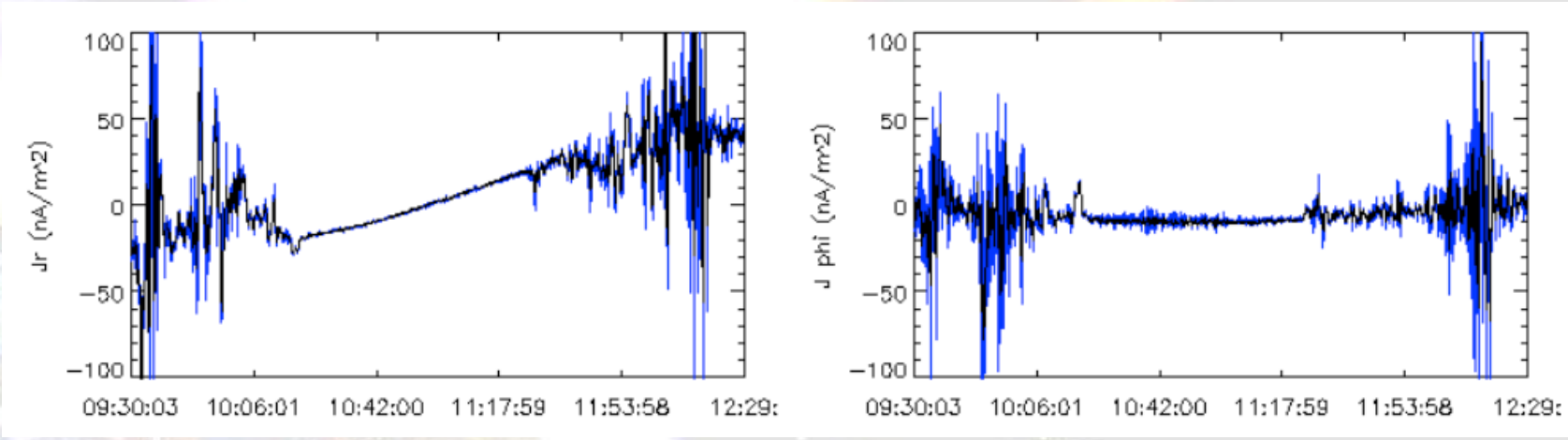




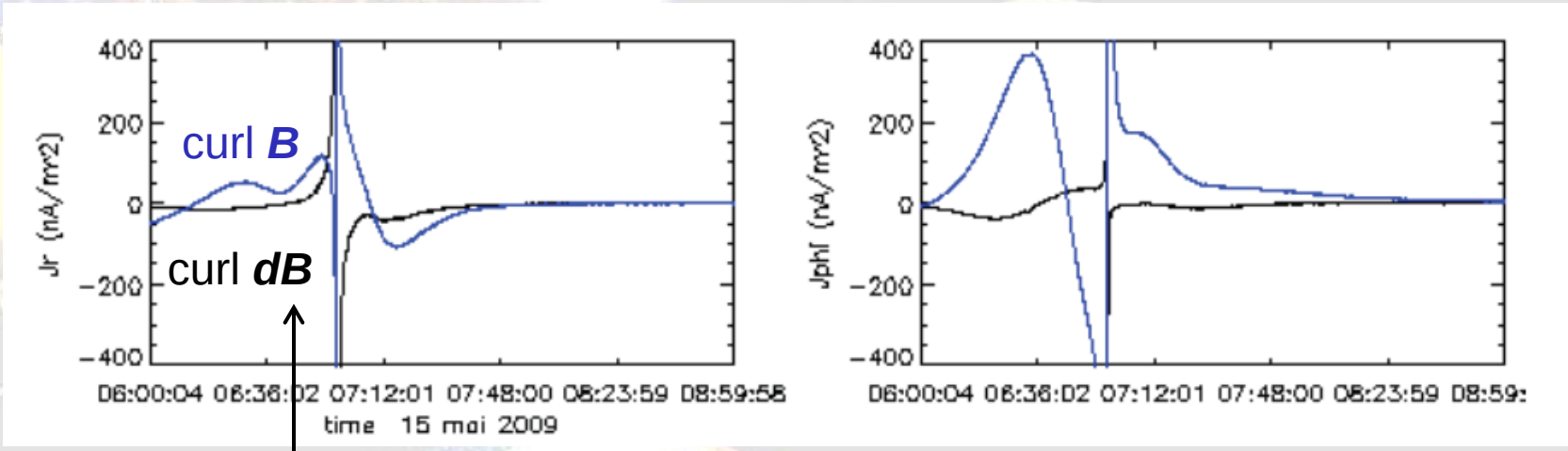
Elongation and Planarity need to be less than 0.8, cf. also Robert et al., 1998

Analysis of the applicability of the curlometer technique: II. B-field linearity hypothesis

2002



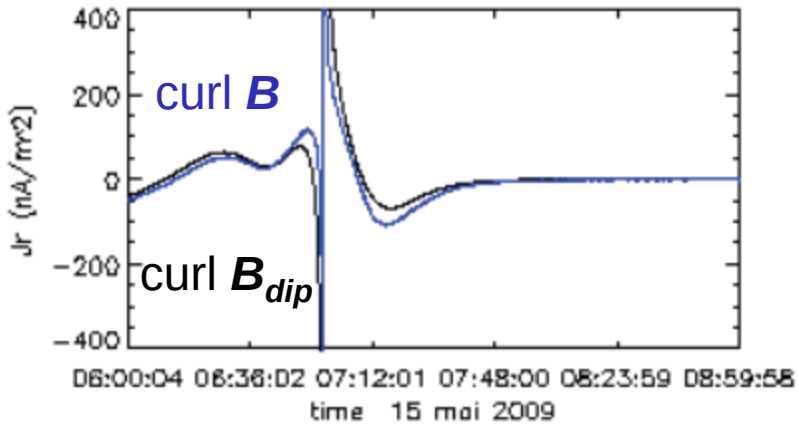
2009

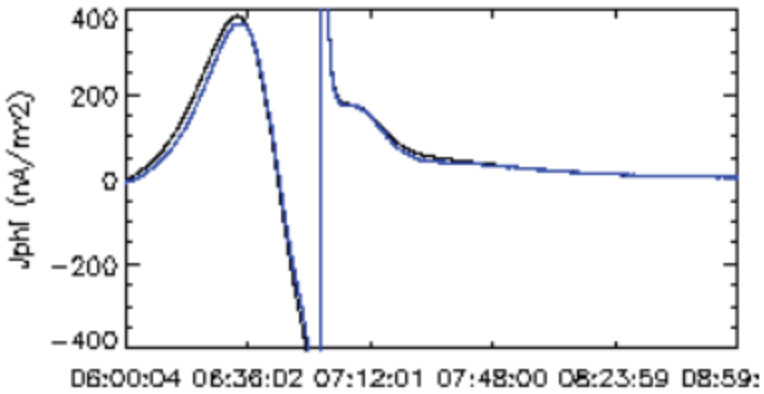


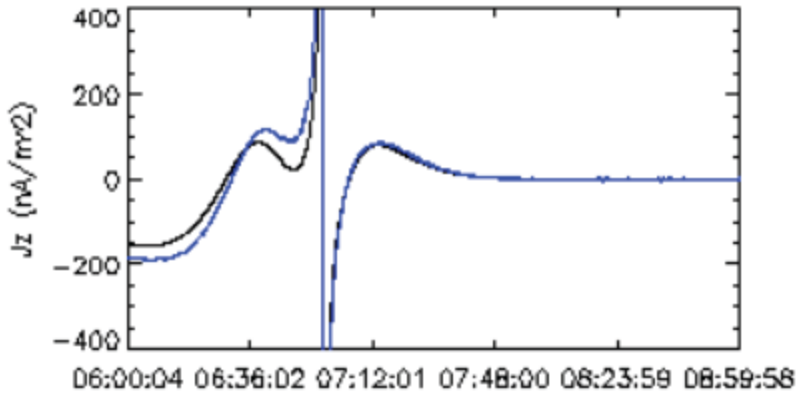
$B - B_{dipole}$

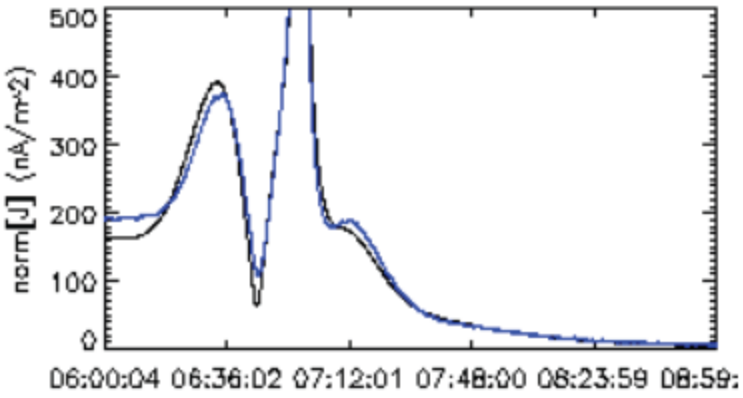
curl ***B*** and curl ***dB*** should be the same

2009





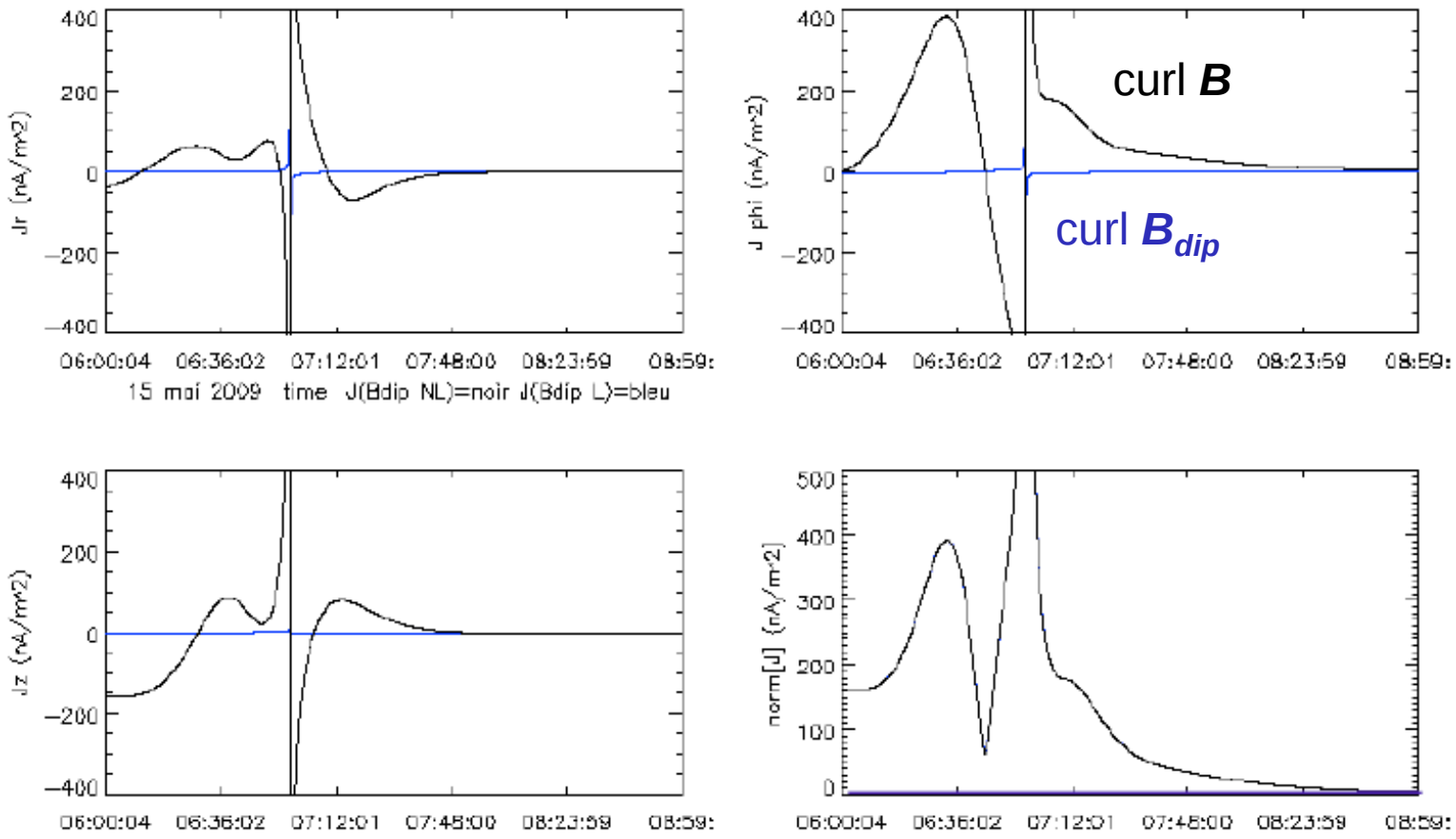




Very large curl $\boldsymbol{B}_{dip}$ for a dipole field !

(It should be zero)

2009



curl $\boldsymbol{B}_{dip}$ is ~zero, as it should,

when calculated <u>without the linearity approximation</u>

Inter-satellite distance: ~400 - 7660 km

Blanchet et al., IRAP, 2012

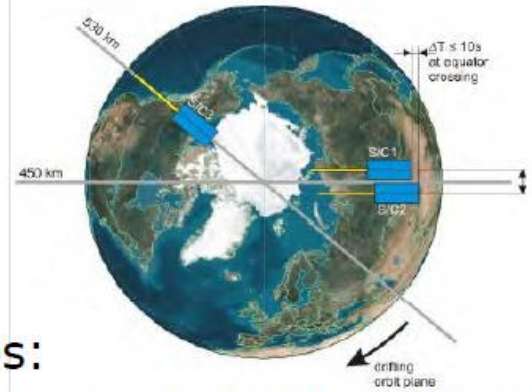
Analysis of the applicability of the curlometer technique in the innermost magnetosphere: Results

- Elongation and Planarity need to be less than 0.8
- Most of the error in the innermost magnetosphere comes from the linearity hypothesis on the magnetic field.
- If curl $\boldsymbol{B}_{dip}$ << curl $\boldsymbol{B}$, then the curlometer technique gives good results (very small error due to the non-linearity of $\boldsymbol{B}$) .
- Otherwise $\boldsymbol{B}_{dip}$ has to be subtracted from $\boldsymbol{B}$, and errors due to the non-linearity can be strong.
- **Closer than 3.5 R_E the non-linearity of *B* is dominant**.

The future:
Cluster - Swarm Conjunctions

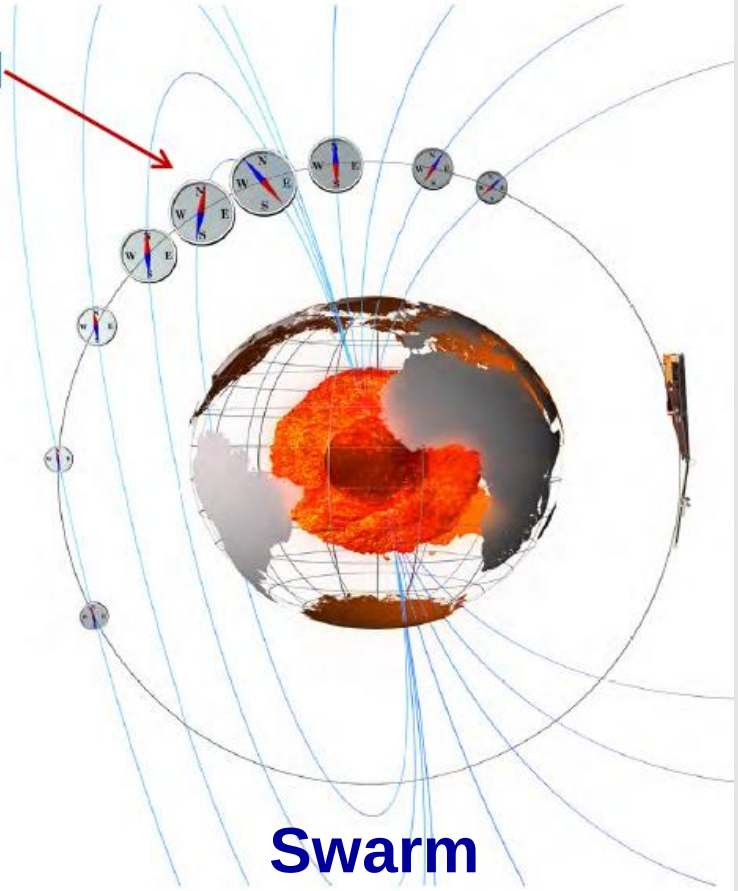
Each satellite is measuring:

- Strength and direction of the magnetic field
- Plasma conditions and characteristics
- Location



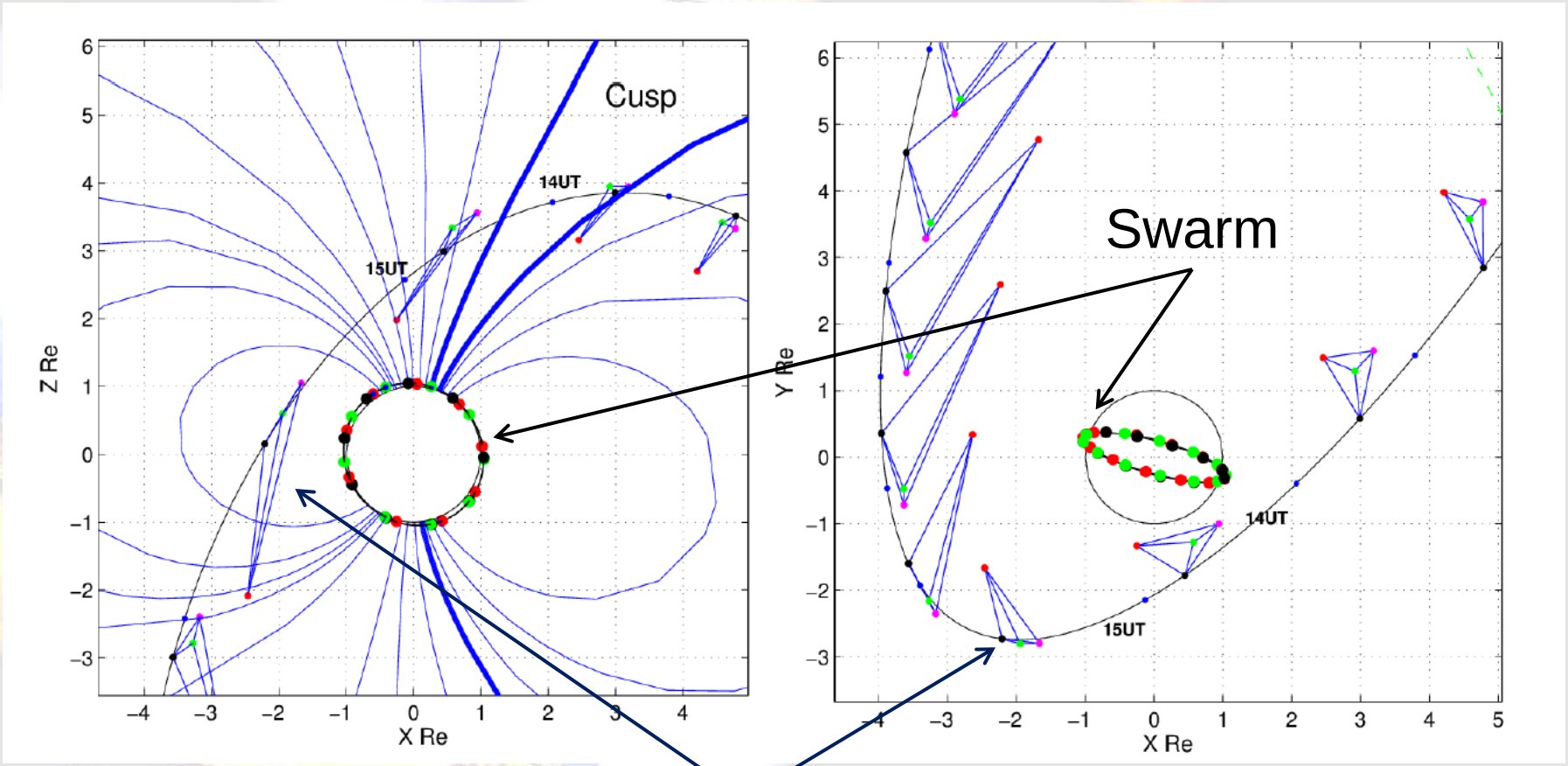
The Constellation:

- 3 identical satellites:
  - 2 side-by-side in low orbit (<460km)
  - 1 in higher orbit (< 530km)
- three orbital planes for optimal coverage in space and time
- Launch 2013: 4 years operations



ISSI Forum on Near-Earth electromagnetic environment monitoring with the Swarm-Cluster combination, 2013

Cluster - Swarm Conjunctions:
1st Observations during Swarm Commissioning, Dec. 2013



Dunlop et al., 2014

Cluster - Swarm Coordination:
Cluster "Guest Investigator" Program


Thank you !