# Cluster: Highlights and Case for Extension


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RAS Discussion Meeting:

The Geomagnetic Field: Preparing for the SWARM Multi-satellite mission 09 October 2009

## Contents

What is the Cluster mission?

Cluster and magnetospheric currents

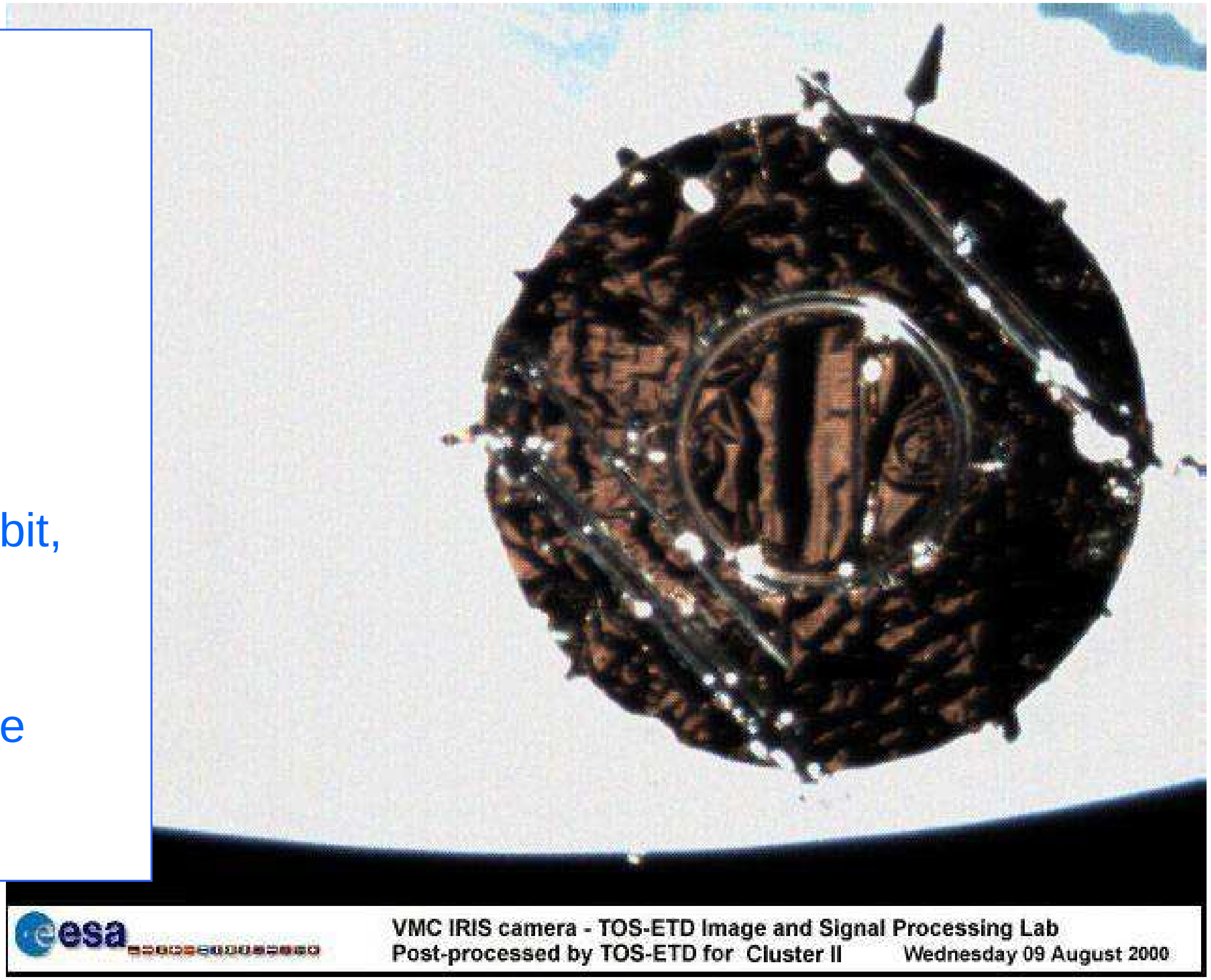
Selected additional Cluster Science highlights

Cluster extended mission and possible SWARM overlap

# Cluster: Introduction

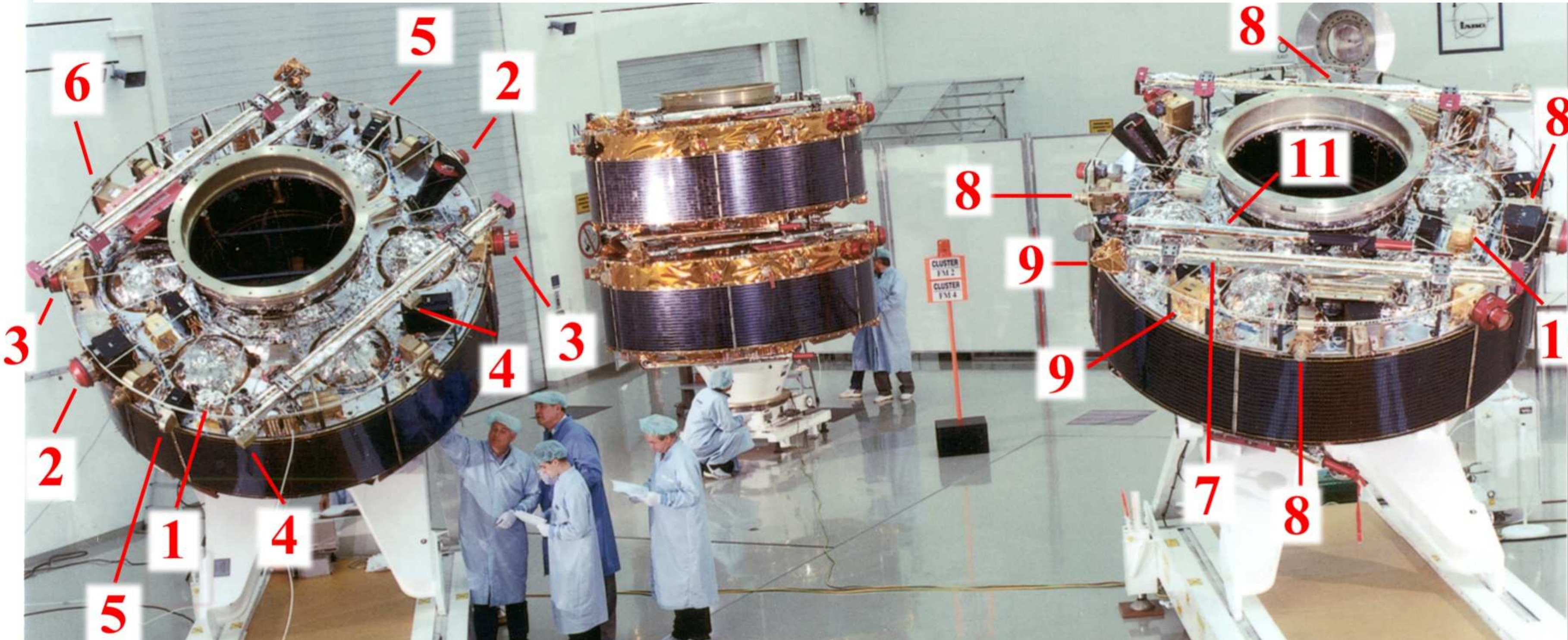
- ESA/NASA cooperative project
- Four spacecraft,

  co-orbiting, with variable separation distances
- Launched into a polar orbit, nominally 19.6 x 4 $R_E$
- Science Operations since February 2001



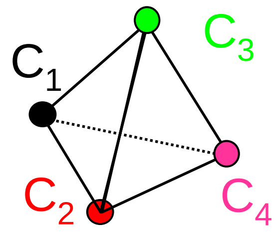
# Cluster : instrumentation

11 experiments; 44 identical instruments (41 in operation) measuring magnetic and electric field, ion and electron plasma properties and plasma waves




| | | | |
|---|---|---|---|
| 1 ASPOC, | potential control | 7 DWP, | digital wave processor |
| 2 CIS, | plasma ions | 8 EFW, | 2D electric field (booms) |
| 3 EDI, | 3D electric field (electron drift) | 9 STAFF, | plasma waves (search coil) |
| 4 FGM, | magnetic field | 10 WBD, | plasma waves (wideband) |
| 5 PEACE, | plasma electrons | 11 WHISPER, | plasma waves and sounder |
| 6 RAPID, | energetic ions, electrons | | |

# Cluster: Why 4 Spacecraft ?



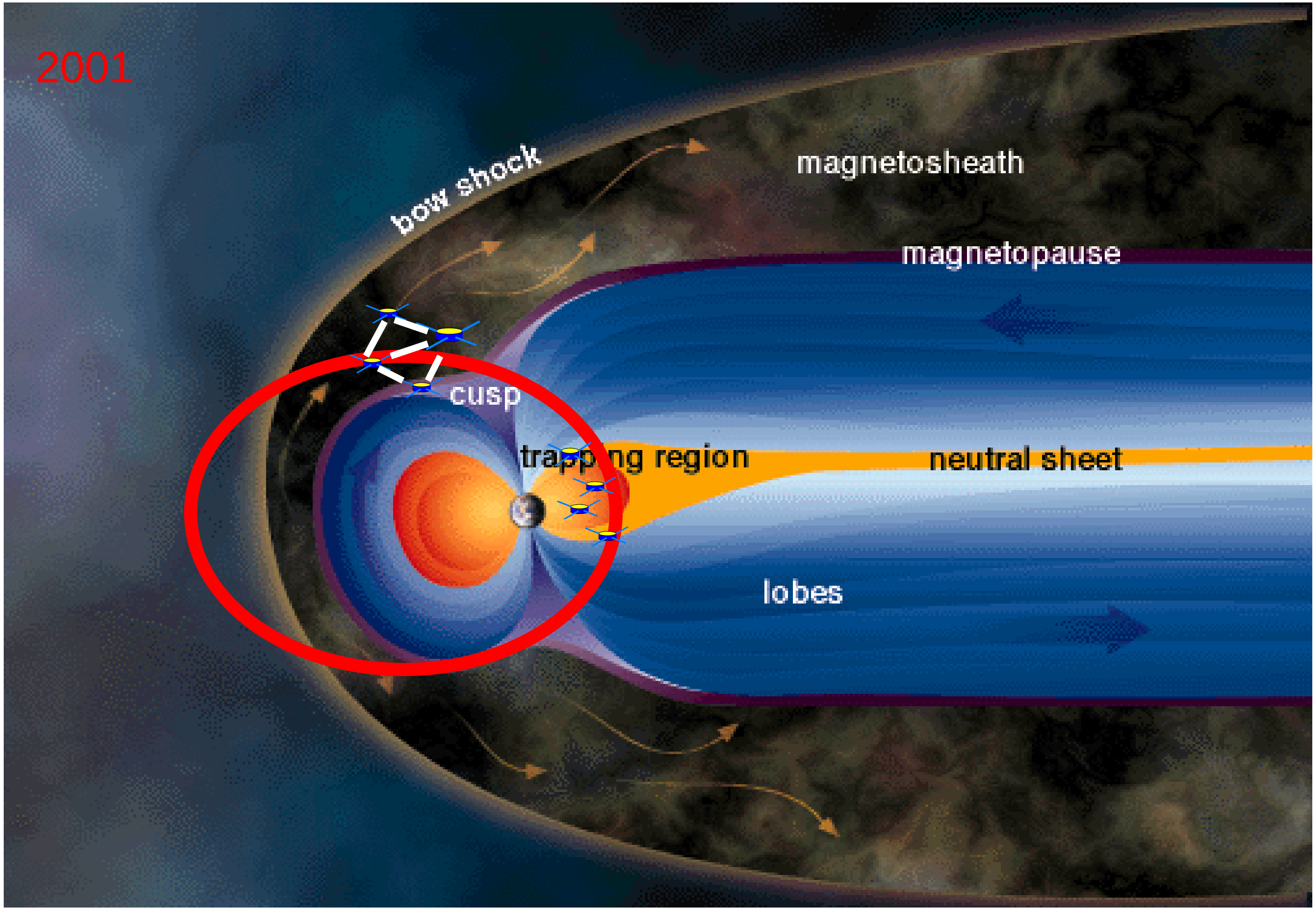

For the first time, Cluster four-point data enable us to :

- distinguish encounters with structures, from transient phenomena, and characterise waves
- use $\nabla \mathbf{B}$, $\nabla n$ for timing boundary motions in any direction
- determine current density $\mathbf{j} = \nabla \times \mathbf{B} / \mu_0$ (for $\partial E/\partial t \sim 0$) and hence local $\mathbf{j} \times \mathbf{B}$ force
- determine $\mathbf{\Omega} = \nabla \times \mathbf{v}$, hence contribution of flow shear to field aligned current $\mathbf{j}_{||} = \int dt\, \mathbf{B}.\nabla\, \mathbf{\Omega}_{||}$, (magnetic helicity $\alpha = j_{||}/B$)
- determine $\nabla \mathbf{P}$, in steady state $\partial\alpha/\partial s = (\nabla \mathbf{P} \times \nabla \mathbf{B}^2)/B^4$

And more…

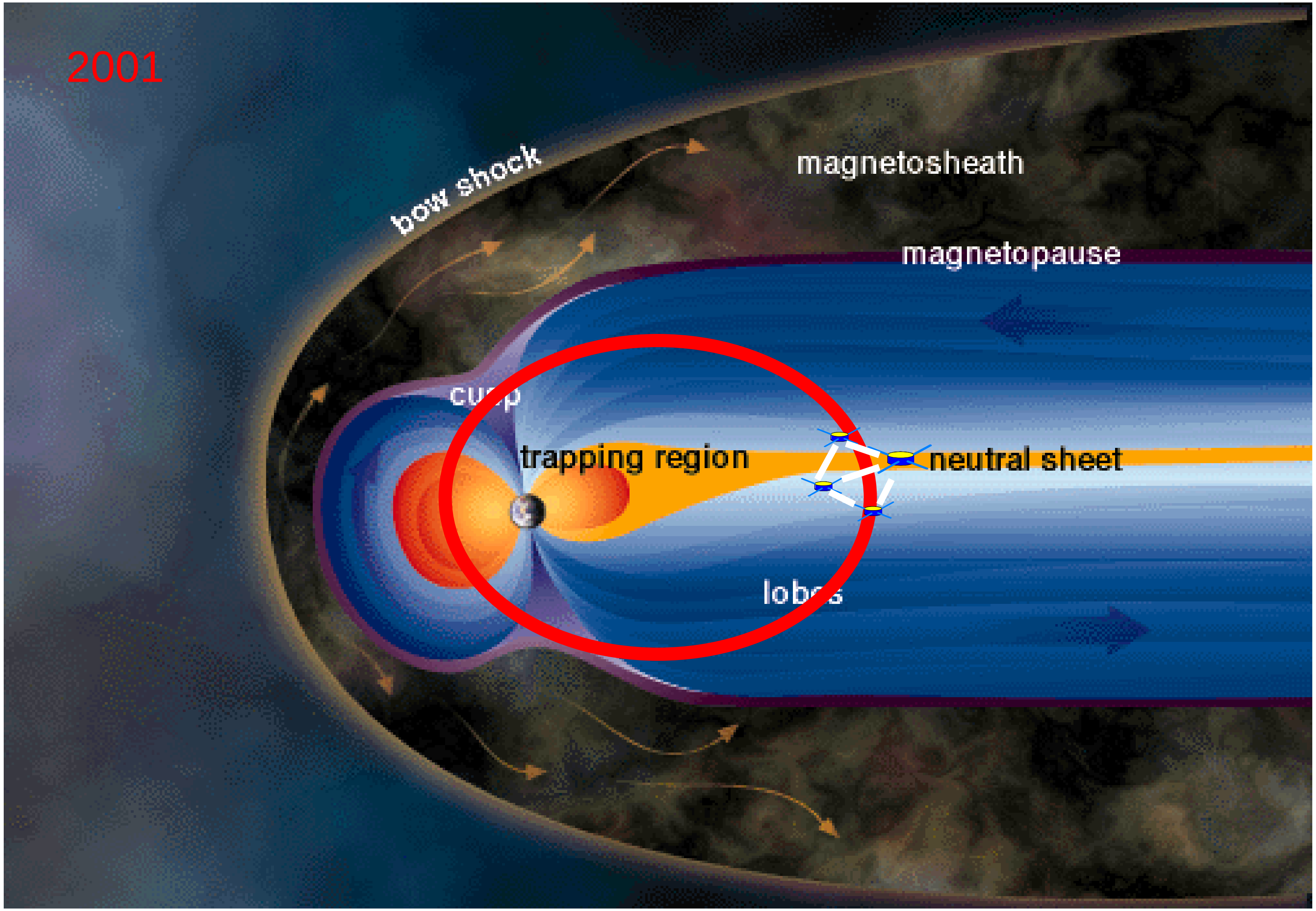
# Cluster : early mission phase

## dayside targets: high latitude magnetopause, cusp, bowshock

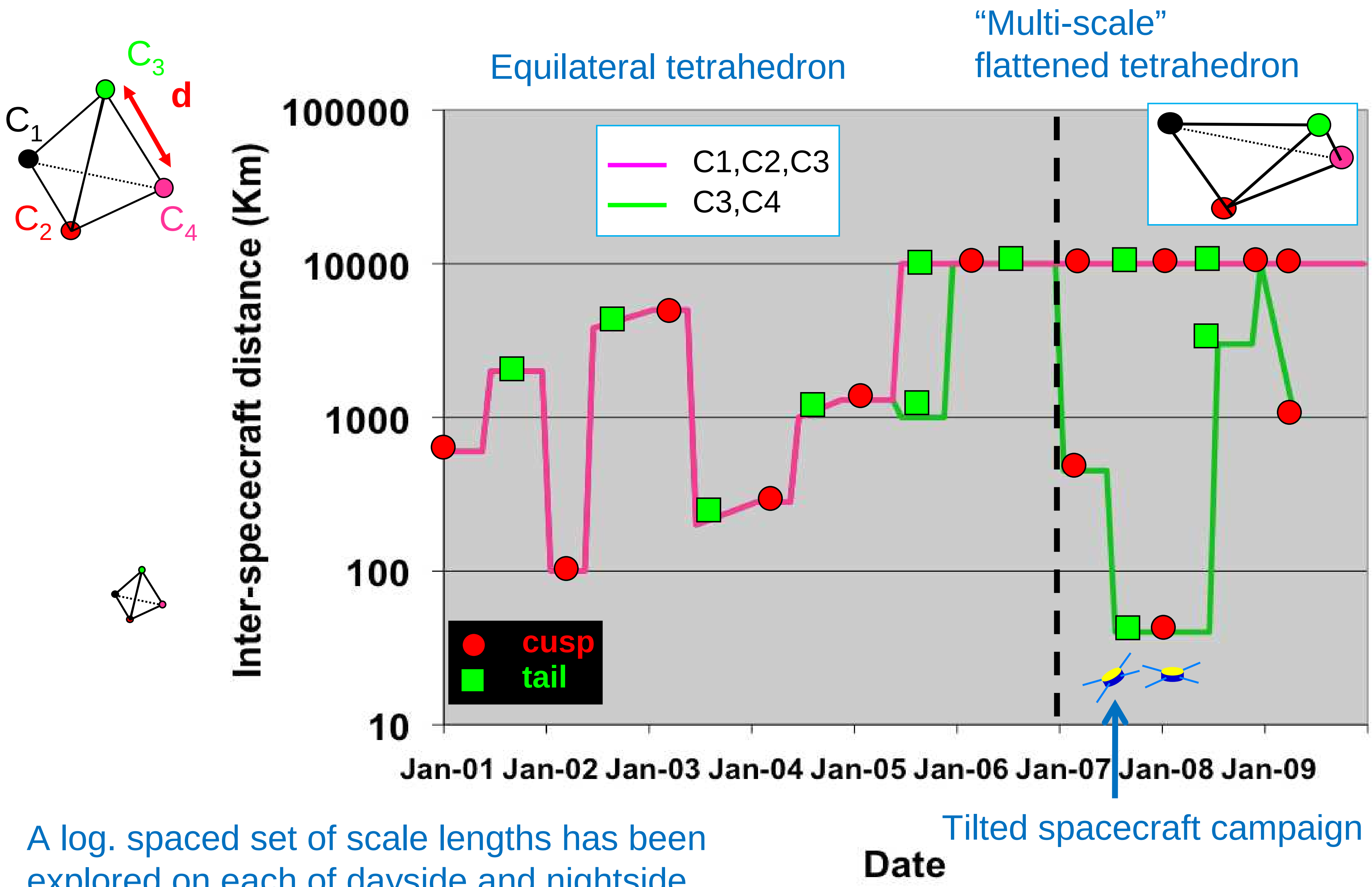


# Cluster : early mission phase

## nightside targets: mid latitude cusp, magnetotail plasma/current sheet



## Cluster: Spacecraft Separation Strategy



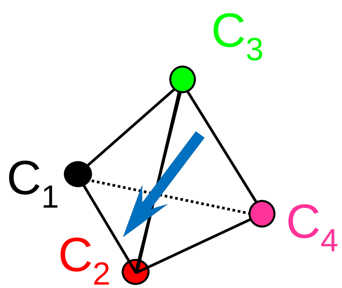

A log. spaced set of scale lengths has been explored on each of dayside and nightside

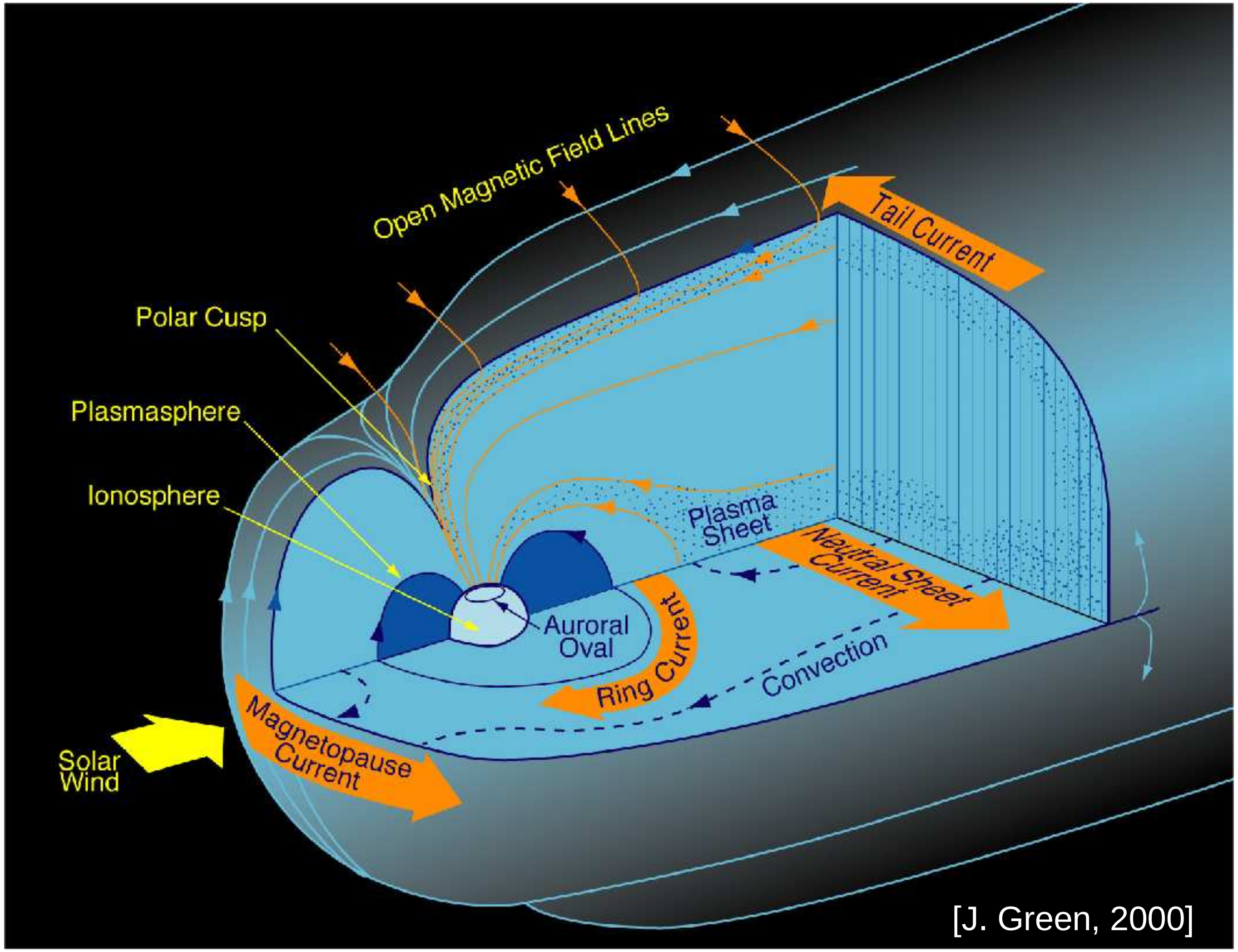
# Selected science highlights

- Measuring magnetospheric currents
- Measuring boundary motion
- Magnetic reconnection discoveries

# The magnetosphere: shaped by electric current

The boundary, ring and field-aligned currents vary as solar wind pressure and magnetic field changes, producing magnetic perturbations that SWARM will observe.



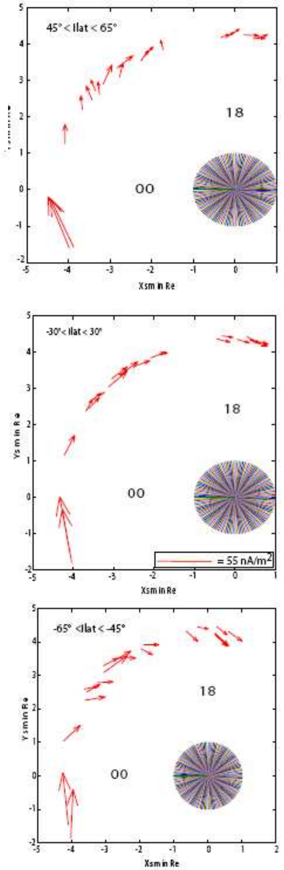




Ampère's law

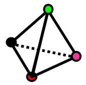
$\vec{J}_o = \text{curl } \vec{B}$

## Ring current

$Y_{SM}$




45°<ILAT<65°



100, 200 km

-30°<ILAT<30°

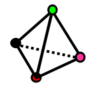
-65°<ILAT<-45°

$X_{SM}$

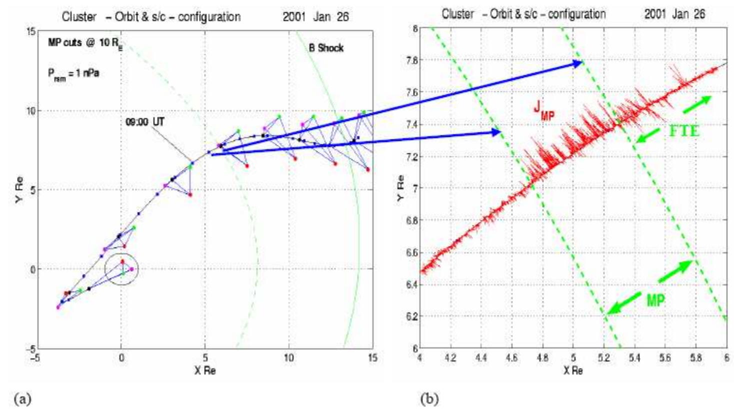
Current density from curlometer, using many passes, mean value *20 nA/m²*. Inter-hemispheric differences seen

[Vallat et al., Annales Geo., 2005]

## Magnetopause current



200 km




(a) (b)

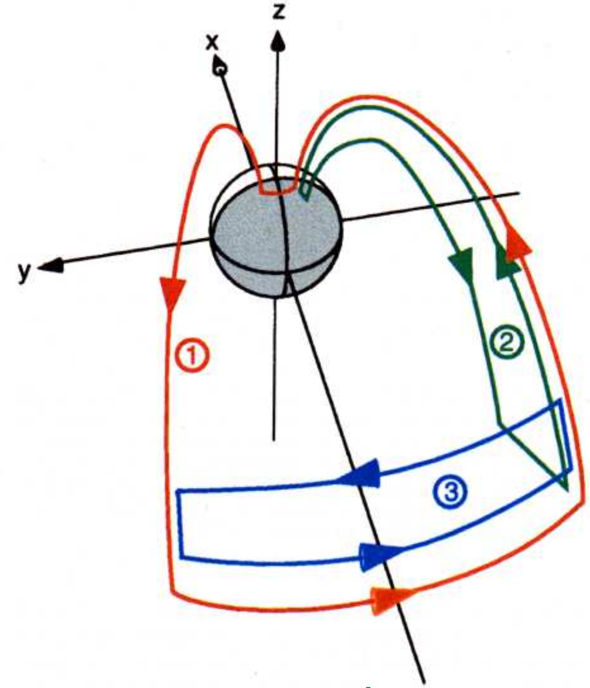
Current density from curlometer, at a magnetopause crossing. The boundary is in motion, hence multiple current spikes.

Typical current densities range from *9 to 40 nA/m²*, in the direction expected from the Chapman-Ferraro model.

Typical current layer thicknesses from 300 to 1,500 km, typically ~ an ion gyroradius

[Dunlop and Balogh, Annales Geo., 2005]

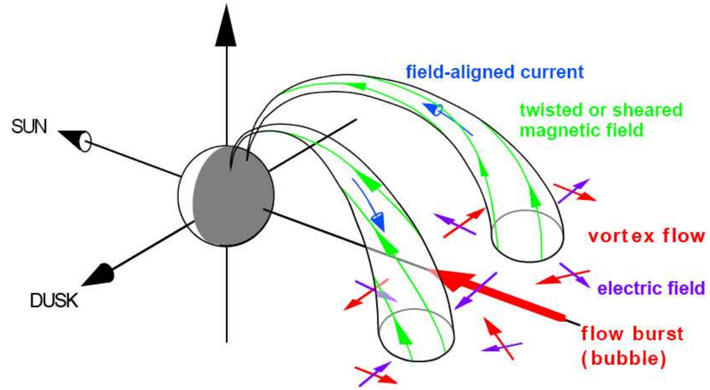
# Field-aligned currents:
## examples of FACs due to dynamic phenomena




Substorm current wedge FAC system e.g. modelled by Birn et al, 1999 observed by many authors

Cusp and FTE FACs studied with Cluster by several authors

[e.g. review by Amm et al. Annales Geo., 2005; also Marchaudon et al., Annales Geo., 2006,9]




Plasma bubble (identified with bursty bulk flow) e.g. modelled by Birn et al, 2004

First detailed observations by Cluster confirm main “bubble” model predictions and add new aspects

[Walsh et al., Annales Geo., 2009]

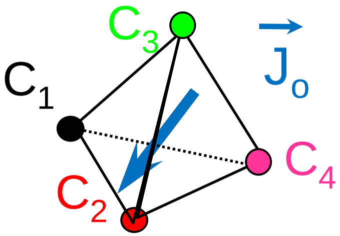
Cluster case study also determined a field-aligned current density at *5 nA/m²*; translated to the ionosphere this is *18,000 nA/m²*

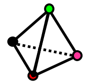
[Forsyth et al., Annales Geo., 2008]

# Strongest and thinnest current sheet measured in the tail

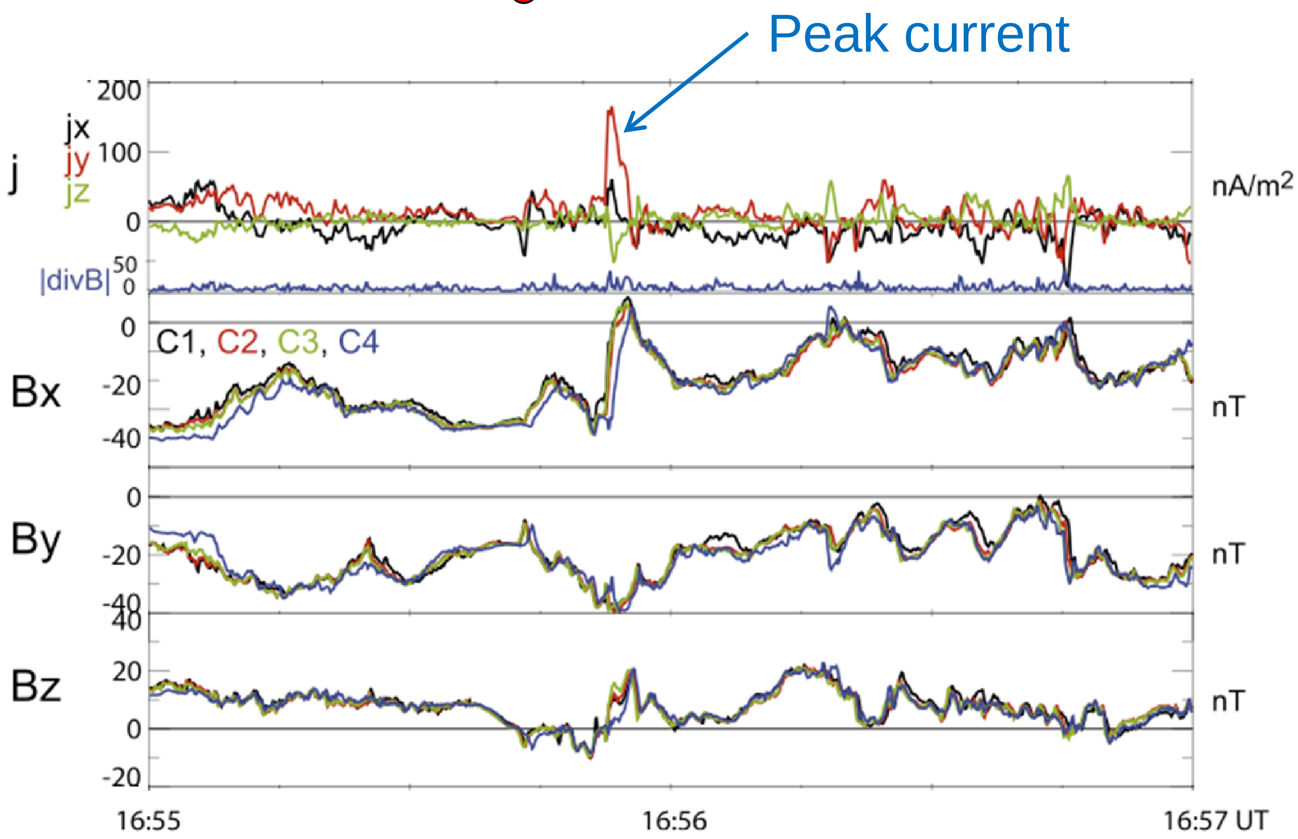
Ampère's law

$\vec{J}_o = \text{curl } \vec{B}$

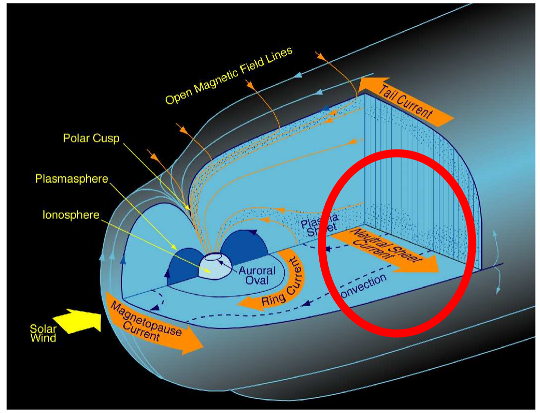


200 km




17 Aug. 2003



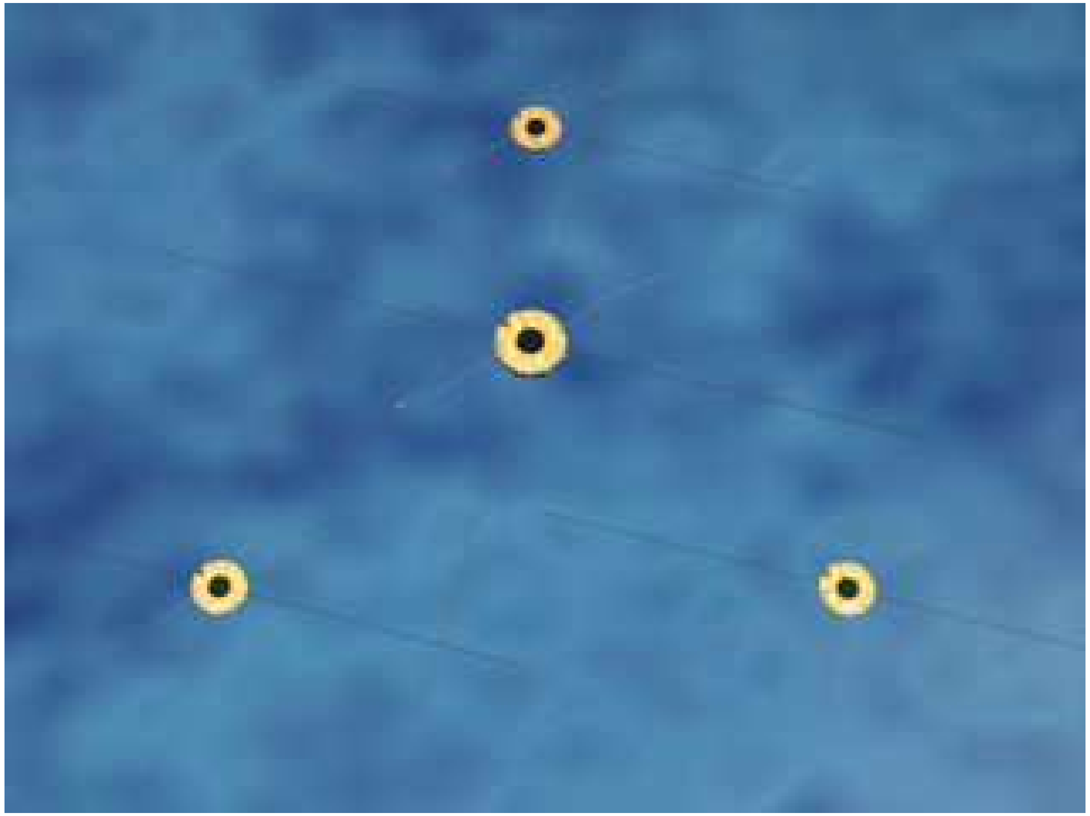

$J_o$= *180 nA m$^{-2}$* max

Thickness=300 km

= ion skin depth $c/w_{pi}$

[Nakamura et al., JGR, 2008]

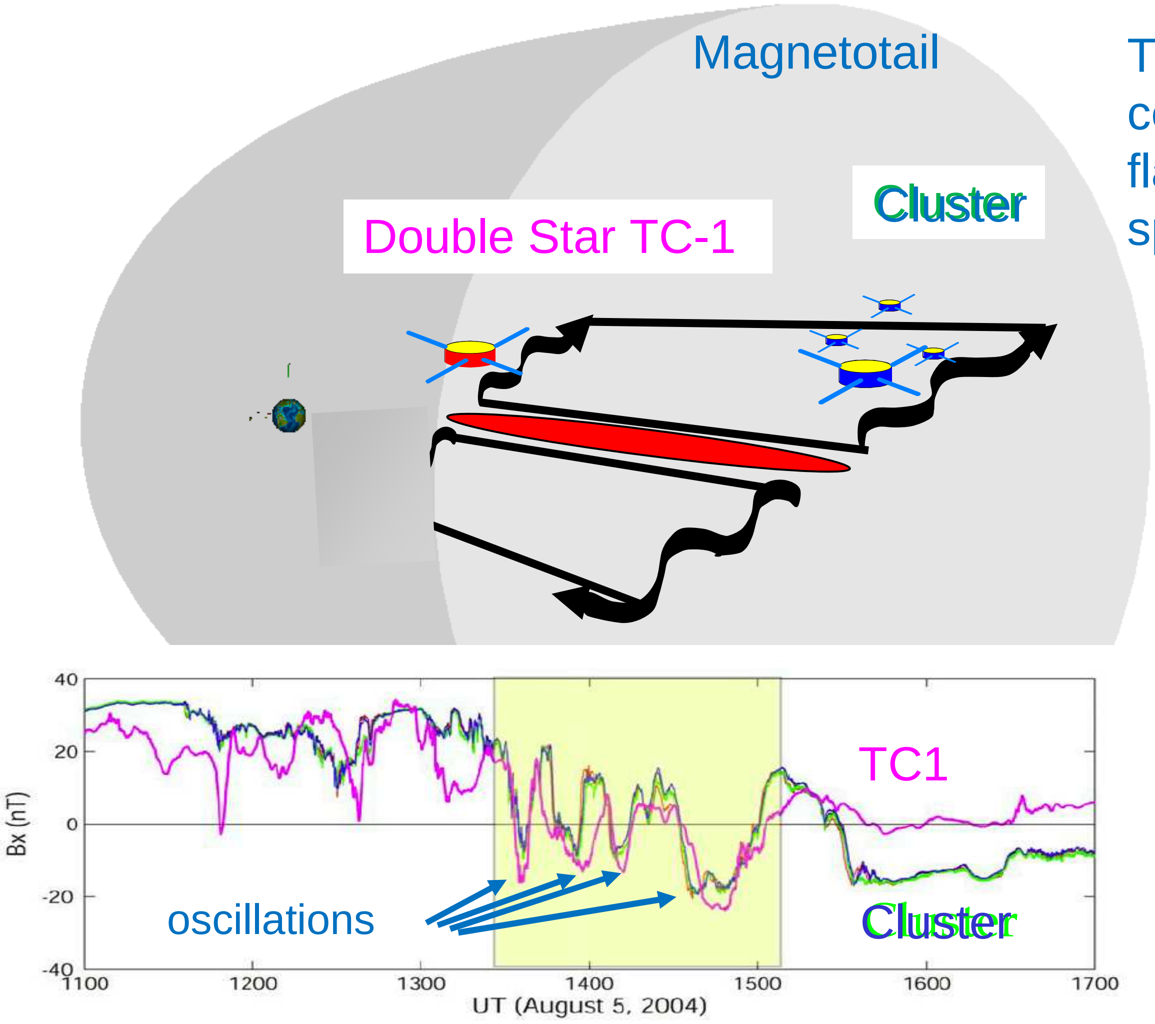
# Boundary motion: surface waves

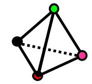


- 4 spacecraft minimum to fully characterise them

# Tail plasmasheet: wavy motion

The motion of the plasmasheet was known from earlier missions but not understood



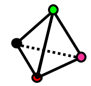

The waves originate from the central plasmasheet and travel flankwards (east and west). Their speeds are 50-150 km/s.
[Sergeev et al., GRL, 2004]

The waves are found to be in phase at widely separated sites along the tail (11 and 16 $R_E$), suggesting a common source.
[Zhang et al., Ann. Geophys., 2005]

The waves are “kink” type, seen with “bifurcated” current sheets
[Runov et al.,GRL, 2003a]

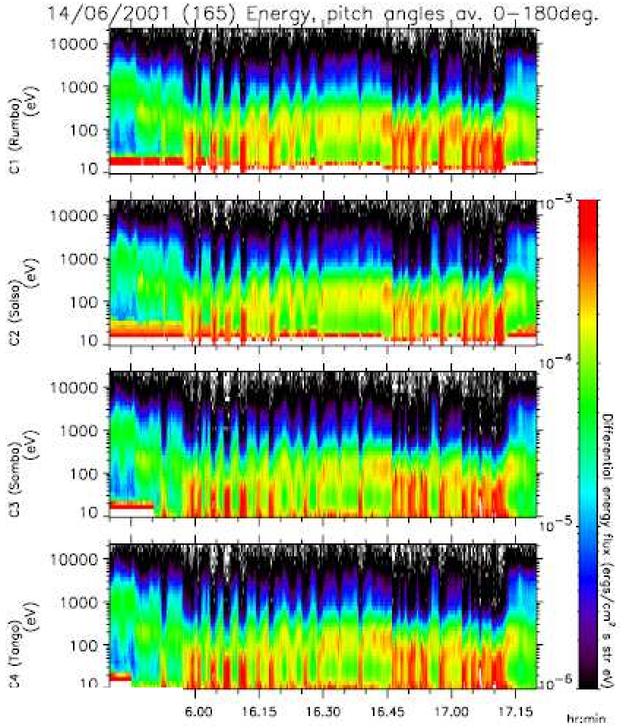
A suggested explanation is that “bursty bulk flows” trigger a Kelvin-Helmholtz instability
[Volwerk et al, GRL., 2007]

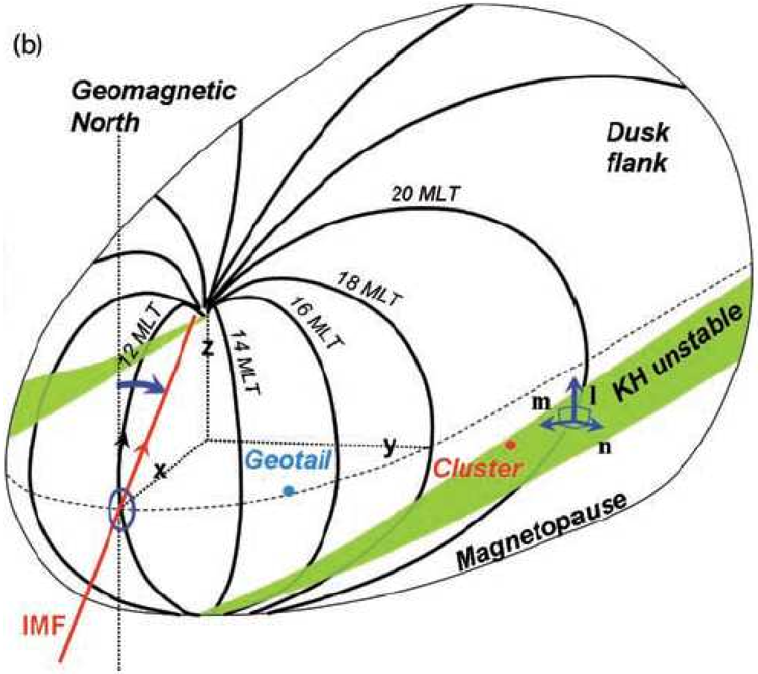
# Magnetopause: Kelvin-Helmholtz waves

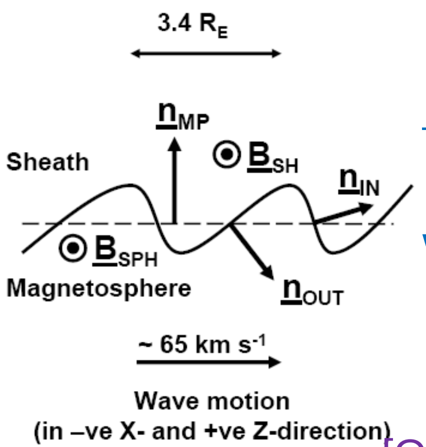


2000 km

Electron energy spectra from the 4 spacecraft, showing periodic boundary crossings




## Dawn flank waves

KH wavelength ~3 $R_E$

Waves not sinusoidal

Northward component of wave motion (minimises k.B)

[Owen et al., Annales Geo., 2004]

## Dusk flank waves

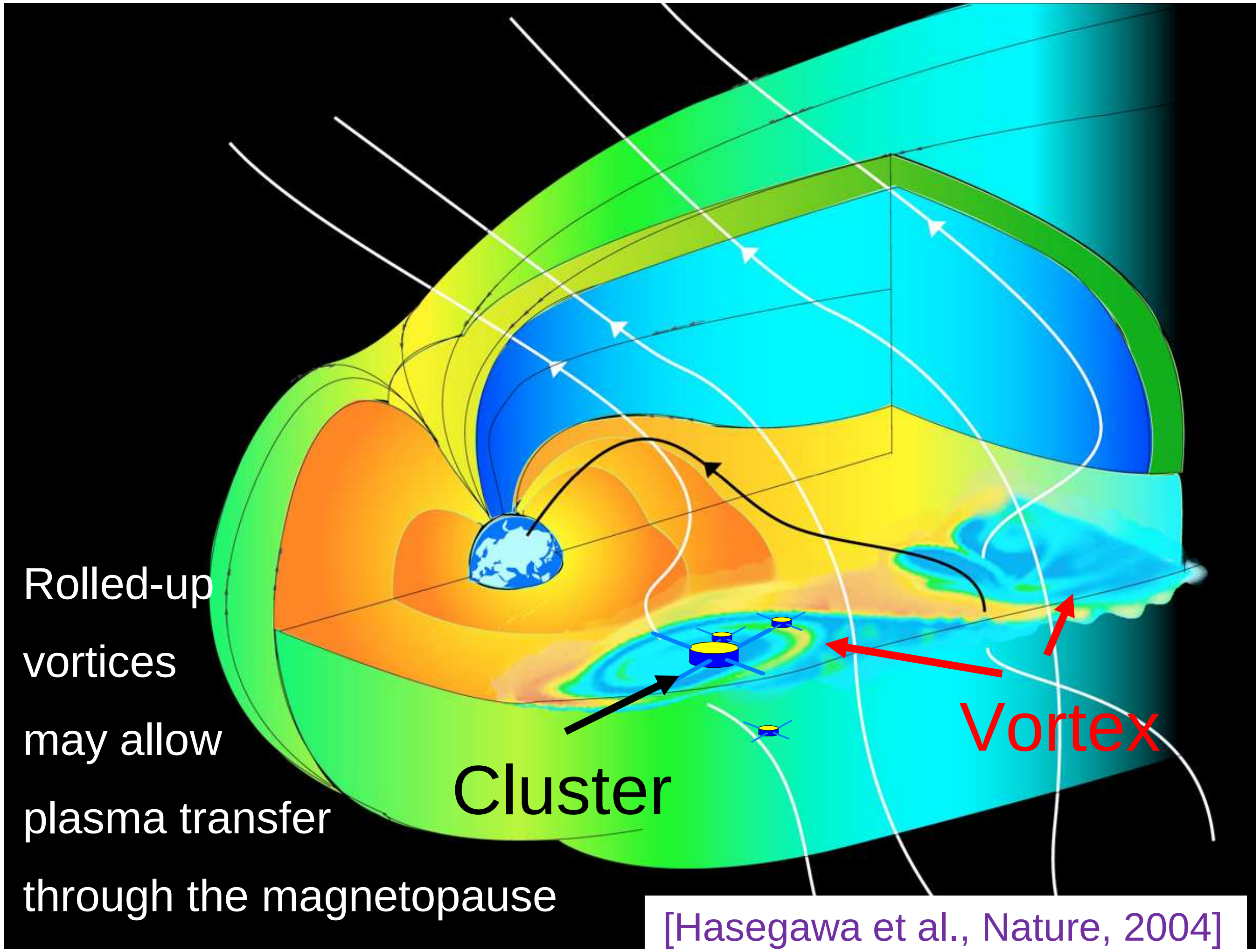
LLBL thickness grows tailward

KH wavelength controlled by IMF clock angle (IMF more northward larger length)

KH instability widens LLBL

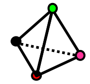
[Foullon et al., JGR, 2008]

# Magnetopause: From waves to vortices, and reconnection



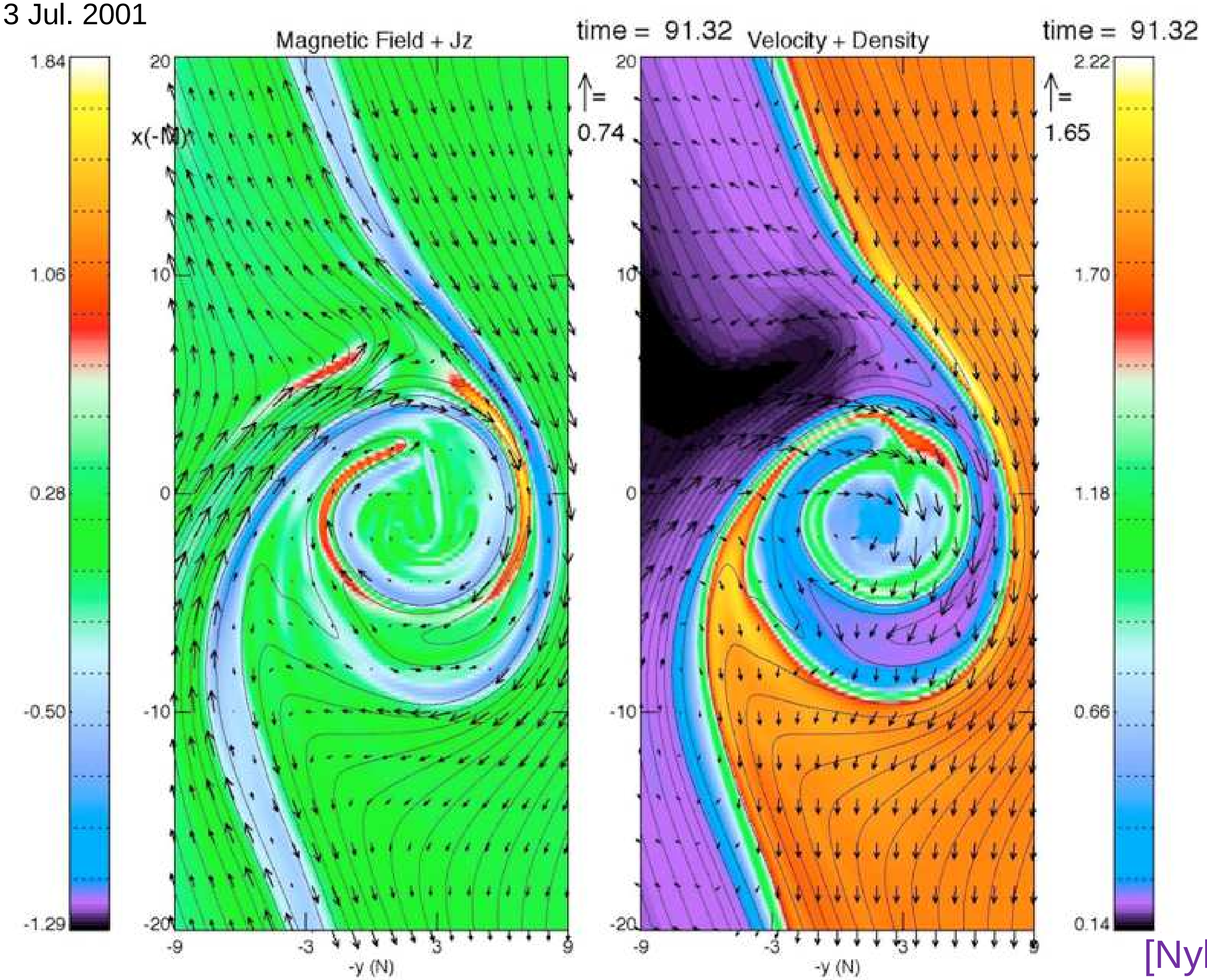

[Hasegawa et al., Nature, 2004]

# Kelvin-Helmholtz vortices and reconnection in flanks



2000 km

3 Jul. 2001




MHD simulation of Kelvin-Helmholtz vortices

Reconnection taking place inside vortex

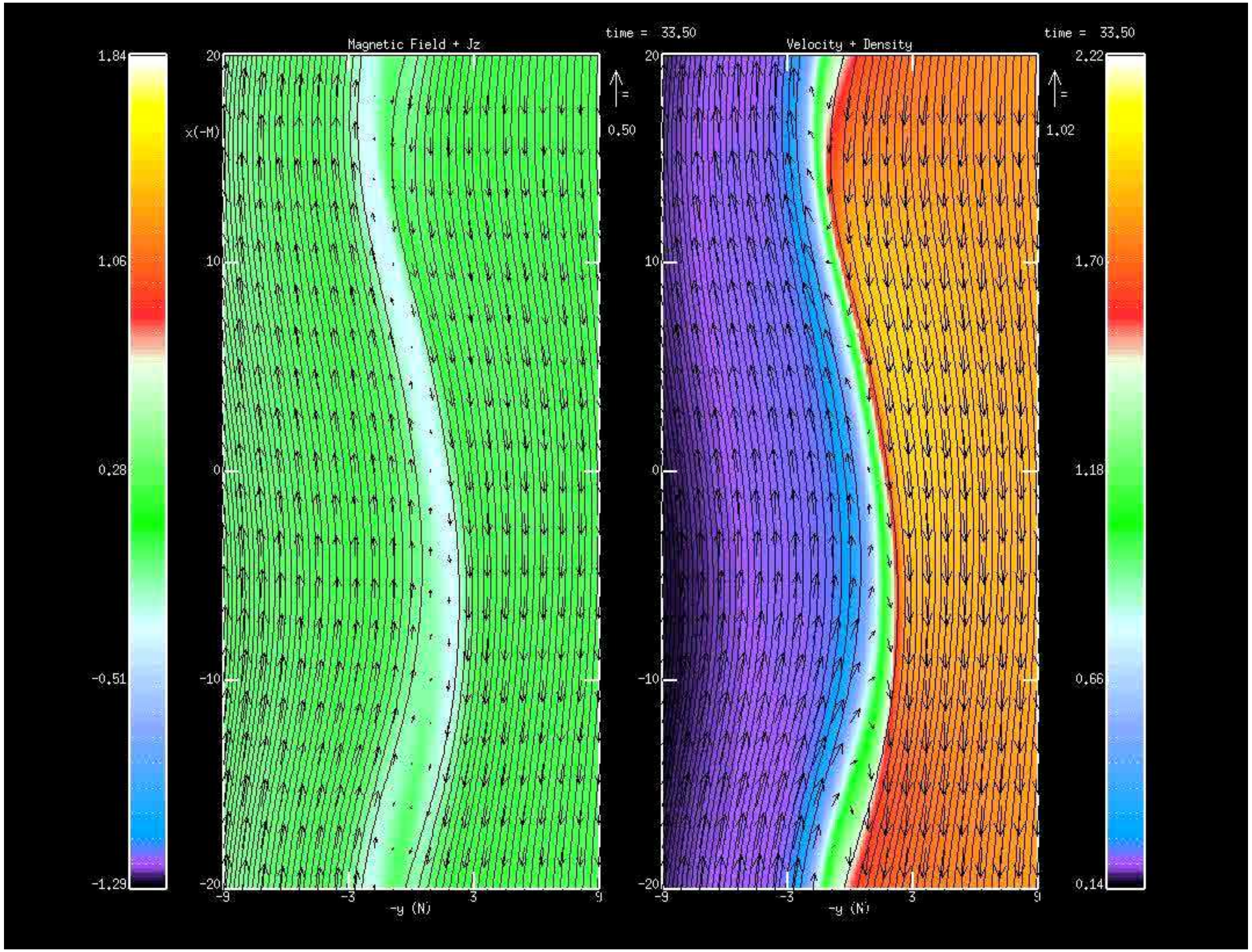
Reconnection evidence observed on Cluster ion data (Walen test)

wave length ~ $6R_E$

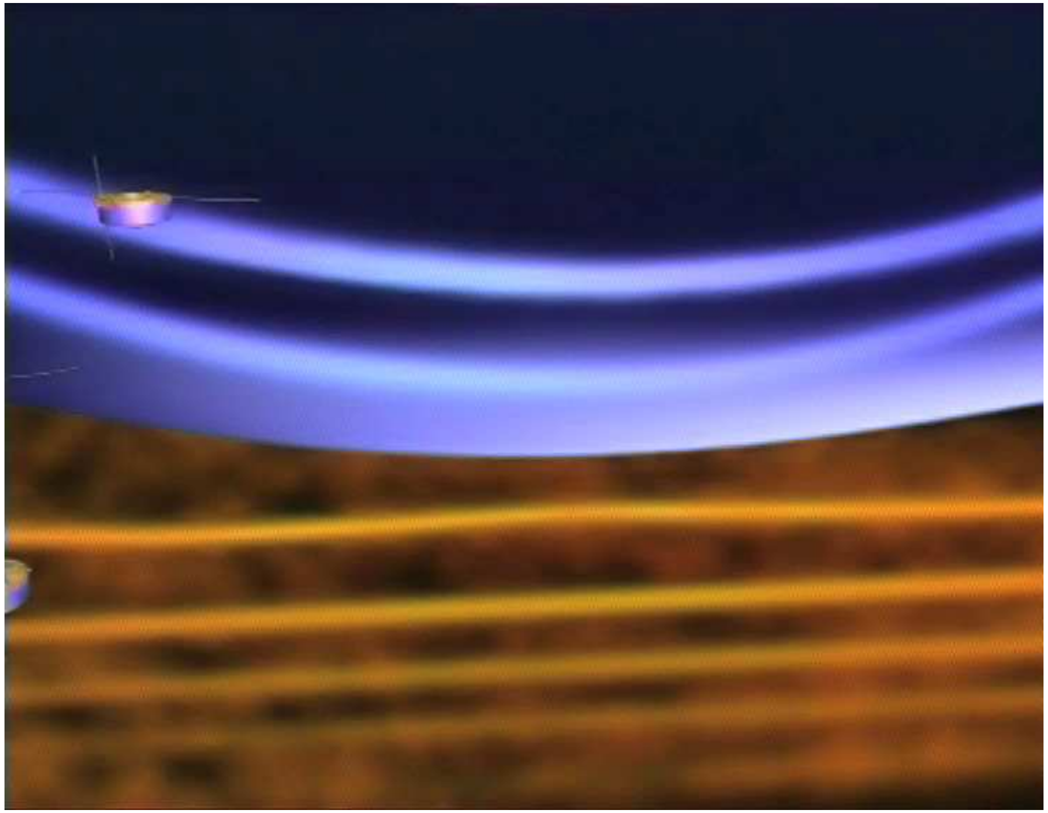
Interesting to think about how this might create ionospheric signatures and field-aligned currents

[Nykyri et al., Annales Geo.,2006]

# Simulation of Kelvin-Helmholtz vortices

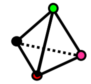


# More magnetic reconnection discoveries



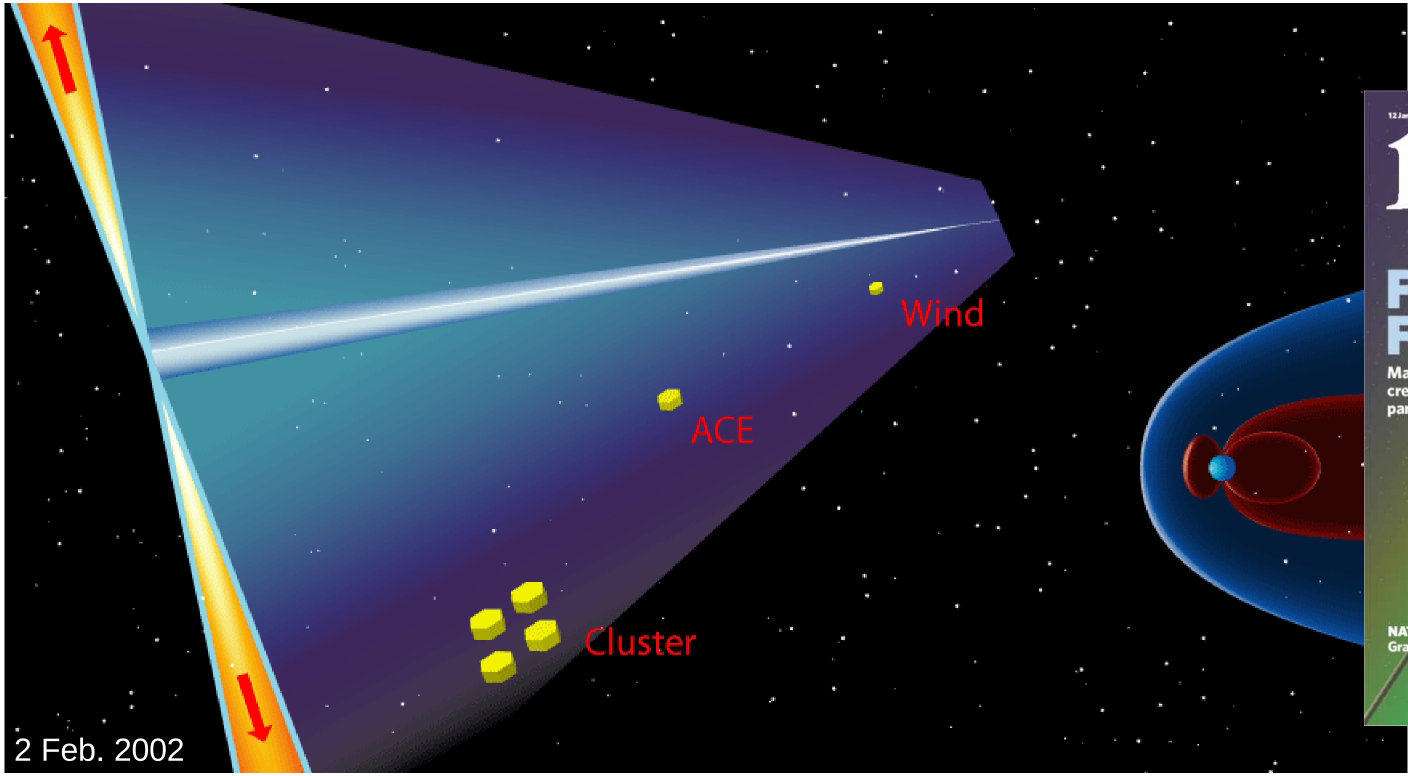
- First time observed with 4 spacecraft
- Reconnection review paper: Paschmann, GRL, 2008

# Largest reconnection line ever directly measured:



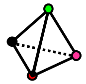
100 km

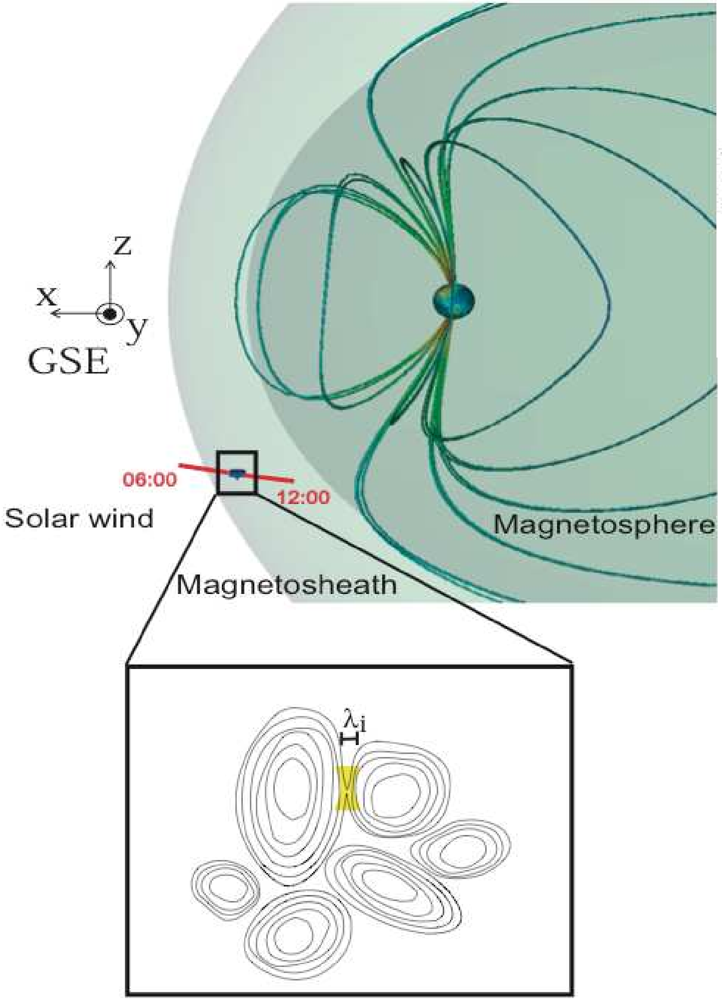
Simultaneous observation of outflow jets from ongoing reconnection at a current sheet in the solar wind, by spacecraft separated by 2.5 million km (~10 times the Earth-Moon distance) [Phan et al, Nature, 2006]

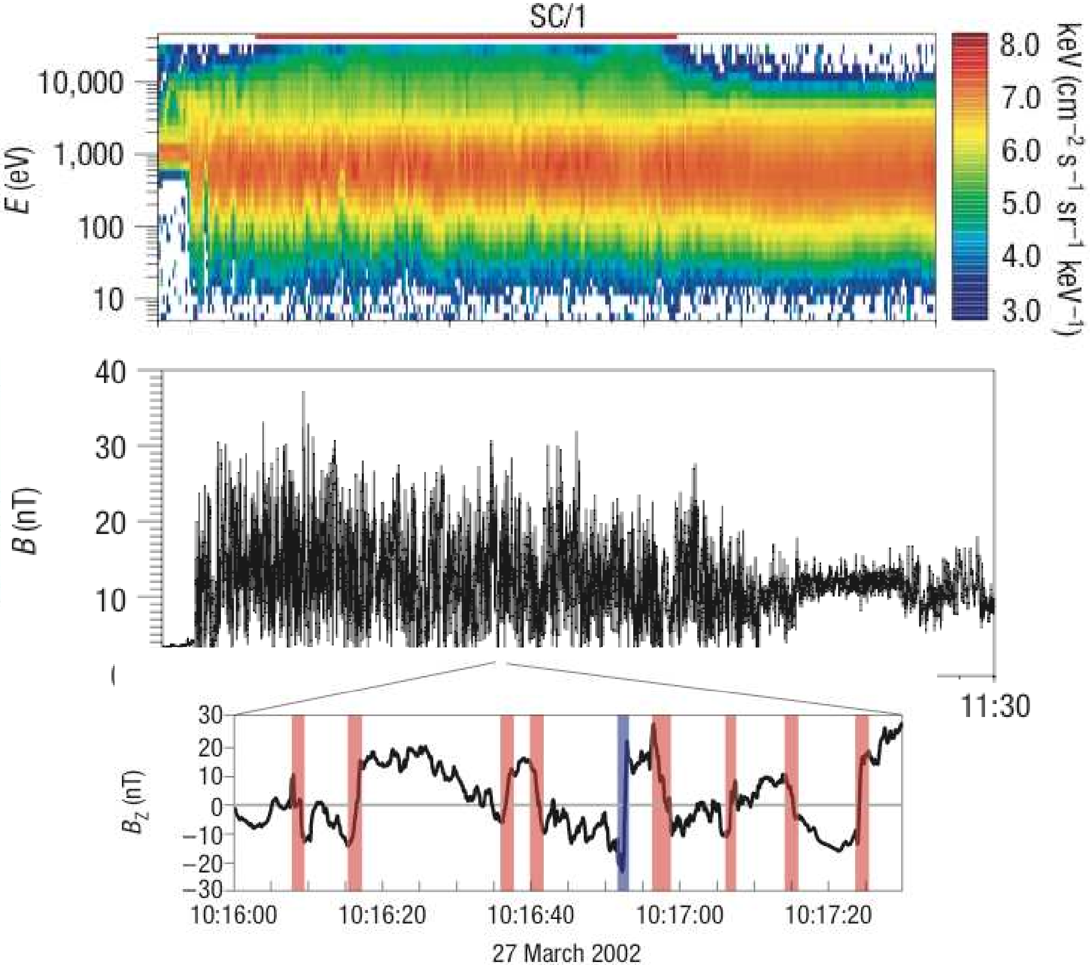



# Discovery of reconnection in a turbulent space plasma

Acceleration of electrons, and electric field up to 2 mV/m are signatures of reconnection at thin current sheets in the magnetosheath



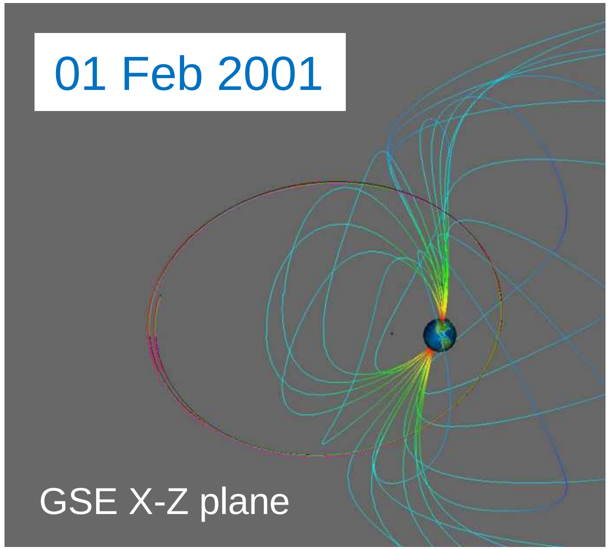

[Retino et al., Nature Physics, 2007]

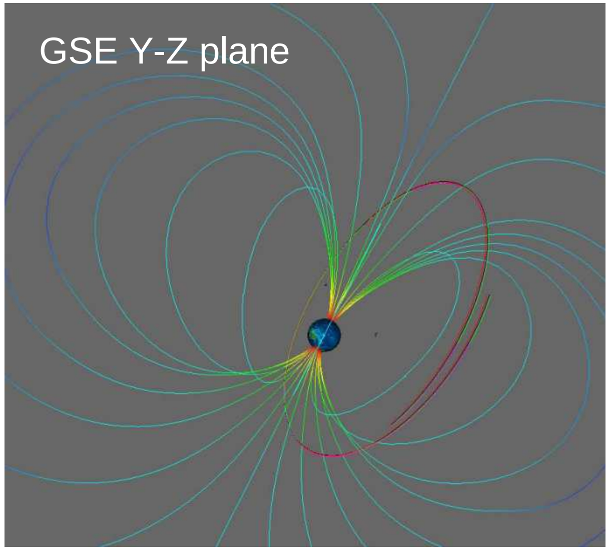
# Cluster extension Jul 2009-Dec 2012

- Orbit evolution
- New science opportunities
- Spacecraft status
- Cluster Active Archive and publications

# Cluster : extended mission phase
## orbit evolution

[OVT tool and ESOC/JSOC orbit predictions used for these plots]

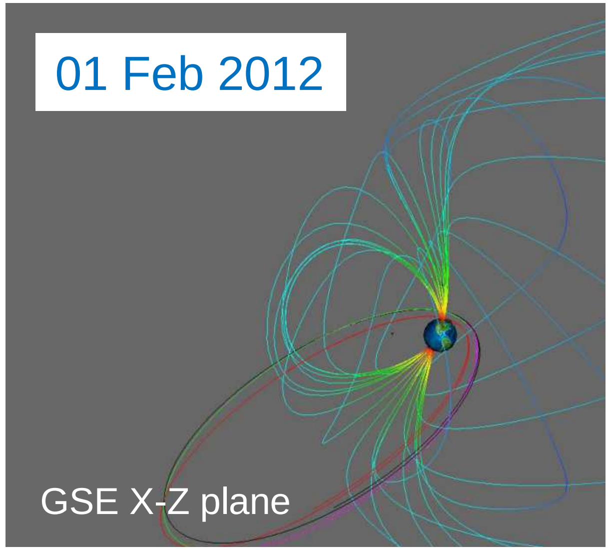


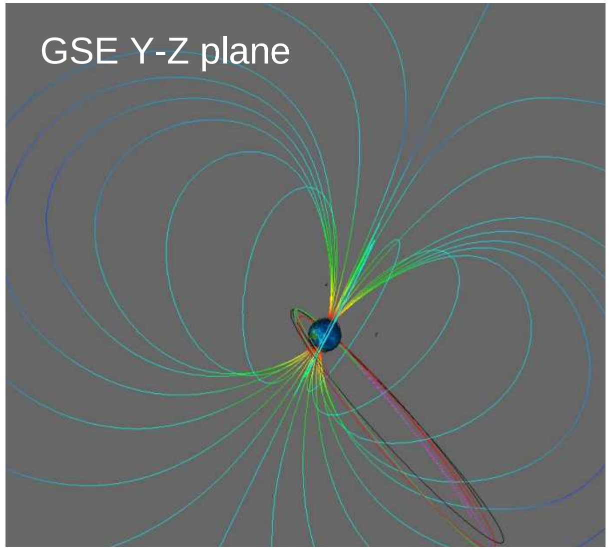




Orbit perigee has fallen from 4 $R_E$ to a fraction of an $R_E$. The min. altitude varies – below 1000km on some s/c in 2011 (enables auroral acceleration studies).

Orbit plane has tilted away from 90° to ~140° (no more high latitudes or cusp, but better mid-latitude inner m'sphere)

Line of apsides rotating southwards (surveys a range of magnetotail crossing distances and magnetpause latitudes)



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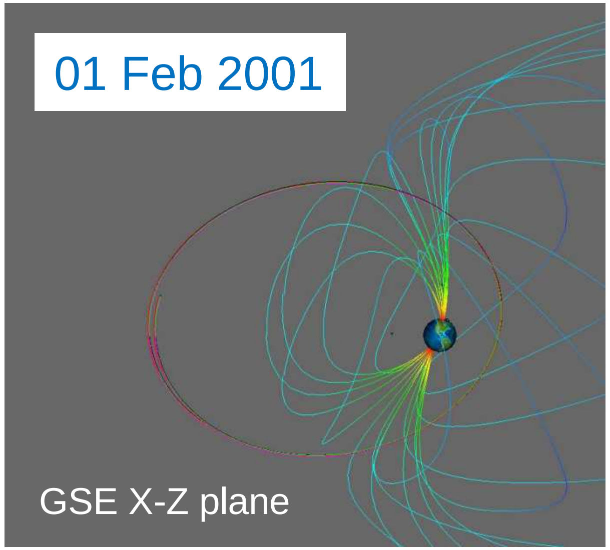


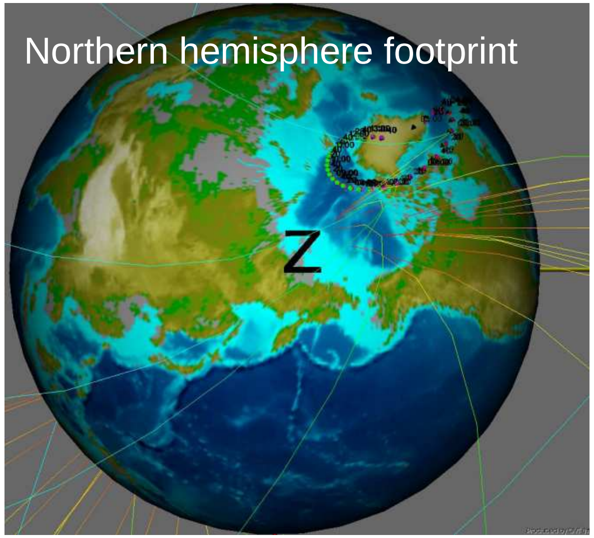


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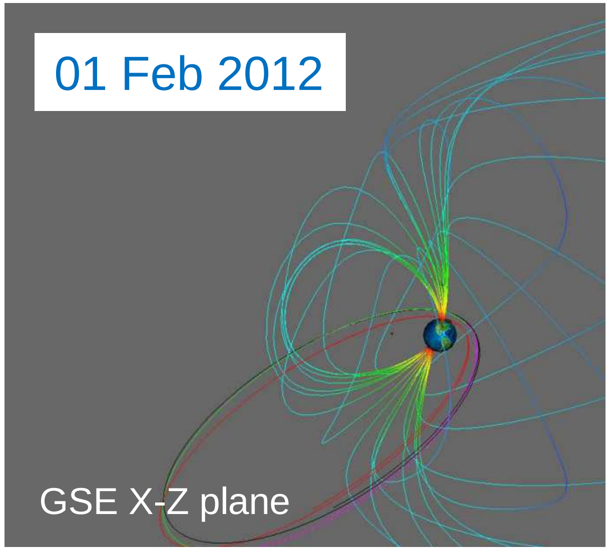


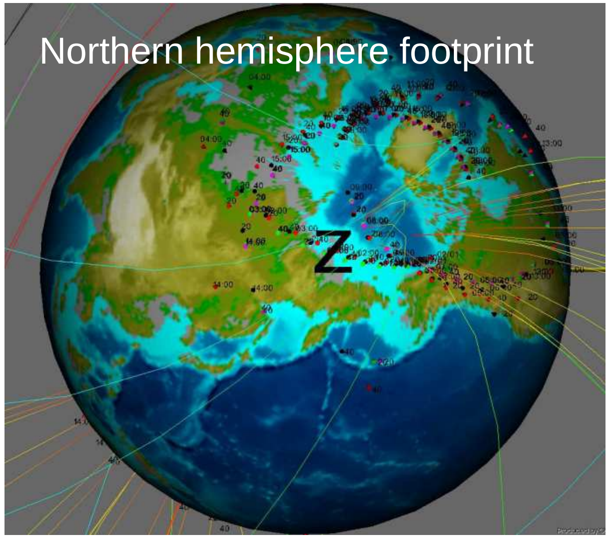

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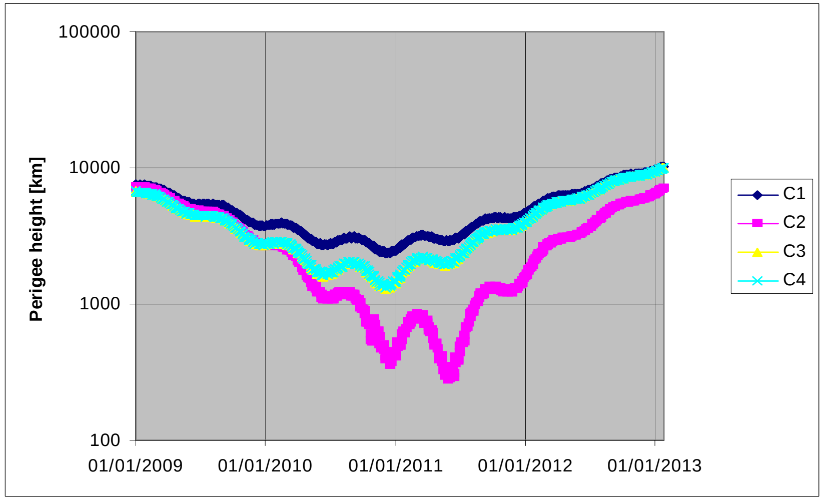


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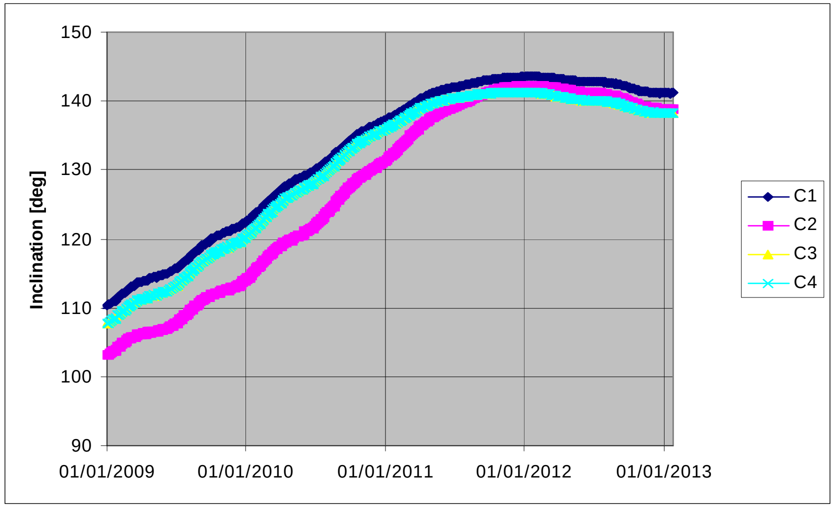
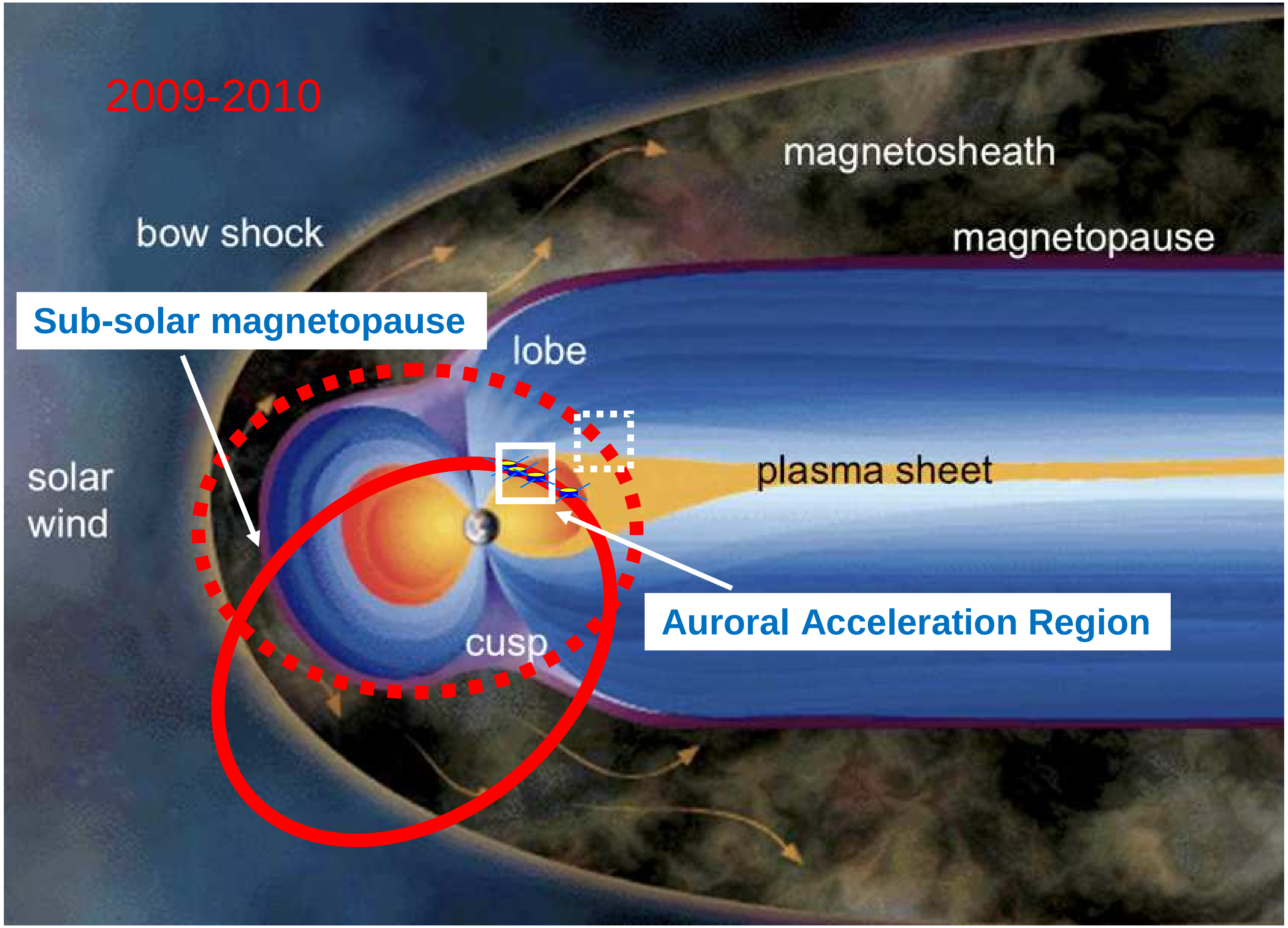


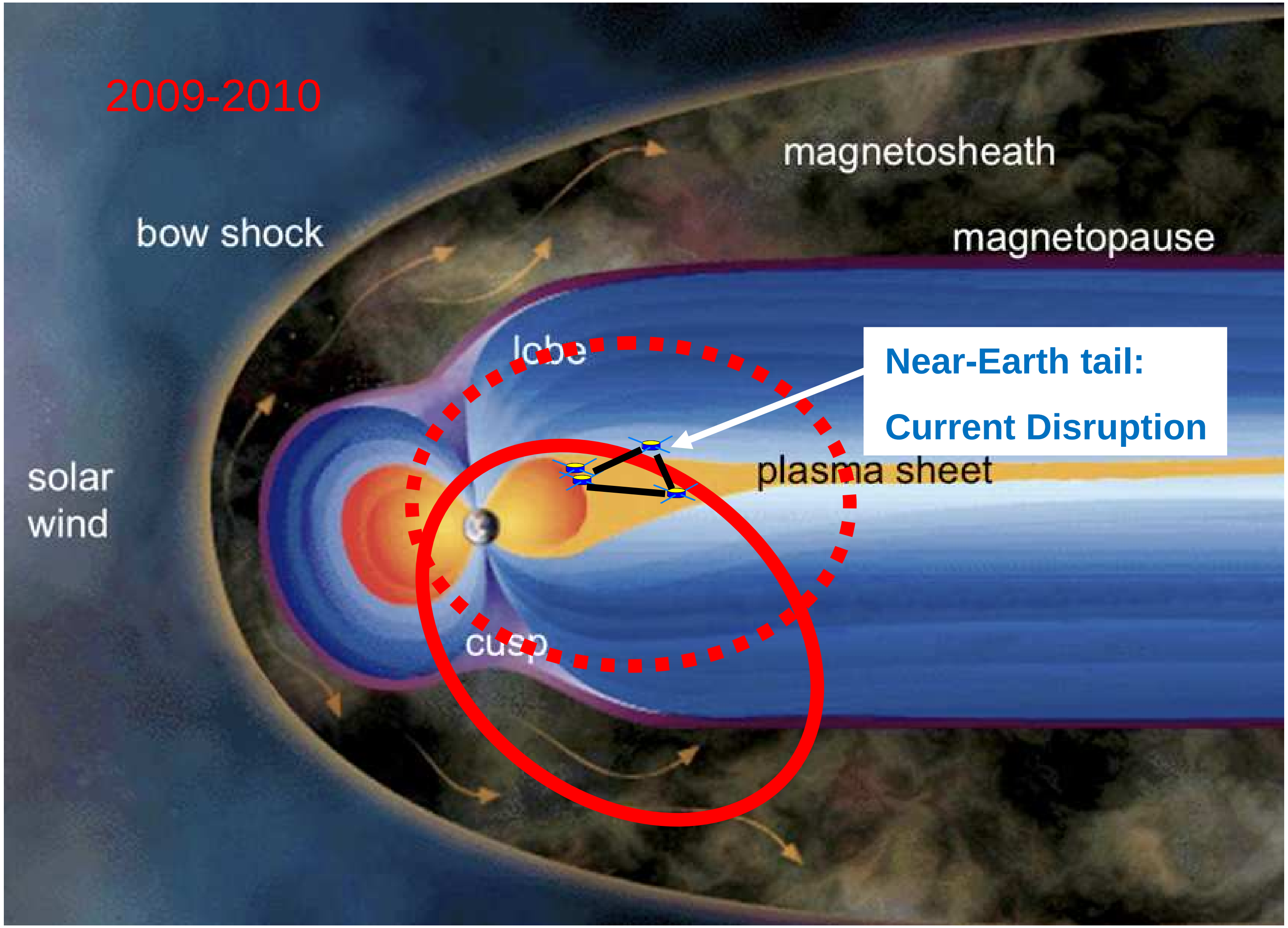
# Cluster : extended mission phase

## dayside targets: sub-solar magnetopause, auroral acceleration region



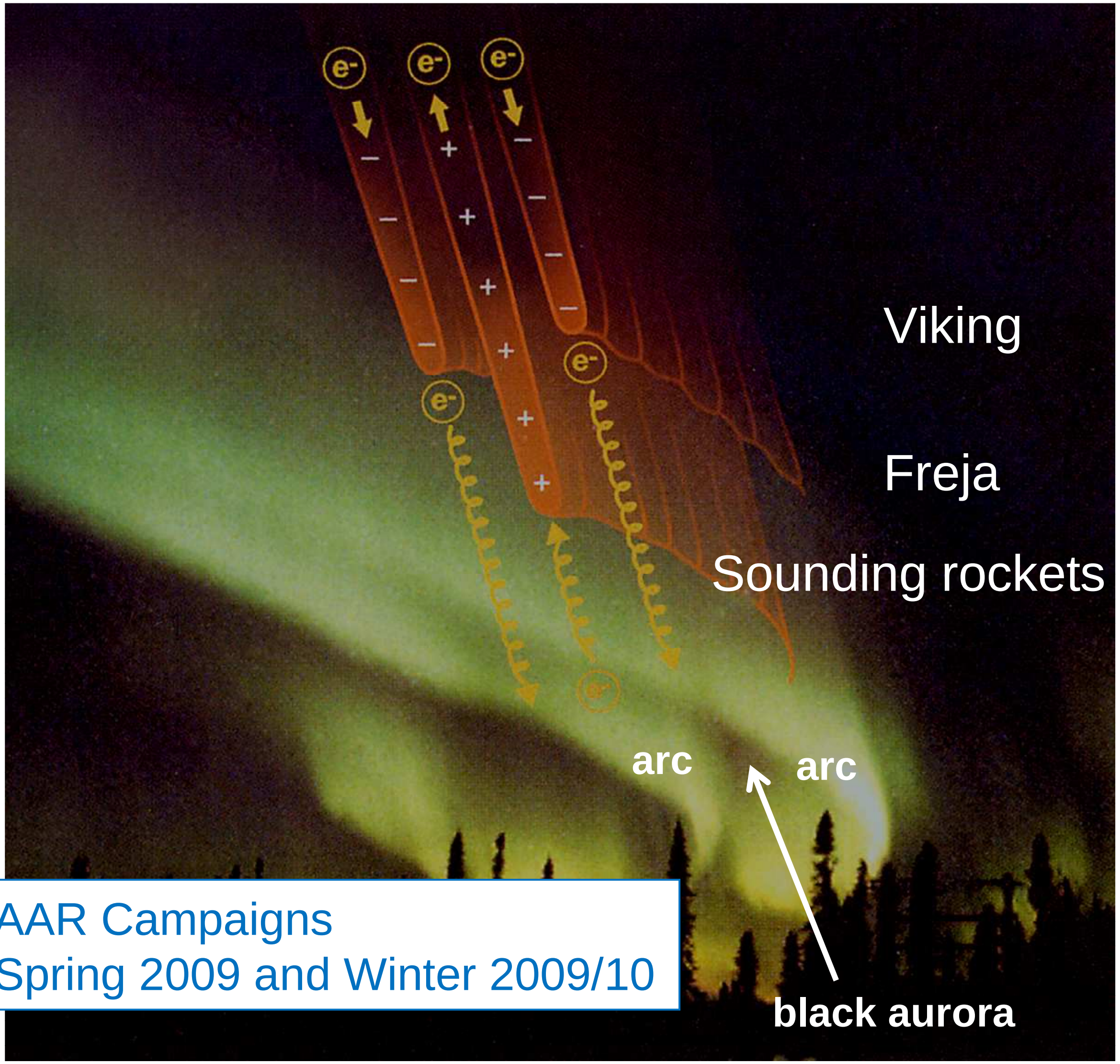
# Cluster : extended mission phase

## nightside targets: near-Earth tail, “current disruption” region



# Cluster : extended mission phase

## auroral acceleration region




AAR Campaigns
Spring 2009 and Winter 2009/10

Altitude (km)

| | | |
|---|---|---|
| | | Cluster 2001 |
| 13000 | | Cluster 2008 |
| | | Cluster 2009 |
| 3000 | | Cluster 2010 |
| 1300 | | |
| 100 | | Cluster 2011/2 (but at lower latitudes) |

From Marklund, 2007

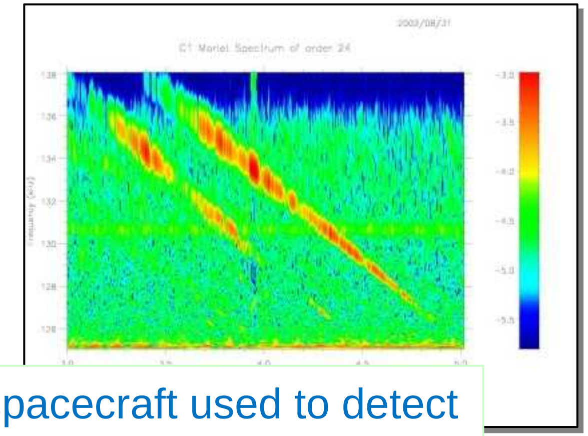
# Cluster : extended mission phase

## auroral acceleration region

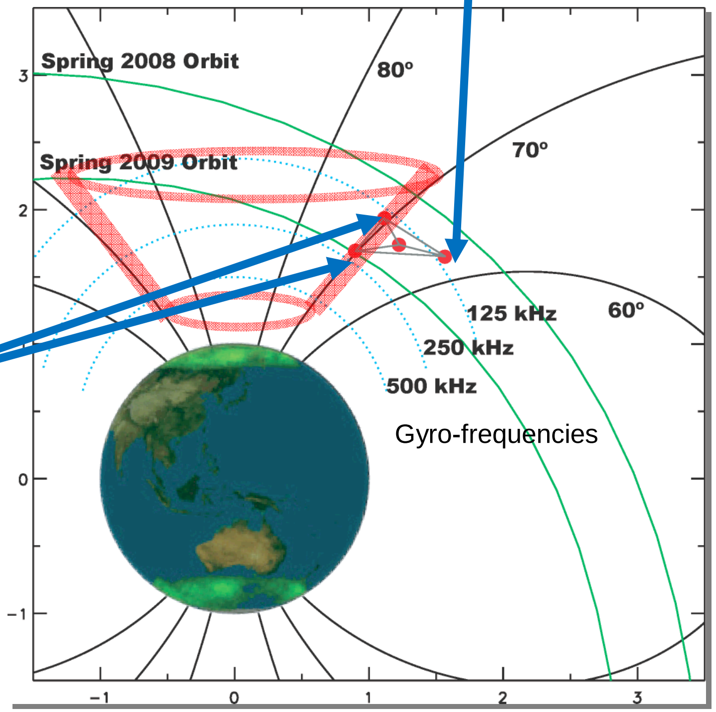
Critical tests of auroral physics :

e.g. investigation of auroral kilometric radiation (AKR)

1. CMI (cyclotron maser instability)-driven radiation: What electron distribution function drives CMI along B-field? (loss-cone, shell, multiple shells?)
2. What is cause of AKR fine structure? (electron holes, ion holes, EMIC waves?)
3. Are AKR drifting features a remote signature of solitary waves?



Remote spacecraft used to detect simultaneous AKR bursts



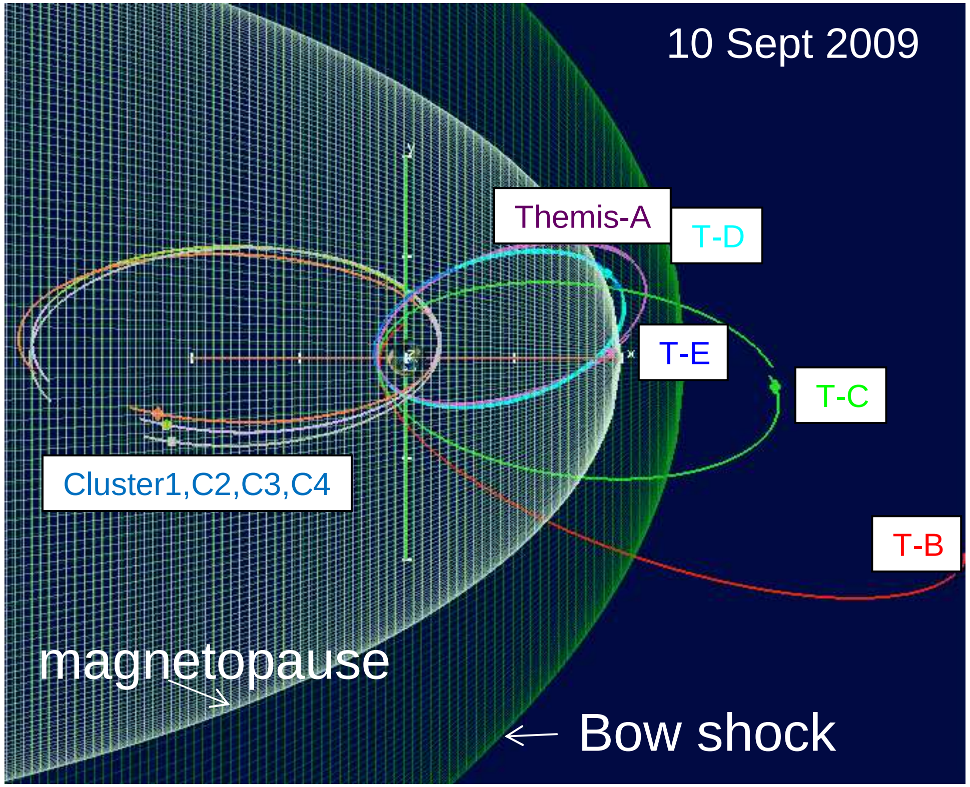

Multiple spacecraft measure particles, electric and magnetic fields along same field line in the upward current (AKR) region.

[Slide courtesy J. Pickett (WBD PI)]

# Co-ordinated operations with THEMIS and SWARM

## Other science objectives

- Study global magnetosphere with Themis co-ordination (Cluster instrumentation is more comprehensive than on THEMIS)
- Study plasmasphere and wave activity in the inner magnetosphere, support studies of radiation belt particle acceleration by waves
- Understand structuring of field aligned currents and energy transfer between the magnetosphere and the ionosphere using co-ordinated observations with Swarm.



# Cluster : extended mission phase

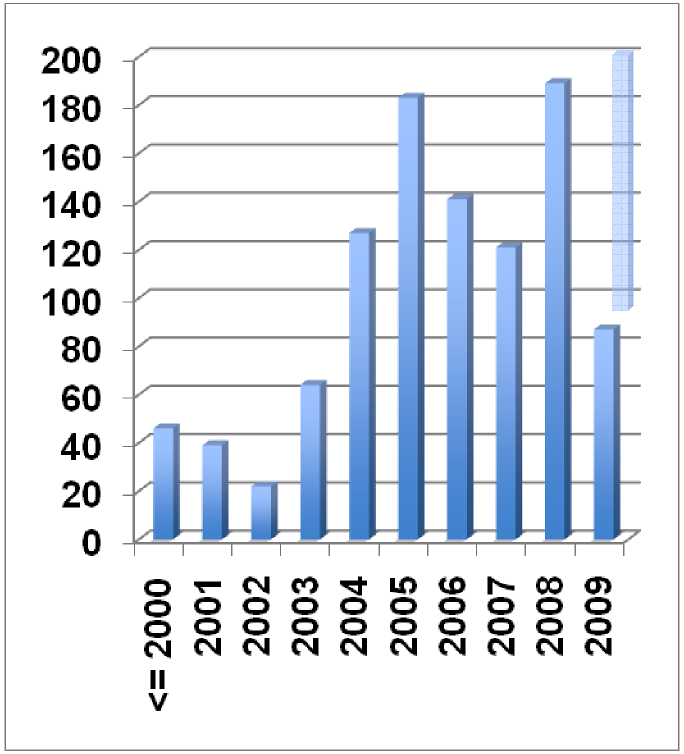
## Spacecraft Status

- Performance of spacecraft is good in sunlight. Instruments health has not changed significantly since last extension.
- Fuel left is now 7 kg (Cluster 4) and up to 11.3 kg (Cluster 3) and will be sufficient for the proposed extension
- Batteries are now minimal on C1 and C3 but recent operations showed that spacecraft can pass eclipse without batteries (though payload operations are restricted on some spacecraft during eclipse orbits)
- Solar panel are aging, but we should be able to get 100% orbit coverage (2009-2010) and up to 75% (2011-2012)

## Cluster Active Archive


- A: High resolution best quality Cluster data open to all users.
- A facilitates extensive ongoing detailed inter-experiment, cross-calibration studies

## Cluster Publications (1034, to July 2009)




- includes 30 published in high impact journals: Nature, Nature Physics and Phys. Rev. Lett.
- 42 PhDs

# Conclusion

- During the next 4 years new science could be done with Cluster alone, and also together with other new missions (Themis, Swarm)
- ESA have recently approved an extension of Cluster operations from Jul 2009 to Dec 2012. Final approval for the 2011-2 interval will be contingent on a review in summer 2010.

- Thus there is scope for overlap of operations with SWARM, depending on the actual SWARM launch date.
- Cluster will provide information on the general state of the magnetosphere, and during low altitude passes may make complementary measurements.
- We need to do a more detailed analysis of the science potential of this overlap – a good first step will be to investigate conjunctions opportunities between Cluster and the SWARM spacecraft, and to define topics for co-operation