Cluster: Highlights and Case for Extension

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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 $19.6 \times 4 \, R_E$
- 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
2 CIS, plasma ions
3 EDI, 3D electric field (electron drift)
4 FGM, magnetic field
5 PEACE, plasma electrons
6 RAPID, energetic ions, electrons
7 DWP, digital wave processor
8 EFW, 2D electric field (booms)
9 STAFF, plasma waves (search coil)
10 WBD, plasma waves (wideband)
11 WHISPER, plasma waves and sounder
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 $\nabla B$, $\nabla n$ for timing boundary motions in any direction
- determine current density $j = \nabla \times B / \mu_0$ (for $\partial E / \partial t \sim 0$) and hence local $j \times B$ force
- determine $\Omega = \nabla \times \mathbf{v}$, hence contribution of flow shear to field aligned current $j_\parallel = \int dt \mathbf{B} \cdot \nabla \Omega_\parallel$, (magnetic helicity $\alpha = j_\parallel / B$)
- determine $\nabla P$, in steady state $\partial \alpha / \partial s = (\nabla P \times \nabla B^2) / B^4$

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
\[ \vec{J}_0 = \text{curl} \ \vec{B} \]
Ring current

Current density from curlometer, using many passes, mean value $20\ nA/m^2$. Inter-hemispheric differences seen

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

Magnetopause current

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

Typical current densities range from $9$ to $40\ nA/m^2$, in the direction expected from the Chapman-Ferraro model.

Typical current layer thicknesses from $300$ to $1,500\ km$, typically $\sim$ 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/m$^2$; translated to the ionosphere this is 18,000 nA/m$^2$
[Forsyth et al., Annales Geo., 2008]
Strongest and thinnest current sheet measured in the tail

Ampère’s law

\[
J_o = \text{curl } B
\]

Peak current

\[J_o = 180 \text{ nA m}^{-2}\text{ max}\]

Thickness=300 km = ion skin depth c/w \(\pi\)

17 Aug. 2003

[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 Re), suggesting a common source. [Zhang et al., Ann. Geophys., 2005] [Volwerk et al, GRL., 2007]

Magnetotail

Double Star TC-1

Cluster

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**

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

![Energy spectrum graph]

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

Rolled-up vortices may allow plasma transfer through the magnetopause

[Hasegawa et al., Nature, 2004]
Kelvin-Helmholtz vortices and reconnection in flanks

3 Jul. 2001

2000 km

MHD simulation of Kelvin-Helmholtz vortices
Reconnection taking place inside vortex

Reconnection evidence observed on Cluster ion data (Walen test)
wave length $\sim 6R_E$

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

(B V Nykyri et al., Ann. Geophys., 2006)
More magnetic reconnection discoveries

- First time observed with 4 spacecraft
- Reconnection review paper: Paschmann, GRL, 2008
Largest reconnection line ever directly measured:

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)

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.
Cluster extension Jul 2009-Dec 2012

- Orbit evolution
- New science opportunities
- Spacecraft status
- Cluster Active Archive and publications
Cluster : extended mission phase
orbit evolution

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 $90^\circ$ to $\sim 140^\circ$ (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 magnetopause latitudes)

[OVT tool and ESOC/JSOC orbit predictions used for these plots]
Cluster: extended mission phase
orbit evolution

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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

Viking
Freja
Sounding rockets

altitudes (km)
13000
Cluster 2001
Cluster 2008
Cluster 2009
Cluster 2010
Cluster 2011/2 (but at lower latitudes)

cold aurora

AAR Campaigns
Spring 2009 and Winter 2009/10

From Marklund, 2007
Critical tests of auroral physics:

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?

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

Remote spacecraft used to detect simultaneous AKR bursts
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

Welcome to the Cluster Active Archive

The Cluster Active Archive is a depository of processed and validated high-resolution Cluster data, raw data, processing software, calibration data, documentation and other value added products.

CAA News

21 Apr 2008 CAA position in LPCE: LPCE/DNRS is seeking a Research Associate (level Bac+5) to assist in the production and archiving of scientific satellite data. Read more.

30 Feb 2008 PEACE moments online: We announce the first CAA release of PEACE moments data for 2001-2005, for all spacecraft. The data are. Read more.

08 Feb 2008 WBD products online: The CAA has added more WBD products online. The multi-spacecraft summary plots of the WBD experiment can be browsed through the quick look browser. Read more.

16 Jan 2008 7th Cross-calibration workshop: The next cross-calibration workshop will be organized on 9 March 2008 in Hotel Playa de Arena, Puerto Santiago, Tenerife, Canary Islands. For more detail, see the workshop webpage. Read more.

15 Nov 2007 Subscribe to Cluster News: We have opened four different mailing lists that are used to distribute a variety of information about the Cluster Active Archive and the Cluster mission. Read more.


42 PhDs

\(\Lambda\): High resolution best quality Cluster data open to all users.

\(\Lambda\) facilitates extensive ongoing detailed inter-experiment, cross-calibration studies
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