Cluster-II: Scientific Objectives and Data Dissemination

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The Cluster-II mission is designed to study the near-Earth space environment in three dimensions. This will be the first scientific mission with four identical spacecraft flying together in the Earth's environment. The relative distance between the four spacecraft will vary between 200 and 18 000 km, according to the scientific region of interest. Cluster-II and the Solar and Heliospheric Observatory (SOHO) together make up the Solar Terrestrial Science Programme, the first 'Cornerstone' of ESA's Horizons 2000 long-term science plan.

Scientific objectives

The study of the interaction between the solar wind, the extension of the solar atmosphere, and the magnetosphere, the cavity that contains the Earth magnetic field, is a key element in the Solar Terrestrial Science Programme (Fig. 1). One example of this interaction is the direct entry of solar-wind particles into the magnetosphere through the polar cusps (Fig. 2). These consist of two magnetic funnels, one in each hemisphere, which focus the solar-wind particles. The polar cusps, located near the geomagnetic poles, are the 'windows' through the Earth's magnetic shield for high-energy solar particles.

The solar-wind particles (mainly electrons and protons) enter the broad outer cusp, which has a diameter of approximately 50 000 km, and then follow the converging magnetic field down to the ionosphere, where the cusp size shrinks to about 500 km. This converging magnetic field allows the study of a very large area of the magnetopause through a limited region of space inside the cusps.

Another example of the interaction of the solar wind with the magnetosphere is the acceleration of plasma in the magnetotail during geomagnetic substorms. The enormous, tapering magnetotail is a large reservoir of both solar-wind and ionospheric particles. Under some circumstances, for instance when the solar wind causes the interplanetary magnetic field to reverse in polarity from north to south, the magnetotail releases a large amount of particles towards the Earth.

Both mechanisms - particles entering in the polar cusps and substorms - produce aurorae when the precipitating particles, electrons and

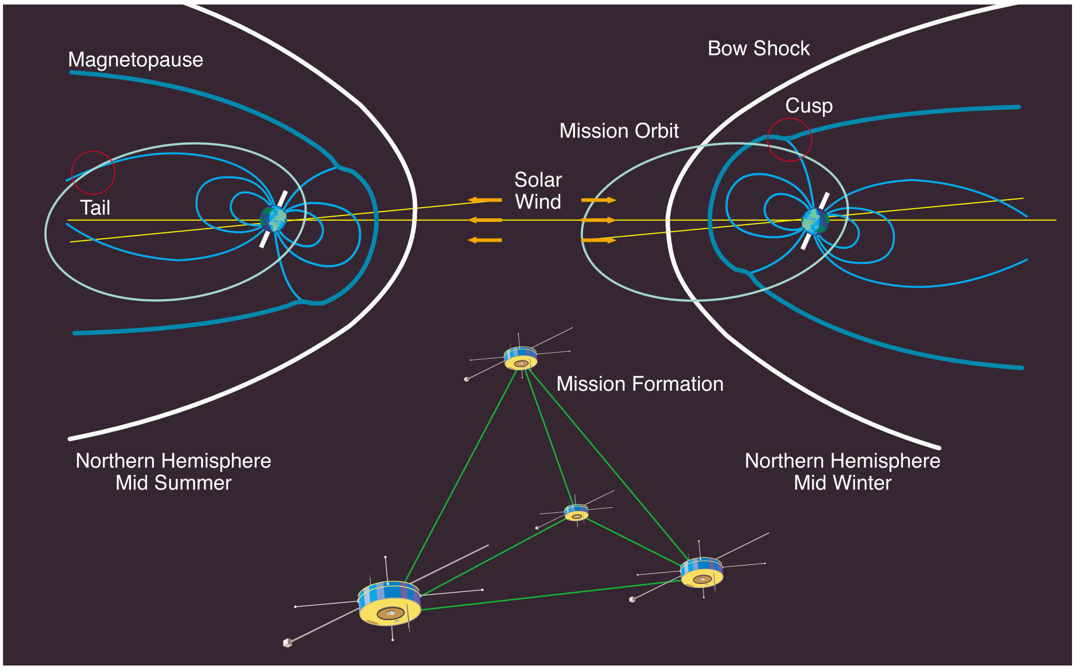


Figure 1. Artist's impression of the Sun-Earth interaction to be studied by the four Cluster spacecraft

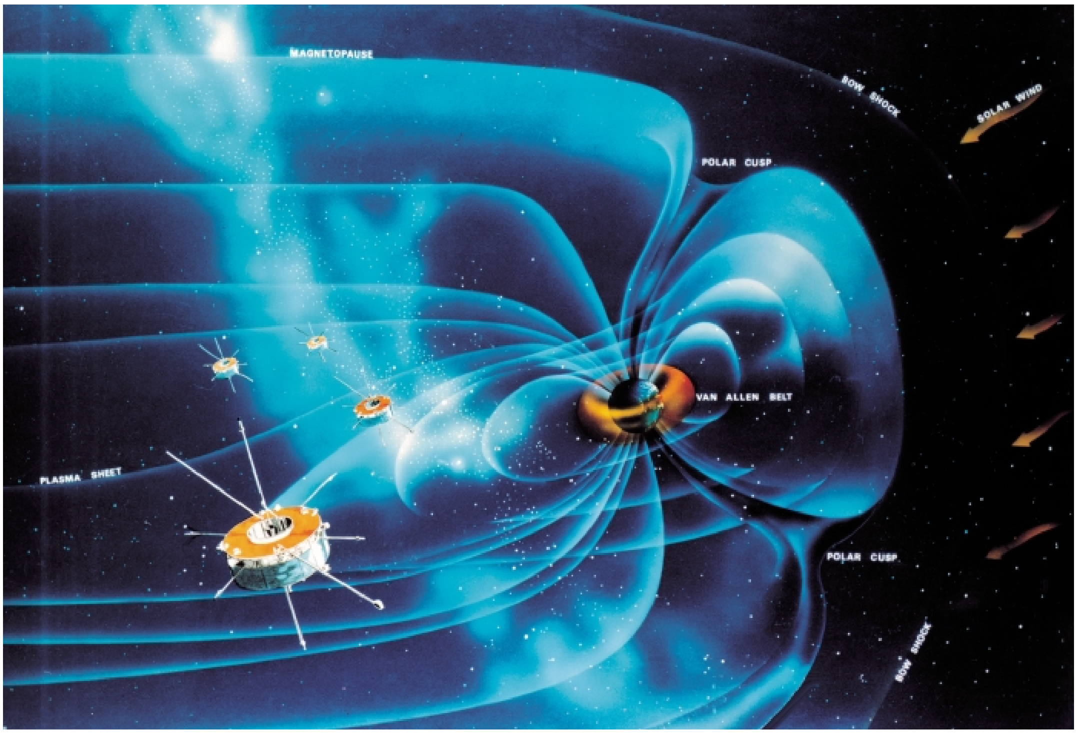


Figure 2. Artist's impression of the Cluster orbit and the main regions/boundaries of the Earth's magnetosphere

Table 1. The Cluster-II instruments and their Principal Investigators

Instrument	Principal Investigator
ASPOC (Spacecraft potential control)	W. Riedler (IRF, A)
CIS (Ion composition)	H. Rème (CESR, F)
EDI (Plasma drift velocity)	G. Paschmann (MPE, D)
FGM (Magnetometer)	A. Balogh (IC, UK)
PEACE (Electrons)	A. Fazakerley (MSSL, UK)
RAPID (High-energy electrons and ions)	B. Wilken (MPAe, D)
DWP * (Wave processor)	H. Alleyne (Sheffield, UK)
EFW * (Electric field and waves)	G. Gustafsson (IRFU, S)
STAFF * (Magnetic and electric fluctuations)	N. Cornilleau-Wehrlin (CETP, F)
WBD * (Electric field and wave forms)	D. Gurnett (IOWA, USA)
WHISPER * (Electron density and waves)	P. Décréau (LPCE, F)

* Wave Experiment Consortium (WEC)

ions, hit the neutral gas of the atmosphere. Sometimes these particles are very energetic and can have dramatic effects on human activities, for example disruption of electrical power and telecommunications and also serious anomalies in the operation of satellites, particularly at the geostationary orbit.

Cluster will determine the physical processes involved in this interaction between the solar wind and the magnetosphere by visiting key regions like the polar cusps and the magnetotail. The four Cluster spacecraft will map the plasma structures contained within these regions in three dimensions. In addition, the simultaneous four-point measurements provided by the satellites will permit scientists to derive differential plasma quantities for the first time. For example, the density of current flowing around the spacecraft will be derived from the magnetic-field measurements taken at four points in space.

The Cluster instrumentation has state-of-the-art capability to measure electric and magnetic fields together with electron and ion distribution functions. The four Cluster spacecraft are identical and each carries 11 instruments (Table 1), giving a total of 44 instruments, a record for a space mission. The instruments are located on the upper external ring of the spacecraft or on radial booms to allow a free field of view for each of them (Fig. 3).

To make accurate intercomparisons between the same instruments on the four spacecraft, it is necessary to make the best absolute measurements. The goal of the PEACE electron sensor, for example, is to achieve a 1% accuracy for the measurements of the density, temperature and velocity of electrons. Being able to achieve these goals has required perfect manufacturing of the instrument and its very precise calibration on the ground, to be supplemented later by a calibration in space. The results of the calibrations on the ground are shown on Figure 4. It is clear that all four models are all very similar and the small residual differences will be taken into account when comparing the measurements made in space.

In the case of the Flux Gate Magnetometer (FGM), an overall single instrument accuracy of 0.1% is required. In addition to ground calibration, a special magnetic-cleanliness programme was conducted to achieve a spacecraft magnetic background of less than 0.25 nT at the magnetometer position (5 m from the spacecraft).

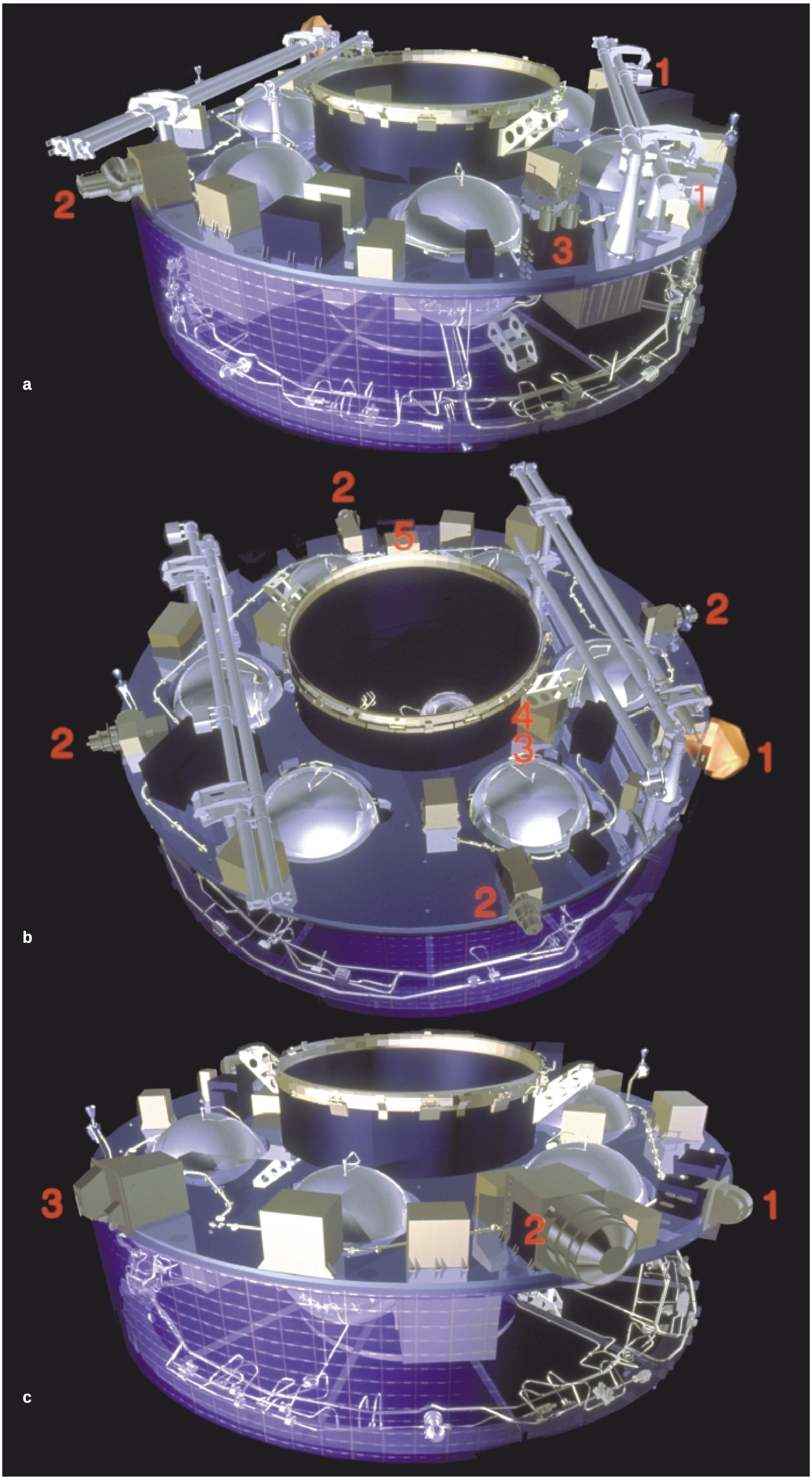


Figure 3. The instruments on the Cluster spacecraft

a: 1 FGM, 2 EDI and 3 ASPOC

b: 1 STAFF, 2 EFW, 3 DWP, 4 WHISPER and 5 WBD

c: 1 PEACE, 2 CIS and 3 RAPID

The measurement of electromagnetic waves requires a very high timing accuracy for each spacecraft. The guaranteed accuracy is ± 2 ms, although we can expect even better precision during the mission. Since this accuracy would not be sufficient to compare waves measured on the four spacecraft, the Wave Experiment Consortium (group of 5 instruments) has developed special algorithms which, together with the use of transputers with parallel processing, achieve an accuracy of a few microseconds.

The ideal spacecraft configuration for measuring plasma structures in three dimensions is a tetrahedron (triangular pyramid) with a spacecraft at each corner. Unlike the Egyptian pyramids, where the base is a square, the base of the Cluster tetrahedron will be triangular and the distances between the spacecraft identical. Unfortunately, this shape cannot be maintained all along the orbit due to orbital mechanics effects, and we have to target it to specific regions of interest. It has been shown, however, that if we form the tetrahedron at two places along the orbit, for instance at the northern and southern cusp, then the configuration stays very close to a tetrahedron over a major part of the orbit (Fig. 5).

Key advances in plasma physics will be achieved using the four Cluster spacecraft. A first example is the measurement of the electric

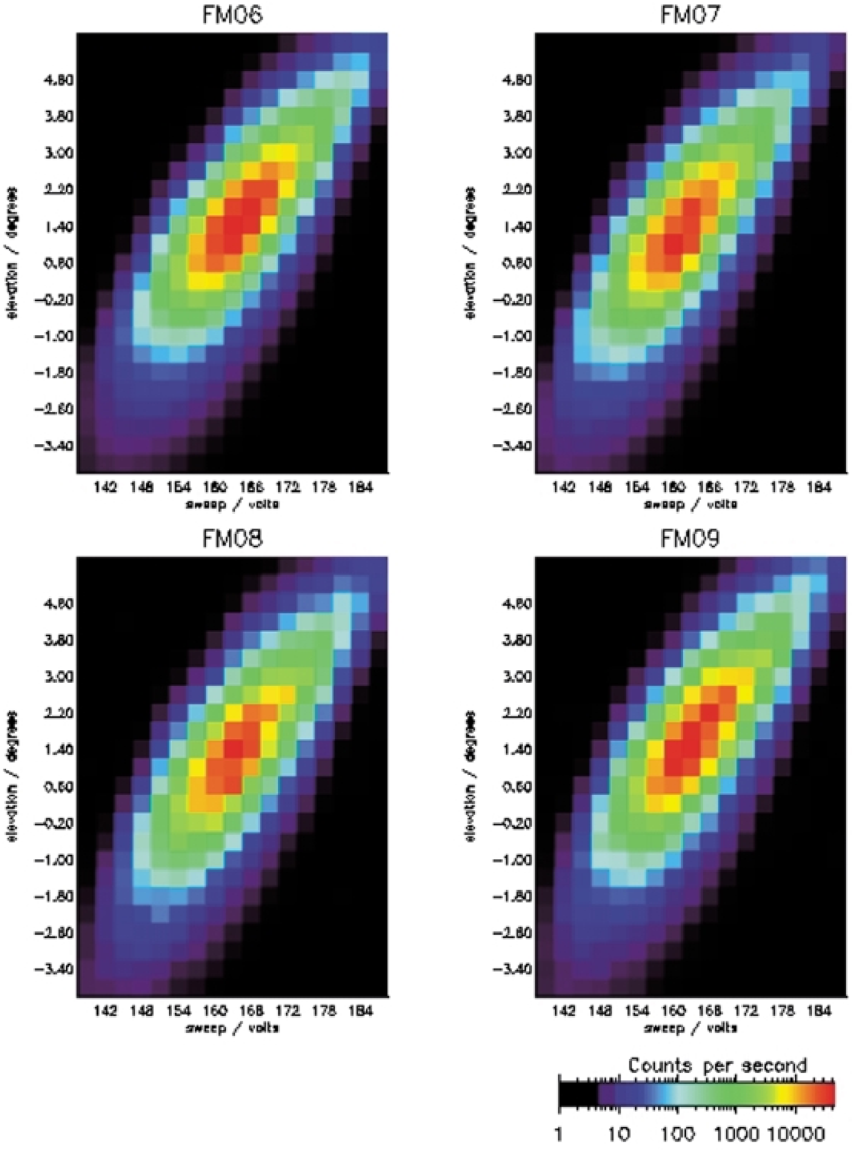
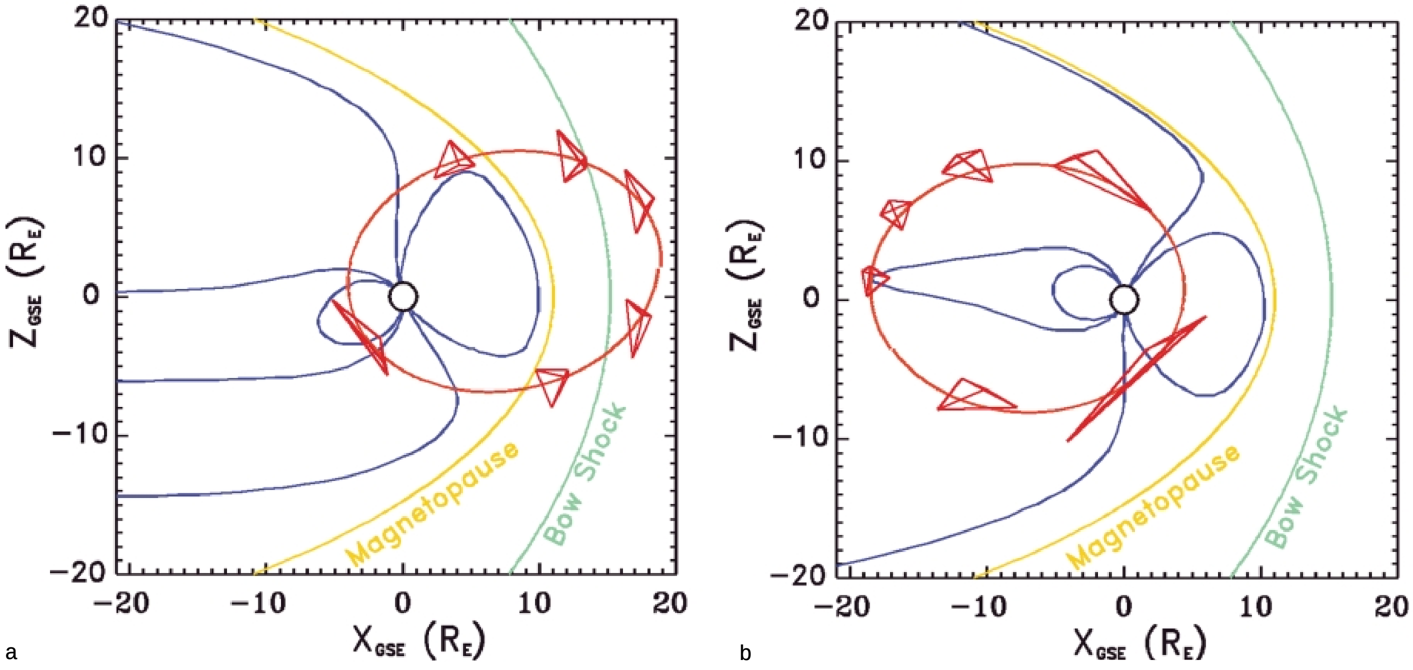


Figure 4. Flux of electrons detected by the four PEACE instruments when bombarded by an electron source
(Courtesy of PEACE Calibration Team, MSSL/UCL)



a

b

Figure 5. Cluster orbit and spacecraft configuration with respect to magnetospheric models at the beginning of the mission when the polar cusp is crossed (a), and 6 months later when the magnetotail is crossed (b). For clarity, the inter-spacecraft distances have been enlarged by a factor 30 in panel (a), and by a factor 2 in panel (b)

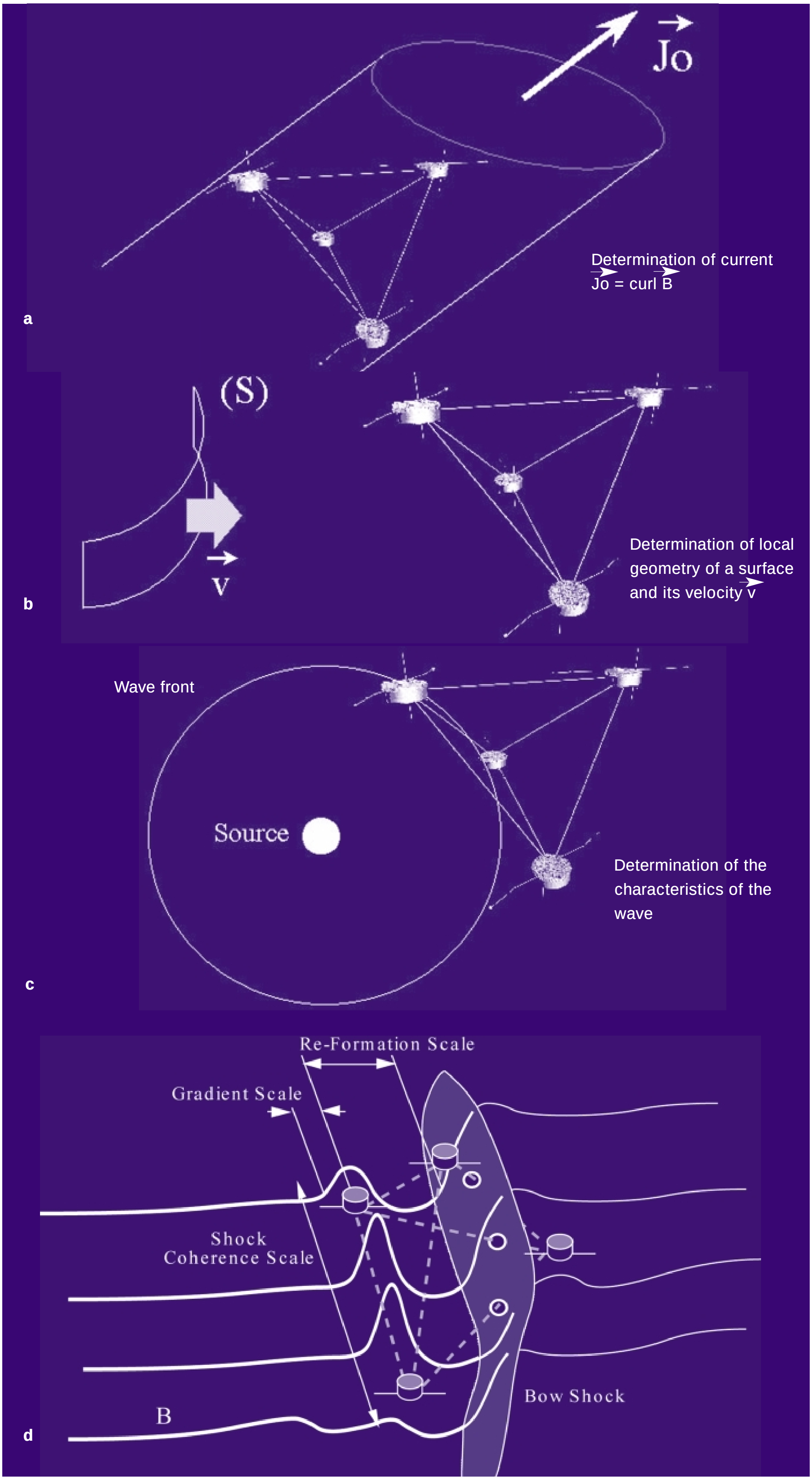


Figure 6. Examples of Cluster-specific capabilities (Panel (d) courtesy of E. Moebius, Univ. of New Hampshire)

current J flowing through the Cluster fleet and given by Ampere's law, curl B = μ_0 J (Fig. 6a). The measurement of the difference of B between the four spacecraft will give curl B and then J.

The currents are key parameters in magnetospheric physics because they are present in all regions and contribute to the magnetosphere's shape. For instance, the magnetopause is a narrow current layer that separates the solar wind from the magnetosphere (Fig. 2). Other quantities can also be derived using this formalism, such as the plasma vorticity, which is given by the curl of the plasma velocity.

Another example is the analysis of discontinuities (Fig. 6b). When the Cluster-II spacecraft cross a boundary like the magnetopause, each of them will determine the normal to that boundary. By combining these measurements, we will obtain information on the boundary curvature, e.g. either convex or concave, and its radius of curvature. In the case of the magnetopause, this information will enhance our knowledge of the interaction between the solar wind and the magnetosphere. Theoretical studies have predicted that when clouds of dense solar-wind particles arrive at the magnetosphere, they can produce an 'indentation' in the magnetopause and eventually penetrate it. The four Cluster spacecraft should tell us if this process exists.

The particle-acceleration processes involved in producing aurorae generate intense electromagnetic emissions. These processes are not yet fully understood and the four Cluster spacecraft will bring us additional information. Using four measurements in space, each giving the direction of the source, we will be able to derive its location, size and speed (Fig. 6c).

A final example of the benefits of four-point measurement analysis is the bow-shock reformation. The bow shock is the boundary where the supersonic plasma from the solar wind is decelerated to a subsonic speed when it encounters the obstacle of the magnetosphere. Depending on the speed of the solar wind, the bow shock moves or reforms itself at another place. Cluster's four spacecraft will enable one spacecraft to be at a former location, another one at the new location and the other two in between (Fig. 6d), so providing new information on the bow-shock reformation process.

Data dissemination

Two centres are in charge of the Cluster-II operations: the Joint Science Operations Centre (JSOC) and the European Space Operations Centre (ESOC) (see accompanying article by M. Warhaut et al. in this issue).

JSOC, located at the Rutherford Appleton Laboratory in the United Kingdom, is coordinating the science operations. Its main task is to merge the input from the individual Principal Investigator (PI) teams into a command schedule. In addition, JSOC will monitor the health of the instruments and disseminate information on the mission. Included in this information is a scientific event catalogue, which will identify the main magnetospheric boundaries (bow shock, magnetopause, neutral sheet, flux transfer events and auroral zone). These data, together with other parameters coming from all instruments, will be accessible to the scientific community through the Cluster Science Data System (CSDS).

This data system has been designed as a distributed system, to enable the joint scientific analysis of data coming from all 44 instruments. The general approach is to have national data centres located near the Principal Investigators (PIs), and thus near the expertise required for processing the data. One of the major tasks of the CSDS is to offer, as a matter of routine, products such as the Summary Parameter Data Base (data products coming from one spacecraft with 60 sec resolution) and the Prime Parameter Data Base (data products coming from the four spacecraft with 4 sec resolution).

Table 2: Cluster-II Principal Investigators (PI) and Co-Investigators (CoI) and the Data Centre locations

Country	PIs or CoIs	Data Centre
Austria	6	yes
Belgium	2	
China	4	yes
Czech Republic	1	
Denmark	3	
Finland	4	
France	39	yes
Germany	23	yes
Greece	2	
Hungary	2	yes
India	2	
Ireland	1	
Israel	1	
Italy	6	
Japan	3	
Norway	11	
Russia	4	
Sweden	13	yes
Switzerland	1	
The Netherlands	5	yes
United Kingdom	20	yes
USA	68	yes
Total:	221	

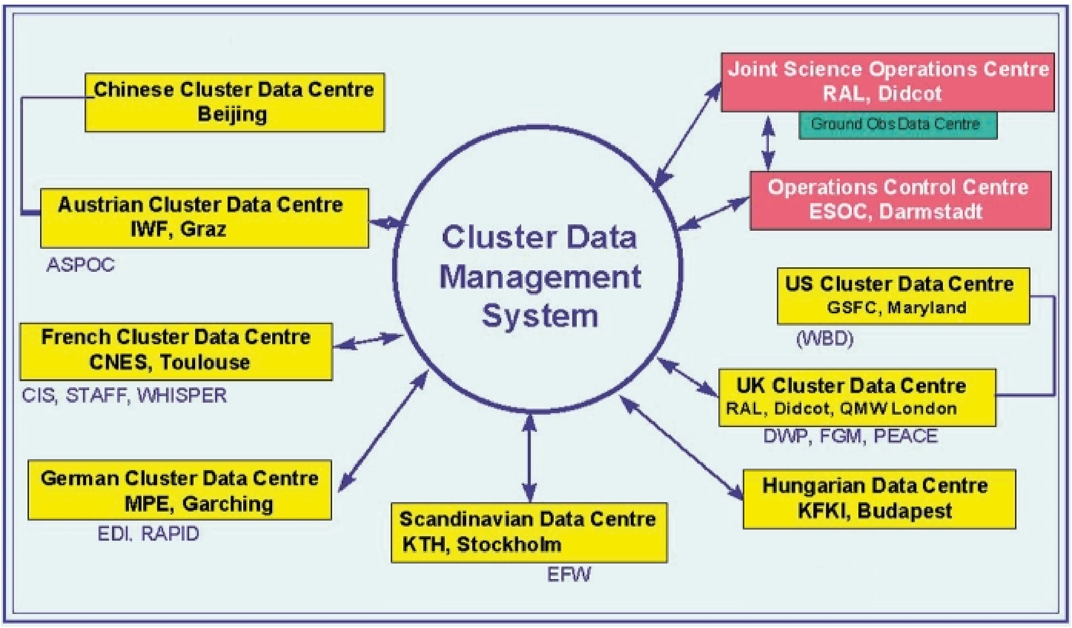
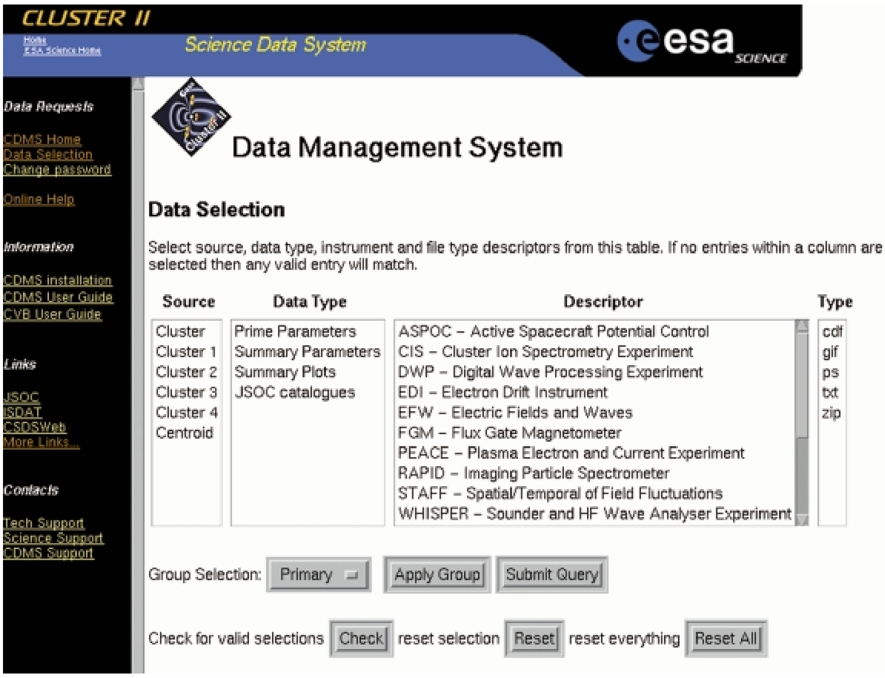


Figure 7. The Cluster Science Data System (CSDS) architecture

The CSDS consists of eight nationally funded and operated data centres (Fig. 7). In most cases, the data centres produce data products on behalf of the national PI teams. Members of the Cluster-II science community (Table 2) wishing to access the CSDS will do this via their national data centre or via an assigned data centre. It should be noted that all data centres offer the same data products. Scientists from outside the Cluster-II community will also have access to the CSDS, according to the policy on data rights agreed by the Principal Investigators. Full access can be granted to the Summary Parameters.

The scientists will interact with CSDS via the Cluster Data Management System (CDMS), as shown on Figure 8. The main purpose of the CDMS is to provide the scientific community with uniform access to CSDS. For the individual data centres, the CDMS offers local file handling, distribution of validated data files to other data centres, data ordering, user administration, catalogue browsing and data-manipulation functions. The CDMS allows a user to browse the CSDS catalogues, fetch prime and/or summary data, manipulate and display prime and summary parameters, and retrieve summary plot files. The CDMS can be accessed with any Web browser.



Data Selection

Select source, data type, instrument and file type descriptors from this table. If no entries within a column are selected then any valid entry will match.

Source	Data Type	Descriptor	Type
Cluster	Prime Parameters	ASPOC – Active Spacecraft Potential Control	cdf
Cluster 1	Summary Parameters	CIS – Cluster Ion Spectrometry Experiment	gif
Cluster 2	Summary Plots	DWP – Digital Wave Processing Experiment	ps
Cluster 3	JSOC catalogues	EDI – Electron Drift Instrument	txt
Cluster 4		EFW – Electric Fields and Waves	zip
Centroid		FGM – Flux Gate Magnetometer	
		PEACE – Plasma Electron and Current Experiment	
		RAPID – Imaging Particle Spectrometer	
		STAFF – Spatial/Temporal of Field Fluctuations	
		WHISPER – Sounder and HF Wave Analyser Experiment	

Figure 8. Web interface of the Cluster Data Management System (CDMS). A user will have access to the Cluster-II data in Common Data Format, ASCII and Summary Plots

The CSDS has been designed to allow fast and easy access to all physical parameters measured by the four spacecraft. In addition, the CSDS is fully compatible with data from other magnetospheric and solar missions and will be the perfect tool with which to conduct collaborative studies in the framework of campaigns defined by the Inter-Agency Consultative Group (IACG).

Conclusion

Monitoring the effect of the Sun on our near-Earth environment is a key task for the upcoming years of solar maximum, and Cluster-II will be the ideal mission with which to undertake this activity. Now, with the Cluster-II launches scheduled to take place in just a few weeks' time and the agreed extension of the SOHO mission, the scientific community is looking forward to the exciting results emanating from these missions as they jointly study the dramatic interaction between the Sun and the Earth's environment.