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CLUSTER – A FLEET OF FOUR SPACECRAFT TO STUDY PLASMA STRUCTURES IN THREE DIMENSIONS

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ABSTRACT

Cluster has been designed primarily to study small-scale structures (from a few to a few tens of ion Larmor radii) in the Earth's plasma environment. Although of relatively small scale, the processes leading to the formation of such structures are believed to be fundamental in determining the behaviour of key interaction processes between two cosmic plasmas.
The four Cluster spacecraft are spin-stabilized spacecraft which are designed and built under stringent requirements as far as electromagnetic cleanliness is concerned. Conductive surfaces and an extremely low spacecraft-generated electromagnetic background noise are mandatory for accurate electric field and cold plasma measurements. The mission will be implemented in collaboration between ESA and NASA. The Institute of Space Research, Moscow, intends to implement a mission which will be closely coordinated with Cluster.

Keywords: Cluster, STSP, ESA Long Term Programme, Instrumentation

1. INTRODUCTION

Cluster, together with Soho, is a collaborative mission between the European Space Agency, ESA, and the U. S. National Aeronautical and Space Administration, NASA. Both missions together form the 'Solar-Terrestrial Physics Programme' (STSP). STSP is also the first out of four major missions of ESA's long-term Programme: 'Space Science: Horizon 2000'.
The Phase A study, during which NASA joined the project, was completed in December 1985. The mission concept was presented to the community in January 1986. Finally, in February 1986, Cluster and Soho were approved as new scientific projects by ESA's Science Programme Committee.
The Institute of Space Research (IKI) of the Soviet Academy of Science, Moscow will scientifically enhance the Cluster mission by executing a multi-spacecraft mission that will be launched at about the same time as Cluster and both missions will be operated in close collaboration. Discussions on a working group level are under way to identify possible scenarios.
Solar-terrestrial physics deals with the cause and effect relationship between the interior of the Sun, its surface features, the coronal dynamic features, and the characteristics of the solar wind as it envelops the Earth to create the geospace. The importance of understanding the complex processes that control and define the Earth's environment in space has long been realized. Reflecting the continuing interest, Cluster and Soho were independently proposed by European scientists in solar-terrestrial physics to ESA in 1982. They underwent in parallel assessment studies and later detailed design studies.
Cluster has been primarily designed to study small-scale structures (from a few to a few tens of ion Larmor radii) in three dimensions in the Earth's plasma environment. Although they are of relatively small scale, the processes leading to the formation of such structures are believed to be fundamental to the key processes of interaction between the solar wind and the magnetospheric plasmas. For example, we know that the internal convection within the Earth's magnetosphere is determined by coupling processes acting at the magnetopause. These processes involve small-scale structures with a scale length of a few thousand kilometers, such as flux transfer events, which appear to be an important manifestation of the field line merging process.

2. SCIENTIFIC OBJECTIVES OF CLUSTER

Space projects carried out in the past have revealed that the plasma in the Solar System has a cellular structure with thin boundary layers separating plasma regions of widely different characteristics. An example of such a boundary is the magnetopause, which separates the Earth's magnetosphere from the plasma and magnetic field of the extended solar atmosphere (the solar wind). Some plasma penetrates this magnetic shield and mixes turbulently with the local plasmas. The examination of this transfer of mass, momentum and energy across the boundary is among the prime scientific objectives of

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Cluster.
The magnetopause possesses two particular loci where Earth's magnetic field lines change from mapping to the dayside equator to mapping in the lobes of the geotail. The resulting indentations in the magnetopause form the outer boundaries of two funnel-shaped openings known as the northern and southern cusps. Through these openings, magnetosheath plasma gets access to the dayside ionosphere. The magnetic field line topology of the exterior cusps (Fig. 1) exhibits strong curvatures. As a result, the magnetosheath plasma may become separated from the bulk flow and the flow may break up into vortices. The cusp region is essentially unexplored and Cluster would provide basic information on the three-dimensional structure of this area. The spacecraft encounter the cusp on their outbound leg of the orbit.

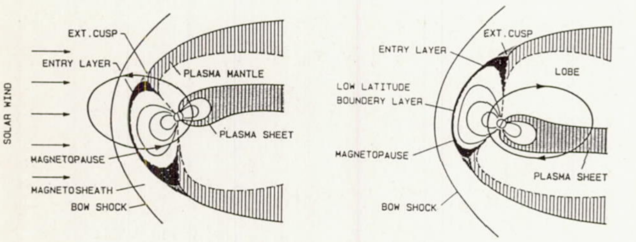

Fig. 1 Cluster orbits in relation to the magnetosphere at intervals of 6 months. The inter-spacecraft distances are smaller (<1 R_E) on the dayside (left) and up to 3 R_E in the nightside (right).

Inbound, they will return into the magnetosphere south of the ecliptic and encounter the mid-latitude magnetopause. The foremost example of investigations performed in this region concerns field line merging. This happens whenever a large shear occurs between the magnetic fields carried by the solar wind and the one generated by Earth. This so-called merging or reconnection process varies with time because it depends strongly on the relative orientations of the two magnetic fields. The orientation of the solar magnetic field is highly time dependent because of solar activity. There is in-situ evidence for an occasional quasi-steady reconnection at the dayside magnetopause. However, patchy, impulsive reconnection (flux transfer events) occur much more frequently (Ref. 1). A wide variety of evidence suggests that merging is the dominant contributor to momentum transfer (Ref. 2), and the resulting large-scale electric fields may be strong enough to maintain the convection of plasmas in the inner magnetosphere.
The solar wind is composed of a complex assemblage of electromagnetic and electrostatic structures including hydro-magnetic waves and fluctuations, discontinuities and many microscale phenomena. Identifying the nature of the observed fluctuations basically requires independent measurements of the frequency and the wavelength of the waves. This implies multipoint measurements of field and plasma properties from at least four spacecraft that are not in the same orbital plane.

During the low-perigee segments of the orbit Cluster will encounter the auroral acceleration region. Very thin and short-living double layers, Langmuir solitons and ion beams, indicative of outward acceleration of ions, have been detected by low orbiting spacecraft. The double layers are thought to provide enough parallel potential drop to explain the observed acceleration of particles (Ref. 3). Investigations of their variability in space and time will be part of the objectives of Cluster.
Earth's magnetotail is formed by a current in the magnetopause, which branch into a dawn-dusk current flowing through the plasma sheet. The plasma sheet, the most important reservoir of energetic plasma in the magnetotail, is fed by cool plasma from the solar wind and the ionosphere. It is subject to enormous variations in size and structure. Mantle and ionospheric plasmas flow tailward and are convected toward the center of the plasma sheet by large-scale dawn-dusk electric fields. The average kinetic energy of this mixed plasma is increased to a few keV by electric fields as it is convected into regions of stronger magnetic fields (Refs. 4, 5). All present models are essentially qualitative and no global theory exists yet. Three-dimensional measurements will provide an enormous contribution to the better understanding of the global tail dynamics. The magnetospheric substorm (Ref. 6) is one of the most obvious phenomena. It reveals many impulsive phenomena occurring nearly simultaneously in the tail, the auroral ionosphere, and the equatorial magnetosphere. One of these phenomena is the occurrence of spontaneous reconnection in the tail with the formation of a neutral line and a magnetic island, or plasmoid, that is ejected downtail. Cluster would provide the tool to investigate the geometry of the cross-tail current, the formation and dynamics of the neutral line and the plasmoid.

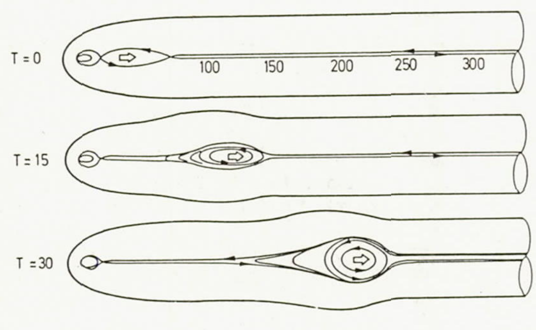

Fig. 2 Creation of a neutral line and a magnetic island is a way to release energy from the magnetotail. The island is ejected downtail and the near-earth field resumes a more dipolar configuration. T = 0 .. 30 refers to a time sequence (Ref. 8).

3. CLUSTER INSTRUMENTATION

The Cluster instrumentation is composed of an advanced set of instruments to measure electric and magnetic fields, plasmas and energetic particles. Table 1 lists all the investigations with their Principal Investigators, the instrument's acronym and a few key technical parameters. With the exception of the WBD instrument, the four payloads are identical.

The accurate measurement of the cold plasma population demands that the electrostatic potential of the spacecraft with respect to the ambient plasma be maintained at a very low level. Cluster is the first mission that will be equipped with an ion emitter to routinely control this potential. This ion emitter is specifically designed to stabilize the fluctuating spacecraft potential by emission of indium ions up to a total current of 20 μA. A hardwired link with PEACE and EFW provides the measured surface potential against which the emission is controlled. ASPOC will also undertake investigations of the surface charging behaviour under varying plasma conditions and of the interaction of the weak ion beam with the ambient plasma.

The suite of five instruments, EFW, STAFF, WHISPER, WBD and DWP forms the 'Wave Experiment Consortium' (WEC).

EFW is being specifically designed for the investigation of fast time- and space-varying vectorial electric fields but covers also the DC to low-frequency range. For instance, spiky electric fields near the magnetopause with peak amplitudes of ~ 100 mV/m have been found previously. On the other hand, inner-magnetospheric quiet-time convection electric fields may be as small as a fraction of a mV/m. This demands the measurement of the vector electric field over a wide range in amplitude and frequency. The dynamic range spans more than four decades in amplitude. The double probe technique enables also the measurement of the ambient plasma density fluctuations and of the spacecraft potential.

STAFF, the search coil magnetometer, measures the magnetic components of electromagnetic fluctuations. A built-in spectrum analyzer performs auto- and cross-correlation between electric and magnetic components. Such measurements will allow to characterize the shape, current density and motion of small scale current structures and to identify the source of plasma waves and turbulence. To this end, STAFF covers the frequency range up to 4 kHz.

The relaxation sounder WHISPER is an intermittent transmitter/receiver instrument that can also be operated in a passive (receive only) mode. The transmitter emits a short pulse to stimulate plasma resonances. After each transmission, the receiver part is activated to detect plasma echoes in a narrow frequency range. By switching rapidly both modes, the receiver scans the frequency range 4 - 80 kHz. Echoes at characteristic frequencies let the investigators determine the plasma density under widely varying plasma conditions.

The objective of the wide band receiver system (WBD) is to provide high resolution electric field waveforms and frequency-time spectrograms of terrestrial plasma waves and radio emissions. These measurements are of high importance for analyzing the highly structured and complex waves that occur in the Earth's magnetosphere. The receiver accepts signals in the frequency range up to 600 kHz, but only a narrow range of ~ 100 kHz is windowed out and transmitted to ground. Presently, this instrument is only foreseen on two of the four spacecraft.

The digital wave processing (DWP) system contains a wave/particle correlator. Such an experiment forms the correlation function of the time series of counts in the electron and ion analysers or, alternatively, the cross-correlation function between particle counts and wave measurements. These correlation functions are an important tool for investigating non-linear wave-particle interactions which are believed to be the source process of many plasma transport processes.

On WEC level, the instruments provide a further enhancement of the scientific return. The DWP is the 'heart' of the WEC's on-board data processing by performing event selection, mode control, data compaction/compression and the resonance frequency identification and tracking for WHISPER. Furthermore, the interconnection between, for instance, EFW and STAFF will permit time- and phase-coordinated measurements that will help to both localise and characterize electrostatic (e. g. double layers) and electromagnetic structures (e. g. field aligned currents) and to assess the role played by low-frequency plasma waves in the 'anomalous' behaviour (diffusion, parallel acceleration, thermalization) of plasmas.

The fluxgate magnetometer (FGM) performs important investigations that make use of the 4-point measurements in space. The capabilities of inferring from true measurements in space the current density vectors (from curl $\underline{B}$), wave propagation characteristics and field discontinuities are 'firsts' in space plasma physics. It also provides onboard measurements of the static and quasi-static magnetic field for all other instruments.

Cluster carries another instrument to measure electric fields. EDI is based on the emission and subsequent detection of tracer electrons to derive the ambient electric field. The instrument employs two different methods. In case of stronger ambient magnetic fields, the displacement of the gyrating electron over one gyration can be measured by a triangulation method. At smaller magnetic field values, the instrument works in a mode whereby two beams are emitted into opposite directions and the time of flight is measured. By additionally varying the electron energy, the instrument can also characterise gradients in the local magnetic field.

The Cluster plasma instrumentation aims at the three-dimensional measurement of the distribution functions of both electrons and major ion species. The science objectives will address, among others, heating and plasma flows near reconnection x-lines, the mid-altitude energization mechanism for electrons and ions, and the mechanism for plasma thermalization and the structure of plasma populations during substorm growth, onset and decay. Special emphasis will be given to the cold plasma component. The package consists of CIS and PEACE.

TABLE 1 INVESTIGATIONS TO BE PERFORMED ON CLUSTER

Instrument	Principal Investigator	Measurement	Technique
Fluxgate Magnetometer, (FGM)	A. Balogh, Imperial College, London, U. K.	B, wave form DC to ~10 Hz; resolution ≥ 6 pT.	Two 3-axes fluxgate sensors on 5 m boom.
Spatio-Temporal Analysis of Field Fluctuations, (STAFF)*	N. Cornilleau-Wehrlin, Centre de Recherche en Physique de l'Environnement Terrestre et Planetaire, Paris, F	B, wave form up to 10 Hz, compressed data up to 4 kHz. Cross-correlator for <E,B>	3-axes search-coil sensor on 5 m boom.
Electric Fields and Waves, (EFW)*	G. Gustafsson, Swedish Institute of Space Physics, Uppsala, S	E, wave form up to 10 Hz, compressed data up to 100 kHz, sensitivity < 50 nV/m(Hz)$^{1/2}$.	Double probes, two pairs wire booms, each 100 m tip to tip.
Waves of High Frequency and Sounder for Probing of Density by Relaxation, (WHISPER)*	P. M. E. Décréau, Laboratoire de Physique et Chimie de l'Environnement, Orléans, F	Active: Total electron density. Passive: Natural plasma waves up to 400 kHz.	Sounding, using parts of EFW wire booms. Filter banks.
Wide Band Data, (WBD)[1]*	D. A. Gurnett, Univ. of Iowa, U.S.	Transmission of E-field wave form up to ~ 100 kHz, variable centre frequency.	Using sensors of EFW.
Digital Wave processor, (DWP)*	L. J. C. Woolliscroft, Univ. of Sheffield, U.K.	Data compaction & compression, event selection, particle/wave correlation, control of WHISPER.	CMOS multiprocessor unit
Electron Drift Instrument, (EDI)	G. Paschmann, MPI für extraterrestrische Physik, Garching, FRG	E, (0.1 - 10mV/m, < 100 Hz), ∇B, |B| (5 - 1000 nT), emission & tracking of 2 electron beams.	Two emitter/detector assemblies, each with 2π field of view (FOV).
Cluster Ion Spectrometry (CIS)	H. Rème, Centre d'Etude Spatial des Rayonnement, Toulouse, F	CODIF: Composition and Distribution Functions analyzer, ~0 - 40 keV/q.	Symmetric hemispher. analyzer with RPA and TOF, 2π×8° FOV, split geometric factor.
		HIA: Hot Ion Analyzer for high time resolution (e.g. solar wind), ~3 eV/q - 40keV/q.	Symmetric quadrispher. analyzer, 2π x 8° FOV with high resolution (≥ 2.8°).
Plasma Electron and Current Analyser, (PEACE)	A. D. Johnstone, Mullard Space Science Laboratory, Holmbury St. Mary, U.K.	LEEA: Low Energy Electron Analyzer, 0-100 eV.	Spherical electrost. analyzer, π x 3.8° radial FOV.
		HEEA: High Energy Electron Analyzer, 0.1 - 30 keV.	Toroidal electrost. analyzer, 2π x 4.6° FOV.
Research with Adaptive Particle Imaging Detectors, (RAPID)	B. Wilken, MPI für Aeronomie, Lindau/Harz, FRG	IIMS: Imaging Ion Mass Spectrometer, ion distribution and species, energy 2 - 1500 keV/nuc.	Position-sensitive solid state detectors with TOF section.
		IES: Imaging Electron Spectrometer, distribution of energetic electrons, energy 20 - 400 keV.	Position sensitive solid state detector
Active Spacecraft Potential Control, (ASPOC)	W. Riedler, Institut für Weltraumforschung, Graz, A	Spacecraft potential control, emission current ~ 20 μA, indium ions.	Field ionization, liquid metal ion emitter.

Note: * Members of the wave consortium
[1] Only on two spacecraft

CIS, the plasma ion spectrometer, employs two sensors to obtain the full three-dimensional ion distribution of the major species with high time resolution and mass per charge plasma composition. CODIF takes care of the typical plasma populations encountered inside the magnetosphere. It also includes a retarding potential analyzer for the low-energy ions. The second sensor, HIA, is specifically designed for the highly directional, beam-like ion flows in the solar wind.

The plasma electron measurements are performed by PEACE. This instrument has two separate sensors which cover, respectively, the very cold electrons (LEEA) and the medium and higher energies (HEEA). The detection of cold electrons requires a very careful design to eliminate spurious effects introduced by photo-electrons which are known to be abundant near the spacecraft skin. PEACE will provide the three dimensional electron distribution with high time resolution.
Energetic particles are sensitive probes for remote sensing techniques in nearly all

plasma regions of geospace. These particles help identify distant acceleration regions and they can be used to trace plasma flows. RAPID consists of two spectrometers, each containing position sensitive solid state detectors: a mass discriminating energetic ion spectrometer (IIMS) and another sensor to determine the distribution in velocity space of supra-thermal electrons (IES). Both spectrometers provide high angular and time resolution.

The payloads can be commanded to alternatively generate two bit streams, totalling 16.8 (normal mode) and 100 kb/s (high speed), respectively. Routine real time operation of the payload is not foreseen and therefore data will be stored on one of two redundant tape recorders (capacity: 1 Gigabit/each). As for the high-speed mode, the filling of the tape may be performed either in one contiguous sequence or in several, shorter blocks. This sequence, however, must not exceed an accumulated time period of about 150 min and, for operational reasons, it may only happen once per orbit. The tape content will be dumped at the subsequent ground station pass.

The striving for highly accurate measurements imposes requirements on the spacecraft design concerning the attitude reconstitution, the electromagnetic cleanliness, the timing accuracy (± 2 msec) of the data taking and the separation strategy.

4. SPECIFIC CAPABILITIES OF CLUSTER

Single satellite measurements suffer from the intrinsic inability to distinguish unambiguously between spatial and temporal variations. With two satellites, this ambiguity is removed only for simple motions of essentially one-dimensional structures. An unambiguous determination of the shape and dynamics of three-dimensional structures requires, as a minimum, four spacecraft in a tetrahedral configuration and equipped with instruments which measure fields and flows in three dimensions.

The most obvious applications of the four-spacecraft technique are the determination of the current densities (from the curl of the magnetic field $\underline{B}$), the vorticity of the flow (from curl $\underline{v}$), shear flows (from div $\underline{E}$), and the momentum balance (from the divergence of the pressure and magnetic stress tensors).

The characterization of the low-frequency turbulence can be achieved from correlations. Besides the standard fast Fourier transform (FFT) and auto- and cross-correlation studies (wave spectrum and the polarization at the four points in space), Cluster also allows derivation of new, important information from inter-satellite correlations. For instance, wavelengths of ultra-low frequency fluctuations can be determined in their three-dimensional extent. Unique information will be derived about dispersions (group velocities) and coherence lengths. The latter features are due to orbital mechanics that makes the spatial configuration of the spacecraft changing between a nearly tetrahedral configuration and a more trainlike arrangement.

The objectives, as discussed above, demand that Cluster be based on four suitably instrumented spacecraft. The need for accurate determination of vectorial quantities, for instance the current density $\underline{j} = \nabla \times \underline{B}$, requires that four spacecraft be placed in orbits that are not coplanar and be equipped with essentially identical sensors to ensure that the data can be compared with maximum confidence. Magnetically 'clean' spacecraft and highly accurate sensors are necessary to accurately compute the small differences of fairly large fields. Other vectorial quantities or tensors can be inferred from the data of the electric field or plasma instruments. The precise knowledge of the spacecraft separation distances is as important as accurate onboard timing.

5. CLUSTER IN RELATION TO OTHER MISSIONS

Several cooperative scenarios with other space missions are presently under consideration. In the mid 1990's, the Global Geospace Science (GGS) Programme implemented by NASA and encompassing WIND and POLAR and the joint NASA/ISAS GEOTAIL satellite will be in their extended mission phase. In the framework of the Inter-Agency Consultative Group for Space Science (IACG), formed by ESA, Interkosmos Council of the Soviet Academy of Science, ISAS (Japan) and NASA, a working group has been set up to identify means of maximizing the science return from these and other missions that will still be in orbit in the mid 1990's.

The closest cooperation will be with IKI, as their satellites will be launched at about the same time as Cluster itself. The mission objectives of the IKI/Cluster mission will be harmonized with those of Cluster.

The orbits of the IKI provided spacecraft are still under discussion. The instruments still have to be selected; however, model payloads have been defined to provide the same measurements as envisaged for Cluster.

6. SPACECRAFT DESIGN AND GROUND SEGMENT

The spacecraft will be spin stabilized at 15 rpm. The configuration is driven by the large amount of fuel needed to inject the spacecraft from the equatorial transfer orbit into the final near-polar orbit. Additional fuel is required for the in-orbit separation maneuvers. The dry mass of the each spacecraft is 354 kg, with an additional fuel load of 570 kg at launch. The launch is scheduled for December 1995 by the second test flight of Ariane 5.

The spacecraft are cylindrical in shape, being approximately 2.9 m in diameter and 0.9 m high (Figure 3). The platform will accommodate on one side the instruments. Each satellite will carry two high capacity redundant tape recorders which will yield a data return of 50 % per orbit. The recorders will have selectable input data rates and enable high speed data taking over short intervals.

Two rigid booms, each 5 m, will carry the magnetometers. Two pairs of wire booms, each with a tip to tip length of 100 m, allow electric field measurements based on the wire boom technique. The EMC specifications aim at a background magnetic field of ~ 0.25 nT

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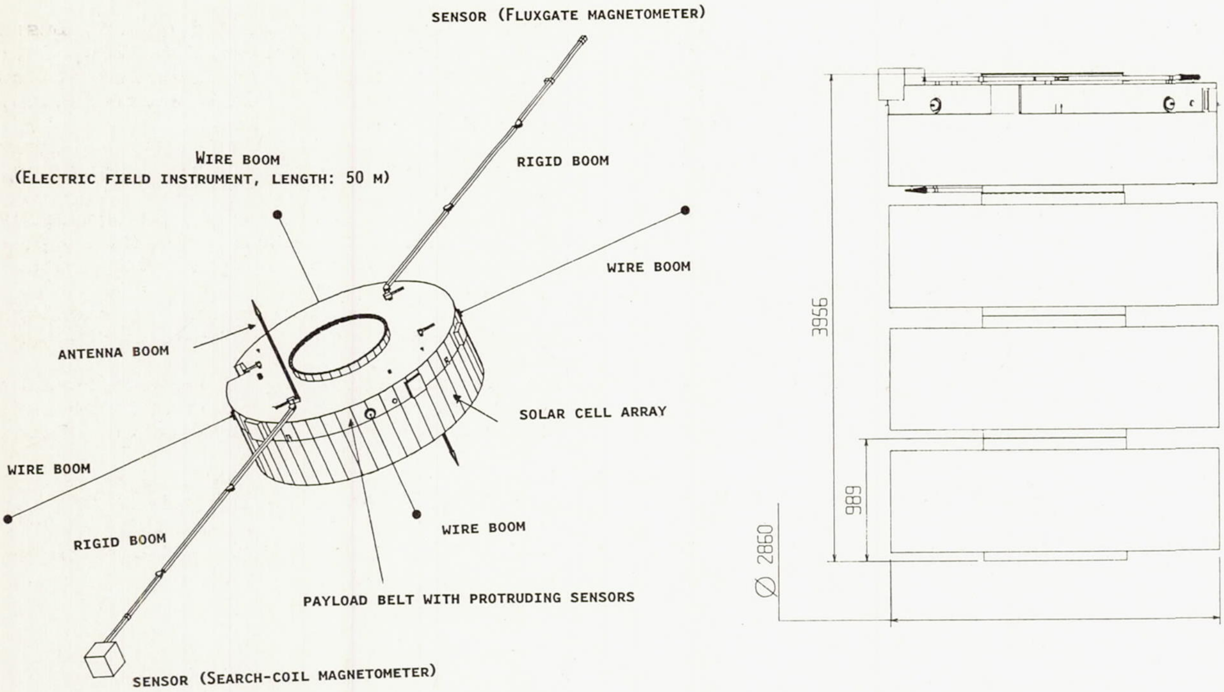

Fig. 3 One of the four spacecraft in its operational configuration (left). During launch the spacecraft are stacked (right). Note that only the top spacecraft is shown in more details.

at the position of the fluxgate magnetometer sensor. Because the attitude reconstitution is important for the derivation of vectorial quantities, the designers are aiming at an accuracy of 0.25°.

The 3 by 20 R_E near-polar orbit is depicted in Figure 1 (left), with the apogee in the solar wind. Six month later, the apogee swings through the geotail (Figure 1, right). To match the varying 'characteristic scale lengths' of plasma phenomena in the different magnetospheric regions, a separation strategy has been conceived that provides smaller separations in the dayside magnetosphere to match the typical scale lengths of a few hundred km to 1 R_E. At times when the apogee is in the geotail, larger separations (up to 3 R_E) will be established.

Cluster operations will be performed by ESA, with support provided by NASA's Deep Space Network. Because of financial limitations, ESA is not in a position to set up a science operations center; however, in recognition of the importance of such a facility for the success of the mission, the provision through other means is being sought. Each Principal Investigator will be provided with the entire decommutated data set of all four payloads on optical discs. Most recent raw data will be accessible through a computer link which would also provide the possibility of indirectly commanding the instruments from home institutes. Prior to execution, commands will be validated by the control center.

Real time operation of the payloads is not foreseen, except for the initial commissioning phase of the instruments. Commands are to be pre-stored for execution by time tag and data will be recorded onboard by the large-capacity tape recorders for later dumping.

The cooperation with IKI is based on the assumption that the complete data sets will be exchanged between the respective operations centers. It will be up to the respective Science Working Teams to devise the procedures. To ensure proper coordination of the missions, ESA and IKI intend to establish voice and computer links; the latter may also serve for the shipping of the bulk data.

7. COMMON SCIENTIFIC OBJECTIVES WITH SOHO

The in-orbit operational overlap of Cluster and Soho can not be accurately predicted yet. The present launch dates call for a Soho launch on STS in March 1995 while Cluster will be launched about 9 month later. If these dates can be maintained then Soho would serve Cluster as a solar wind monitor for about 15 months. This would be an additional direction for the interpretation of the Cluster data.

More importantly, however, considerable mutual illumination and cross-fertilisation is expected from a coordinated study of the physical problems investigated individually by each of the two missions. As part of an ESA sponsored workshop, several working groups formulated common scientific objectives and cross-fertilization aspects between Cluster and Soho (Ref. 7).

Their recommendations point out that some of the processes studied by the one of the STSP components - Soho or Cluster- have counterparts, or at least analogues, to be studied by the other component. For example, plasma transport into and out of regions of closed magnetic field lines occurs near the Sun and in the Earth's magnetosphere, as well as in many astrophysical contexts. Explosive releases of energy occur both on the Sun (coronal mass ejection), and in the geotail (plasmoid). Merging of magnetic field lines is a fundamental process that occurs at the Sun and in the magnetosphere, and perhaps also in the solar wind. It is particularly associated with extended, thin current sheets, which are observed in the Earth's magnetosphere and are inferred to exist at the Sun.

Joint studies by Cluster and Soho will illustrate the roles of the different parameter regimes and the limit of our analogy. This process is particularly important to our attempts to extrapolate and apply knowledge gained in solar-system studies to remote astrophysical objects.

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