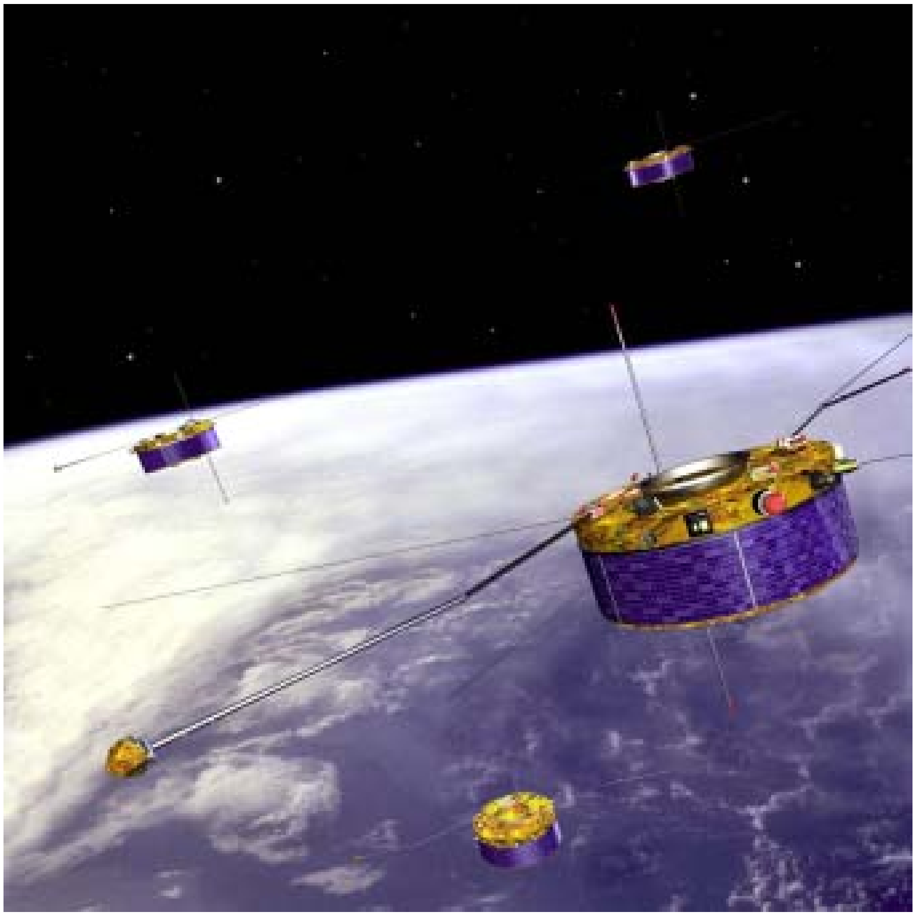
A Proposal Prepared for the *Senior Review* to Fund Analysis of Data from CLUSTER



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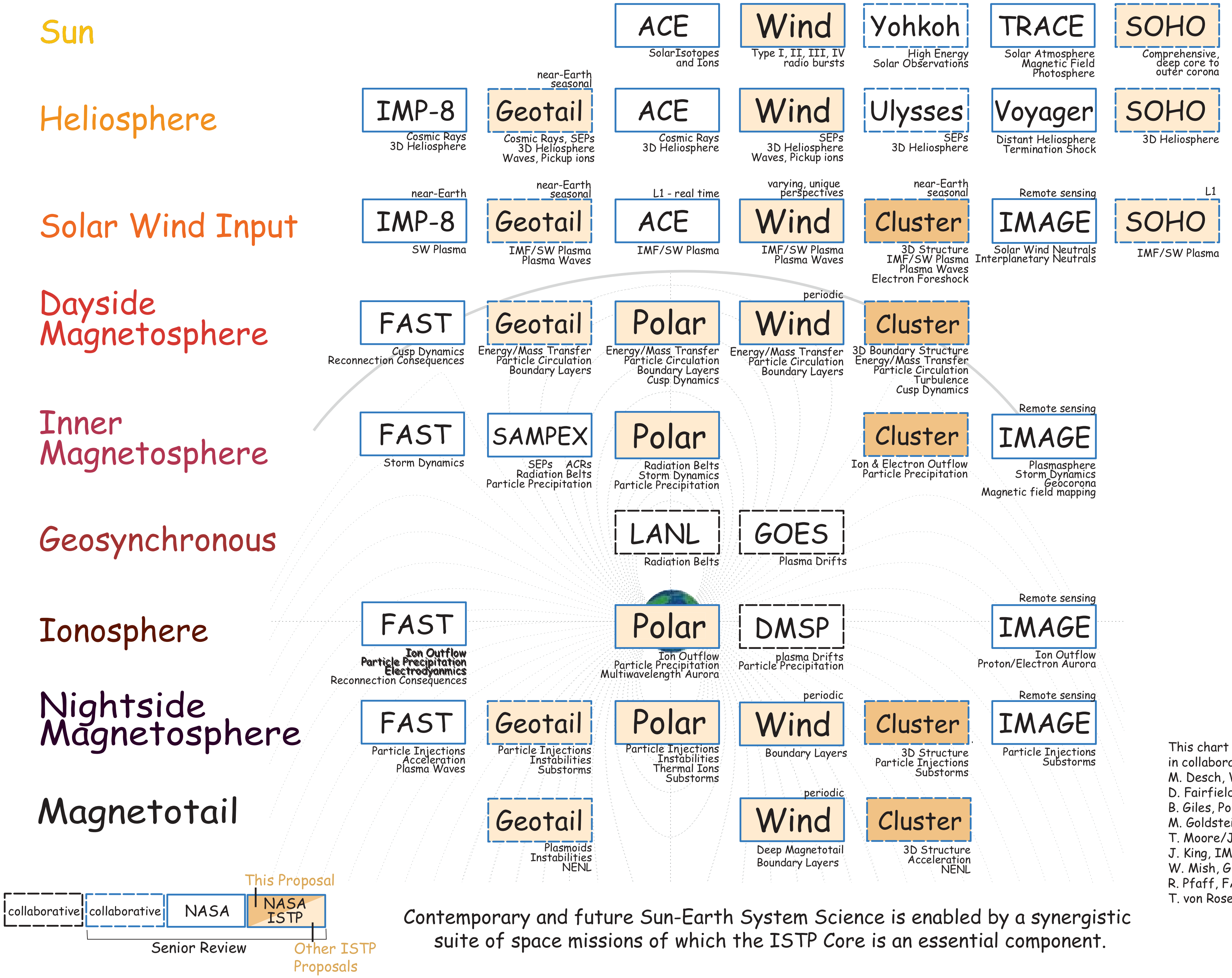
Sun-Earth Connection Science Infrastructure



Contemporary and future Sun-Earth System Science is enabled by a synergistic suite of space missions of which the ISTP Core is an essential component.

This chart developed
in collaboration with:
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B. Giles, Polar
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Executive Summary

CLUSTER is a pioneering, unique, and exciting mission that for the first time in the history of space science has deployed advanced particle and fields experiments on four identical spacecraft. The four spacecraft orbit in a tetrahedral configuration of variable separation allowing separation of space and time as data are collected across plasma boundaries in geospace. CLUSTER is the culmination of a 15-year joint program between NASA and the European Space Agency to launch a suite of spacecraft designed to explore geospace in unprecedented detail. The high time resolution measurements made by CLUSTER provide the first clear view of structures in three dimensions, making CLUSTER the microscope of the International Solar-Terrestrial Physics Program. CLUSTER'S unique capabilities include the ability to use VLBI techniques to determine the location, size, and motions of magnetospheric sources of radio and plasma waves. In addition, the wire booms of the Electric Fields and Waves experiment (EFW) together with the Electron Drift Instrument (EDI) provide all three vector components of the electric field at the four points of the tetrahedron.

The US involvement in CLUSTER is significant and critical to the scientific success of the mission. Wide Band Data (WBD) is a US PI instrument that was built at the University of Iowa. Data from this instrument is received from the DSN and processed at Iowa before being distributed to the CLUSTER Science Data Centers around the world. The boom mechanisms and power supply for EFW were built in the US and the EFW team has major responsibilities for both data analysis and data analysis software. The detector system, sensor, controller and flight software for the EDI experiment are US responsibilities. Similarly, the FGM sensors and analog electronics and many data validation tasks are US responsibilities. The time-of-flight COmposition and DIstribution Function analyzer (CODIF), part of the Composition Ion Spectrometer (CIS) was built in the US. The flight software for CODIF was written and is maintained by the US CIS/CODIF team. The Research with Adaptive Particle Imaging Detectors (RAPID) experiment, which measures energetic ions and electrons, includes an Imaging Electron Spectrometer (IES) that was built in the US. The flight and data analysis software for IES was written and is maintained by the US RAPID team. The data analysis software for the Plasma and Electron Current Experiment (PEACE) was written and is maintained in the US. The responsibilities of the US teams for both flight and data analysis software highlight how critical it is to the success of the entire mission that adequate funding be found by NASA to support CLUSTER.

CLUSTER was launched last summer and commissioned last fall. During the commissioning period and since the official start of the mission on February 1, 2001, the US investigators have succeeded, under very tight fiscal constraints, to commission the experiments, conduct an intensive experiment interference campaign, and perform necessary data validation tasks to put the data into formats appropriate for scientific data analysis. Preliminary science studies have been initiated. Some were presented at the European Geophysics Society meeting in Nice, France, this past spring. Many of the most intensive collaborations to date were carried out as a result of preparing this Senior Review proposal. Those studies are described in the body of the proposal and include: an analysis of the structure of the Earth's bow shock, a study of particle fluxes (electrons and ions) associated with the Plasma Sheet Boundary Layer (PSBL) and bright auroral arcs at the footpoint of the magnetic field threading the position of CLUSTER, auroral outflow and transport observed near perigee in the auroral zone, an analysis of a passage through the polar cusp that involved a collaboration of investigators from nearly every experiment on the mission, and VLBI studies of Auroral Kilometric Radiation (AKR) and chorus emissions. These science efforts provide a tantalizing glimpse of the revolution in our perception of the magnetosphere that will emerge if CLUSTER is allocated sufficient financial resources to carry out the scientific data analysis necessary to achieve the science goals of the mission.

Details of the data analysis tasks that are proposed for funding are given in the proposal. The major difference between the "minimal" and "optimal" scenarios lies in the number of co-investigator teams, postdoctoral associates, and graduate students that can be supported. In all, 76 US investigators were selected to participate in CLUSTER — they are eager for the opportunity to help fulfill the science promise of a unique mission that is already revolutionizing our concepts of the three-dimensional structure of the magnetosphere and its boundaries.

TABLE OF CONTENTS

SCIENCE SECTION

UNIQUE CLUSTER CAPABILITIES

The four spacecraft fleet known as Cluster is a joint program of NASA and ESA, originally developed under the umbrella of NASA's Cooperative Solar Terrestrial Research (COSTR). Cluster represents a major contribution by Europe to NASA's International Solar Terrestrial Physics Program (ISTP). The Cluster mission was conceived more than 15 years ago under the auspices of the Inter-Agency Consultative Group (IACG) following a very successful collaboration on the exploration of comet Halley in 1986. Cluster is one of the cornerstone missions of ESA's Horizon 2000 Program and together with SOHO, a major component of ESA's Solar Terrestrial Science Program (STSP). Much of the funding for Cluster and its launch came from ESA (~$800M), but the NASA contribution to the instruments and spacecraft has been substantial (>$91M). Some 76 US scientists are involved in Cluster. The majority of the US participants, however, have received little or no funding since the inception of this program and they are anxious to begin working with the unique Cluster dataset to achieve the science goals and to solve the science problems that inspired the development of this pathfinder mission. The involvement of these US investigators represents the scientific return on NASA's Cluster investment. Without sufficient funding for US investigators, NASA will lose this unique opportunity to enhance mankind's understanding of space plasma physics. The critical role played by the US in achieving the science objectives of Cluster cannot be overemphasized and has been addressed by several NASA advisory committees, such as SSAC, CSSP, SEC and others.

Cluster represents a breakthrough in space physics measurement. For the first time in the history of spaceflight, there are four, dedicated, identical spacecraft with modern instrumentation flying in a coordinated group. This configuration creates the unique ability to distinguish between temporal and spatial structures in the Earth's magnetosphere by comparing data across the four spacecraft. As such, Cluster as a spacecraft configuration, is a fundamentally new instrument for the measurement of the Earth's environment over a broad range of spatial scales and plasma parameters. Because of its ability to capture information across its (variable) tetrahedral orbital configuration, Cluster is the microscope of ISTP, providing the first clear instantaneous view of structure heretofore inferred only statistically. The mission has the ability to determine the topology of small-scale structures and the detailed nature of discontinuities in both the magnetosphere and solar wind. Figure 1 shows two snapshots of the Cluster orbit; during northern hemisphere winter, when the spacecraft apogee is in the solar wind; and during summer, when the apogee is in the magnetotail. Beyond the Cluster configuration itself, the unique instrumental capabilities include the ability to use Very Long Baseline Interferometry (VLBI) to determine the location and size of the sources of magnetospheric radio and plasma wave emissions and the ability to measure electric fields parallel to the magnetic field across narrow boundaries. Although parallel

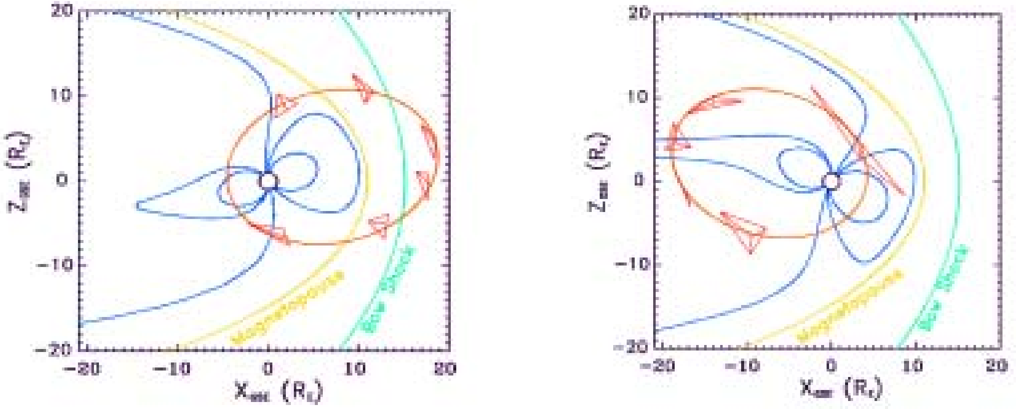

Figure 1. Two views of the polar orbit of the Cluster spacecraft in the x-z *plane. On the left, the view during northern hemisphere winter when apogee is in the solar wind. On the right is the situation during northern hemisphere summer when Cluster is positioned to explore the tail and plasma sheet. The size of the tetrahedron has been increased by a factor of 100 for visual emphasis.*

electric fields have been measured in the auroral acceleration region and in a polar cap reconnection site, such fields have never before been measured at the magnetopause or the bow shock. By providing three-dimensional descriptions of the boundaries that define the magnetosphere and its interaction with the solar wind, the role of these boundaries in energy and momentum exchange between the solar wind and magnetosphere can finally be understood.

CLUSTER, therefore, is a critical tool for understanding the vulnerability of the Earth to solar variability, a major science objective of the Office of Space Science Strategic Plan. CLUSTER is also poised to revolutionize our understanding of the space environment of the Earth (another major science objective of the Strategic Plan). Both of these capabilities, if realized with an adequate data analysis program, will enhance greatly the scientific and societal returns from the Sun-Earth Connection and Living with a Star programs.

CLUSTER is truly a unique pathfinder for the development of future (NASA) multi-spacecraft missions. The lessons learned from the design, fabrication, and calibration of four sets of identical experiments and the experience gained from commissioning the four spacecraft with their total of 44 separate instruments, and most importantly, operating and analyzing data from four spacecraft will be invaluable in the planning for MAGNETOSPHERIC MULTI-SCALE (MMS) and other similar NASA missions.

PHASING OF CLUSTER WITH RESPECT TO THE SENIOR REVIEW PROCESS

The format of this proposal does not follow all the guidelines for a Senior Review proposal because CLUSTER is neither a *continuing mission*, as that term is customarily understood, nor is it a *new mission.* While CLUSTER was launched only last year, its budget derives totally from plans developed for the original CLUSTER mission that ended with the explosion of the first launch of the Ariane 5 in June 1996. No new monies have been allocated to address the successful launch last summer of CLUSTER II. Therefore, not only does CLUSTER not have an adequate data analysis budget line for the current fiscal year, it has currently only $1 M in the budget guidelines (POP-01) for next fiscal year and nothing thereafter[*].

Given the obligations undertaken by NASA for support of many of the CLUSTER experiments, and given the fact that CLUSTER is comparable to four POLAR spacecraft, the guideline budget is wholly inadequate for achieving the science goals of CLUSTER and, if not augmented, will ensure that this international mission will realize little of its science potential. Consequently, we have chosen to present in this proposal a scenario for a budget that will permit the various experiment teams to maximize the science from this mission and to fulfill their previously agreed upon obligations to their European colleagues. These are obligations undertaken when the mission was first defined and the experiments were selected; those obligations have been underscored by the approval by ESA and NASA of the revived CLUSTER mission.

As the first mission capable of resolving spatial and temporal structure at the relevant scales for many key processes in space physics, CLUSTER will make pioneering advances in our physical understanding. It is essential to NASA, and to the United States scientific community, that we participate as strong partners with our European colleagues in exploiting the science that will stem from these revolutionary measurements.

To put the budgetary situation of CLUSTER in perspective, we first review some history: The original plan for CLUSTER was for a launch in 1996 to be followed by a reasonably funded data analysis program that included a significant theory and modeling component. In all, 75 US scientists were selected as Co-Investigators, together with one Principal Investigator, Prof. D. Gurnett of the University of Iowa. The majority of the Co-Investigators were to get support for data analysis only after launch. When the Ariane 5 exploded, CLUSTER as a mission was suspended; funding for US Investigators ended, including cessation of all theory and modeling efforts. Following an intensive 10-month effort on the part of ESA, and some imaginative fiscal efforts by NASA, CLUSTER

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[*] Code SR succeeded in finding nearly $5 M in funding for this fiscal year, a sum which included leftover development funds.

rose Phoenix-like and was re-authorized as the ESA Cornerstone mission.* The new mission, originally referred to as CLUSTER II, was essentially a full rebuild of the lost CLUSTER spacecraft. The US contributions to the instruments were made possible by allocating approximately 60% of the previously anticipated data analysis funding to replicate the US hardware. The remaining portion of the original CLUSTER budget was to support an initial data analysis program. During the period before the second launches, funding was provided only for investigators involved directly in the hardware rebuild. It was anticipated that additional funds would eventually be found to support a full data analysis program once a successful mission was underway. Rebuilding the US hardware contribution for the relatively modest sum of approximately $13M was possible because the decision to replicate as precisely as possible the original instruments greatly reduced costs. The hardware was rebuilt on schedule and within budget. The new launches occurred last summer from the Baikonur Cosmodrome, spaced one month apart, on two Soyuz launch vehicles.

This tightly constrained program, however, left unresolved the problem of adequate funding for data analysis. The problem was recognized several years ago and plans were made in late 1998 to prepare for a presentation to the then-scheduled Senior Review in 1999. When that review was cancelled, there was no obvious avenue available to solve the CLUSTER funding problem.

Following a presentation to headquarters in the spring of 2000, which highlighted the funding shortfall for the post-launch phase of CLUSTER, a vigorous effort on the part of Code SR led to the rephasing of most of the total allocation for CLUSTER data analysis to FY01. That reallocation of the DA budget, together with the nearly $1M of unspent development funds, allowed the CLUSTER experiments to be commissioned, for the interference campaign to be undertaken, and for initial data validation to proceed. However, funding has not been adequate to support any of the so-called Category C Co-Investigators who had been selected only for data analysis. The nominal two-year prime mission of CLUSTER (II) will run through 2002, with a high probability for at least a one-year extension.

In the following section, we review the US role in the CLUSTER experiments. For many of the experiments, the role of the US teams is crucial for the scientific objectives to be met. In some cases the US contributions are critical to the nominal operation of the experiments. The experiments with significant US involvement include the Wide Band Data (WBD) experiment (Prof. D. Gurnett, Univ. of Iowa, PI), the Electron Drift Experiment (EDI) (Dr. J. Quinn, Univ. New Hampshire, PI for NASA†), the Electric Fields and Waves (EFW) experiment (Prof. F. Mozer, Lead Co-I for NASA, Univ. of Calif., Berkeley), the Composition Ion Spectrometer (CIS) (Dr. G. Parks, Lead Co-I for NASA, Univ. of Calif., Berkeley), the Plasma Electron And Current Experiment (PEACE) (Dr. M. Goldstein, Lead Co-I for NASA, GSFC), the Research with Adaptive Particle Imaging Detectors (RAPID) (Prof. T. Fritz, Lead Co-I for NASA, Boston Univ.), and the Flux Gate Magnetometer (FGM) (Dr. M. Acuña, Lead Co-I for NASA, GSFC). NASA also has limited involvement with the Active Spacecraft Potential Control (ASPOC) experiment (Prof. R. Torbert, Lead Co-I for NASA, Univ. of New Hampshire). With the exception of the WBD team, NASA has little involvement with the active sounder (WHISPER), the search coil magnetometer (STAFF), and with the particle correlator and other features of the data processor (DPW) of the Wave Experiments Consortium (WEC).

NASA'S ROLE IN CLUSTER

Besides the contribution of NASA (Goddard Space Flight Center) of the high power RF amplifiers on the spacecraft, US scientists contributed in critical ways to the following experiments:

WBD

The WBD experiment makes high-resolution measurements of both electric and magnetic fields in selected frequency bands from 25 Hz to 577 kHz. Continuous waveforms are digitized and transmitted in either a 220 kbit/s real-time mode that is received directly by NASA's Deep-Space Network (DSN), or a 73 kbit/s burst

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[*] The first recorvery plan following the Ariane debacle was to launch the spare spacecraft under the name *Phoenix.*

[†] Dr. G. Paschmann is the PI for ESA science and was the original PI of the experiment.

mode transmitted to the spacecraft solid-state recorder for later playback. In the real-time DSN mode the relative timing of the received waveforms can be determined with microsecond accuracy. This precision timing makes possible a variety of new studies of magnetospheric radio emissions and plasma waves using the techniques of VLBI, including determination of the source locations and sizes of Auroral Kilometric Radiation (AKR). The experiment was built at the Univ. of Iowa under the direction of the PI, Prof. D. Gurnett. Unique to this instrument team is responsible for scheduling with the DSN for receiver operations, all data processing to basic Level 1 standards, and data archiving.

EFW

The EFW experiment measures quasi-static electric fields of amplitudes up to 700 mV/m with high time resolution and waveforms with a bandwidth of 4 kHz over short time periods using four orthogonal cable booms carrying spherical sensors. The booms were deployed to nearly 50 m in the spin plane of the spacecraft. From these measurements, one can determine the motions of plasma structures and wavefronts with velocities up to thousands of km/s. In the magnetosphere, the combination of EFW and EDI provides a full three-dimensional measurement of the ambient electric field. The scientific objectives of EFW include studies of nonlinear wave phenomena that result in acceleration of plasma as well as large- and small-scale interferometric measurements. With four spacecraft for large-scale differential measurements and with Langmuir probes useful for small-scale interferometry, the motion and shape of plasma structures over a wide range of spatial and temporal scales can be studied. The wire boom deployment mechanisms and power supply were built under the direction of the Lead Co-I Prof. F. Mozer at UC Berkeley. US team members have major responsibilities for data analysis and are responsible for the analysis software. In addition, the team participates in operating the instrument in orbit.

EDI

The new and pioneering Electron Drift Instrument measures the drift of a weak beam of test electrons that, when emitted in certain directions, return to the spacecraft after one or more gyrations about the ambient magnetic field. This drift is caused by the electric and magnetic fields. The fields themselves can be determined separately by using different electron energies. As a by-product, the magnetic-field strength is also measured. The EDI team at the Univ. of New Hampshire under the direction of the PI for NASA, Dr. J. Quinn, built the detector system, sensor, controller, and has responsibility for all flight software. The team also has major responsibility for data validation.

Together, EFW and EDI have the unique capability of measuring all components of the electric field, including that parallel to the magnetic field. EFW measures the electric field in the spacecraft spin plane, while EDI measures the component of the electric field in the plane perpendicular to the magnetic field. Thus, one obtains four measurements of three components of the vector electric field. The common measurement is along the line of intersection of the two planes, and as shown in Figure 2, the two techniques agree very well. The remaining three measurements give the three components of the electric field including the parallel component. Parallel fields of the order of 1 mV/m are measurable with combined EDI and EFW data.

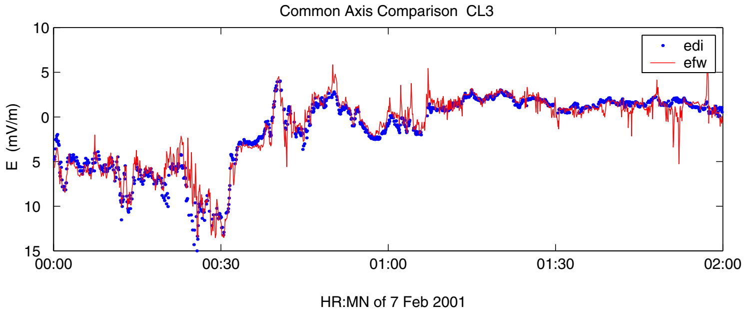


Figure 2. Comparison of eletric field measurements by EFW and EDI on SC 3.

FGM

The instrumentation of the Flux Gate Magnetometer (FGM) experiment consists of two high performance tri-axial fluxgate magnetometer systems with advanced signal processing capabilities. High vector sample rates (up to 67 vectors/s) at high resolution (up to 8 pT) are combined with an on-board event detection and a burst memory to capture signatures of dynamic phenomena. Four-point measurements of the magnetic field enable analyses of three-dimensional structures and the dynamics of phenomena that shape the magnetosphere. Difference measurements of the magnetic-field data can be combined to derive current density, wave vectors, and discon-

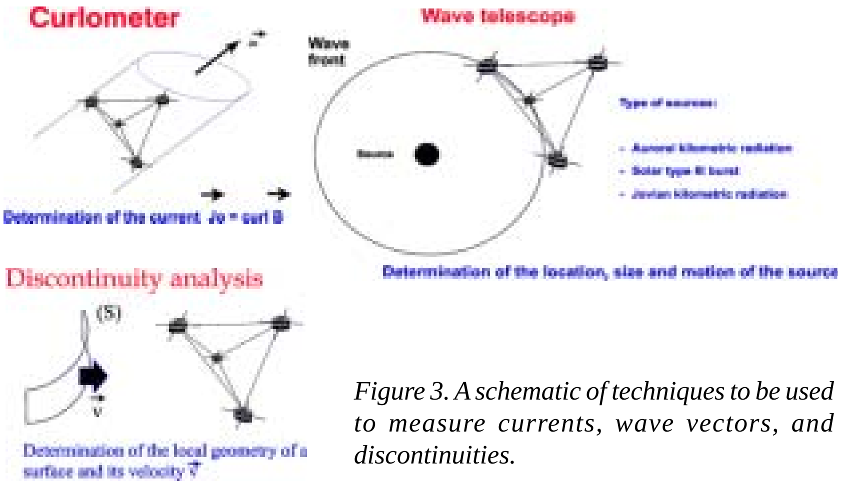


Figure 3. A schematic of techniques to be used to measure currents, wave vectors, and discontinuities.

tinuity normals and curvatures (Figure 3). The magnetometer sensors and the analog electronics were built under the direction of the Lead Co-Investigator Dr. M. Acuña of NASA's Goddard Space Flight Center. Various calibration and data validation/analysis tasks are handled by US FGM team members at UCLA (Prof. M. Kivelson) and JPL (Dr. Bruce Tsurutani).

CIS

The CIS package is capable of obtaining full three-dimensional ion distributions once per spacecraft spin (4 s), and can determine the mass per charge composition of the ambient plasma. The experiment consists of a Hot Ion Analyzer (HIA) and a time-of-flight ion COmposition and DIstribution Function analyzer (CODIF). CODIF was built in the US (at the Univ. of New Hampshire) and France under the direction of the PI, Prof. Henri Rème and the US Co-Investigator, Prof. George Parks (now at UC Berkeley). The flight software was also written in the US. The instrument measures the distributions of the major ions (H^+, He^+, He^{++} and O^+) with energies from ~0–40 keV/e with medium (22.5°) angular resolution and two different sensitivities. HIA has greater dynamic range and an angular resolution of 5.6°×5.6° for ion-beam and solar wind studies. Major responsibility for calibrating the instrument, validating the data, and maintaining the within specification operation of the instrument resides at the Univ. of New Hampshire and UC Berkeley.

RAPID

The RAPID is designed to detect suprathermal plasma distributions in the energy range 20-400 keV for electrons, 40–1500 keV for hydrogen, and 10–1500 keV/nuc for heavier ions. Novel detector concepts in combination with pinhole acceptance allow the measurement of angular distributions over a range of 180° in polar angle for either species. Identification of the ionic component is based on a two-dimensional analysis of the particle's velocity and energy. Electrons are identified by the well-known energy-range relationship. The IMAGING ELECTRON SPECTROMETER (IES) together with its flight and data analysis software was built in the US under the direction of the Lead US Co-Investigator, Prof. T. Fritz, now at Boston University.

PEACE

The PEACE instrument measures electron velocity distributions over all directions and covers the energy range ~0.7 eV to 30 keV. Each instrument consists of two hemispherical electrostatic energy analyzers and position sensitive microchannel detectors. LEEA (Low Energy Electron Analyzer) and HEEA (High Energy Electron Analyzer), mounted on opposite sides of the spacecraft differ in geometric factor (HEEA admits more electrons than LEEA in identical plasma distributions). Moments, estimates of spacecraft potential, pitch angle distributions and low-resolution distribution functions can be transmitted in normal mode. In Burst Mode, three-dimensional velocity distribution data are transmitted. The primary US responsibility to PEACE is for the data analysis and display software written at the Southwest Research Institute under the supervision of Dr. D. Winningham (SwRI) and the Lead US Co-Investigator, Dr. M. Goldstein (NASA/Goddard).

Before describing in detail exactly what financial and technical resources are required to support the US contribution to CLUSTER, we review the mission science objectives and give a few examples of results from the first few months of operation.

SCIENCE OBJECTIVES

A pervading theme of all astrophysics is that particles are accelerated to extremely high energies, very much beyond the energies predicted by theories. The processes responsible for this acceleration are important to the physics ranging from scales attainable in the laboratory to that of cosmological structures. Acceleration cannot be studied experimentally at these two extreme spatial scales, in the former case because of the limited dimensions of the system and, in the latter case, because *in-situ* measurements cannot be made. It is thus, of importance to fundamental physics and to all of astrophysics that *in-situ* measurements be made in the local, solar system plasmas to understand such processes. These measurements also delineate the physics of geospace. They have contributed to our understanding of collisionless shocks, reconnection, and the creation and maintenance of narrow boundaries in space plasmas, to name but a few of the achievements of the NASA space physics program. With the advent of CLUSTER, these measurements take on a new dimension. The primary goal of CLUSTER is to use four point measurements to unravel the spatial and temporal components of structures in geospace. The mission provides unique opportunities to characterize the physical properties of plasma structures on scales ranging from a few ion Larmor radii (the cyclotron radius of ions) to larger scales of the order of an Earth radius. Each region in the magnetosphere and solar wind to be visited by CLUSTER has associated with it specific science objectives that were set forth in the original Announcement of Opportunity (AO). The regions visited and the associated science goals include:

The Dayside Cusp, Magnetopause and Plasma Sheet Boundary Layer: CLUSTER will study the spatial thickness and convective motion of the boundaries between these regions to determine the physical processes that lead to the transfer of mass, momentum, and energy across such boundaries in space plasmas. For the first time, it will be possible to define the morphology and the dynamics of the polar cusp. Initial results are discussed below.

The Geomagnetic Tail: CLUSTER will study the kinetic physics behind the large-scale reconfiguration of plasmas and electromagnetic fields associated with magnetospheric substorms. CLUSTER is also uniquely capable of determining how the tail plasma is energized and where it flows. The first tail campaign will be conducted this summer when CLUSTER will move through the geomagnetic tail at 20 R_E with a spacecraft separation of ~2000 km. During this period, POLAR will also be in the tail, but at 9 R_E. This conjunction of spacecraft (see, Figure 17) in the vicinity of the Near Earth Neutral Line (NENL) will be nearly ideal for studying the flow of energy before and during substorm onset. Questions that can be answered include: How large in cross-sectional area and how far down the tail is the region where bursty bulk flows are found? Do bursty bulk flows contain sufficient energy to power the aurora? What happens first at substorm onset: dipolarization, outward flow, or bursty bulk flows?

The Interplanetary Shocks and the Earth's Bow Shock: The three-dimensional capabilities of CLUSTER enable detailed studies of the collisionless shock waves that define these boundaries, including their spatial structure, associated particle acceleration, and wave generation mechanisms. As demonstrated below, CLUSTER can determine the thickness of the shock and its velocity. Preliminary CLUSTER results that measured the speed and thickness of these discontinuities indicate that these boundaries are generally non-planar.

The Magnetosheath and the Solar Wind: The tetrahedral configuration of CLUSTER and the variable separation of the spacecraft will permit CLUSTER to study how solar wind particles gain entry into the magnetosheath and magnetosphere. Processes that can be investigated include direct entry through the polar cusp, reconnection, instabilities, boundary layer turbulence, and other processes occurring at the magnetopause. CLUSTER will characterize the microstructure of solar wind plasmas and fields, both as an example of a stellar wind, and as a laboratory for the determination of how MHD turbulence propagates, evolves and dissipates. The tetrahedral configuration will provide spatial scales from a few hundred km to several thousand km. Spatial scales associated with the dissipation range of the power spectrum of solar wind magnetic and velocity fluctuations will reveal the nature of the fluctuations at scales on the order of a few ion Larmor radii. The relatively high time resolution of the CLUSTER particle detectors can be used together with the electric field measurements of EFW (as well as EDI when it is operating, *e.g.*, in the magnetosheath, and WBD when wideband data is available) to determine unambiguously the plasma wave modes that constitute the dissipation range of the turbulence.

Energetic Particles in the Magnetosphere: A scientific goal of CLUSTER is to identify particle storage and acceleration regions and their relationships. The radiation belts and the ring current represent major particle and energy storage regions of the Earth's magnetosphere. With CLUSTER we will be able to ascertain the injection mechanisms for different energetic charged particle species into the stable trapping regions during geophysical events. In the past, these Space Weather events have been labeled "magnetic storms" and "magnetospheric substorms," but it is becoming increasingly evident that this old descriptive nomenclature may encompass an array of different dynamically intercoupled phenomena involving different regions of geospace and their interface to the solar wind. One of the most interesting regions that CLUSTER has been examining is the high altitude, and high latitude magnetospheric cusps. Initial analysis of energetic particle data indicates that these particles are often found on the dayside magnetosphere in regions where they cannot be stably trapped and where their lifetime in the magnetosphere ranges from seconds to tens of minutes. CLUSTER will help answer the question of how these particles are accelerated and/or transported, and will establish the causal connections of these energetic particles with the inner magnetosphere and the ring current, the major dynamic storage regions of the magnetosphere.

The Equatorial Magnetosphere: CLUSTER passes through the equatorial plane at both at apogee and perigee. At perigee CLUSTER will investigate the plasmasphere and plasmapause, which will allow for determination of the shape of the plasmapause with unprecedented resolution. In this region, CLUSTER data will also be used to characterize the source regions and spatial extents of those whistler-mode plasma waves responsible for the acceleration and loss of energetic particles within and immediately outside this boundary, including chorus, plasmaspheric hiss, and lightning-generated whistlers. Simultaneous WBD measurements of chorus on the four CLUSTER spacecraft have been realized and are discussed below. These observations reveal fascinating differences at the four spacecraft and raise new questions as to how these intense coherent and discrete emissions are produced by the energetic magnetospheric plasmas at both the Earth and at other magnetized planets. At apogee, CLUSTER will cut through the near-Earth plasma sheet and the three-dimensional configuration of CLUSTER will determine the shape and plasma flow characteristics of the plasma sheet boundary layer, including the how the boundary layer transitions into the central plasma sheet. CLUSTER will also investigate reconnection and particle acceleration processes in the near-Earth plasma sheet and will give a new detailed, three-dimensional view of the NENL.

The Auroral Zone: The CLUSTER instrumentation will characterize the flow of plasma from and to the ionosphere during the perigee passes and will determine the spatial scales of acceleration processes occurring within the auroral zone. CLUSTER, in conjunction with ground-based experiments, will study the low- and mid-latitude projections of boundary field lines that map into the Earth's auroral zone. Some preliminary results on particle flows associated with bright auroral arcs and on the source location of Auroral Kilometric Radiation are given below.

In all regions, CLUSTER makes differential measurements of electric currents, density gradients, plasma waves, eddy diffusion, and vorticity to ascertain how particles are transported and accelerated in geospace by a variety of plasma wave modes and plasma structures.

CLUSTER is a unique and revolutionary tool that will enable the Office of Space Science to achieve, at low cost, several of the goals discussed and included in its Strategic Plan. Specifically, (pp. 9 and 10) CLUSTER will enhance our understanding of the effect of solar variability on the Earth and will help to quantify the vulnerabilities of the Earth to solar energetic particle events and to solar wind disturbances. CLUSTER will further our understanding of the space environment of Earth (p. 15). CLUSTER is included in the strategic plan as a part of the overall NASA efforts using FAST, IMAGE, and many ISTP collaborating missions to understand the magnetosphere on micro- and macro-scales. In short, CLUSTER is the microscope of the current fleet of geospace missions. More generally, the strategic plan emphasizes (p. 87) that "Without a vigorous R&DA program it would not be possible to conduct a scientifically meaningful flight program." And again on p. 89, the point is made, referring to data, that *“After we have obtained them, we must* ***analyze and interpret data*** *returned by NASA’s space science missions to fully exploit them for addressing our strategic science objectives.”*

To be consistent with its own strategic goals, it is essential and of critical scientific importance that NASA now fund an adequate data analysis program for the duration of the prime and any extended mission.

SCIENCE INSIGHTS AND PROMISE

Many important scientific questions concerning the transport, acceleration, and loss of charged particles through the magnetosphere remain unanswered due to our incomplete knowledge of the global structure of the magnetic and electric fields. The multi-point particle and field measurements on CLUSTER offer unprecedented opportunities for the first time to construct self-consistent descriptions of the magnetic field, electric field and particle phase space densities in localized regions. The determination of the plasma gradients will establish the direction of transport and/or the existence of localized acceleration or loss processes during disturbed and quiet times. The local electric and magnetic field measurements can be used as boundary conditions for the determination of the regional field structure. Determination of phase space density maps and magnetic and electric field parameters will allow a quantitative description of the plasma in the volume of space surrounding the CLUSTER constellation, a volume that will vary as the spacecraft separation is changed throughout the mission.

PHYSICS OF BOUNDARIES

The Bow Shock

In the seventies and early eighties the Earth’s bow shock was primarily described using magnetohydrodynamics (MHD), and particle acceleration was seen as diffusive acceleration arising from the compression of the upstream and downstream fluids at the shock. With few exceptions, the observations were made by single satellites with substantial spatial and time averaging. Over the past decade, advances in hybrid simulations and the ability to measure ion distributions led to a revolution in our understanding of the microphysics of the acceleration processes in the shock. Our knowledge can be further advanced with simultaneous observations of fields and particles at four different locations with high time resolution. In addition, ACE and SOHO can provide observations of undisturbed boundary conditions upstream of the “simulation box” containing the shock and the CLUSTER satellites (Figure 4). These unique capabilities permit study of bow shock processes in unprecedented detail, comparable to that obtainable from simulations.

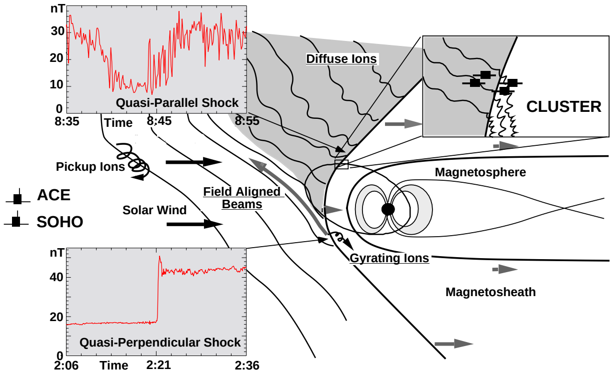
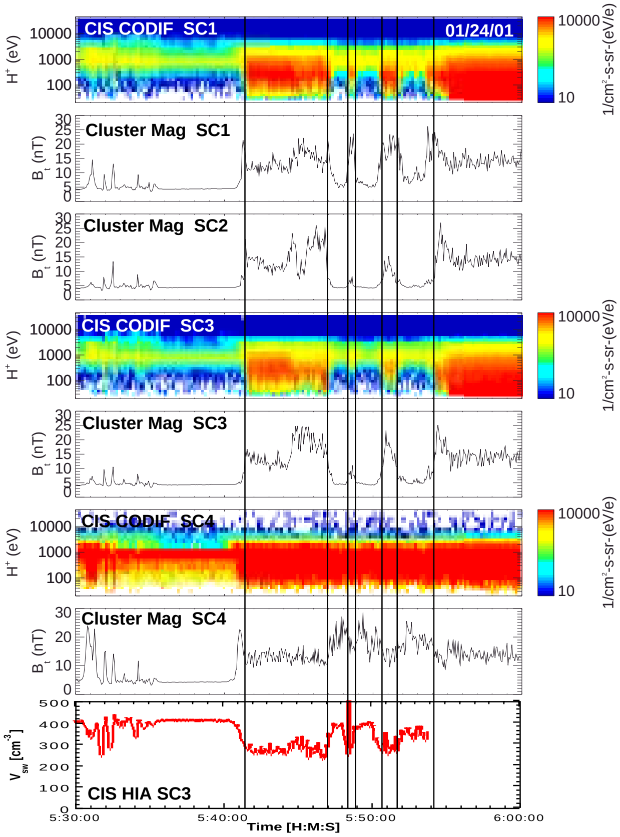


Figure 4. Schematic view of the bow shock and the different ion distributions in front of quasi-perpendicular and quasi-parallel bow shocks. Typical crossings of these shocks as seen by a magnetometer are shown in the inserts on the left. A blow-up of the CLUSTER configuration at the shock is shown in the insert on the right. Magnetic field data are from FGM observations in January 2001.

Two distinct particle populations, reflected or diffuse, are associated with the quasi-perpendicular or quasi-parallel shocks, respectively, that characterize the interaction of the solar wind magnetic field with the magnetosphere. The reflected ions form a field-aligned beam resulting from their reflection off the quasi-perpendicular shock. Diffuse ions are found upstream of quasi-parallel shocks and have nearly isotropic distributions with energy spectra extending to ≈200 keV/e. The different particle populations are indicated in Figure 4. The shock structure is quite distinct in these two cases. A sharp and stable transition is usually observed at the quasi-perpendicular shock with a distinct step in the magnetic

Figure 5. Repeated crossing of the quasi-perpendicular bow shock by Cluster. From top to bottom: spectrogram of H$^+$, magnetic field magnitude B from SC 1, B from SC 2, H$^+$ and B from SC 3 and 4, and solar wind speed from SC 3. The vertical lines indicate the bow shock crossings as seen at SC 3, the reference SC.



field and often an overshoot (Figure 4, bottom left), whereas the quasi-parallel shock appears to be less steep and is highly variable in space and time (Figure 4, top left). Typical transitions as seen in the magnetic field are shown as inserts in the figure for the two cases (data from FGM).

Cluster first encountered a quasi-perpendicular bow shock on the dusk side of the magnetosphere. Figure 5 shows a series of crossings on January 24, 2001, when the spacecraft were hovering at the shock for an extended time. Shown are colored spectrograms of H$^+$ fluxes on SC 1, 3 and 4, magnetic field magnitude on SC 1, 2, 3 and 4, and the ion flow speed on SC 3. While SC 1, 2 and 3 crossed the shock repeatedly, SC4 remained downstream after its first inbound crossing at 05:41 UT. This is evident from the magnetic field compression and the slowing and heating of H$^+$. Although there is an overall stable quasi-perpendicular shock topology, the fluctuations at the shock and in the magnetosheath show considerable variation at the four spacecraft.

During the 05:41 UT crossing, CODIF observed both reflected ring and beam particle distributions. Figure 6 shows a schematic view of the spacecraft at the shock along with the reflected ions (right) as observed in the color-coded angular distributions (center) and the fluxes of ring and beam distributions as a function of time

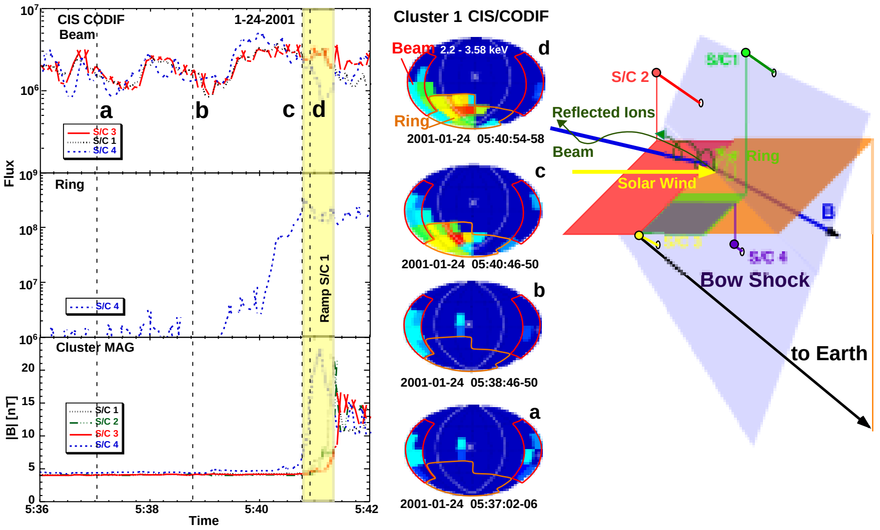


Figure 6. Right: Three-dimensional view of Cluster at the quasi-perpendicular bow shock. The colored areas and the vertical lines indicate the position of SC 1, 2 and 4 relative to the reference SC 3. The orientation of the vector pointing toward the Earth is shown similarly (not to scale). The short lines from the SC towards the shock (light blue shaded area) indicate the relative distance of the spacecraft from the shock. Typical trajectories of reflected ions with different pitch-angles are shown in green. Center: 4π angular distributions of H$^+$ at 2.2-3.6 keV. The magnetic field points out of the plane at the star, the white line is at 90° pitch angle. From top to bottom are shown the shock ramp (d), the edge of the ramp (c), and two views upstream of the shock (b and a). The red line surrounds the reflected beam and the orange line the gyrating ions. Left: Fluxes of beam distributions from SC 1, 3 and 4 (upper panel) and gyrating ring distributions (center panel) from SC 4 and magnetic field strength from FGM on all four SC (lower panel) as a function of time. The low geometric factor side of CODIF on SC 4 is chosen for the ring distribution because the high geometric factor side is saturated for this distribution, while it shows excellent statistics for the beam.

(left). Upon encounter with the shock, a fraction of the solar wind ions are reflected upward forming a ring distribution with a wide range of pitch-angles. While ions with pitch-angles close to 90° (outlined by an orange line as ring distribution) are swept downstream, those with a large parallel velocity component in the upstream direction escape as a beam (outlined by a red line). Consequently, the flux of the ring distribution falls off quickly with distance from the shock, and the flux of the beam remains almost at the level established in the shock ramp. It is evident that both ring and beam are part of the same reflected distribution. Apparently, specularly reflected ions are quickly pitch-angle scattered in the ramp. Such scattering by Alfvén waves is consistent with recent simulations. Note that there is substantial structure in the beam fluxes that is almost identical on SC 1, 3, and 4, but very distinct from variations induced by the varying shock distance (see Figure 5 and FGM data in Figure 6). Detailed study of such shock-associated distributions, in combination with simulations, will provide the basis for the solution of the injection problem at quasi-perpendicular shocks. As demonstrated in this first example, the coordinated observations made with Cluster present an unprecedented opportunity to extract the spatial and temporal structure of the solar wind interaction with the shock and its thermalization in the downstream region.

In contrast to the quasi-perpendicular shock, the quasi-parallel shock is a broad transition zone where the upstream flow heats and slows before passing downstream. The transition is neither smooth nor monotonic, but consists of large-amplitude pulsations that are convected into the shock, causing the shock to fracture and reform on a short time scale. It has been proposed that the quasi-parallel shock itself is a patchwork of these large-amplitude pulsations running into each other. A key question is the spatial extent

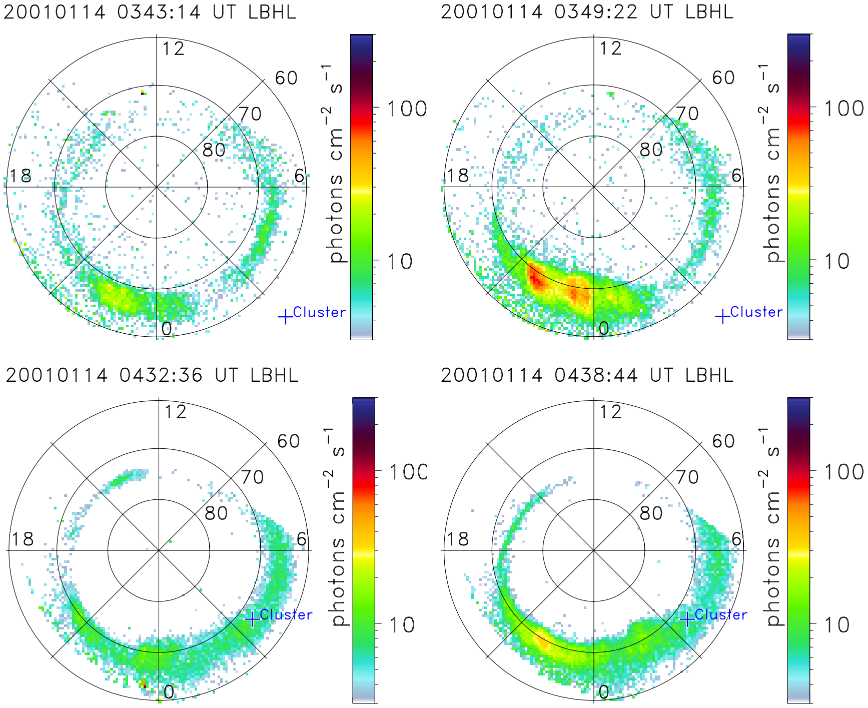


Figure 7. UV auroral images from Polar on January 14, 2001. The magnetic footprint of the position of the Cluster spacecraft is indicated by the notation "+Cluster."

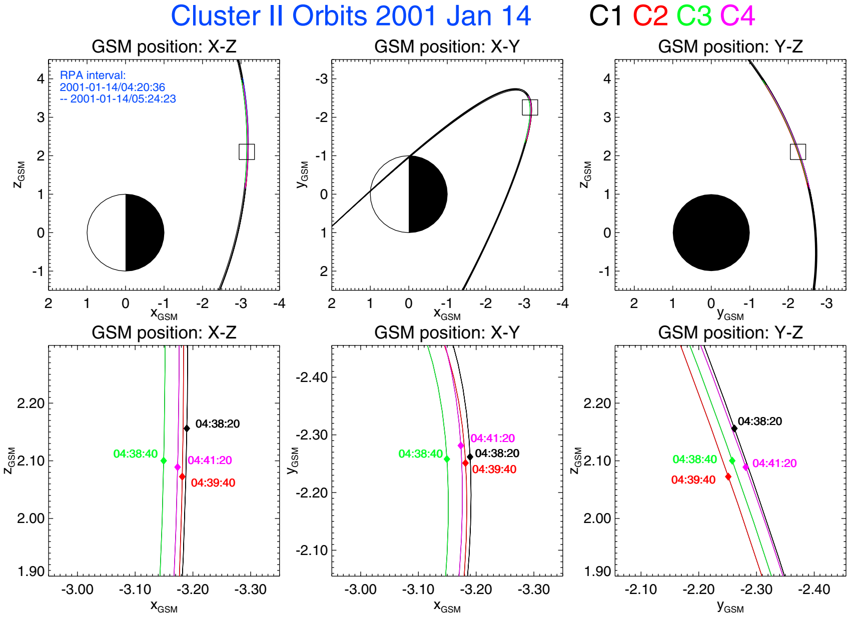


Figure 8. The orbital positions of the four Cluster spacecraft at the time of the January 14, 2001 event.

of these structures perpendicular to the shock normal and the separation of the structures parallel to the shock normal. Cluster has the capability to unravel the nature and the size of these structures. Furthermore, the Cluster ion and electron observations, together with numerical simulations, will be able to answer the question of how these structures originate. They will also determine their relationship to diffuse and specularly reflected ions and upstream waves.

PLASMA ACCELERATION DURING LARGE-SCALE SUBSTORM RECONFIGURATION

Substorm Triggering and Aurora in the Magnetosphere

Aurorae appear to be driven by plasma instabilities in the magnetosphere. The "trigger" is associated with the dipolarization of the geomagnetic tail during which time the tail current is abruptly disrupted or destroyed, resulting in large-scale reconfiguration of the magnetosphere. From single spacecraft observations, we know that large "bursty bulk flows," with velocities exceeding 400 km/s are associated with dipolarizations. We also know that the plasma distributions associated with these flows consist of nongyrotropic ion and electron beams with energies up to several MeV. The electron distributions are unstable and emit radio waves at kilometric wavelengths.

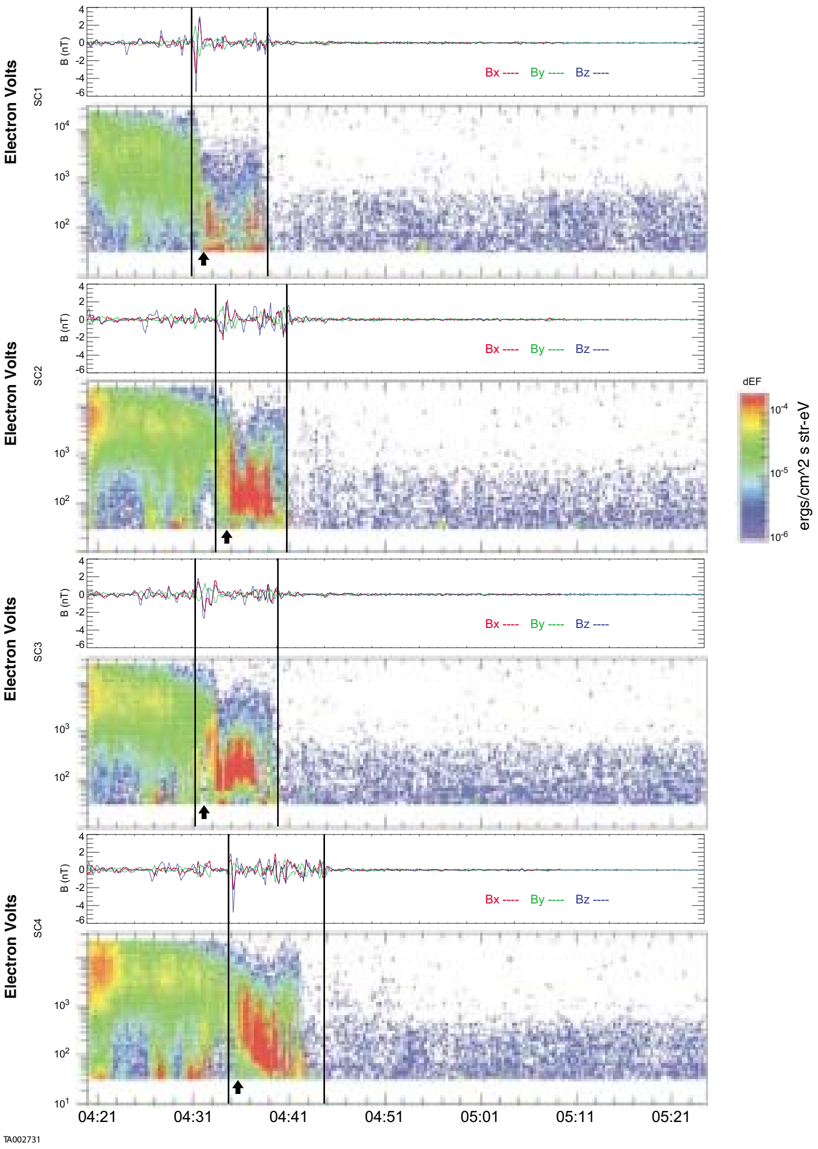


Figure 9. PEACE and FGM δB (components) data for January 14 from 04:20 to 05:25 UT. From top to bottom the panels are for SC 1 to 4. The PSBL and field aligned current region is observed between the vertical lines when PEACE observes up- and down-going field-aligned cold beams.

Studies of ion dynamics in the plasma sheet indicate that the instabilities producing small- and large-scale auroral features ("pseudobreakup" and expansive types of aurora) are nearly identical and involve large-amplitude Alfvén waves, unstable plasma distributions and currents. The results suggest further that plasma sheet processes, like the aurora, include a continuum of disturbance levels and sizes that have been observed within about 10-25 R_E distance on the night side. However, single point observations have not provided quantitative information about the size or motions of the disturbance regions and many fundamental questions about substorm initiation remain unanswered.

We illustrate the uniqueness of Cluster capabilities with an example from January 14, 2001. The four spacecraft were outbound at a distance of about 4 R_E where they detected particle and field signatures associated with auroral activity in the ionosphere. Figure 7 shows the UV images of the aurora from Polar displayed in magnetic latitude and local time coordinates. The auroral activity proceeded as a sequence of four well-defined intensifications. The onset of the first brightening occurred around 03:43 UT, the maximum was reached at 03:49 UT. The aurora then faded and was relatively quiescent by 04:08 UT (not shown). A rekindling of the aurora occurred around 04:32 UT that lasted until past 04:40 UT. During this rekindling, the footprint of the magnetic field line of Cluster mapped to the northern boundary of the auroral oval (indicated by + in Figure 7). The orbits of the four spacecraft during this period are shown in Figure 8.

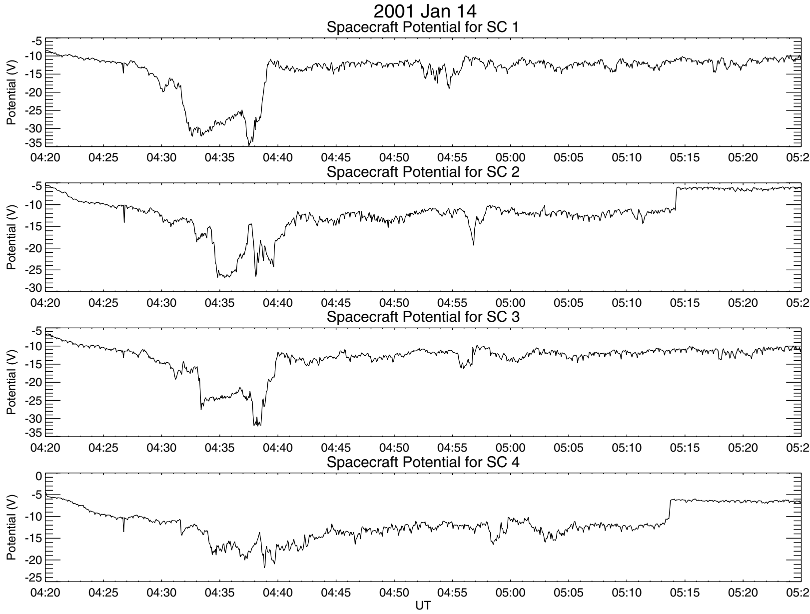


Figure 10. The spacecraft potential as determined by EFW during the January 14, 2001 event.

The electron and magnetic field data from PEACE and FGM are shown in Figure 9.The PEACE data are in an energy spectrogram format. The panels go from SC 1 to 4 from top to bottom. The vertical lines indicate the region of largest currents deduced from detrended FGM data. The maximum δB_i (components of the magnetic field) are observed at the position of the arrow in each panel. While all four spacecraft observed magnetic variations, the detailed features differed. It can be seen that the current region corresponds to the PSBL region in each panel. The maximum current is coincident with the initial burst of ~100 eV electrons as is especially apparent on SC 1. The magnetic field fluctuations extend into the polar cap region only on SC 4 indicating the current can extend into the polar cap (Figure 9 at 4:42:UT). The PSBL plasma is a mixture of a hotter component extending to ~8 keV plus the lower energy (~100 eV bursts). Some of the energy variation in the ~100 eV component are actually spacecraft potential variations as can be seen from the EFW data shown in Figure 10. The potential is inversely proportional to the local plasma density. The magnetic field indicates that Cluster

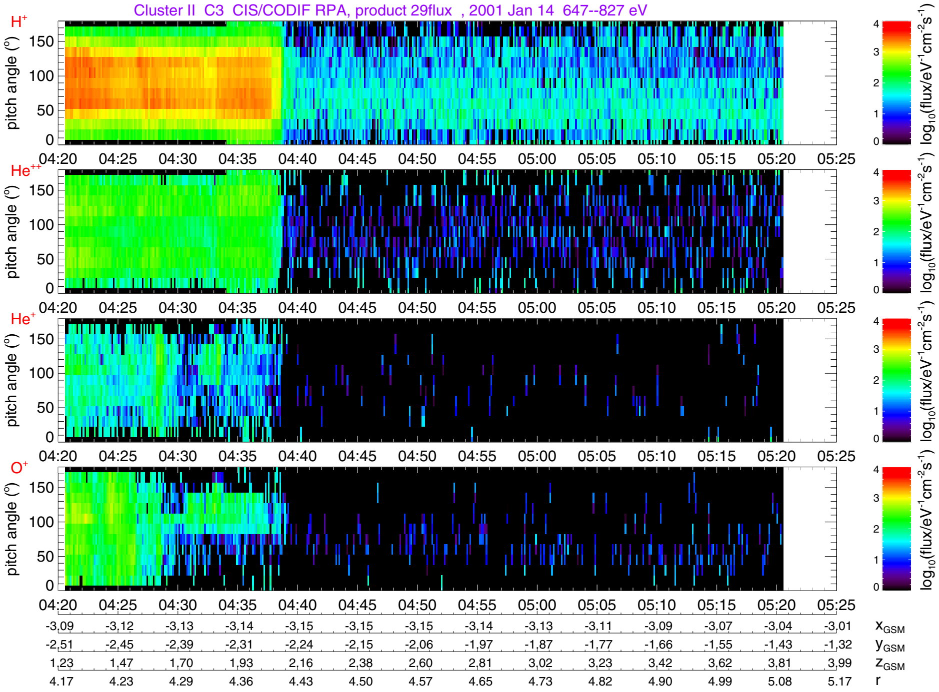


Figure 11. The pitch-angle spectrograms from SC 3 of the four principal ion species (H^+, He^{++}, He^+ and O^+) from CIS/CODIF. CIS was operating in the fixed energy mode and measured ions with energies of about 700 ± 100 eV/charge.

encountered current structures and/or waves from about 04:30–04:45 UT, overlapping the auroral activity shown in Figure 7.

The pitch-angle spectrograms of the four principal ion species (H^+, He^{++}, He^+ and O^+) from one of the CIS-CODIF instruments are plotted in Figure 11. CIS was operating in the fixed energy mode and measured ions with energies about 700 ± 100 eV/charge. The top panel shows the H^+ ions, the next panel He^{++}, then He^+ and O^+ (caution: He^{++} has contribution from H^+ due to spillover). Note that both electron and ion instruments first detected plasma sheet-like particles until about 04:32 UT and later detected PSBL-like particles until about 04:40 UT (the PSBL is most clear in O^+ and He^+ data). Afterwards, particle fluxes decreased by two orders of magnitude, indicating that CLUSTER had entered the lobe-like region of the polar cap.

Comparison of the magnetic field variations to Figure 9 shows that the largest variations observed (at 04:31-04:32 UT on SC 1) occurred when the potential (density) was sharply increasing (decreasing) (Figure 10). The potential (density) profiles from SC 1 and 3 are best correlated. SC 2 has a similar profile but shows additional features and SC 4 profile is least similar. These results are surprising because SC 1 and 3 were furthest apart, about 600 km (Figure 9) and SC 2 and 4 were closest (200-300 km). This suggests that the observed features cannot be planar because in that case SC 2 and 4 would see the best correlation and SC 1 and 3 the worst. Further analysis is needed to describe the three-dimensional shape of this region. The conclusion that the region is not planar is also consistent with the time sequence shown in Figure 9, where one sees that SC 1 enters and leaves the PSBL earliest, followed by SC 3, then SC 2, and finally SC 4. *Note that the largest region of currents is coincident with the PSBL. If this region corresponds to visible arcs at auroral heights, then considerable acceleration has to occur in transit to the Earth.* The CLUSTER observations indicate that the structure is complicated, probably non-planar with temporal and spatial evolution during the interval of observation.

Another important feature is associated with where the outward flowing ionospheric ions are located. Comparison of Figure 11 with Figures 7 and 9 shows that the He^+ ion conic (120-150^o pitch-angle) at 04:33 UT coincided with the largest magnetic field variation (current) and these ions were located at the edge of the boundary (where the density is sharply decreasing). The O^+ overlaps this region but extends deeper into the plasma sheet. H^+ shows conics from both hemispheres superposed on the plasma sheet population (we do not discuss He^{++} due to spillover of H^+ fluxes that have not been corrected for in these plots). Tsyganenko 92 model shows the footprint of the CLUSTER spacecraft maps to the northern boundary of the aurora at 4:40 UT (Figure 7). *Hence, the CLUSTER spacecraft were sampling upward and downward going auroral particles and the simple interpretation is that CLUSTER detected particles contributing to field-aligned currents.*

Auroral Ion Outflow and Transport

The spatial distribution of the outflow of ionospheric plasma from the auroral regions has previously been determined only statistically. CLUSTER provides the first opportunity to determine the instantaneous spatial scales of the outflow and to deconvolve spatial structures and temporal changes. Knowing the spatial scales is critical for testing current theories of ion acceleration and other magnetosphere-ionosphere coupling processes. In addition, CLUSTER allows one to estimate the instantaneous input of ionospheric plasma into the plasma sheet, thus characterizing a critical element in the initiation of substorms.

In February 2001, CLUSTER observed auroral outflow close to perigee when passing through the southern and the northern auroral zones close to local midnight. During these perigee passes, the spacecraft were at about 5 R_E. In all cases, strong field aligned flows of predominantly O^+ and H^+ with energies from 20 eV to 1 keV as observed. Figure12 shows a pass through the southern auroral region on February 21. The top four panels show electron energy spectrograms from PEACE; the next three panels show the electron convection velocity in the plane perpendicular to **B** in the spacecraft frame as measured by EDI on SC 1. The bottom five panels show H^+ and O^+ energy spectrograms for SC 1, SC 3, and SC 4. At 03:30 UT, SC 1 enters a region characterized by highly structured electron and ion bursts. As the spacecraft approach this region from the polar cap during the interval prior to that shown here, the steady flow toward the nightside plasma sheet decreases and begins oscillating at about 03:10 UT, while the *VYgy* component shows a growing dawnward component. At the encounter with the auroral structure, the drift velocities become highly variable and the dawn-dusk flow begins a reversal from dawnward to duskward. The convection in the boundary layer varies significantly on the timescale

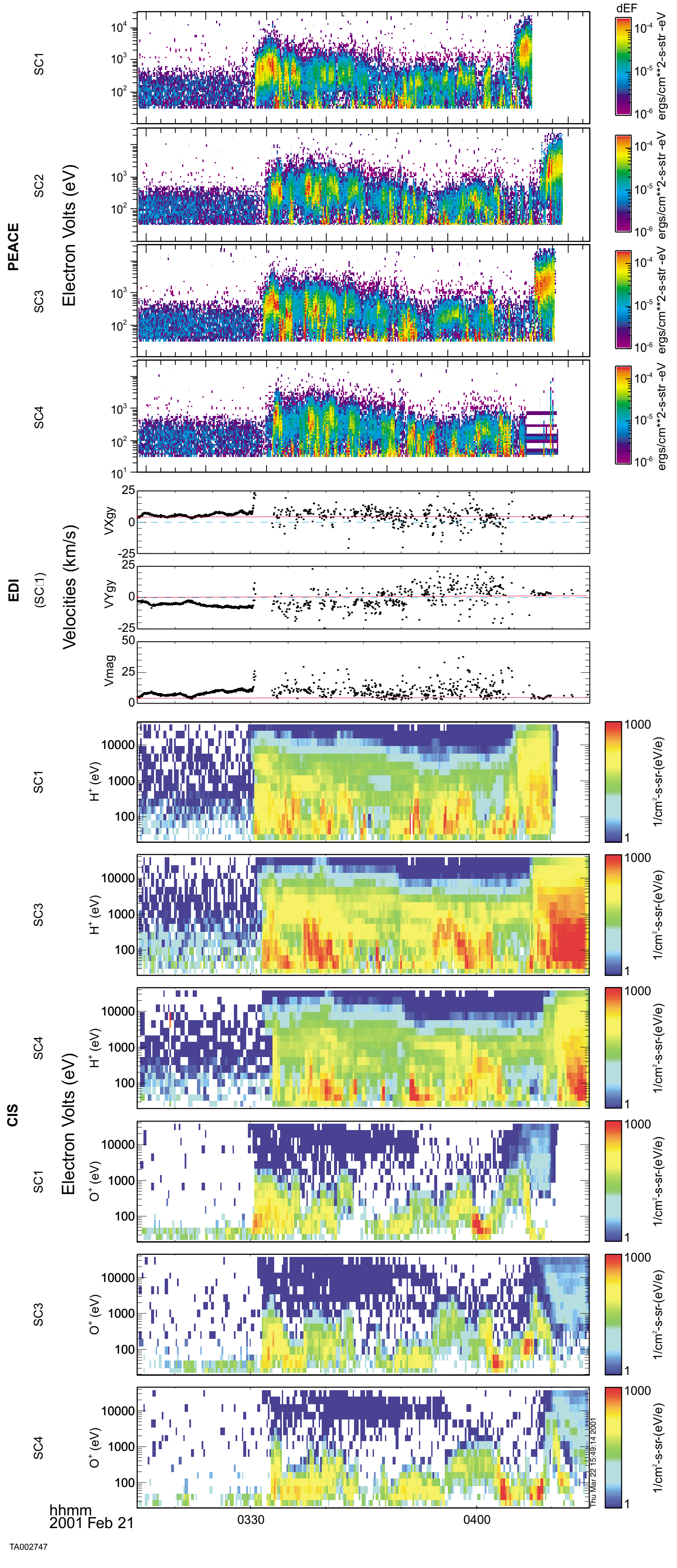


Figure 12. Data from a southern auroral pass on February 21, 2001. The top four panels show electron energy spectrograms from the four spacecraft, followed by three panels showing EDI flow velocities perpendicular to the magnetic field, in a coordinate system perpendicular to the local magnetic field. VXgy is the B-perpendicular component closest to the +Xgse axis, while VYgy is the component closest to the +Ygse axis. The velocities are in the spacecraft frame of reference, with the red line indicating the spacecraft ram component of the measured flow. The following three panels show H^+ energy spectrograms, and the bottom three panels show O^+ energy spectrograms from SC 1, 3, and 4.

shown here as confirmed by examination of higher time resolution EDI data. SC 1 remains in this region until 04:05 UT when the convection electric field becomes steady, and a higher energy, more stable population is observed in both electrons and ions.

A distinct pattern is observed in the O^+ outflow, starting with a burst that first increases in energy up to about 800 eV, and then decreases. A period of low energy outflow (<100 eV) starts at about 03:45 UT. At 03:56 the energy increases to ~300 eV, followed by a more intense low energy outflow. Then the energy increases again, up to almost 2 keV. The pattern is first observed by SC 1, then SC 3, and finally SC 4. There is a delay of about 1.6 minutes between SC 1 and SC 3, and about 1.9 minutes between SC 3 and SC 4. Similar delays are observed in the electron data. Both the electron and ion data show the spacecraft finally entering the central plasma sheet starting at about 04:05 UT. In this case, the majority of the features observed result from the spacecraft crossing over a spatial structure that is apparently steady over time scales of tens of minutes. Motions of the structures can be determined after more detailed analysis.

Cusp Morphology and Particle Acceleration

After 30 years, the exact mechanism(s) of solar wind plasma entry, energization and transport into the outer boundary of the magnetosphere are still poorly understood. An important mission link concerns the mapping of distant regions close to and in the magnetopause to low altitudes. Past measurements have been clumped into three major spatial regions and at most two satellites. These regions are at ionospheric heights, mid to high altitudes approximately over the pole, and spotty spatial coverage of dayside to flank magnetopause crossings. The sampling of parameters such as magnetic field and pressure is statistically poor and the space/time resolution has been coarse in all regions, especially at large distances outside the low altitude ionospheric region.

CLUSTER represents a revolutionary advance in our ability to resolve microphysical structures in four dimensions over a broad range of length and time scales. During its lifetime, CLUSTER will cover the region from mid cusp to high cusp including the magnetopause itself. In conjunction with the multipoint space/time coverage, CLUSTER has an unprecedented set of field and particle measurements. Joint multi-spacecraft/multi-instrument high-resolution analysis will show how plasma enters the magnetosphere, becomes energized, and is subsequently transported into the dayside cusp. Combining CLUSTER data with global kinetic and MHD models will lead to a truly revolutionary leap in our fundamental understanding of the magnetosphere.

Figure 13 represents a cusp pass that occurred on January 14, 2001 at ~1330 UT. The figure is a composite of data from CIS, RAPID, PEACE, STAFF, EFW, and FGM. The cusp passage is contained between the two vertical dashed lines between 13:30 and 13:32:30 UT. Prior to this event CLUSTER had traversed the polar cap/tail lobe on its outbound leg and just before this event had been in a boundary layer environment with excursions back into the lobe/polar rain environment. The polar rain fluxes increased in intensity as this afternoon boundary layer was approached. Prior to 13:30 UT, **B** has a stretched geometry as expected in the boundary layer region (panels *m* and *n*). Upon entry into the "cusp" region, **B** rotates to a geometry typical of the cusp. (Note that these angles are towards the South Pole, thus the values are northward pointing). In addition, one has to add ~5° due to difference between the spin axis and the celestial pole. SC 3 (4) has an elevation of ~ 105° (140°) that is southward pointing as expected at this time in a stretched, draped afternoon boundary layer. The azimuths (note 22.4° has to be subtracted to get the GSE angle) are ~140° (100°) for SC 3 (4) as expected for an afternoon outward flare of the magnetosphere. Upon entry into the cusp event (between the dashed lines) **B** increases to ~41 nT (58 nT) at maximum. There is a symmetric change observed in the polar (θ) and azimuthal (ϕ) angles in the cusp. From edge to center, θ shifts by ~25° (15°) to a more vertical orientation. The azimuth shifts to 158° (130°), *i.e.* more antisunward. Initial spatial analysis of EFW data indicates this feature is due to motion at ~66 km/s. However, the evidence for nonplanar geometry has to be included in the analysis before the velocity can be known with certainty. Nonetheless, the true spatial size could be as large as several 1000 km.

Next, we turn to the other CLUSTER instruments. Only SC 3 (left) and 4 (right) are shown. Four SC data were used to calculate shape and velocity of the feature. The DC electric field components from EFW are shown in panels *j, k,* and *l*. These data are in GSE and assume no parallel electric field. In the cusp region, one can clearly see the presence of an electric field that is approximately in the spin plane. Outside the cusp, the electric field is close to zero.

Panel *g* shows the PEACE electron data from one polar zone. Prior to the cusp event one sees the more energetic boundary layer (or plasma sheet) electrons to ~13:27 UT which are followed by a mixed region of softer intense electrons and a weaker energetic flux above ~500eV. This mixed region is characteristic of the outer boundary layer. The electrons measured by RAPID (20–400 keV) show a maximum centered at 13:22:30 UT, but extending over the entire time period at the lowest energies. RAPID also sees ions throughout this time, except for a dropout centered on the cusp. CIS (panels *a, b, c, d*) observes energetic ions (O^+, He^+, He^{++}, H^+) throughout this period, again with the exception of the cusp region itself.

We focus now on the cusp event period (note that CIS on SC 4 is in a more sensitive mode than on SC3). CIS ions shown in panels *a-d* indicate an onset of softer H^+ ions mixed with a more energetic component, an onset of lower energy He^{++} and He^+ mixed with a higher energy population, and an energetic flux of O^+ everywhere except in the cusp, where it greatly weakens. In addition, a lower energy (~100 eV) O^+ population appears that is moving up the field line from the ionosphere. Within the cusp one sees an increase in the lower energy

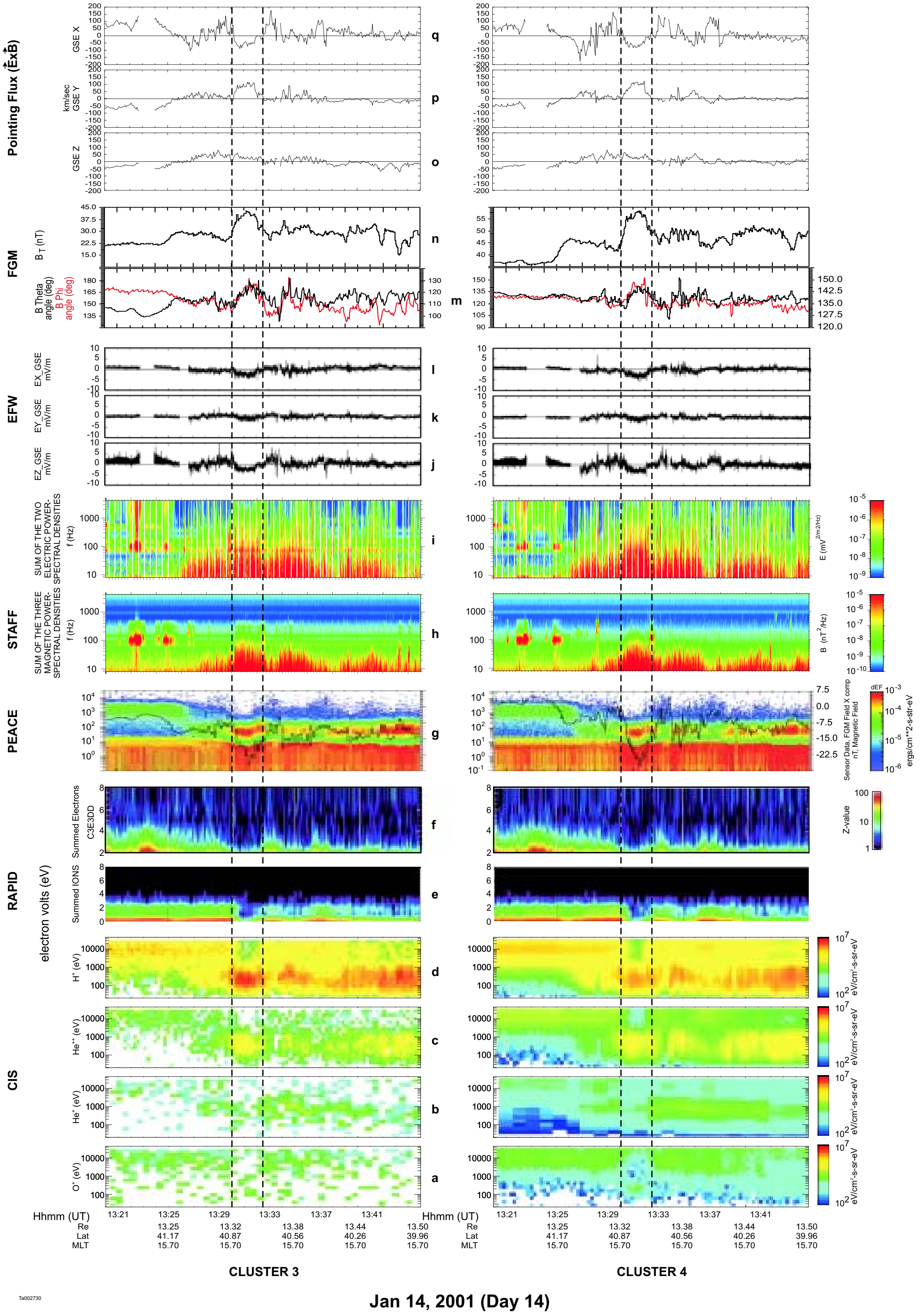


Figure 13. Data from CIS, RAPID, PEACE, STAFF, EFW, and FGM, for SC 3 (left column) and SC 4 (right column) on January 24, 2001 from 13:20 to 13:45 UT. The spacecraft are at ~13 RE and a MLT of ~ 15.7 hours. A "cusp event" is observed between the vertical dashed lines. All measurements indicate a unique set of related changes in this region that is distinctly different from its surroundings. Four spacecraft analysis indicates that the feature is moving.

population and a dropout of the energetic component. The He^+ and high energy ions (RAPID, panel *e*), while in the cusp the energetic ion fluxes almost disappear (panel *e*).

The PEACE electrons (panel *g*) exhibit a hot magnetosheath population during the cusp traversal. The drop in energy is due to a drop in spacecraft potential, caused by increasing ion fluxes. RAPID also sees an electron dropout (panel *f*) in the cusp region. This dropout is more pronounced in SC 3. STAFF magnetic and electric AC data from 10 Hz to several kHz are shown in panels *h* and *i*. In the cusp, an abrupt increase is seen in the power below 400 Hz. Increases are seen after the cusp, but they are not as intense. The same abrupt increase is seen in the AC electric data in panel *i*. An increase in the electric and magnetic fields is seen afterwards with some similarities to the cusp encounter, but not nearly as dramatic. These wave characteristics are similar to those observed in the magnetopause current layer. Upwelling O^+ is only observed in the cusp event.

The components of the Poynting flux are shown in panels *o, p, q* for both satellites. The maximum value is seen in the cusp with a direction of propagation towards Earth (absolute units are not yet available).

These tantalizing data exhibit the power of the four spacecraft, advanced multi-instrument complement, to reveal clearly how plasma enters the magnetosphere and links to the Earth via the dayside cusp region. This example illustrates the level of resources required to grapple with these exciting and extensive data.

RADIO AND PLASMA WAVE SOURCE REGIONS

Auroral Kilometric Radiation

Auroral kilometric radiation is the most intense electromagnetic radiation emitted by natural processes at the Earth. Similar emissions are generated at other magnetized planets such Jupiter and Saturn. It is a right-hand polarized extraordinary mode wave emitted in the frequency range 50-500 kHz. An example of AKR measured on three CLUSTER spacecraft is shown in Figure 14. The bottom three panels show a narrow frequency band extending from 250-262 kHz as measured by WBD on CLUSTER spacecraft 1, 3, and 4. The bright red narrow-band emission features are AKR.

Although AKR has been studied extensively, and is generally thought to be produced by a relativistic electron maser instability driven by resonance with the Doppler shifted (relativistic) gyrofrequency, the motion and size of the source region has not yet been determined. The highly coherent variation in frequency of narrow band AKR features has been hypothesized to be caused by the motion of the source region along the field line. (As the source region moves, the electron cyclotron frequency changes with the changing magnetic field magnitude leading to the observed fine structure). However, no such motion of the source has until now been measurable.

Because AKR is a free-space, electromagnetic mode and propagates away from the source, its source location can be determined using standard interferometric techniques. For such techniques to work effectively, signals must be received by three or more spacecraft. On January 11, 2001, the Deep Space Network acquired signals from three of the CLUSTER spacecraft in a carefully time-calibrated reception mode. Portions of these data are shown in the bottom three panels of Figure 14. To make clearer the detail at expanded time scales, the fourth panel from the bottom of Figure 14 shows an expanded view from SC 3 of a set of rapidly rising, narrow-band AKR frequency structures that span about 5 s from 20:55:37.03 UT to 20:55:42.15 UT. Because of their rapidly rising frequencies and their coherent nature, these structures are particularly good candidates for VLBI.

The top three panels of Figure 14 show an example of the results of preliminary analysis on these signals to determine the relative time delay of the AKR signatures detected between the three baselines defined by all pairs of the three spacecraft for which we have data. Each of the top three panels shows the result of a time-domain cross-correlation analysis between the waveform data received on pairs of spacecraft for the boxed window shown in the middle panel of the figure. The cross-correlation analysis yields sharp peaks around a few ms relative time delay.

The width of the envelope of fringes is related to the bandwidth of the source signal. However, the precision of the peak is significantly better than this peak and is estimated to be about 150 μs. In terms of distance, for a wave propagating at light speed, this translates into a distance error of 45 km. For good triangulation, three

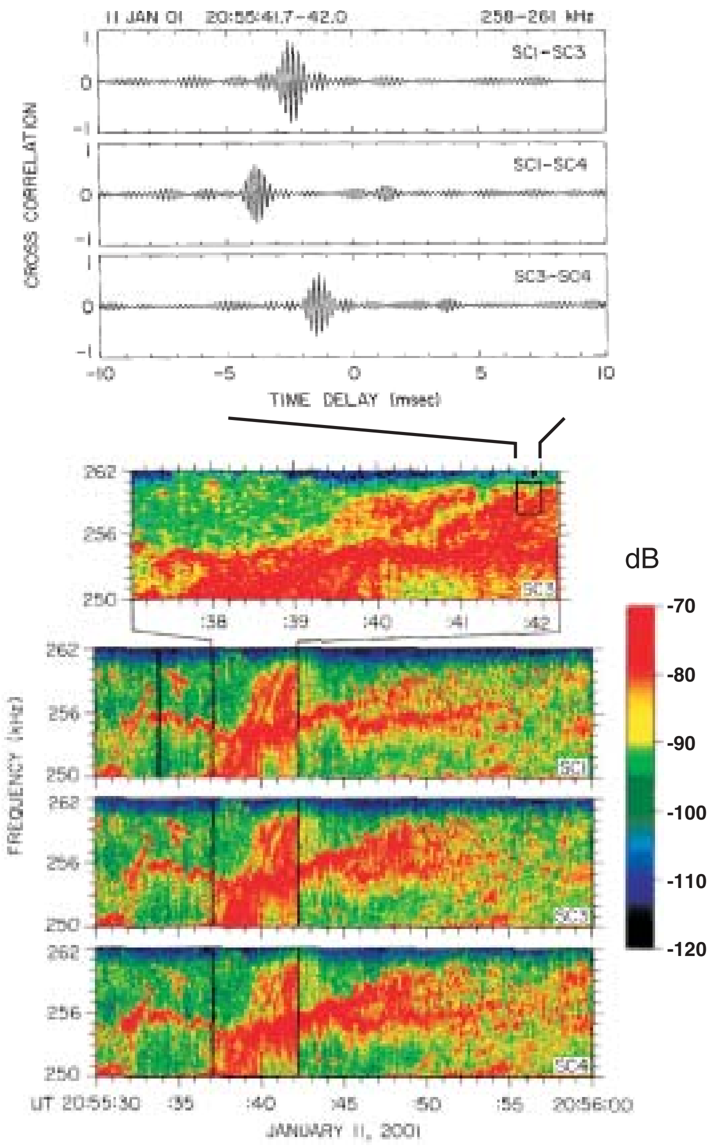


Figure 14. An example of AKR measured on three of the Cluster *spacecraft. The bottom three panels show a narrow frequency band extending from 250-260 kHz as measured by the WBD on SC 1, 3, and 4. The bright red emission features are AKR.*

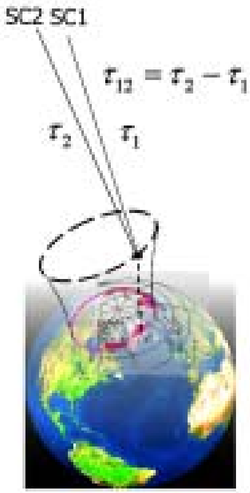


Figure 15. Schematic diagram of the technique for finding the location of Auroral Kilometric Radiation with a single pair of spacecraft. For the data in Figure 14, the location of the emission maps to a bright spot on the auroral oval as shown.

baselines that are much larger than the distance error are required. For this example, only two of the baselines meet this criterion, making the problem under-constrained.

An additional constraint exists because the AKR source frequency is determined by the local electron cyclotron frequency in the generation region. For the AKR frequencies studied here, that translates to a background magnetic field of 0.09 G. We use an average position for the auroral zone of 70° invariant latitude and then follow these field lines to where the correct field magnitude is reached. The observations map to an annulus of points above the Earth's northern pole as shown schematically in Figure 15. We can then compare the expected travel times from points around this annulus to each of the spacecraft with the measured delays. There are only two points on the annulus that will generate the correct difference in travel times to a given pair of spacecraft. For this case, the two baselines that are sufficiently large give the same position to within less than 5° azimuthally around the annulus. Also shown in Figure 15 is the UVI auroral image from the Polar spacecraft for the time corresponding to the AKR emissions in Figure 14 (courtesy G. Parks). The location determined this way is a bright spot of increased auroral emission as shown in Figure 15. This demonstrates the success of the interferometric technique as well as one of the ways in which data from other spacecraft can be combined with Cluster measurements to provide increased understanding of magnetospheric processes. As the Cluster spacecraft separate, the baseline separation will improve and we expect that WBD will succeed in measuring the motion of the AKR source, potentially leading to a first understanding of the underlying physical cause of the coherent structure exhibited by AKR and other planetary radio emissions.

Wave Particle Interactions in the Outer Radiation Belts

One of the important manifestations of Space Weather in the Earth's outer magnetosphere is the fact that these regions are often populated to a surprising degree by relativistic electrons as observed at geosynchronous orbit. The source of the pronounced fluctuations in intensity of these energetic particles is not known, although they are generally correlated with the onset of substorms. Enhancements occur with relatively regular 27-day periodicity and are well associated with solar wind stream structures. Since the energies of these particles are much higher than that in the solar wind, their acceleration to energies of up to many MeV must occur by processes within the magnetosphere. These acceleration processes are largely undetermined, although wave-particle interactions are believed to play a crucial role. Simultaneous observation of waves and energetic electrons (*e.g.*, by RAPID) on Cluster during near perigee passes of the equatorial region of the outer radiation belts provide unique opportunities for identifying the types of waves that are the most important in this acceleration. In addition, multi-spacecraft observations of plasma waves provide unprecedented opportunities for determination of the source regions and generation mechanisms of waves, so that their role in the dynamics of the outer belts can be quantified.

A primary example of the types of waves that can be studied by Cluster is Chorus. Chorus emissions are the most intense plasma waves in the outer magnetospheres of the Earth and other magnetized planets and are believed to be drivers of electron precipitation, being responsible for pulsating aurorae as well as the morningside diffuse aurora. Chorus is primarily an electromagnetic wave that frequently is observed in the form of narrow-band emissions in the audio frequency range. Typically there are multiple bursts of rising tones which when heard as an audio signal sound like of a "chorus" of birds singing at dawn. The emission is believed to be generated in the outer radiation belt by 10-100 keV electrons via a cyclotron resonance and typically propagates away from the equatorial plane, its presumed generation region. The discrete structure of chorus emissions is remarkably similar in form to that of AKR. The physical mechanisms that lead to this highly coherent nature are not yet understood, although they are likely to be due to non-linear effects such as phase trapping of the electrons by the wave field, and highly localized and structured source regions. Cluster provides the first opportunity for definitive measurements of chorus in or near its source region at multiple locations, so that the spatial extent of the coherent wave packets and the source regions can be determined. Such a determination would allow us to understand the underlying mechanisms and would constitute a major advance in understanding the physics of wave-particle interactions, the pervasive means of energy and momentum exchange in near-Earth space.

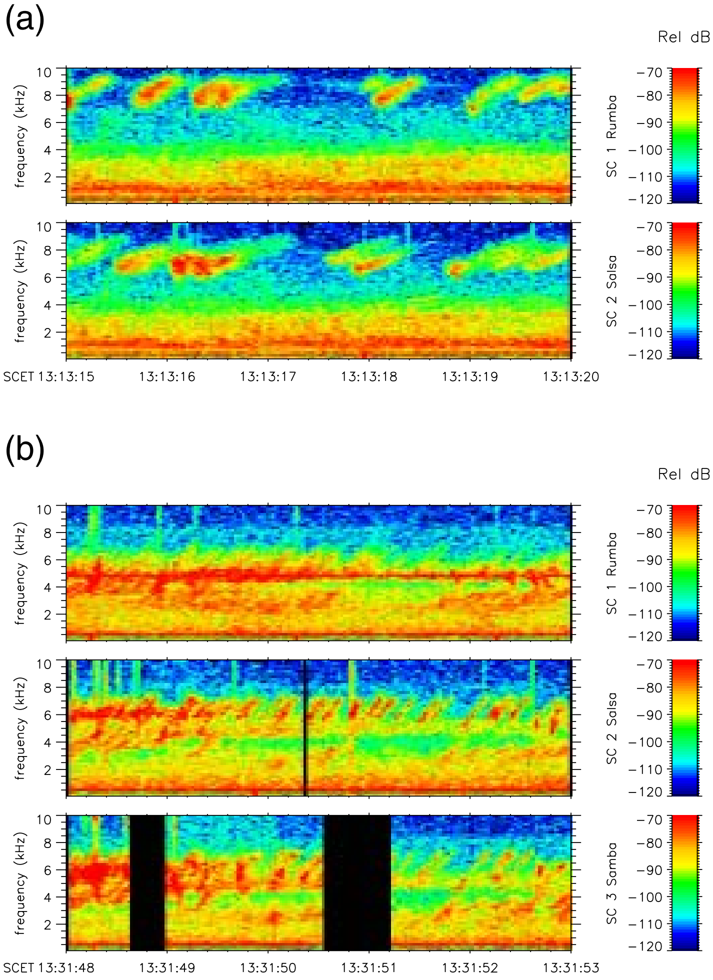


Figure 16. Two examples of chorus emissions on November 27, 2000 when Cluster was near equatorial plane at perigee. Panel (a): Early in the pass when only two receiving antennas were configured to receive WBD data. Panel (b): End of the pass when data were received from three spacecraft.

Two examples of chorus emissions are shown in Figure 16, both are from November 27, 2000 when Cluster was near the equatorial plane at perigee. The example in panel *a* comes from early in the pass, during a time when only two receiving antennas were successfully configured to receive Cluster data. The chorus emissions appear to be clearly correlated, but the observed frequencies of the signals differ on the two spacecraft: on SC 1, the frequencies range from 7.5 kHz up to the highest measurable at 9.5 kHz, yet on SC 2, the frequencies range from 6 kHz up to about 8.5 kHz. A second example (panel *b*) comes from the end of the pass and at a time when there was data from three CLUSTER spacecraft. Again, we observe narrow-band structures that appear to be correlated across all three spacecraft, particularly in the interval from 13:31:51–13:31:53. The correlation is quite clear between SC 2 and SC 3. Between this pair there also seems to be a very small difference frequency range of the order of 0.5 kHz. The correlation between SC 1 and the other two is more difficult to see. However, in this case the highest frequency observed is much lower, about 6.5 kHz. This covers up much of the rising tone signature of the correlated signals, but there does appear to be reasonable similarity in spacing and width of the signals when SC 1 is compared with SC 2 and SC 3. Work is now underway to perform a numeric correlation analysis to quantify the level of correlation.

The shift in frequency range between spacecraft is a new observation that was impossible to make before CLUSTER and suggests new insights into the generation mechanism. Two possible explanations for the variations seen at the spacecraft are suggested by these data: First, each of the spacecraft is within the wave generation region. Because the frequency of the waves evolves as they interact with the resonant electrons, this would imply that each spacecraft is seeing the evolution of the wave generation at a different stage. The spacecraft seeing the lower frequency band (SC 2 and SC 1 in Figures 16a and 16b, respectively) is observing the wave generation at an earlier stage, while the spacecraft seeing the higher frequency band (SC 1 and SC 2/SC 3 in Figures 16a and 16b, respectively) is sampling a later evolutionary stage when the resonance has evolved to higher frequency. Examination of the energetic electron distributions can test this explanation. Second, all the spacecraft are external to a spatially confined source region. The dispersion relation for VLF waves in this frequency range dictates that different frequencies propagate with different wave vectors and hence do not travel together. Preliminary ray tracing shows that different frequencies will propagate across field lines at varying rates depending on frequency, suggesting that each spacecraft has access to only a range of frequencies determined by the source extent and subsequent wave propagation to the spacecraft. We are currently refining these ray-tracing studies to check this scenario and to infer the spatial extent of the generation region.

SPACE WEATHER – UNDERSTANDING GEOEFFECTIVENESS AT THE MICRO-SCALE

A critical uncertainty in developing a reliable "Space Weather" predictive capability arises from the fact that under superficially similar external conditions, there is a reasonably large variation in the coupling efficiency of solar wind energy into the magnetosphere. A key element in adequately understanding this efficiency, or "geoeffectiveness," will be observations and improved models of the three-dimensional character of the incoming solar wind structures (*e.g.*, magnetic clouds and coronal mass ejections), and the spatial distribution of reconnection at the magnetopause. CLUSTER'S multipoint measurements will provide the first three-dimensional measurements of the key quantities, and will greatly reduce the uncertainties in the present models.

CLUSTER CONTRIBUTION TO ISTP SCIENCE

Cluster will contribute to detailed investigations of global dynamics. In the spring of each year the conjunctions of CLUSTER, GEOTAIL, POLAR, IMAGE, and INTERBALL (shown in Figure 17 left), will provide an unprecedented opportunity to study reconnection, plasma transport, and magnetic pulsations in the range Pc-1 to Pc-5. CLUSTER will be in the high-latitude reconnection regions poleward of the cusp and thus able to complement the measurements from INTERBALL, GEOTAIL, and IMAGE. In the fall of 2001, a configuration of CLUSTER, WIND, POLAR and GEOTAIL (Figure 17 right) will permit intensive investigation of the substorm problem. For example, CLUSTER will make north-south cuts of the plasma sheet near 20 R_E close to local midnight. The perigee of GEOTAIL will be at ≈9 R_E on the night side, while the apogee of POLAR will traverse the equatorial plane with an apogee of 9 R_E. This conjunction will produce particle and field observations in the region of the plasma sheet where substorm instabilities are thought to be triggered. These observations will be made while WIND and/or ACE are observing the solar wind, IMAGE is taking global pictures of the aurora, and numerous geosynchronous altitude satellites will be measuring magnetic field and particle injection events from substorms. These coordinated studies should resolve the controversy about onset mechanisms. We will also be well equipped to study how plasma distributions consisting of beams that result in bursty bulk flows dissipate their energy. We can correlate the Alfvén waves observed at various distances that are propagating toward the ionosphere to power

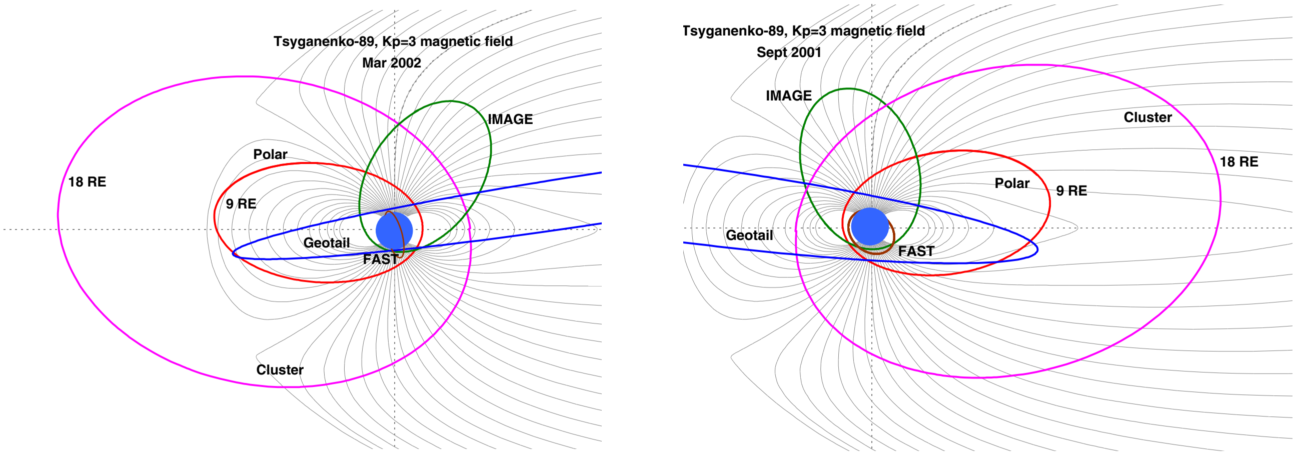


Figure 17. Left: Dayside conjunction of Cluster with other ISTP spacecraft in the spring of 2002. The coordinate system is GSE. Right: The conjunction in the fall of 2001.

the aurora to study how these waves dissipate. We can use the spatial information derived from CLUSTER magnetic field measurements to study field-aligned currents and, correlating these to multi-point observations, determine how the disturbed magnetic fields map to the ionosphere.

DATA SYSTEM

The data from the CLUSTER mission is available to investigators and the public from the CLUSTER Science Data Centers around the world. The U.S. data center (USDC) is an integral part of the ISTP Central Data Handling Facility (CDHF) and uses the same infrastructure. CLUSTER Summary Parameter (SP) and Prime Parameter data files are routinely transferred from the data center in the UK at the Rutherford Appleton Laboratories (RAL) into the CDHF and are accessible from CDAWeb (http://cdaweb.gsfc.nasa.gov). The CLUSTER Summary Parameter Data Base (SPDB) consists of 1-minute averaged parameters from all CLUSTER instruments but from only one of the four CLUSTER spacecraft. The data derived from the SPDB are publishable with the agreement of the responsible PI. ISTP Key Parameter CDs include the CLUSTER SP. The Prime Parameter Data Base (PPDB) consists of spin-averaged data from all four CLUSTER spacecraft.

The spacecraft, instruments, and Cluster Science Data System (CSDS) were declared operational as of February 1, 2001. Experiments currently supplying Summary Parameters (SPs) to CDAWeb include: ASPOC (Dr. Klaus Torkar, PI, Space Research Institute, Austrian Academy of Sciences, Austria), CIS, DWP (Digital Wave Processing, PI, Dr. H. Alleyne, Univ. of Sheffield, UK), FGM, RAPID, STAFF (Spatio-Temporal Analysis of Field Fluctuations, PI, Dr. N. Cornilleau-Wehrlin, CETP, France), WHISPER (Waves of High frequency and Sounder for Probing of Electron density by Relaxation, PI, Dr. P.M.E. Decreau, LPCE, France), and AUX (High-resolution definitive orbit AUXiliary Parameters, Hungarian Data Centre/M. Tatrallyay, KFKI, Hungary). In addition, PP data is available from ASPOC, CIS, DWP, EDI, EFW, FGM, PEACE, RAPID, STAFF, and WHISPER. The CLUSTER PPDB is the principal means for establishing multi-instrument, coordinated data analysis for the Cluster investigator teams.

The national data centers compute the SP and PP for their country's instruments on a daily basis and then electronically distribute the databases to all national data centers, including the USDC. The exception is the WBD experiment. These data are transmitted directly to the DSN and sent to the University of Iowa (burst mode data transmitted to ESOC is also sent directly to the Univ. of Iowa). The WBD team produces the relevant data products and forwards them directly to the French, UK, and Swedish data centers. The Level zero (Cluster telemetry data) are distributed to those US teams that need them on CD-ROM by ESOC. The CLUSTER project has adopted the ISTP/IACGG CDF as the method of encapsulating the PP and SP. Consequently, those data are compatible with the ISTP database and one can use the ISTP-developed tools to display, retrieve, and analyze the CLUSTER parameters.

PUBLIC OUTREACH AND EDUCATION

The CLUSTER mission provides a unique opportunity for outreach activities at all levels. At the simplest level, CLUSTER will give us a new understanding of the variability, uniformity, and motion of structures in the solar wind and magnetosphere. These structure parameters will allow visualizations of magnetospheric boundaries to rise beyond the cartoon stage and become much more realistic, making them very well suited for educational and outreach purposes. These boundary parameters will be incorporated into MHD models, resulting in a more realistic dynamic three-dimensional model of the magnetosphere, which can be then distributed as an educational product. New technologies allow planetarium visitors to "fly" through three-dimensional structures projected on the dome. By processing the results of these new three-dimensional models to allow their use in planetaria, the public will be able, for the first time, to understand the physical relationships that exist among the various structures in the magnetosphere.

CLUSTER data can also be used to provide activities for science and mathematics students. For example, a new Texas law mandates exit examinations in Algebra 1 for all High School students. The passing rate for preliminary versions of this test is only about 60% with word problems, the most difficult type of question. Similar standards and testing for math and science skills are being implemented throughout the country. CLUSTER can be used to provide sample data for mathematics problems, from simple distance, velocity and time calculations (by comparing features in data streams from two spacecraft) to complex cross-correlations. As an example, an exercise can be created in which students work with data examples that demonstrate the difference between flying through a spatially fixed structure and a structure which is moving (such as the plasma sheet boundary layer). This kind of exercise allows students to see just how difficult it is to tell the difference between these two situations with a single spacecraft, but that with more than one spacecraft, these distinctions can be made. This goes to the heart of the reasoning behind the CLUSTER mission, but also illustrates several aspects of calculation, physical reasoning, and how to be careful in drawing inferences from too little data. CLUSTER can also be used to demonstrate physical principles of orbits—why a tetrahedron can't be maintained throughout an entire orbit, why the orbits must cross (otherwise the inner spacecraft will end up traveling faster and leaving the group), *etc*.

The US CLUSTER teams will participate in outreach and educational activities of the types outlined above by working with local schools at the K-12 level. They will contribute through development of web-based informational and instructional materials designed for public access and use; and through interaction with museum and planetarium curators to develop public exhibits, displays, and presentations.

In addition to these activities, the ISTP project at Goddard carries out extensive and well-developed Education and Public Outreach (EPO) programs. CLUSTER will integrate its activities with those of ISTP.

IMPORTANCE TO LONG-TERM HEALTH OF THE FIELD

The previous sections have shown examples of preliminary CLUSTER data and discussed the unique science contributions CLUSTER can make to space physics. CLUSTER will obtain the richest microstructure and dynamics data set of all of the space physics missions flown to date. It will be the first time in the history of space physics that researchers will be able to study space electrodynamic phenomena in three dimensions. With CLUSTER data, we can formulate and solve problems realistically and space physicists will no longer have to guess whether the observed variations are due to spatial or temporal variations.

The CLUSTER data will provide us with snap shots of how different plasmas interact with a time resolution of the spin period (4 s) or better. As discussed briefly above, these high time resolution three-dimensional data will yield unprecedented new information about space plasmas not currently available. We will learn, for example, how different plasmas really interact in three dimensions, how large-scale currents form at boundaries, and their characteristic scale sizes. We can use the new knowledge to evaluate existing theories and develop new theories. Another application of CLUSTER data is use as inputs to simulation models. This will improve existing models, enhance our understanding of global dynamics and will indicate how the solar-terrestrial space environment works in three dimensions. The three-dimensional CLUSTER data will enable us to answer many fundamentally important space plasma questions and resolve controversies that we were unable to previously. In addition, CLUSTER results can be used as a pathfinder to future missions. Analysis and interpretation of the three-dimensional CLUSTER data is of the highest scientific significance. As a pathfinder for subsequent NASA missions, CLUSTER provides a unique and relatively inexpensive opportunity to answer many fundamental questions in magnetospheric physics. At the same time, CLUSTER highlights new questions that can only be answered with more advanced missions, such as MMS, which will build on the experience and understanding gleaned from CLUSTER.

Technical/Budget

CLUSTER is unique for two disparate reasons. Scientifically CLUSTER is unique because it is the first mission to fly four identical spacecraft capable of determining the spatial and temporal scales of structures in geospace. Financially CLUSTER is unique because it is a long-planned mission, finally successfully launched last year, with no data analysis budget of any significance. This proposal will not discuss any scenario for utilizing the $1 M in the guideline budget for FY02. It is a wholly inadequate amount, no science can be done within that guideline, and it is even impossible to support the absolutely necessary tasks of US investigators for experiment operations and data validation. The challenge is to estimate a realistic budget that is adequate for the mission to accomplish its scientific goals, as reviewed above. These are scientific goals that NASA subscribed to both in the original 1987 AO and goals that were reiterated in the *Mission Success Criteria* agreed to by the Office of Space Science in preparation for the CLUSTER launches last summer.

One historical note of relevance to the current situation is that significant cost overruns associated with SOHO instrument development and schedule delays required re-programming of resources earmarked for ground system development for ISTP in general. The result of that reprogramming was the creation of significant liens in ISTP's ability to provide CLUSTER data to the US CLUSTER investigators.

The "minimal" and "optimal" budgets that are attached reflect intensive discussion among the NASA-supported PI and Lead Co-I teams. Without a current guideline, several possible approaches were considered in constructing the attached budget spreadsheet.

EXISTING BUDGET

One possibility would have been to use this past year's experience as a guide, especially as to what is a "minimal" scenario. This year the CLUSTER program has an allocation of approximately $5M (plus approximately $1.2M in DSN costs) and the groups have managed to commission the instruments, conduct an exhaustive experiment interference campaign, ingest, and validate data. But, several groups were able to fund their commissioning and interference campaign activities using their development contract and did not use this year's funding (including the left-over development funds that were reprogrammed for data analysis) until after the mission was commissioned by ESA at the beginning of February 2001. Thus, the $5M in this year's budget represents approximately 9 or 10 months of support, not 12. More importantly, however, it has been difficult to accomplish much in the way of scientific data analysis, notwithstanding the Herculean efforts made by the teams in preparation for the EGS meeting in Nice at the end of March, nor the science results presented above. In fact, it would be fair to say that the preparation of this proposal provided some of the CLUSTER team members their first opportunity to analyze data for scientific purposes and to collaborate with other experimenters in constructing preliminary interpretations of these unique measurements.

The science results presented above are not so much illustrative examples of what CLUSTER has accomplished, as they are a fair sampling of all the science analysis the teams have managed to carry out within highly constrained resources. The $5M budget has simply not allowed for significant data analysis.

PHILOSOPHY FOR MINIMAL AND OPTIMAL SCENARIOS

Thus, this year's budget is not a reliable guide of what is either "minimal" or "optimal" for this program. It is worth noting that all of the teams involved in NASA's contribution to CLUSTER are experienced in conducting space science experiments. They all have considerable experience in carrying out data analysis programs and have an enviable track record of producing scientific results of the highest quality. Their budget estimates during the development phase were reliable and the experiments were delivered within tightly constrained budgets. One constant during the thirteen years of this program following selection is the estimate, adjusted for inflation, provided to the Project and Project Scientist as to how much a data analysis program for the mission would cost. At a mini-SWT held at Goddard during the spring of 2000, the teams were asked, again, to estimate their data analysis needs. When pushed as to what level of funding was needed just for commissioning, interference campaign and data validation with no funding for science, below which it would be impossible to fulfill the teams' obligations to both NASA and ESA, the estimate was $5M. As it turned out, this was the maximum budgetary relief that OSS was able to arrange. The teams have done what they claimed they could do with that amount, but now it is time for NASA to provide funding adequate to accomplish the science goals. *Hence, the "minimal" budget that has been constructed is that amount below which the science goals cannot be achieved. The budget includes the DSN costs required to support data acquisition from WBD. It is a budget that funds several, but not all, Category C investigator teams to carry out research responsibilities as outlined in their original response to the AO. The budget also reflects the fact that many universities require that grant work carried out by their personnel include a substantial science research component. Those universities cannot support budgets for FY02–05 that are based solely on carrying out data validation responsibilities. (This policy affects WBD, EDI, RAPID/IES and CIS/CODIF.)*

As amplified below, the "optimal" scenario provides for additional science analysis support, primarily in the form of additional graduate students and postdoctoral associates. This is the level that should be funded to assure that all scientific objectives will be achieved.

Another assumption made in preparing this budget request is the duration of the CLUSTER mission. CLUSTER is run by ESA and has been approved for a two year prime mission that began with the Commissioning Review on February 1, 2001. Thus, the nominal mission will run through January 31, 2003. However, it is widely expected that an extended mission will be approved, assuming that the experiments continue to perform nominally. Therefore, the budget assumes a full mission for three years in FY2001 dollars. This budget does not reflect expected inflation of approximately 3%/year.

CLUSTER in both its development and operations is complementary to SOHO. In the case of SOHO, NASA assumed most of the mission development and launch costs and NASA operates the spacecraft. The ESA contribution to both phases was relatively modest. For CLUSTER, the reverse is true: ESA assumed the bulk of the development and launch costs, and operates the spacecraft and NASA's responsibilities are primarily to fund US investigators to analyze the data. In addition, NASA, through the DSN, is responsible for obtaining WBD data from the spacecraft.

DEVELOPMENT

CLUSTER has no further development costs.

DATA SERVICES REQUIREMENTS

The only Data Services required for CLUSTER are those associated with use of the DSN to acquire the WBD data. The budgeted amount is based on the formal agreement with the DSN for 8 hours of single-spacecraft DSN coverage per orbit plus 30 minutes of multi-spacecraft operations once per month. Implementation of this commitment is being modified to convert single-spacecraft coverage to multi-spacecraft coverage, most of which will be for three spacecraft. Nonetheless, the total number of hours budgeted for DSN support of WBD remains unchanged under this plan to augment the multi-spacecraft acquisitions.

MISSION SERVICES

CLUSTER has no mission services costs.

SCIENCE CENTER FUNCTIONS

Science center functions for CLUSTER are carried out by the CDHF and are not charged to CLUSTER. The role of the CDHF in making CLUSTER data available to CLUSTER investigators and to the wider scientific community has been discussed above and is covered in detail in a separate proposal to the Senior Review.

DATA ANALYSIS

Consequently, the overwhelming funding and person-power requirement in the budget is the data analysis line. Below is a brief summary of the data analysis tasks to be carried out along with a description of the distinguishing features of the “minimal” versus “optimal” scenarios. The tasks below fund the responsibilities detailed above on page 6 (*NASA’s Role in CLUSTER*).

WBD

The WBD budget reflects the efforts required by the WBD team to carry out the processing and analysis of the WBD data. Three critical tasks are performed at Iowa that are unique to the WBD investigation. These are: (1) Level 1 data processing: WBD is the only experiment on CLUSTER that receives data in raw form directly from the DSN ground station center. Iowa must then remove the DSN headers, determine the onboard time of the data using algorithms supplied by ESOC, byte align the data, and produce Level 1 CDs to be distributed to various data centers. ESOC does this for all of the other experiments. Due to numerous problems with the spacecraft onboard data handling system, this task has become extremely complex and time consuming. (2) Operations Planning. WBD is the only experiment that must plan its own multi-spacecraft operations. Planning for all other experiments is done by JSOC. Due to numerous constraints as to when these operations can take place, this task is very time consuming. (3) Microsecond Timing Accuracy. Because the VLBI studies deal primarily with emissions at high frequency, microsecond timing accuracy is required. Microsecond timing accuracy is achieved by using the DSN ground receive time and making numerous corrections for delays from when the data were recorded onboard to when they were received on the ground. This is an extremely complex and time-consuming operation. The WBD “minimal” budget reflects the funding required at Iowa to carry out these critical tasks, as well the funding needed to perform the WBD-specific scientific analysis of its primary and secondary scientific objectives at a reduced level that includes participation by the PI and some of the Iowa Co-Investigators. The “optimum” budget reflects the funding required at Iowa to carry out the critical tasks and mount a well-rounded research effort that includes adequate funding for all Co-Investigators at Iowa and Stanford, and collaboration with other CLUSTER and ISTP investigators. WBD’s primary scientific objectives include a study of the propagation and generation of chorus and hiss using multi-spacecraft measurements and AKR source characteristics using VLBI techniques. Secondary objectives include the study of waves and their interactions at the bow shock, magnetopause, and plasma sheet boundary layer, and in the cusp, plasma sheet, plasma mantle, and auroral zones using high resolution waveforms and spectrograms.

EDI

The EDI budget reflects scientific data analysis as well as very significant instrument operations responsibilities that are shared between the Max Planck Institute (MPE) and UNH. The “minimal” budget includes the mandatory operational responsibilities as well as a minimal scientific participation by EDI Co-Investigators. The “optimal” budget includes an augmentation for additional science participation by the Co-I’s, as well as moderate support for other associated scientists. The tasks budgeted include the following: UNH is fully responsible for Controller and Sensor operations, including preparation and test of all flight software uploads; in-flight Sensor calibrations; ground analysis and display software for the verification and revision of in-flight gun calibrations, onboard FGM offsets; and FGM+STAFF matching. UNH shares responsibility with MPE for optimization and verification of instrument operation algorithms. UNH maintains the front-end “pick library” that is the first step in all EDI data processing and is responsible for maintaining and updating the primary interactive science, housekeeping, and validation display tools. The EDI team has a diverse range of scientific objectives, which the EDI hardware has been developed to address in conjunction with measurements from other CLUSTER instruments. These objectives, outlined in detail in the EDI instrument proposal, include studies of small-scale structures; shocks; the magnetopause, boundary layer, and polar cusp; ULF waves; convection and plasma “injection;” plasma sheet boundary phenomena; and current sheets and filaments.

CIS

The CIS budget reflects scientific data analysis as well as very significant instrument operations responsibilities that are shared between CESR, Toulouse, UNH, UW and UCB. The “minimal” budget includes the mandatory operational responsibilities as well as a minimal scientific participation by CIS Co-I’s. The “optimal” budget includes an augmentation for enhanced science participation by the US data analysis Co-I’s, as well as moderate support for graduate students and postdoctoral scientists. The tasks budgeted include the following: UNH has the major responsibility with in-flight calibration and operation of the CODIF sensor, including: ground analysis and verification of the efficiency calibrations, preparation of MCP bias modifications and related monitoring of in-space operation. UW and UCB are responsible for the calibration and in-space operation of the RPA portion of CODIF, including: ground analysis and verification of the efficiency calibrations, preparation of MCP bias modifications and related monitoring of in-space operation. In addition, UCB is responsible for preparation and test of DPU flight software uploads. UNH, UW, and UCB share responsibility with CESR for optimization and verification of instrument operation algorithms and telemetry settings. The CIS team has a diverse range of scientific objectives, and the CIS hardware has the capability to address individually and in conjunction with measurements from other Cluster instruments. These objectives, outlined in detail in the CIS instrument proposal, include, but are not limited to, studies of boundary structures; reconnection at the magnetopause and in the tail, shock formation and related acceleration and thermalization processes, ion outflows from the ionosphere, identification of magnetospheric source populations and their acceleration mechanisms, and plasma sheet dynamics associated with substorms.

EFW

The EFW investigators at the University of California, Berkeley, are responsible for the main data analysis software that is being used by an estimated 50 people around the world for EFW analyses on Cluster and particle and field analyses on other experiments on Cluster and other Sun-Earth-Connection-related spacecraft. Berkeley is also responsible for the flight software, for daily monitoring of the scientific quality of the data, and for proposing operating modes such as bursting, *etc*. In addition, a variety of data analysis tasks have been assigned to investigators at other institutions, including, Univ. of Minnesota, Cornell University, Goddard Space Flight Center, and others. The budget for the “minimal” scenario includes all of the flight software and data validation tasks and little for the science data analysis. The “optimal” scenario includes support for data analysis to be carried out by both Berkeley and other EFW Co-Investigators.

FGM

The responsibilities of the US FGM Co-I’s are the validation and calibration of the magnetometer data and making available the data to US Cluster investigators. The Goddard Space Flight Center has the major responsibility for distribution of the data to other team members in the US. Consequently, the FGM budget includes funding for data distribution and validation capability at Goddard where the data are calibrated and validated and then made available to other team members. More refined data validation tasks are delegated to other investigator teams at The University of California Los Angeles and the Jet Propulsion Laboratory. Those tasks involve, among other things, correction for zero-level offsets, removal of the spin component of the magnetometer signal, and intercalibration of the sensors among the four spacecraft. The budget also supports scientific data analysis at Goddard, UCLA, and JPL.

PEACE

The major operational responsibility for the US Co-I’s on PEACE is the development and maintenance of the data analysis, data archiving, and data display software. These software packages are used by all PEACE investigators. The responsibility for that software rests with the Southwest Research Institute (SwRI). The budget includes funding for continued development and upgrades of these software packages. Furthermore, it is the responsibility of the PEACE teams in the US to archive the data that are preprocessed at the PI institution (University College London, Mullard Space Science Laboratory) and then made available to Co-Is around the world. SwRI archives this data for US investigators, making it unnecessary to continually download the data from the UK. Under the “minimal” budget scenario, SwRI will continue to upgrade and maintain this software plus operate the US archive site. In addition, the budget includes science data analysis tasks related to the nature of wave-particle interactions in the electron foreshock, the dissipation of turbulence in the solar wind and magnetosheath, the study of the cusp, and the characterizations of electron distributions in the auroral zone, the boundary layer, plasma access to and energization in the nightside plasma sheet and magnetopause. Co-Is at Goddard Space Flight Center, Rice University, SwRI and Los Alamos National Laboratory will be funded to carry out those research efforts. The “minimal” scenario provides funding primarily to the Co-Investigators. The “optimal” scenario includes additional funding for graduate students at Rice University and Postdoctoral Associates at Goddard, LANL, and SwRI.

RAPID

The RAPID “minimal” budget supports the instrument operations of the IES sensor. These operations include the need to track on-orbit the pedestal offsets of the nine sensor channels on each of the four satellites. The budget also includes support for scientific data analysis. This on-orbit tracking and calibrations are necessary to maintain a meaningful energy-calibrated sensor response to energetic electrons. CLUSTER RAPID is an integral part of the energetic particle CCR consortium involving the NASA POLAR satellite experiments CAMMICE and CEPPAD. The RAPID research and operations will make full use of CCR developed resources, including its web site. CCR will be the central clearing house for data products and summary plots developed in the US and will provide access for the RAPID investigators and the larger science community to both the latest summary plots and digital data products. There are no current tools for the analysis and display of data from four spacecraft, which presents an entirely new challenge and opportunity for CLUSTER science. However, almost all of the new CLUSTER science objectives depend on parameters derived from four-spacecraft measurements. The budget will support the development of new visualization tools capable of displaying the three-dimensional parameter surface defined by the CLUSTER constellation to facilitate exploration of the spatial and temporal structure of steep gradients encountered at magnetospheric boundaries and larger structures that will be studied intensively now that the separation has been increased to 2000 km. As a first step these tools will be used for the crucial data inter-calibration between spacecraft, a requirement for the absolute measurement of gradients. The funding will also further scientific interactivity via the CCR web site. Many of the unanswered questions concerning the transport, acceleration and loss of charged particles through the inner magnetosphere are a consequence of our incomplete knowledge of the global structure of the magnetic and electric fields. This limitation currently prevents our determining the most important parameter of a particle distribution, *viz.*, the phase space density throughout a volume of space. The multi-point particle and field measurements on CLUSTER offer unprecedented opportunities in establishing for the first time a self-consistent description of the magnetic field, electric field and particle phase space densities in a localized region, giving a regional measure of phase space density gradients that establish the direction of transport and/or the existence of localized acceleration or loss processes during normal and disturbed times. These “minimal” efforts will involve co-investigators, research associates, graduate and undergraduate students at four US institutions. The “optimal” budget is designed to give greater support to the education and support of students as well as provide additional support for data analysis at the four institutions involved in RAPID.

ASPOC

The budget includes a small sum to support the US Co-I’s travel to team meetings and some data analysis activities.