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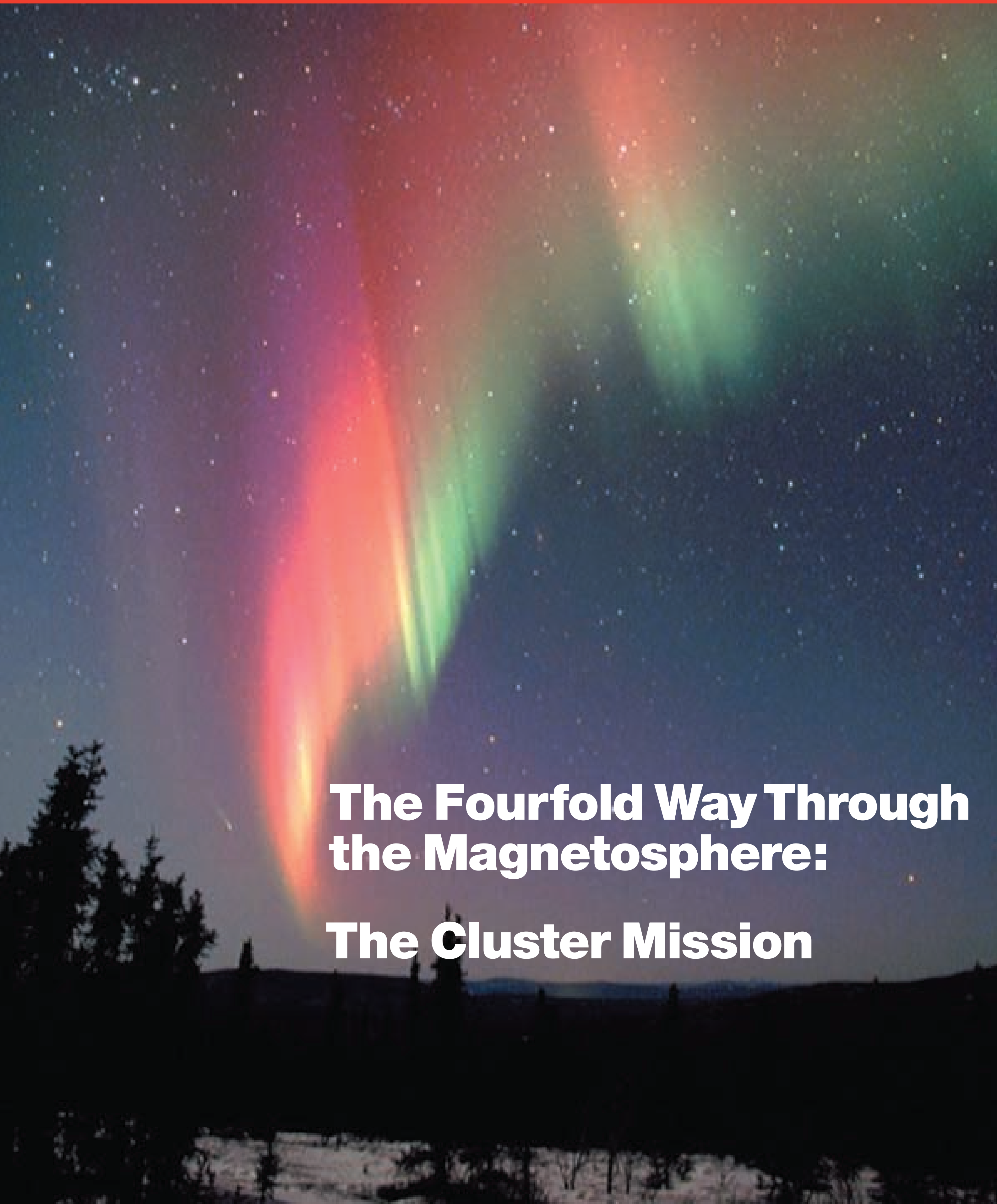

The Fourfold Way Through the Magnetosphere: The Cluster Mission

Editorial

Imagine a lonely spacecraft travelling through space. Its mission is to probe the value of, say, the strength of the local magnetic field. Its instruments continuously monitor the field strength and deliver the data to the on-board telecommunication system, which forwards them to the ground control station on Earth. There, scientists try to interpret the data.

But now a basic dilemma arises: due to the continuous motion and temporal evolution of the ambient medium and its boundaries, the recorded data are a complicated mix. The observer cannot distinguish whether the magnetic field experienced a change in time or it varied spatially or both happened simultaneously.

That was the problem faced by the fathers of the European Space Agency's Cluster mission in 1982 intended to exploring the Earth's magnetosphere. Their idea was to solve the problem by flying a quartet of closely spaced identical spacecraft, since time and space need a set of three co-ordinates to be defined completely. The instruments aboard the four spacecraft may now take measurements at identical times but at different places in space allowing the scientists to work out the relevant temporal and spatial characteristics of the magnetic field and the other quantities that characterize the ambient medium, such as the electric field, and plasma density, velocity and temperature.

The author of the present issue of Spatium, Dr. Götz Paschmann, currently Director of the International Space Science Institute in Bern and Senior Scientists at the Max Planck Institute for extraterrestrial Physics in Garching (Germany) is one of the fathers of Cluster. He is also the Principle Investigator of the Electron Drift Instrument designed to determine the strength of the local electric field around the spacecraft.

In November 2001, very shortly after the commissioning of the Cluster spacecraft G. Paschmann presented the first results to our members. In the mean time, this mission has delivered a wealth of additional data, which partially could be considered in the present revised version of his lecture. We are very indebted to G. Paschmann for his kind permission to publish the present text on the fascinating world of magnetic fields.

Hansjörg Schlaepfer
Bern, June 2002

Impressum

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Front Cover: The aurora is the only visible proof of the Earth's magnetosphere. This wonderful picture shows the glow from outbursts of ionic particles from the Sun in the ionosphere. (Credit & Copyright: Dennis Mammana, Skyscapes)

The Fourfold Way Through the Magnetosphere: The Cluster Mission *)

Götz Paschmann, International Space Science Institute, Bern and Max Planck Institut für extraterrestrische Physik, Garching

Introduction

The Earth's magnetosphere has been investigated by direct in-situ measurements since the beginning of the space age and has turned out to be the site of many fascinating phenomena and processes that must be studied in-situ because they are not accessible by remote sensing techniques. Examples are shock formation, magnetic reconnection, particle acceleration, wave-particle interaction and turbulence. While interesting in their own right, as part of the exploration of the Earth's environment, they can also guide our understanding of similar processes on the Sun or the distant universe, places where one can never make in-situ measurements. **Figure 1** shows a view of the magnetosphere that emphasizes its main features, except for the bow shock that has been left out for clarity.

While much has been learned about the magnetosphere through measurements from single satellites, a limitation has been the fundamental inability of a single observer to unambiguously distinguish spatial from temporal changes. The magnetosphere is constantly changing its shape and size, and many of the processes governing it are known to vary on short spatial and temporal scales. A solution to this dilemma is a fleet of mobile stations, very much like what one does to study weather patterns and their temporal evolution. Cluster is the first attempt to do this in space, admittedly with only the minimum number that can be arranged in three dimensions, namely four. There have previous attempts with two spacecraft (ISEE and AMPTE), but with two stations one can only infer variations along the line between the spacecraft, and three stations always form a plane. Thus Cluster is a giant step forward. One should not forget though that because of the complex structure of the magnetosphere and the strong interrelationship between its parts, there is the danger that spacecraft flying in close formation will miss the large-scale context. Fortunately, observations from the ground and from other spacecraft are available that serve to fill in this global context.

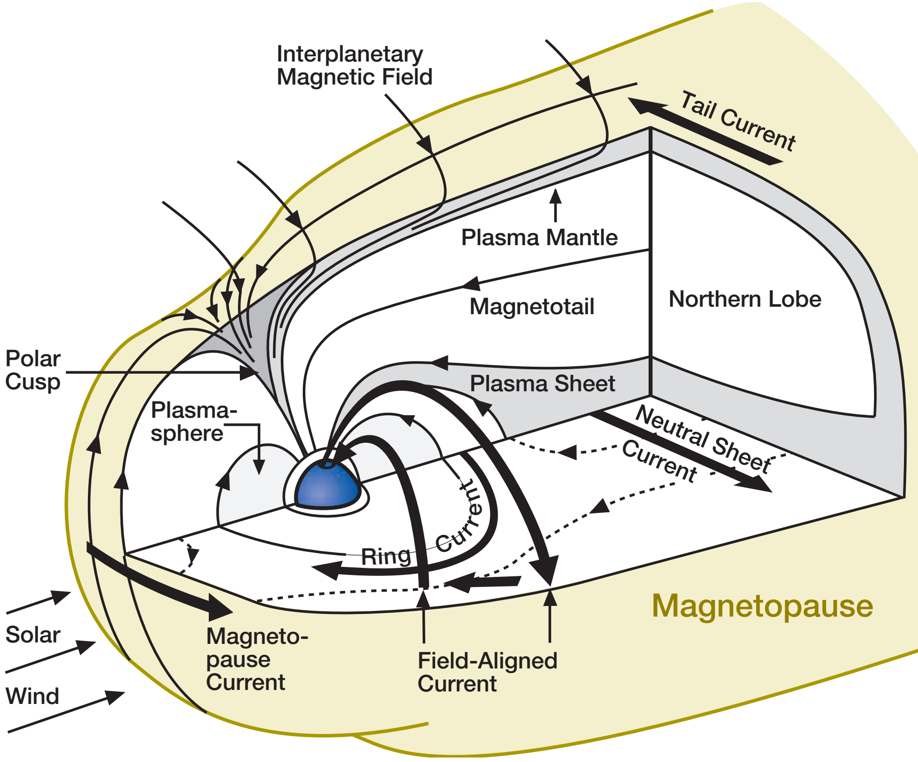


Figure 1
Cutaway view of the Earth's magnetosphere that identifies the key regions encountered by Cluster: the solar wind approaching from the left; the magnetopause (yellow surface) that is the outer boundary of the magnetosphere; the polar cusp, a funnel-shaped indentation in the magnetopause; the magnetotail, with the hot plasma sheet at the centre and the lobes on either side. Thin black lines with arrows are the magnetic field lines, dashed lines show plasma flow. The black arrows mark electric current flow. The bow shock that stands in the solar wind ahead of the magnetopause, and the region in between, the magnetosheath, have been omitted for clarity.

*) Pro ISSI lecture, Bern, 8th November 2001

The Cluster Mission

History

Cluster's history goes back to November 1982, when a group of European scientists proposed the mission. In February 1986 ESA chose Cluster and the Solar and Heliospheric Observatory (SOHO) as the first "Cornerstone" in its Horizon 2000 Science Programme. SOHO was launched in December 1995 and has sent back a stream of exciting data about the Sun, as vividly described in Spatium Nr. 2. Cluster was not so fortunate. Ready for launch in 1995, the four spacecraft were destroyed when the Ariane 5 rocket exploded during its maiden flight on 4 June 1996. At first it seemed that the only remaining option was to put together a single spacecraft from the leftover parts, appropriately named Phoenix after the mythical bird that rose from the ashes. But recognizing the unique importance of the mission, the ESA Science Programme Committee (SPC) on 3 April 1997 agreed that three new Cluster spacecraft should be built alongside Phoenix, and thus Cluster was reborn. Through a tremendous effort by all involved, the fully instrumented satellites were rebuilt in only three years and successfully launched on two Soyuz-Fregate launchers from Baikonur on 16 July and 12 August 2000, respectively. After extensive commissioning of the payload, the science phase officially began on 1 February 2001.

This being a Pro ISSI lecture, I should point out that several people associated with ISSI were deeply involved in Cluster. Two of its directors, Bengt Hultqvist and myself, and a long-time member of its Science Committee, Gerhard Haerendel, were among the seven who proposed the mission in 1982. Roger Bonnet, then Director of Scientific Programmes at ESA, was the key force behind the recovery initiative, and Hans Balsiger was chairman of ESA's

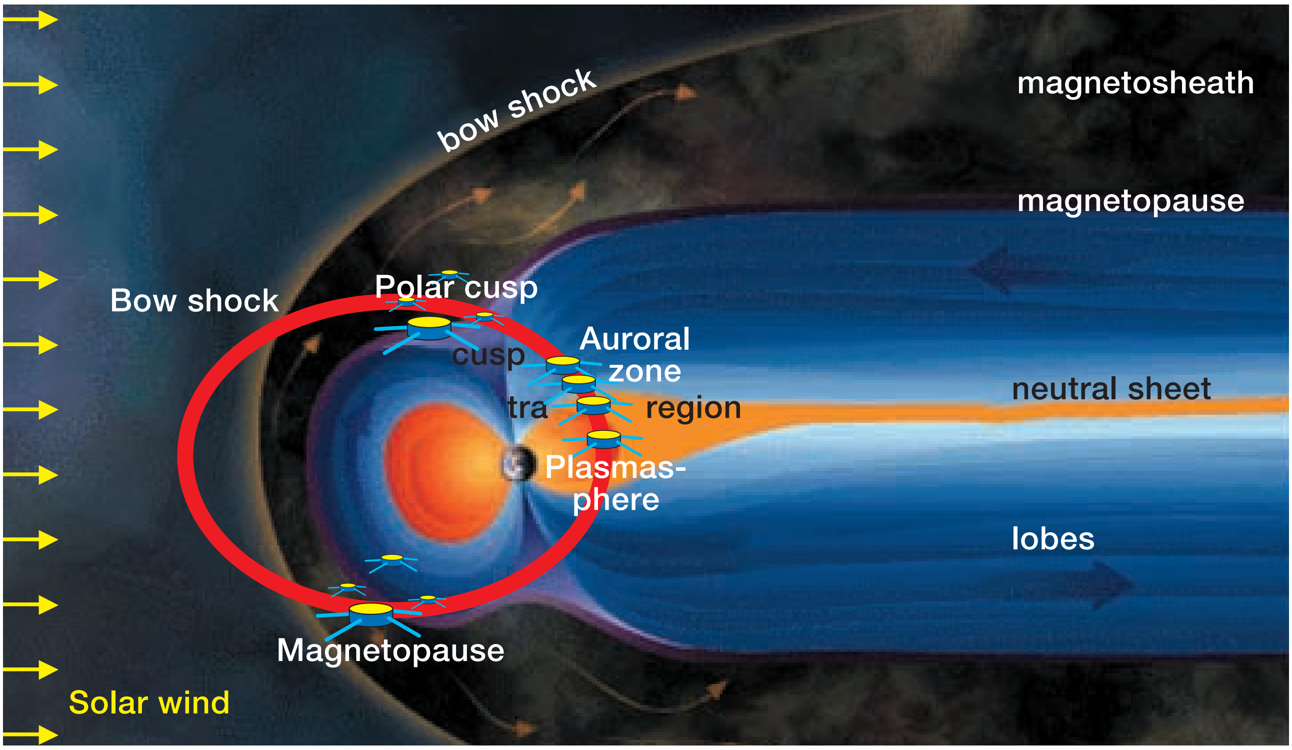


Figure 2
Cluster orbit in February, as it cuts through the key regions of the magnetosphere.

SPC, when the decision to repeat Cluster was finally made in April 1997. Last but not least, Hans Peter Schneiter and Contraves Space had a leading role in the revival efforts by the industry that had built Cluster. It is therefore only natural that the interpretation of the Cluster measurements will be one of ISSI's future workshop activities.

Orbits and Separations

After their successful launch from Baikonur, the Cluster spacecraft were placed in nearly identical, highly eccentric polar orbits, with an apogee of 19.6 Earth, a perigee of 4 Earth radii, and a period of 57 hours. **Figure 2** shows the orbit superimposed on a cut of the magnetosphere, and illustrates that Cluster moves outbound over the northern polar cap, crosses the magnetopause and bow shock into the solar wind, before recrossing those boundaries in reverse order and moving over the southern polar cap back towards perigee. **Figure 2** applies to February of each year. As the orbit is inertially fixed, it rotates around the Earth once a year, as the latter revolves around the Sun. As a result, the apogee of the orbit will be located in the geomagnetic tail half a year later, as shown in **Figure 3**. In the course of the mission Cluster will thus encounter the regions of interest several times. The orbits are tuned so that the four spacecraft are located at the vertices of a nearly

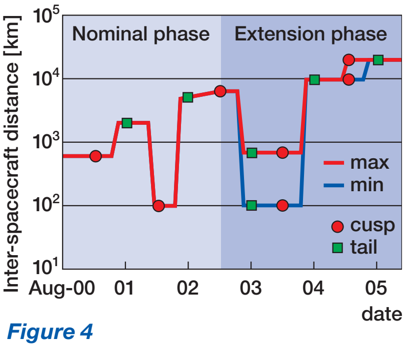


Figure 4
Spacecraft separation distances as planned for the entire mission.

regular tetrahedron when crossing the major boundaries. The separation distances between the spacecraft are being changed between 100 km and tens of thousands of km during the mission. This allows studying the phenomena at sufficiently different scales. **Figure 4** shows the sequence

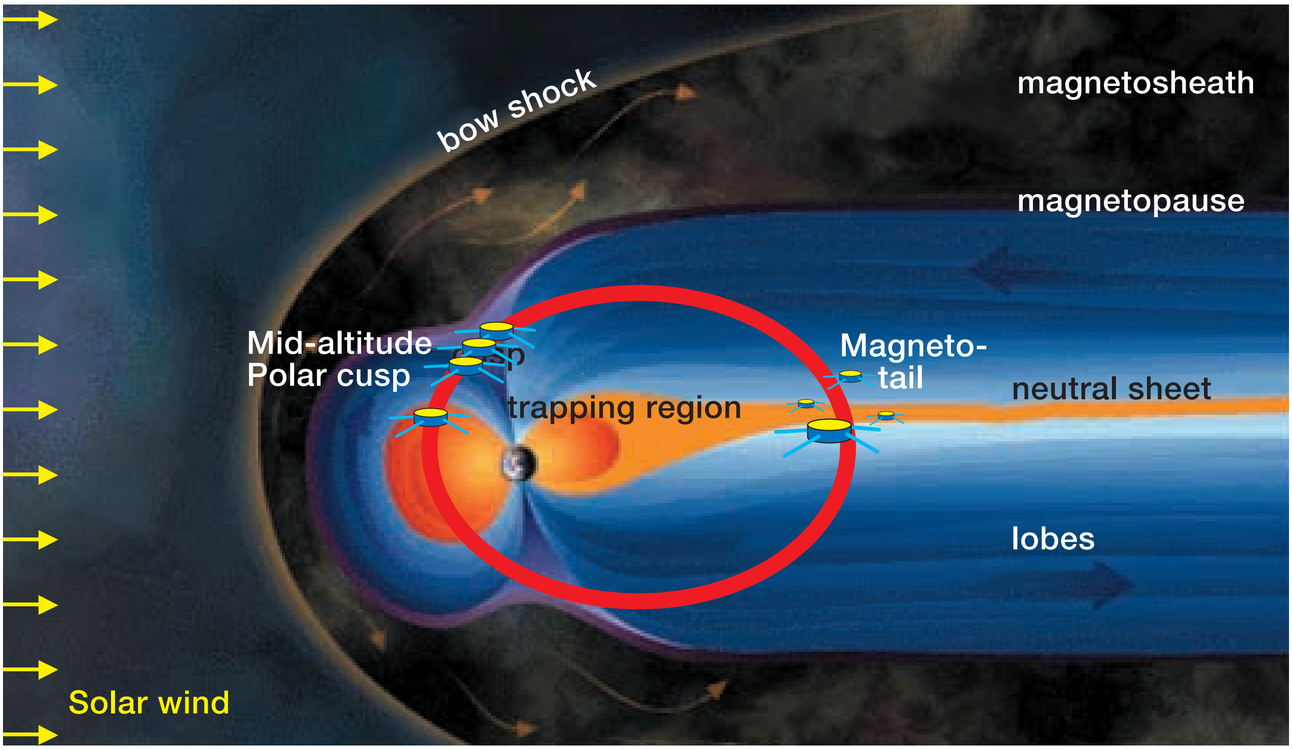
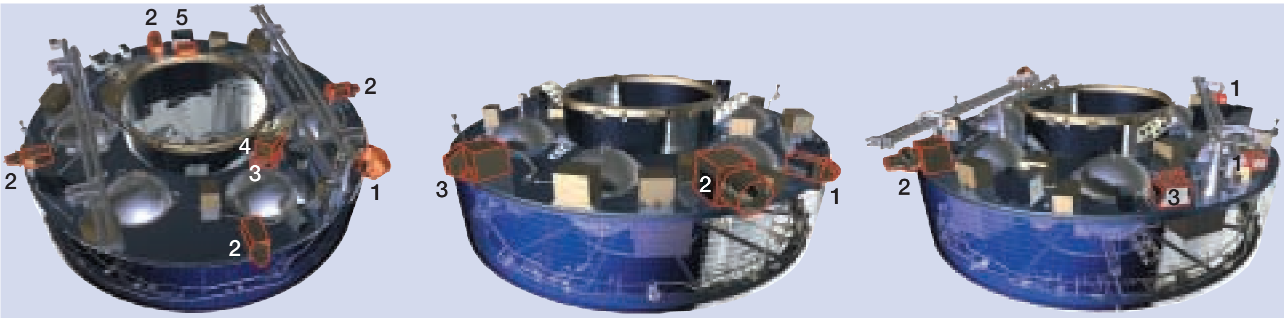


Figure 3
Same as Figure 2, but for the month of August.



1 **STAFF** (N. Cornilleau-Wehrlin, F)
Magentic and electric fluctuations
2 **EFW** (M. Andre, S)
Electric fields and waves
3 **DWP** (H. Alleyne, UK)
Wave processor
4 **WHISPER** (P. Decreau, F)
Electron density and plasma waves
5 **WBD** (D. Gurnett, USA)
Electric field wave-forms

1 **PEACE** (A. Fazakerley, UK)
Electrons (E < 30 [keV])
2 **CIS** (H. Reme, F)
Ion composition (E < 40 [keV])
3 **RAPID** (P. Daly, D)
High energy electrons and ions
($2 < E_{ions} < 1500$ [keV/nuc],
$20 < E_e < 400$ [keV])

1 **FGM** (A. Balogh, UK)
Magnetic field
2 **EDI** (G. Paschmann, D)
Plasma drift velocity
(0.1 < E < 10 [mV/m],
5 < B < 1000 [nT])
3 **ASPOC** (W. Riedler, A)
Spacecraft potential control

Figure 5
The science payload carried by each of the 4 Cluster spacecraft. The group listed on the left comprises the Wave Experiment Consortium, the three in the middle deal with the particle component, and the top two on the right address measurements of the magnetic field and the plasma drift velocity, respectively, while the last controls the spacecraft potential.

of separation distances planned until the end of the mission. This separation strategy is possible because each Cluster spacecraft carried 600 kg of fuel at launch, of which about half was expended in order to reach the operational orbit.

Science Payload

The four Cluster spacecraft carry identical sets of 11 scientific instruments, designed to measure the ambient electromagnetic fields and particle populations over a wide range of frequencies and energies, respectively (see **Figure 5**). Each instrument was built by a team under the leadership of a Principal Investigator (PI). There are more than 200 Co-Investigators from ESA member states, the United States, Canada, China, the Czech Republic, Hungary, India, Israel, Japan and Russia.

Figure 5 also gives an impression of the large size of the spacecraft. Its diameter is almost 3 m and its mass at launch 1200 kg, of which half was in form of fuel needed to reach the final orbit and to carry out the separation strategy. The mechanical structure of the spacecraft was developed and built by Contraves Space, while Dornier was ESA's Prime Contractor for Cluster, which included integration and test of the entire system, including instruments.

Almost unnoticed by even the teams involved, one of the spacecraft is carrying an extra piece of hardware, namely an engraved 10-by-10 cm Titanium plate that is part of a "kinetic sculpture" called Moving Plates by their creators, Viennese artists Eva Wohlgemuth and Andreas Baumann. Other such plates are mounted on stationary as well as moving objects all over the world.

Excursion: The Electron Drift Instrument

The Cluster payload contains one instrument, the Electron Drift Instrument (EDI), which is unique because it actively emits beams of electrons to sense the electric fields in the ambient plasma. This instrument was developed by a consortium consisting of the University of New Hampshire, the University of California at San Diego, Lockheed Palo Alto Research Laboratory, and the

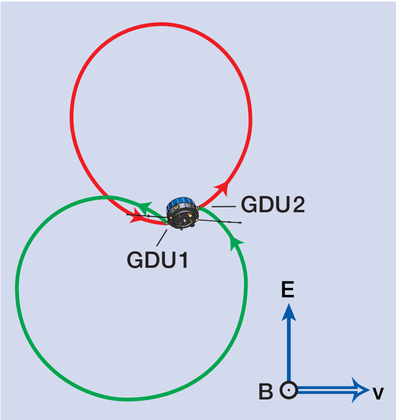


Figure 6
EDI's principle of operation. For any combination of magnetic field B and drift velocity V (induced by an electric field E), only a single electron trajectory exists that connects each electron gun with the detector located on the opposite side of the spacecraft. The two trajectories have different path lengths and thus different times-of-flight.

Max-Planck-Institut für extraterrestrische Physik in Garching. Because I happen to be the PI for the EDI instrument, I will dwell on it in some detail.

When injected perpendicular to a magnetic field, electrons perform a circular orbit (with a radius proportional to their velocity) that returns them to their origin after a complete gyration. Gyro radius and gyro time both are inversely proportional to the strength of the magnetic field. For electrons with 1 keV energy and a magnetic field of 100 nT, the gyro radius is 1000 m and the gyro time 0.35 ms.

In the presence of an electric field, the electrons execute a drift motion in addition to their gyration. As a result, the circular orbits are distorted into cycloid orbits, such that the electrons are displaced from their origin after one gyration. The displacement (the "drift step") is directly proportional to the electric field and inversely proportional to the square of the magnetic field, and ranges from a few centimetres to hundreds of meters. Under these conditions the beam will return to the spacecraft only when emitted in either of two precisely defined directions. By employing two beams and two detectors, the two unique directions can be monitored continuously and the displacement obtained by a triangulation procedure. **Figure 6** illustrates the principle, and also shows that the two beams travel different distances, and thus have different travel times. When the magnetic field becomes small, the electric field is obtained from these time-of-flight differences.

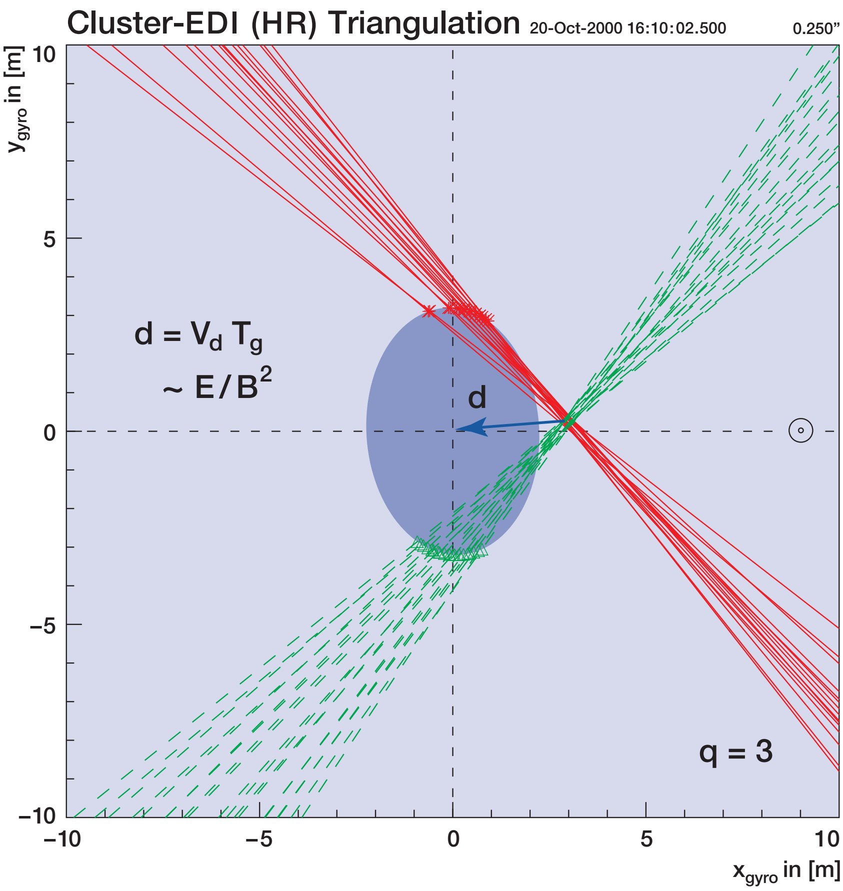


Figure 7
Sample EDI triangulation plot for an interval of 0.5 s duration. Red and green lines are the firing lines of the two electron guns for those times when the beams were properly aimed to return to the detectors. The gun positions, projected into the plane perpendicular to the magnetic field, move on an ellipse because the spacecraft spin axis and the magnetic field direction are not aligned. The 0.5 s interval corresponds to $1/8$ of a full spin. The measured "drift step" is the vector from the beam intersection to the centre of the figure, and is proportional to E/B^2.

While exceedingly simple in principle, it is the implementation that has made the Electron Drift Instrument a formidable challenge. The first difficulty lies in the need to keep the beams precisely perpendicular to the ambient magnetic field, which can have arbitrary direction and can vary rapidly. This is overcome by a unique electron gun design that can emit a narrow beam in any direction within more than a hemisphere, and by having a direct on-board link to the Cluster magnetometer instruments (FGM and STAFF) that allows reconstruction of the instantaneous magnetic field direction. The next difficulty is to find the direction that returns each beam to its associated detector. This is achieved by sweeping the beam in the plane perpendicular to the magnetic field and waiting until the detectors record a signal. While this is going on, the detector look direction is steered in synchronism with the beam firing directions. Once signal has been acquired, the beam is swept back and forth in order to continuously track the target direction.

Because there usually are plenty of natural electrons at the same energy as the beams, care must be taken to distinguish the beam electrons from the natural electrons. This is achieved by coding the beams with a pseudo-noise code, much the same way as in a GPS system. By correlating the received electrons with the code of the emitted electrons, one not only discriminates against the natural electrons, but one also measures the times-of-flight of the electrons. As a by-product, one also obtains a very precise measure of the magnetic field this way (from the average of the two times-of-flight, which is equal to the gyro time). Further difficulties arise because the beams diverge. Thus fewer electrons return to the detectors the larger the distance they have to travel, i.e., the smaller the magnetic field strength is. This is partially overcome by continuously adjusting the beam current (between 0.1 and 300 nA) and the detector sensitivity.

The onboard software runs a 4-ms servo loop to execute the beam acquisition and tracking tasks and to navigate through the various control parameters. More than 50 patches of that software were needed before it worked satisfactorily under the variable conditions experienced along the Cluster orbit. **Figure 7** shows one of the first successful measurements, using the triangulation technique. The vector, d, from the beam intersection to the centre of the spacecraft is the "drift step", which is proportional to the ratio E/B^2. Using the magnetic field, B, measured by the FGM instrument, the electric field, E, is readily obtained. Results obtained with EDI are discussed in the next section.

Following Cluster from the Solar Wind to the Ionosphere

We now will follow Cluster through key regions of the magnetosphere and demonstrate its capabilities with illustrative examples, starting from the solar wind and ending with the aurora in the polar ionosphere.

Solar Wind

The solar wind is a plasma stream that approaches the Earth with speeds between 300 and 800 km/s. It carries with it the magnetic field of solar origin, the interplanetary magnetic field (IMF). Solar wind and IMF are both highly variable, which is one of the reasons the magnetosphere is so dynamic.

As an example, let us look at a sudden change in IMF direction caused by the passage of the heliospheric current sheet (HCS) over the Cluster spacecraft. The HCS is a warped surface dividing the heliosphere into two hemispheres of oppositely directed magnetic fields. Cluster encountered the HCS on 13 February 2001 at 10:48 universal time (UT), and the results are presented in **Figure 8**. The figure shows the magnetic field measurements and their analysis by the FGM team that highlights the unique

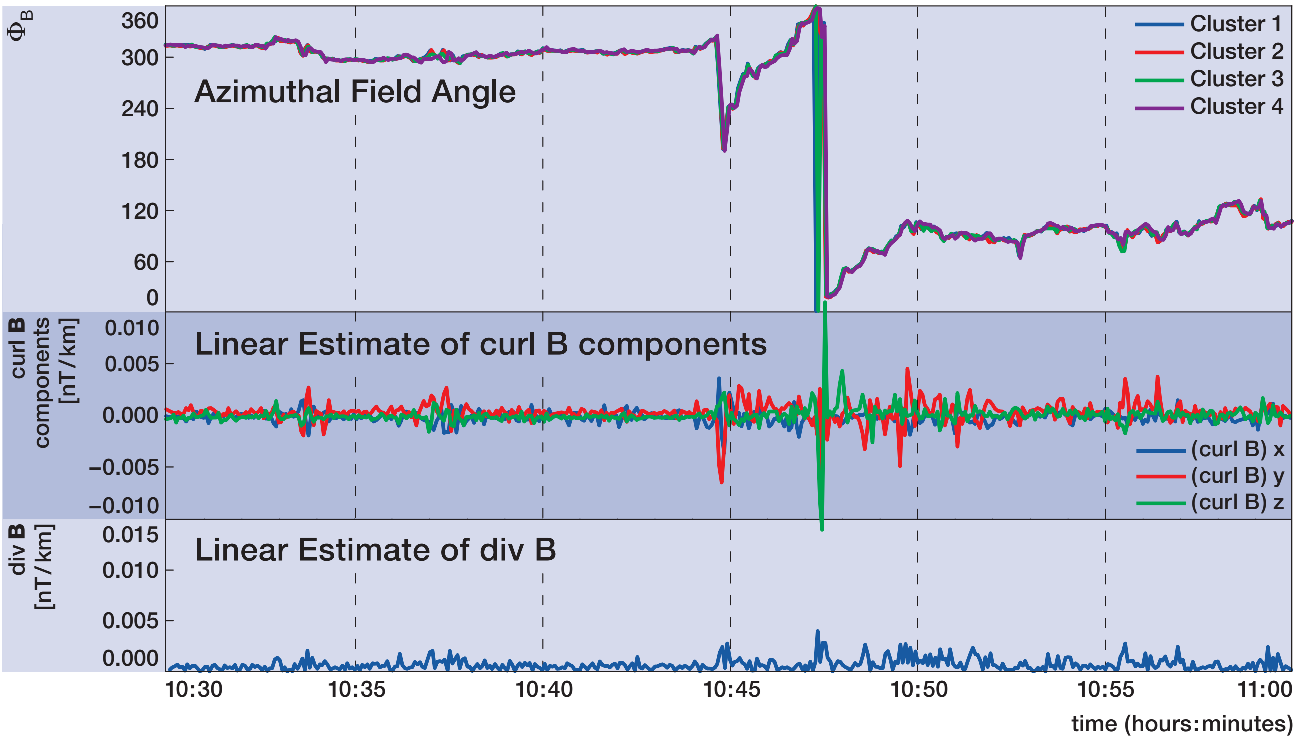


Figure 8

An encounter of the heliospheric current sheet (HCS). The top panel shows the magnetic field direction that showed a large rotation near 10:47 UT as the HCS crossed the Cluster formation. The middle panel shows the curl of the magnetic field, estimated from the four spacecraft magnetic field data: the large values during the passage of the HCS are caused by the current within the structure. The bottom panel shows an estimate of div B: this remains small throughout, providing a consistency check for the estimate of curl B (from Eastman et al., 2001).

capability of Cluster to derive spatial gradients in three dimensions. Assuming that the field varies linearly between the spacecraft positions, the density of electric current flowing in the volume between the spacecraft can be derived from the magnetic field measurements at the four points, using Ampère's law. The figure demonstrates the success of the technique: precisely when the HCS passes over the spacecraft, there is a spike in the computed current density. Note that as a consistency check, one also computes the divergence of B, which according to Maxwell's equations should be zero.

Bow Shock

The first sign of any interaction between the solar wind and Earth's magnetic field is a shock wave in space on the Sun-facing side of the Earth. This bow shock is rather like the sonic boom caused when an aircraft flies at supersonic speed. The role of the bow shock is to slow down the solar wind to subsonic speed such that it can be deflected around the obstacle formed by the Earth's magnetic shield, the magnetosphere.

Simply inspecting the raw magnetometer data already reveals the superiority of a four-spacecraft vantage point. **Figure 9** shows a crossing of the bow shock when the IMF had a direction that made it nearly aligned with the shock surface, a geometry referred to as (quasi-)perpendicular because the field is then perpendicular to the normal to its surface. In such a situation the shock has a very simple step-like structure and the profiles recorded by the 4 spacecraft are essentially just time-shifted copies of each other. From the time shift and the known distance between the spacecraft one obtains the speed at which the shock passed over the spacecraft, about 5 km/s in this case. Together with the measured duration of the shock

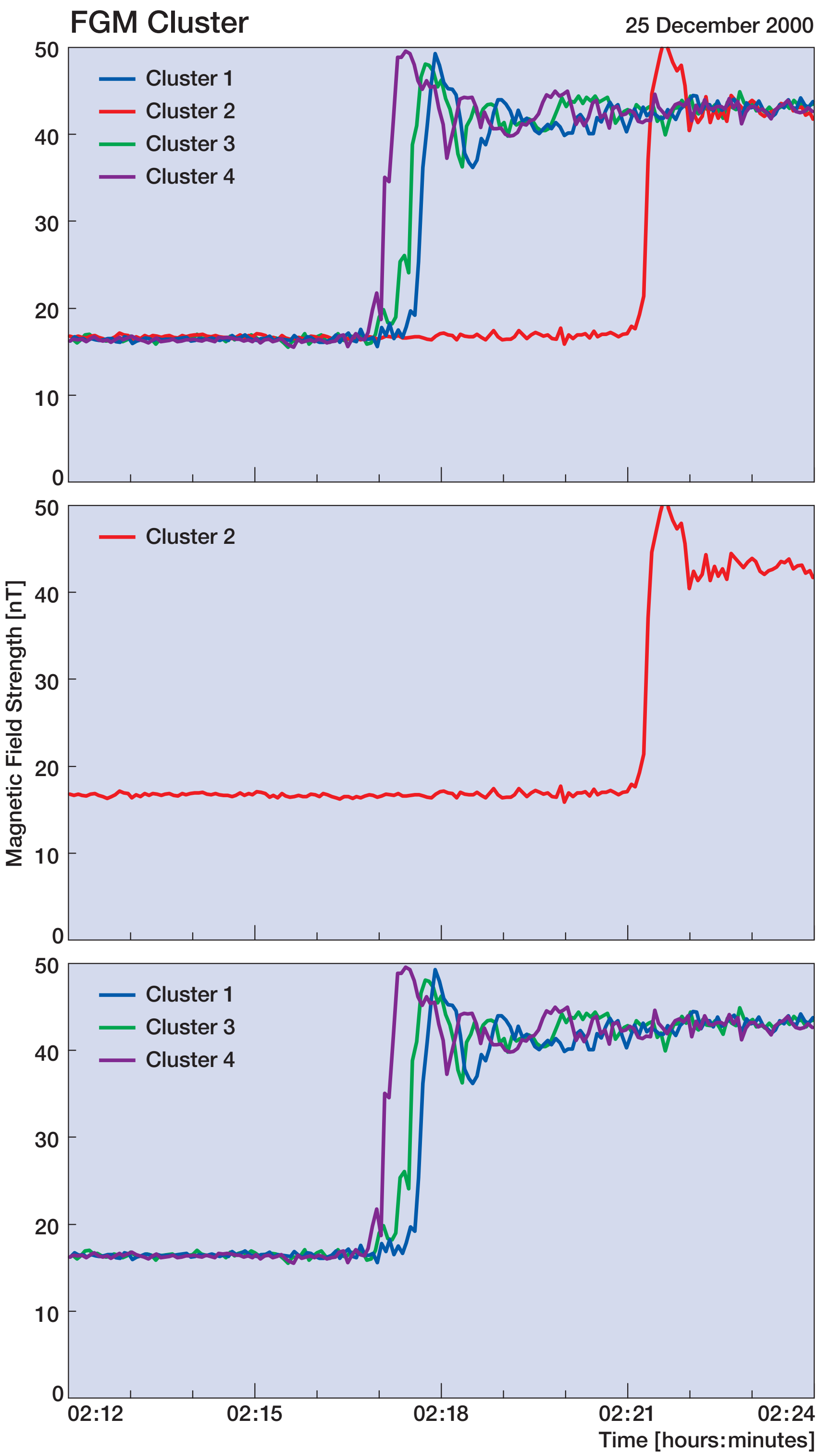


Figure 9
Magnetic field measured by the FGM instruments on the four spacecraft for a crossing of a quasi-perpendicular shock.

transition, this speed yields the thickness of the shock, a quantity that is an important for understanding shock formation in collisionless plasmas.

When, by contrast, the IMF is more nearly aligned with the shock normal, it becomes a (quasi-)parallel shock. Parallel shocks are characterized by oscillating transitions, and are much harder to analyse. They are, however, exceedingly important, because it is such parallel shocks (created by supernovae explosions) that are thought to be responsible for acceleration of galactic cosmic rays. As a consequence of the parallel geometry, particles are free to traverse the shock in both directions. This result is an extended "foreshock" region that is characterized by particle beams, waves, turbulence and first-order Fermi acceleration. Deep in this foreshock one finds Short Large Amplitude Magnetic Pulsations (SLAMP's), which are believed to play the dominant role in the thermalisation of the incident plasma (via reflection and subsequent mixing analogous to that at quasi-perpendicular shocks). **Figure 10** shows two SLAMPs observed by Cluster on 2 February 2001, when the spacecraft were separated by about 600 km. Despite both theoretical and previous experimental estimates of SLAMP sizes larger than 3000 km, the Cluster measurements reveal considerable spatial variability on scales less than 600 km. It will be interesting to see how the situation changes when Cluster separations have been reduced to 100 km (see **Figure 4**).

Magnetopause

Because charged particles are deflected by magnetic fields, the Earth's magnetic field is an obstacle that the solar wind cannot simply penetrate. Instead it flows around it, confining the terrestrial magnetic field to a cavity, the magnetosphere (see **Figure 1**). Its boundary, the magnetopause, is located where the plasma pressure exerted by the solar wind is in equilibrium with the magnetic pressure from the Earth's magnetic field. Across the magnetopause, the magnetic field usually undergoes a sharp change in magnitude and direction. The magnetopause is thus a current layer that separates the solar wind and its embedded interplanetary magnetic field from the Earth's magnetic field and plasma.

Density Gradients

The four spacecraft measurements allow the measurement of spatial gradients of scalar quantities, such as the gradient of the plasma density, as shown in **Figure 11**. The plasma density is deduced in this case from the plasma frequency measured by the WHISPER instrument. Using the values of the density measured simultaneously at the four spacecraft, the density gradient can be calculated, as has been done for a magnetopause crossing on 2 March 2002 shown in **Figure 11**. At the top, the figure shows the measured plasma densities on the four spacecraft. At the beginning of the interval, the spacecraft were in the magnetosphere, characterized by a tenuous plasma, then they crossed the magnetopause around 03:31 UT and went into the magnetosheath with a density about 20 cm^{-3} for less than a minute before re-entering the magnetosphere at about 03:32 UT. Note that at this time, the Cluster spacecraft were only about 100 km apart. As a result, they were all located in the thin magnetopause simultaneously, as demonstrated that the times of the four density traces in **Figure 11** clearly overlap. The same is true for the magnetic field traces from the FGM instrument (not shown). From the differences in the densities measured at a given time on the four spacecraft, the density gradients inside the current layer can be determined. Similarly, the current density can be determined from the magnetic field differences, using the method illustrated in **Figure 8**. The gradient vectors are shown at the bottom of **Figure 11**, projected onto one of three orthogonal planes (the other two projections not shown for clarity). Knowledge of the instantaneous density gradients and current densities are essential for understanding the formation of the magnetopause, and for distinguishing different plasma transport mechanisms, but neither information was available before Cluster.

Magnetopause Thickness and Motion

As a result of dynamical variations in the solar wind and interplanetary magnetic field, the magnetopause is in constant motion, which makes determination of its structure virtually impossible from single-spacecraft data.

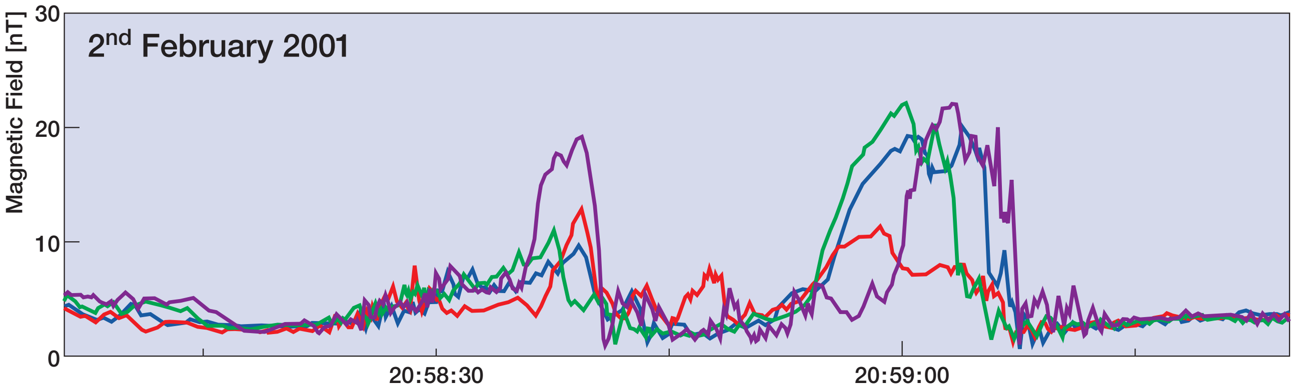


Figure 10
Shock Large Amplitude Pulsations observed by the 4 Cluster spacecraft in the vicinity of the quasi-parallel bow shock. Note the significant differences between the various spacecraft despite their modest (~600 km) separation (from Lucek et al., 2001).

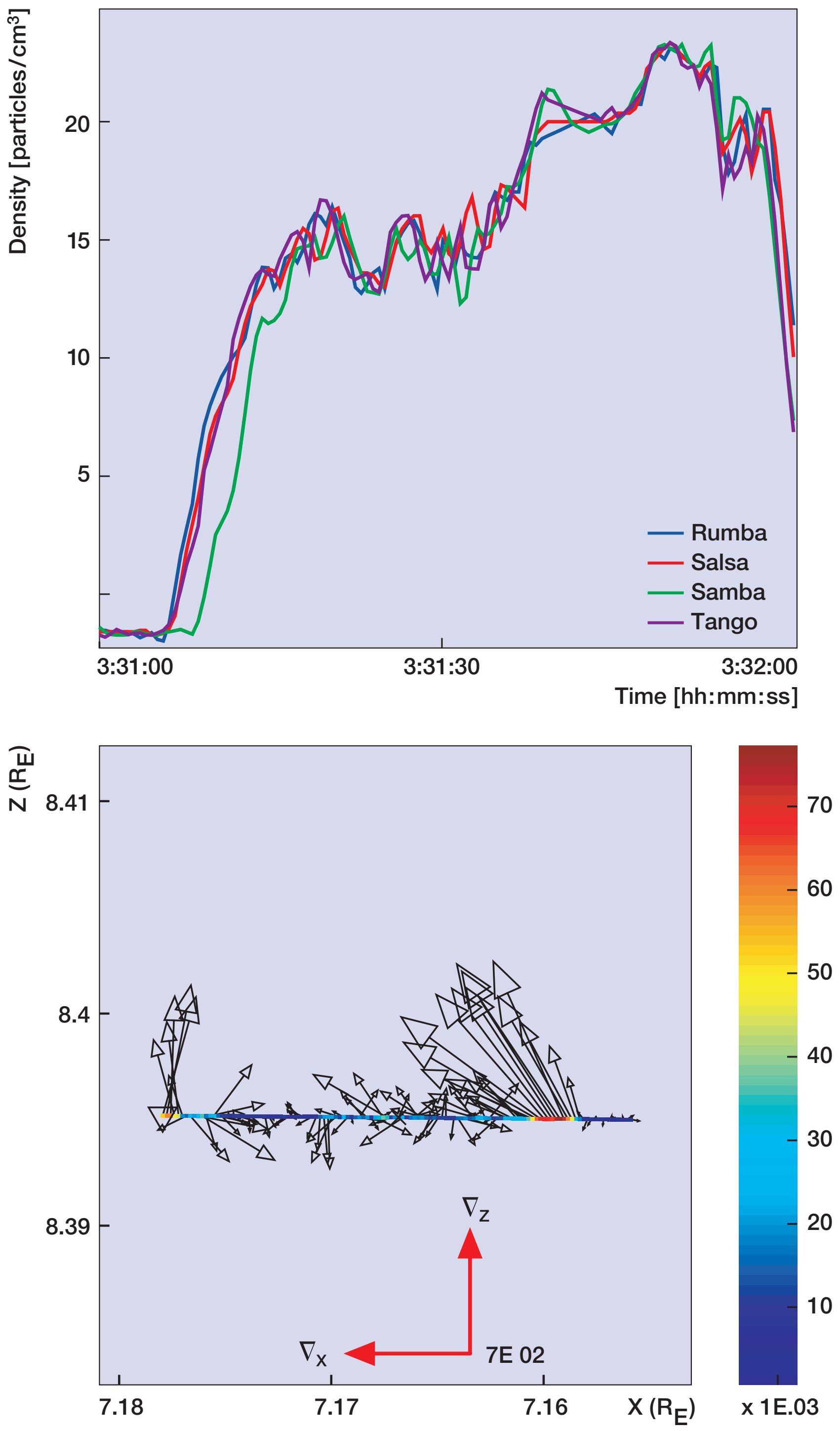


Figure 11
Plasma densities measured on the four Cluster spacecraft by the WHISPER instruments for a magnetopause crossing on 2 March, 2002 (top), when the spacecraft separation distances were only 100 km. At the bottom, the figure shows the gradient vectors inferred from the instantaneous differences in the densities (from Decreau et al., 2002).

Figure 12 (top panel) shows time series of the magnetic field measured by the FGM instruments on the four spacecraft for a magnetopause crossing on 4 July 2001. From the four crossing times and the known spacing between the spacecraft one can derive the magnetopause velocity, 30 km/s in this case. The bottom panel shows an expanded view of the magnetopause crossing by spacecraft C3. From **Figure 12** one infers a thickness of the magnetopause current layer of approximately 200 km, corresponding to about three ion Larmor radii, which is physically reasonable, although theory makes no definite prediction.

While determination of the current layer thickness has importance in its own right, the most striking aspect of the data in **Figure 12** is the sharp rise in plasma density (from 0.1 to 24 cm^3) across the current layer (shown in the bottom panel), because it means that at this time essentiality no solar wind plasma was able to enter the magnetosphere, neither at this location nor further upstream. This is an unexpected result, because it is generally thought that solar wind plasma can enter the magnetosphere by any number of processes.

The four-spacecraft timing provides the magnetopause velocity only at four discrete instances in time, which is often not enough to infer the boundary thickness and its evolution. But it turns out that the measurements of the plasma drift velocity with the Electron Drift Instrument (EDI), referred

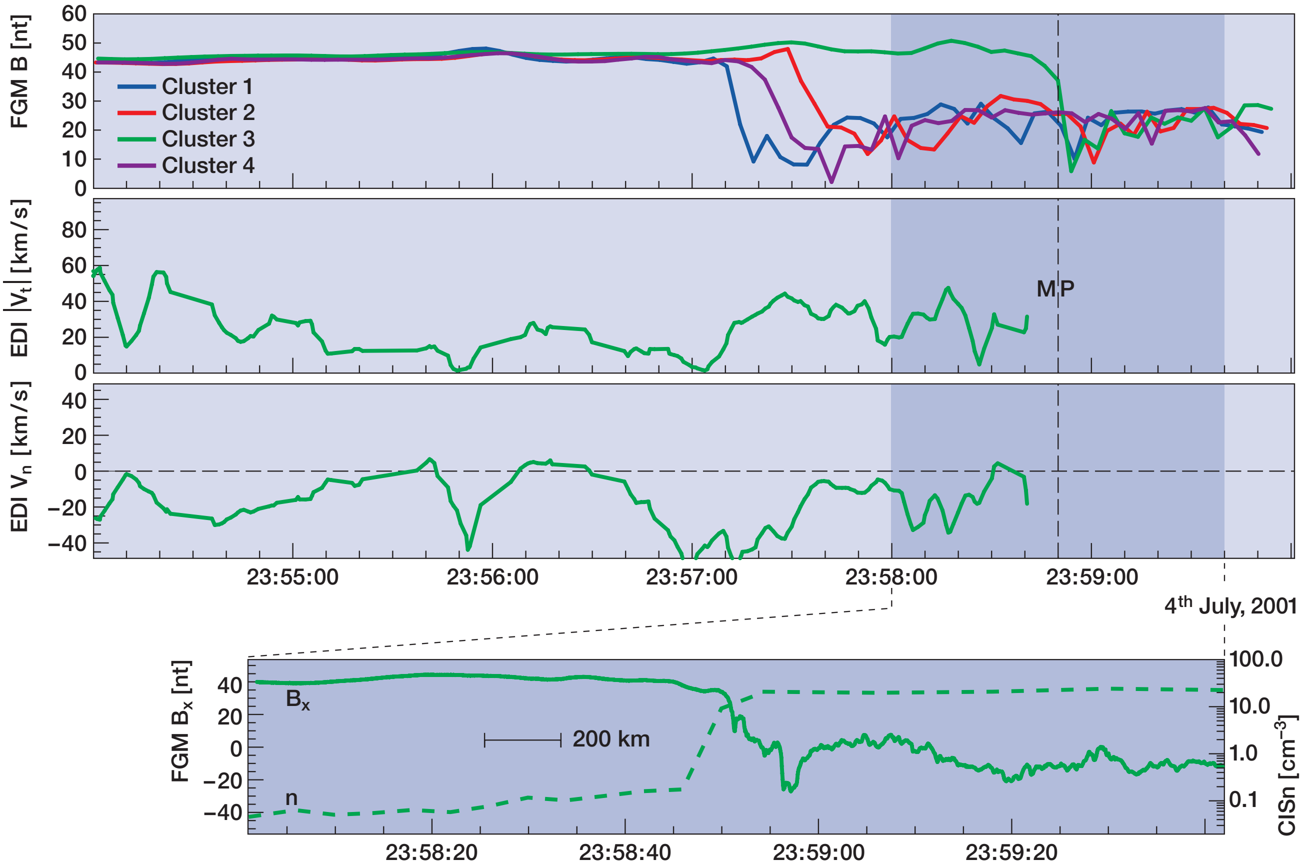


Figure 12
Magnetopause crossings by the four Cluster spacecraft on 4 July 2001, identified by the sudden drop in magnetic field strength measured by the FGM instruments (top panel). The second and third panels show, respectively, the components of the plasma convection velocity tangential (V_t) and normal (V_n) to the magnetopause, as measured by EDI on C3. The velocity V_n is interpreted as the magnetopause velocity. When integrated over time, it gives the instantaneous distance of spacecraft C3 from the magnetopause (not shown). The bottom panel shows, for an expanded time scale, the x-component of the magnetic field (from FGM) and the plasma density (from CIS), measured on C3 across the magnetopause. The horizontal bar shows a distance scale (200 km) obtained from the measured magnetopause velocity.

to earlier, and by the ion spectrometer CIS, can provide a continuous estimate of this motion, because, to first order, plasma and magnetopause move together. **Figure 12** shows, as the third panel, the projection, V_n, of the drift velocity measured by these two instruments on C3 onto the magnetopause normal direction. V_n varies, but is negative on average, corresponding to a net in-ward motion of the magnetopause that eventually causes the spacecraft to exit the magnetosphere. Integrating this velocity over time provides a continuous estimate of the magnetopause distance (not shown. This information permits reconstruction of the complete spatial profile, for example of the plasma density.

Magnetic Reconnection

To first order, the magnetopause is an impenetrable surface that completely separates the Earth's magnetic field and the solar wind. The example in **Figure 12** demonstrates that this situation can actually occur. More commonly, however, that separation is far from perfect, and the investigations of the processes that allow transfer across the magnetopause are at the heart of the Cluster mission. The one process known to play a key role for transfer of mass, momentum, and energy across the magnetopause, is magnetic reconnection. This process is the result of the breakdown of the "frozen-in" picture. Under ideal conditions, the interplanetary magnetic field is frozen into the solar wind plasma, and therefore slips along the magnetopause with the solar wind flow. But when this concept breaks down locally, by processes not yet identified, the IMF can diffuse relative to the plasma and connect with the terrestrial magnetic field across the magnetopause. This is sketched in **Figure 13.** Once reconnected, the magnetic field lines are dragged over the poles and into the magnetotail because they are embedded in the solar wind flow.

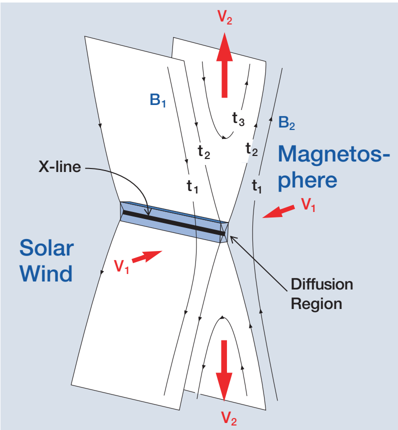
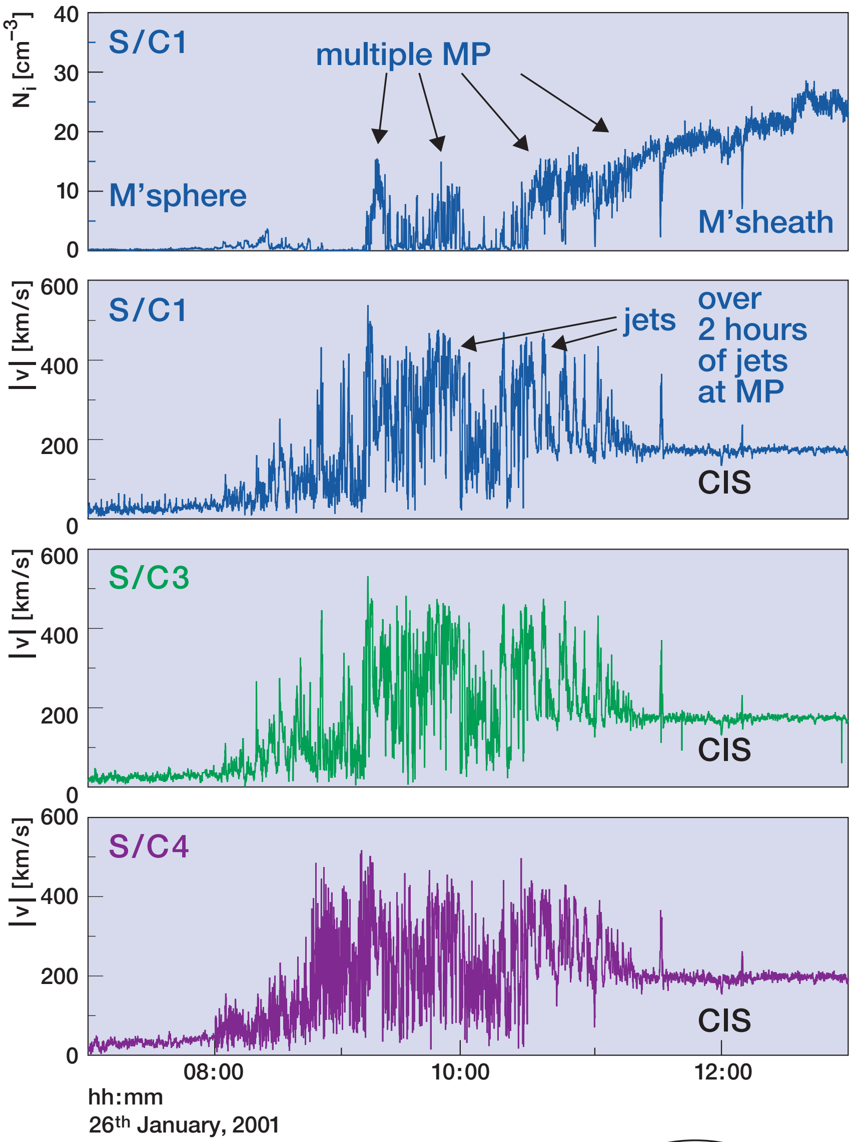


Figure 13
Schematic to illustrate reconnection across the magnetopause between magnetic field lines from the Sun and from Earth. A pair of field lines that at time t_1 are still entirely in the solar wind and magnetosphere, respectively, connect through the magnetopause at time t_2 and become two sharply kinked field lines at time t3 that now have one end on the Earth, the other on the sun. The reconnection site is a line that is termed X-line or reconnection line. The solar wind plasma approaches at speed V_1 and becomes accelerated to V_2 as a result of the tension in the sharply bent field lines. It is those high-speed plasma jets that are the most directly observable signature of magnetic reconnection at the magnetopause.



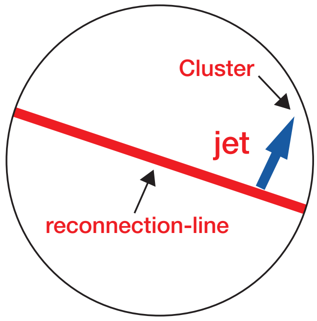


Figure 14
Plasma density (on C1) and velocities (on C1, C3, C4) measured by CIS-HIA for the magnetopause encounter on 26 January 2001. The high velocities indicate the encounter with plasma jets emanating from a reconnection-line located somewhere below the spacecraft (courtesy Phan et al.).

When reconnection occurs, solar wind plasma can enter the magnetosphere by fluid flow along reconnected field lines. Upon entry it is accelerated to large speeds by the magnetic tension forces that exist across the magnetopause because the reconnected field lines are sharply bent, as shown in **Figure 13**. We were the first to observe the resulting plasma jets with an instrument on ISEE in 1979. This discovery formed the "smoking gun" evidence for reconnection at the magnetopause.

One of the open questions is whether reconnection can happen in a quasi-stationary fashion, or whether it is necessarily intermittent. As the plasma jets are localized in thin layers, they can be observed only when this layer passes over the spacecraft. With a single spacecraft one could never be sure that reconnection had not actually stopped in between successive crossings. With Cluster one now has closely spaced crossings that allow to fill the gaps. **Figure 14** shows data from the CIS instrument that demonstrate that the plasma jets are observed whenever any of the spacecraft crosses the magnetopause. For this interval of almost 1-hour duration, reconnection must therefore have happened almost continuously, although not necessarily at a fixed rate.

Polar Cusps

The polar cusps are weak spots in the defence of the magnetosphere against the on-rush by the solar

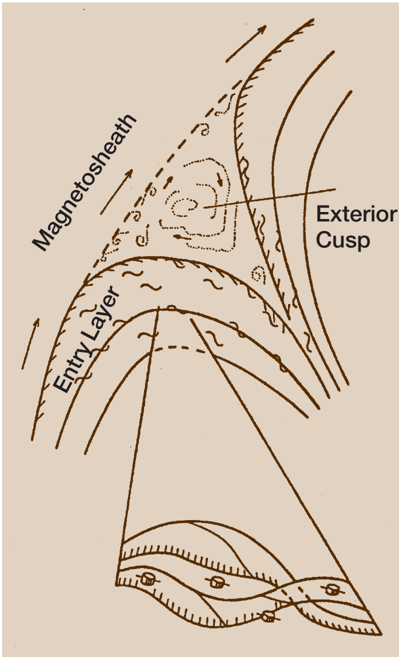


Figure 15
Expectations for the distant polar cusp region, as envisaged in the 1982 Cluster proposal.

wind. This is due to their funnel shape and their small magnetic field. This unique feature was one of the drivers for the Cluster idea, as illustrated by **Figure 15**, taken from the 1982 proposal. As illustrated by **Figure 2**, the Cluster obit crosses the distant cusp region when its apogee is one sunward side. In fact it was this property that drove the selection of the Cluster orbit. By contrast, the orbit crosses cusp magnetic field lines at mid-altitudes when the apogee is on the night side (see **Figure 3**).

Figure 16 shows what is observed at such a mid-altitude cusp crossing and illustrates the successive encounter with the particles entering the magnetosphere through the cusp. Close to perigee, when these measurements are made, the Cluster spacecraft have much larger separation distances than further out along their orbit. This explains the large time shift between the encounters, especially that by spacecraft C3. The difference in appearance is probably caused by a reconfiguration of the cusp before the encounter by C3.

Polar Cap

Moving tailward from the polar cusp, one enters the polar cap region that is permeated by magnetic field lines that extend deep into the geomagnetic tail where the form the tail lobes (see **Figure 1**). The polar cap is often void of any plasma, but CIS/CODIF data show the frequent presence of cold oxygen ions on polar cap magnetic field lines. **Figure 17** shows an energy-time spectrogram of O^+ ions for an hour on 4 March 2001. The feature to note is the narrow band of intense fluxes that proceeds to lower and lower energies while the spacecraft moves from the cusp over the polar cap towards the magnetotail. For three selected times, t_1–t_3, the upper diagram shows the velocity distribution of the oxygen ions, confirming that they have an extremely narrow spread in velocity, with the mean velocity becoming smaller with time.

The schematic diagram at the bottom illustrates the interpretation. Ions injected with a broad energy spectrum from a narrow source at low altitudes on the dayside, all will move up the magnetic field lines, but end up at different locations, depending on the ratio of the speed at which they move along the magnetic field and the speed with which those field lines move over the polar cap, as shown in the bottom panel. The black line is derived from the O^+ distributions, while the red symbols are from the measurements of the drift of artificially injected electrons by EDI. Noting the entirely different nature of the measurements, the agreement is simply remarkable.

Data shown in **Figure 17** are taken from one spacecraft only. But if one compares the measurements on the other spacecraft, one finds that the convection velocities are essentially identical, with zero time shifts. This means that the observed variations in the convection velocity, in particular the short bursts of sunward convection (positive V_x) are temporal in nature, probably caused by "dipolarizations" of the tail magnetic field that occur as a result of a magnetospheric substorm (see below).

Magnetotail

As a consequence of the solar wind flow past the Earth, magnetic field lines are being stretched in the anti-sunward direction, creating a long tail. This magnetotail consists of a northern and southern lobe containing very tenuous plasma and permeated by magnetic fields of opposite polarity that emanate from the northern and southern polar cap. At the centre there is a region of hot dense plasma, the plasma sheet (cf. **Figure 1**). The plasma sheet in turn straddles the so-called neutral sheet, where the magnetic field reverses direction, and which therefore is an ideal site for magnetic reconnection. Through magnetic reconnection in the tail, magnetic field lines that were opened by reconnection at the subsolar magnetopause (see **Figure 1**), and were carried into the magnetotail by the action of the solar wind flow, are being closed again, convect sunwards, and start

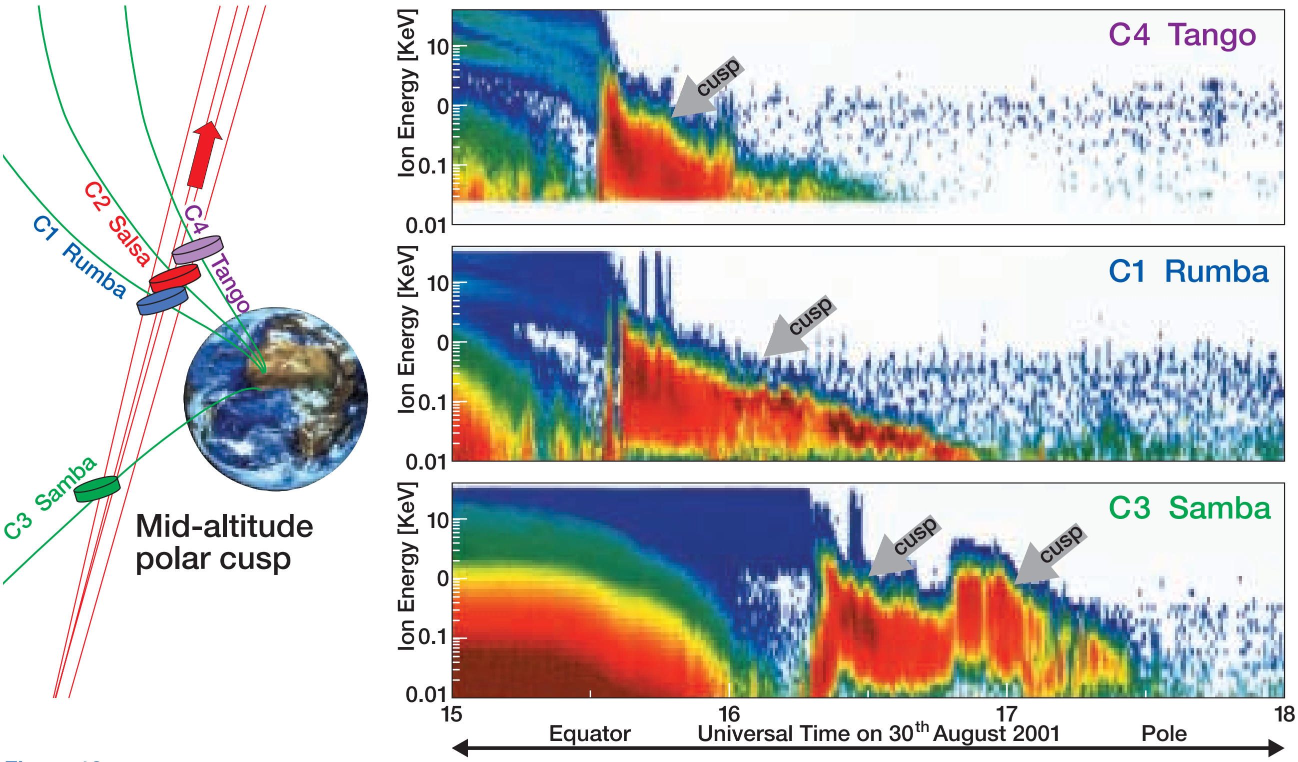


Figure 16
Crossing of the mid-altitude cusp (around 5 Re altitude) by the 4 spacecraft on 30 August 2001. The energy-time spectrograms from CIS on C1, C3 and C4 on the night show the encounter with the ions entering the magnetosphere through the cusp (from Bosqued et al., 2001).

the process all over again once they have reached the subsolar magnetopause. The combination of magnetic reconnection at the dayside magnetopause and in the magnetotail sets up a global circulation of the plasma and magnetic field in the magnetosphere.

The plasma sheet is the site of violent events referred to as magnetospheric substorms, which form one of the most intriguing phenomena in the magnetosphere. Substorms are manifestations of the sudden release of energy stored in the geomagnetic tail. For reasons not yet understood, the energy is not released at the same rate as it is stored, but quite suddenly, with enormous consequences for the entire magnetosphere, including an intensification and expansion of the aurora. **Figure 18** shows how, at the onset of such a substorm, the magnetic field measured by the Cluster spacecraft suddenly changes from a very stretched configuration, where the magnetic fled is essentially along the tail axis, indicated by a small elevation angle, λ, to an orientation characteristic of a magnetic dipole, i.e., having a large λ. This dipolarisation is not simultaneous, but propagates as a front passing over the four spacecraft in succession. This allows for the first time to precisely determine the speed and direction of such a front.

Plasmasphere

The upper atmosphere and ionosphere are important sources of plasma for the magnetosphere. In

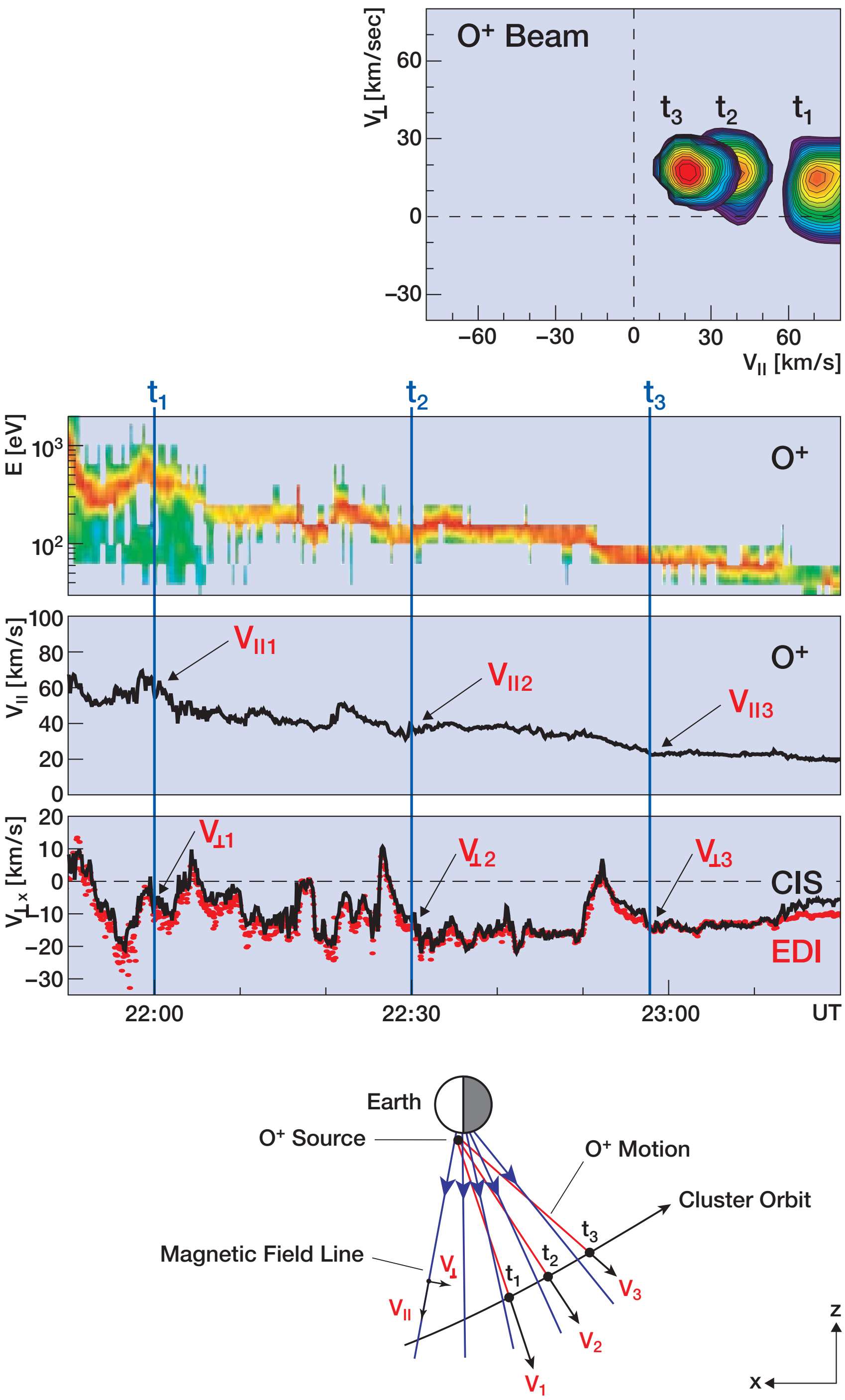


Figure 17
Oxygen ion observations and field line convection velocities for a polar cap pass on 4 March 2001. The top panel shows the distributions of O^+ ions in velocity-space, measured by CIS-CODIF at three different times; below are the energy time spectrograms of these ions, their inferred parallel velocity, and the convection velocity, V_x, inferred from the O^+ measurements (solid black line) and from EDI (red symbols). The interpretation of these observations is illustrated by the sketch at the bottom.

the region of closed magnetic field lines in the inner magnetosphere, outflow of ionospheric plasma produces the so-called plasmasphere, with a usually sharp outer boundary, the plasmapause.

Figure 19 shows a traversal of the plasmasphere, first inbound and then outbound, as illustrated by the insert in the lower left. In addition to the central plasmasphere, the figure shows some density structures further outward. The shape of these structures looks strikingly similar in the four profiles. Replotting the density measurements against the McIlwain L-parameter confirms that these structures are fixed in space and do not vary much over time-scales of about one hour. (The L-parameter is a measure of the equatorial distance of magnetic field lines in the inner magnetosphere, originally introduced to characterize the radiation belts)

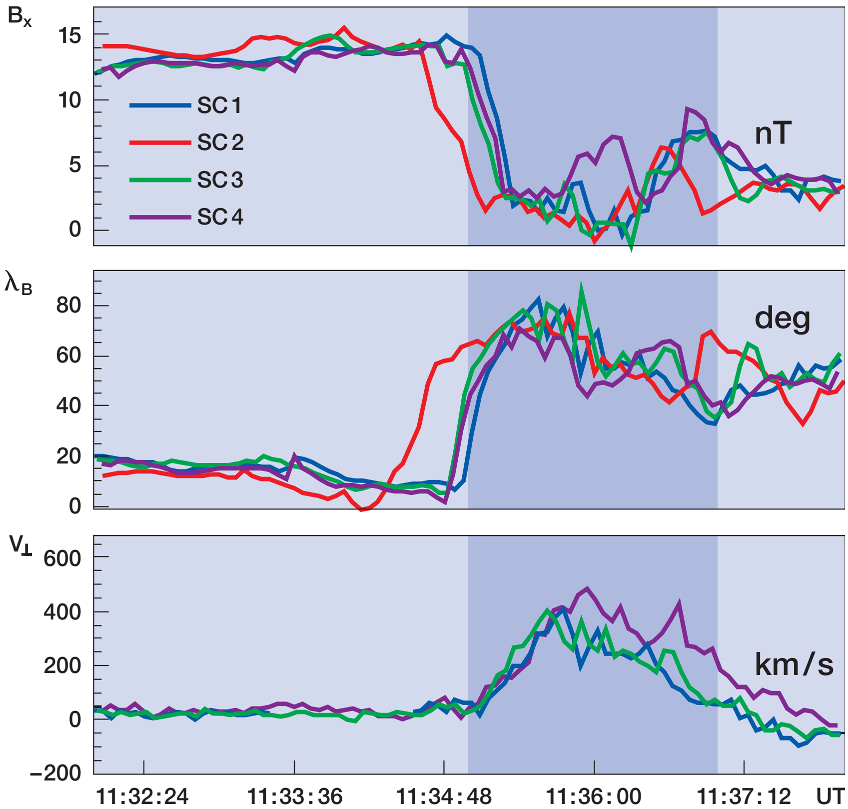


Figure 18

Magnetic field observations from the four Cluster spacecraft during the onset of a magnetospheric sub storm, when the stretched magnetic configuration, indicated by large values of the magnetic field along the tail axis, B_x, and small values of the field elevation angle λ, suddenly relaxes to a more dipolar configuration, characterized by small values of B_x and a large angle λ.

Aurora

The only visible consequence of the interaction between the solar wind and Earth's magnetic field is the aurora. It occurs in an oval around both magnetic poles and is generated by energetic particles that precipitate into the upper atmosphere and cause light emission as well as ionisation. The cusp and boundary layers on the dayside and the plasma sheet on the night side are the sources of this precipitation. On the other hand, ions escaping from the auroral oval contribute to the plasma in the magnetotail and in the magnetopause boundary layers.

Black Aurora

The visible aurora is associated with converging electric field structures producing an upward directed electric field that accelerates electrons towards Earth, generating the auroral light emission and upward field-aligned currents. The opposite happens in the auroral return current region: there the electric field structures are divergent and accelerate electrons upwards into space, causing a void of electrons and a lack of auroral light emissions. This is why this region is often referred to as "black aurora". **Figure 20** schematically illustrates the juxtaposition of visible and black aurora.

Figure 21 shows, schematically, the observations by the EFW and PEACE instruments from a crossing of a U-shaped potential structure around 04:30 UT on 14 January 2001. At the time of the first overpass, the electric field measurements by EFW showed a weak bipolar signal (signifying a sign reversal of the field, as required by **Figure 20**), which then became stronger during the second and third overpasses, but which had

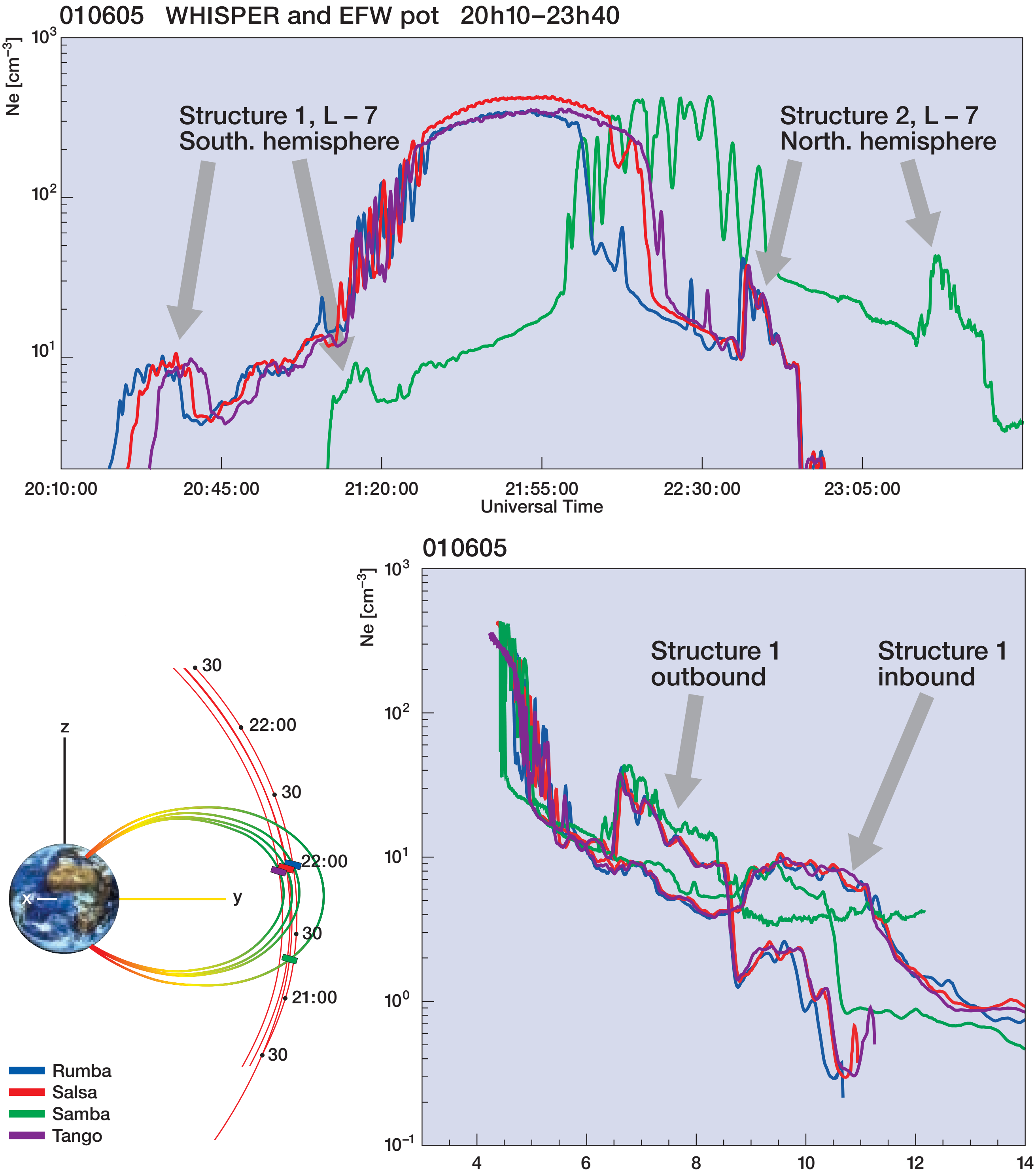


Figure 19
Plasma density deduced from the WHISPER and EFW instruments during the crossing of the plasmasphere on 5 June 2001 (top panel). The spacecraft orbit is shown on the lower left. When plotted against the McIlwain L-parameter (lower right), the density structures prove to be spatially fixed (from Decreau et al., 2001).

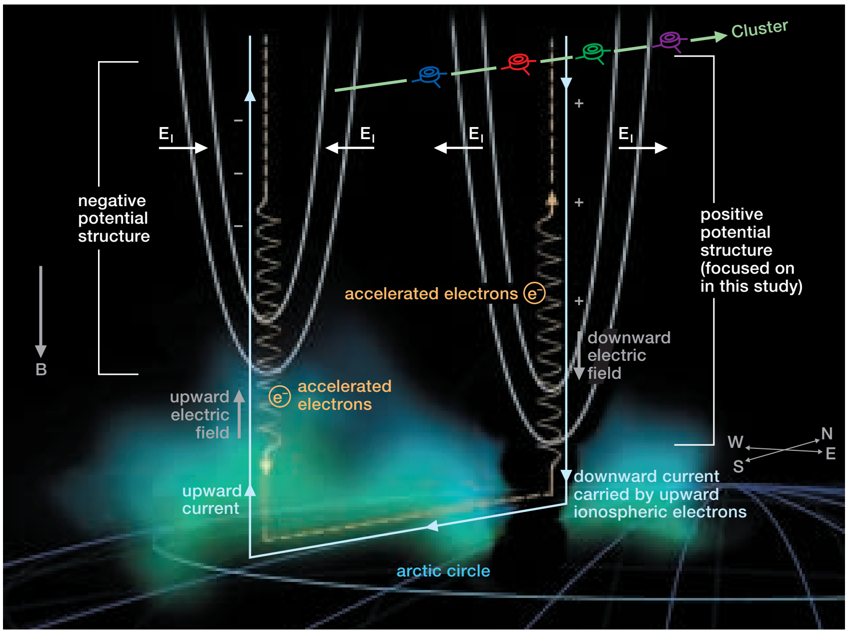


Figure 20
U-shaped electric potential configuration over an aurora (left) and its counterpart over a dark region referred to as black aurora (right). In the structure on the left, electrons are accelerated downward into the atmosphere to cause the characteristic auroral emissions, while the structure on the right accelerates electrons upward, causing a lack of aurora emissions, hence its name.

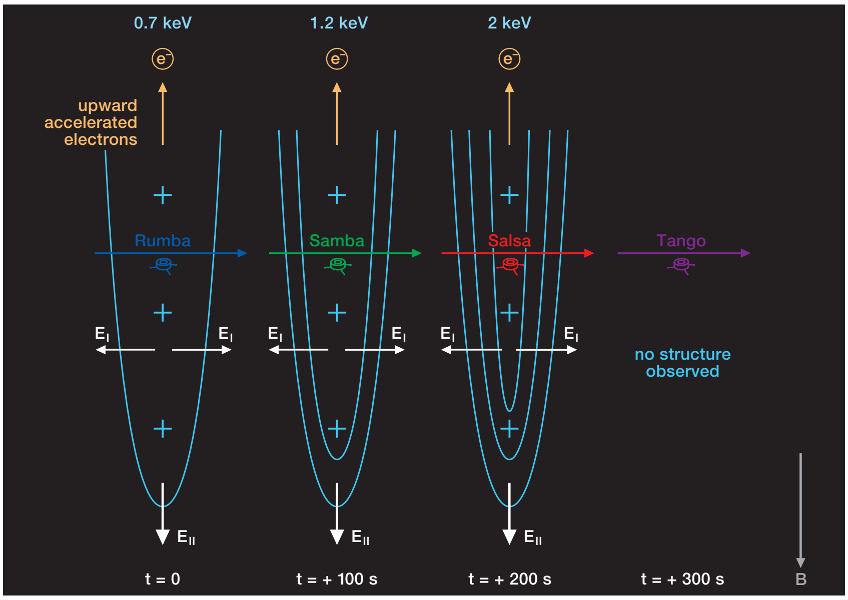
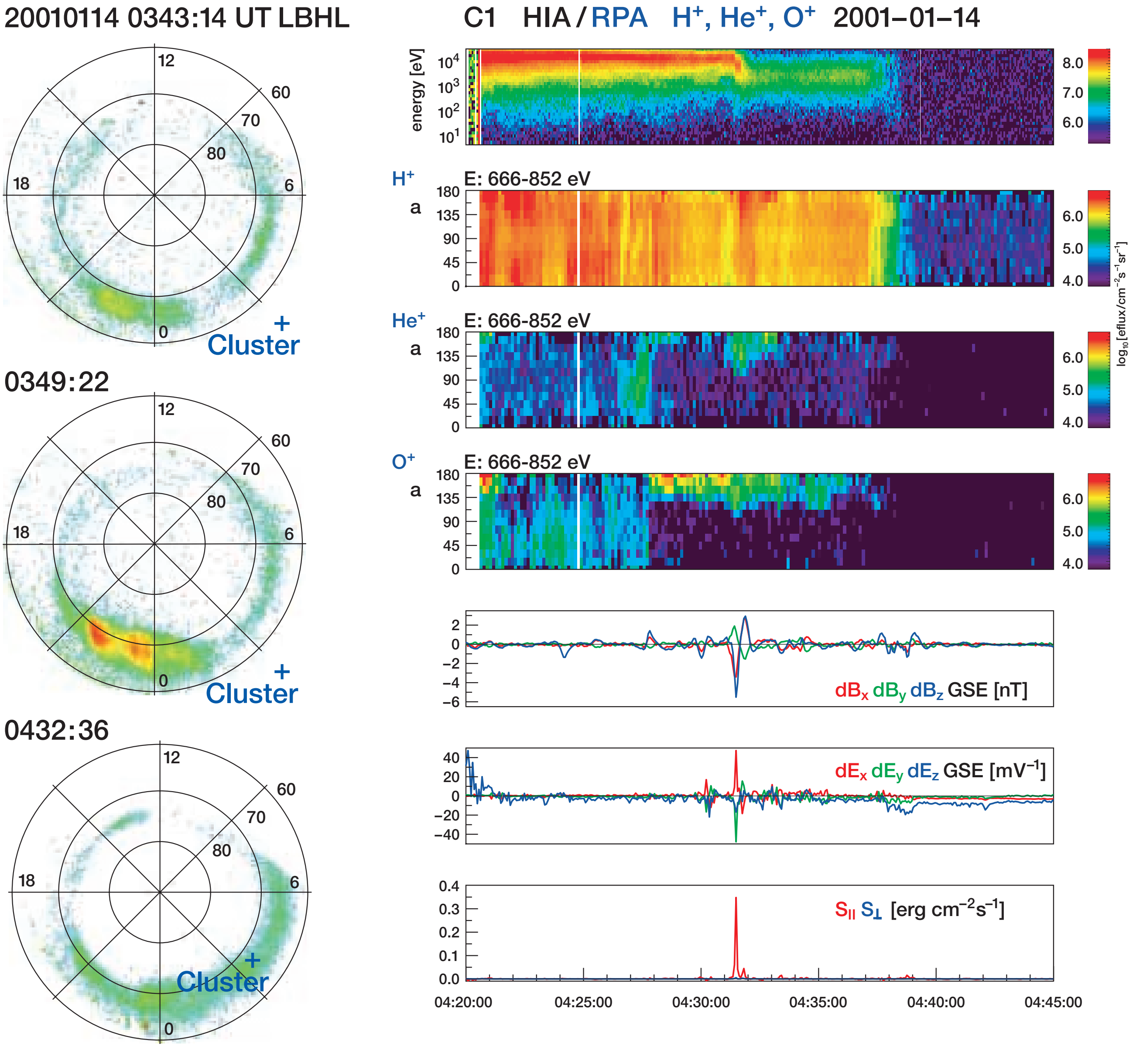


Figure 21
Schematic representation of the evolution of the electric potential pattern that Cluster observed at around 04:30 UT on 14 January 2001 when the four spacecraft sequentially flew over a black aurora, recording initially growing electric fields and electron energies, before electric field and electrons disappeared altogether (after Marklund et al., 2001).

essentially disappeared when the fourth spacecraft flew over the same region. Quite consistent with this, the PEACE instrument observed upward directed electron beams with increasing energy, before the electrons disappeared as well. The results show that this diverging electric field structure extends to altitudes greater than 20,000 km and that it grows in size, intensifies and decays over time scales of a few hundred seconds.

Ion Outflow and Energy Input

Electric fields directed such that they accelerate (negatively charged) electrons downward into the ionosphere to cause auroral displays will at the same time accelerate ions from the upper atmosphere/ionosphere in the opposite direction because of their positive electric charge. **Figure 22** shows a sequence of auroral images, together with Cluster ion measurements taken during a traversal of the plasma sheet, recognized as the intense flux (shown in red) of energetic ions in the spectrogram in the top panel. Inspection of the fourth panel on the right shows that oxygen ions are flowing up the magnetic field lines, as indicated by the predominance of large fluxes at pitch-angles of 180 degrees, and are detected on Cluster whenever Cluster is magnetically connected with the auroral region. In return, the plasma sheet is a source of electromagnetic energy for the aurora. At 04:31:30 UT, when Cluster crosses the edge of the plasma sheet, recognized as



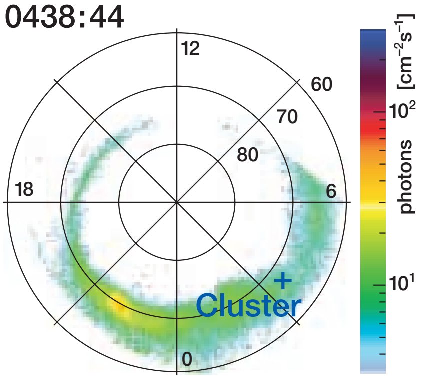


Figure 22

On the left, a sequence of four auroral images from the UVI instrument on NASA's polar spacecraft, with the mapped Cluster positions shown as blue crosses. On the right, Cluster particle and field measurements for the same time interval. The top panel shows an energy-time spectrogram of ions with energies between 5 eV and 27 keV from the CIS-HIA instrument. The next three panels show the pitch-angle distribution of hydrogen, helium and singly charged oxygen, respectively. The magnetic and electric field fluctuations measured by EFW and FGM are shown in the third and second panels from the bottom. The bottom panel, finally, shows the energy flux density, S, computed from these electric field and magnetic field fluctuations. The key features are the appearance of upflowing oxygen ions at pitch-angles near 180°, and the large earthward directed energy flux right at the edge of the hot plasma sheet, which serves to power the aurora (from Wilber et al., 2002).

the drop in flux of energetic ions in the spectrogram in the top panel, a high flow of earthward directed electromagnetic energy, S, is observed. This energy flux provides a way to power the aurora.

Auroral Kilometric Radiation

Since the mid 1960s it is known that the Earth is a powerful radio source in the frequency range from 50 to 500 kHz. Because electromagnetic radiation in this frequency range has wavelengths in the kilometer range, and because of the close association with the aurora, this radiation is now called auroral kilometric radiation, abbreviated AKR. One of the primary objectives of the WBD instrument on Cluster is to use the unique four-spacecraft configuration to conduct very-long-baseline interferometry (VLBI) investigations of AKR, because they have the potential of locating the AKR source better than can be achieved with any other technique. **Figure 23** illustrates the differential delay location determination method, simplified to only two spacecraft.

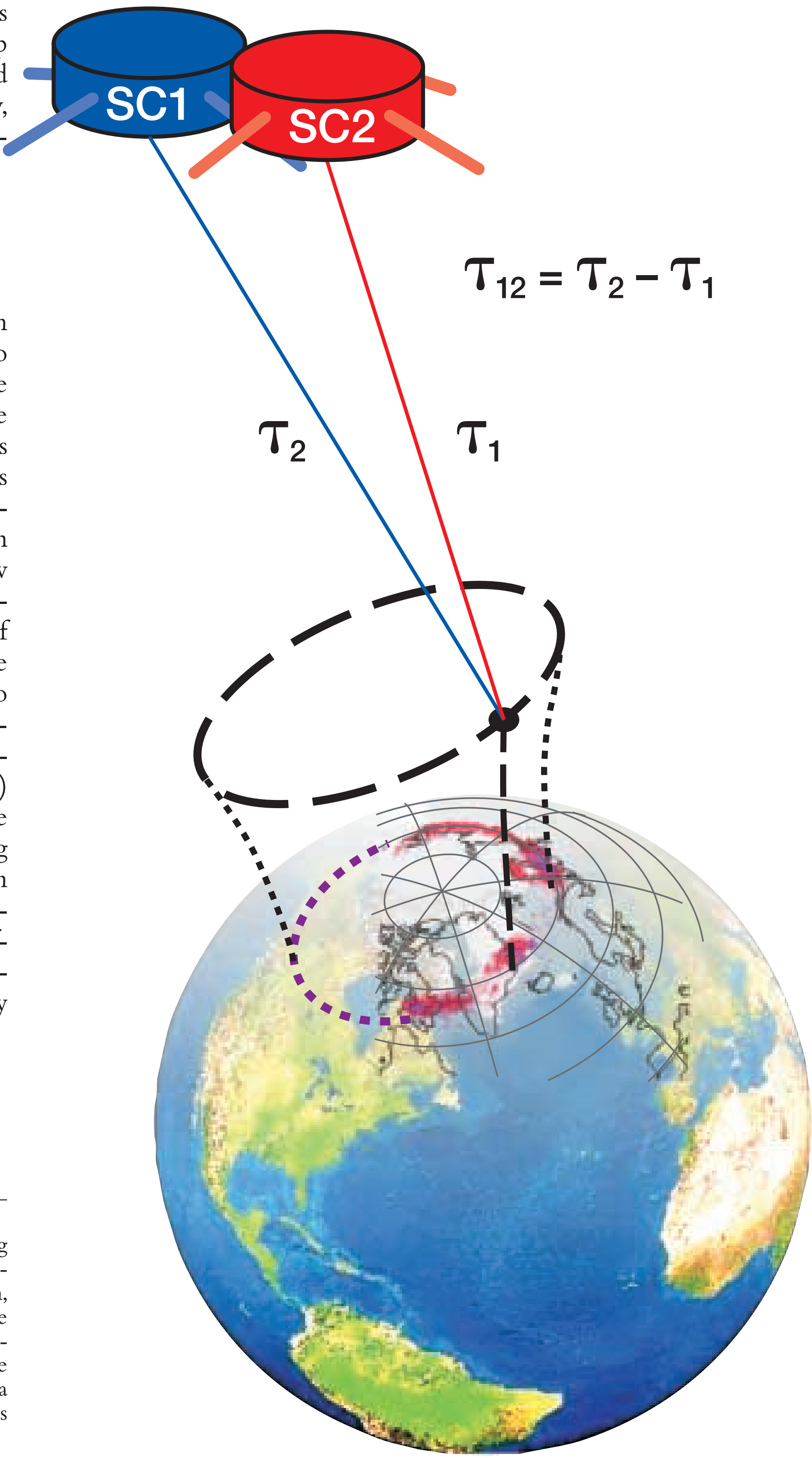


Figure 23
Illustration of the scheme for locating the source of the Auroral Kilometric Radiation (AKR) by triangulation, based on differential delays between the radiation recorded by pairs of spacecraft. With only two spacecraft, the source is constrained to locations in a ring at some distance from the Earth's centre (courtesy WBD team).

Future

Originally intended for a two-year lifetime, the Cluster mission has now been extended until late 2005. Although at the time of this writing, the Cluster teams are still busy with final calibrations and validation of the analysis methods, it is clear from even the cursory glance at the data provided in this lecture, that at the end we will have a highly improved understanding of the various physical processes and phenomena operating in collisionless plasmas. However, it is also clear that in view of the many scale sizes that are involved, four spacecraft are simply the minimum. Ideas to fly swarms of dozens of spacecraft are presently being debated. Such a fleet would allow coverage of multiple spatial scales simultaneously. Coupled with global measurements, this would improve our understanding of the complex linkage between the various processes and regions, an important goal in its own night, but also a key in understanding space weather.

Acknowledgment

The author is indebted to his colleagues in the Cluster community for their help in putting this lecture together.

The author

Götz Paschmann was born in 1939 in Schwelm/Germany. He studied physics, first at the Universität Tübingen, then at the Technische Universität München, where he got his Diploma in 1965. Fascinated by the emerging field of space science, he asked Prof. Lüst, then Director of the newly founded Max-Planck-Institut für extraterrestrische Physik (MPE) in Garching for a PhD thesis opportunity. The theme was related to Earth's Van Allen belts and depended on data to be obtained from a sounding rocket flight into these radiation belts. When this failed, he was sent to the Lockheed Palo Alto Research Laboratory, where he worked in R. G Johnson's group on auroral particle precipitation. Back at MPE, he then wrote his thesis on this subject, under the supervision of G. Haerendel and got his PhD from the Technische Universität München in 1971.

At MPE G. Paschmann worked on instrument development and on the analysis of data from ESA's Heos2 spacecraft on the polar regions of Earth's magnetosphere. He then joined forces with S. J. Bame and his group at the Los Alamos Scientific Laboratory to build plasma detectors for the NASA/ESA ISEE mission launched in 1977. The discovery of high-speed plasma jets at the magnetopause as the "smoking gun" evidence of magnetic reconnection is one of the highlights of this work. Later, G. Paschmann was involved in further magnetosphere research missions like the ill-fated Firewheel project and the highly successful AMPTE mission.

In 1982, G. Paschmann was among the group of European scientists that proposed to ESA a mission called Cluster, intended to explore the magnetosphere with a fleet of four spacecraft flying in close formation. The article in this issue of Spatium describes Cluster's long history, including its failure in 1996 and eventual recovery, ending in the successful launch in the summer of 2000. G. Paschmann is the Principal Investigator for the Electron Drift Instrument on Cluster .

At the time of the failure of the first Cluster attempt, G. Paschmann had already started his involvement with ISSI, initially as the leader of a team that wrote a book on Analysis Methods for Multi-Spacecraft Data that has become the reference for much of the Cluster data analysis. In July 1999 he became a Director at ISSI in Bern, where he now spends 50% of the time, and the other 50% still at MPE in Garching.