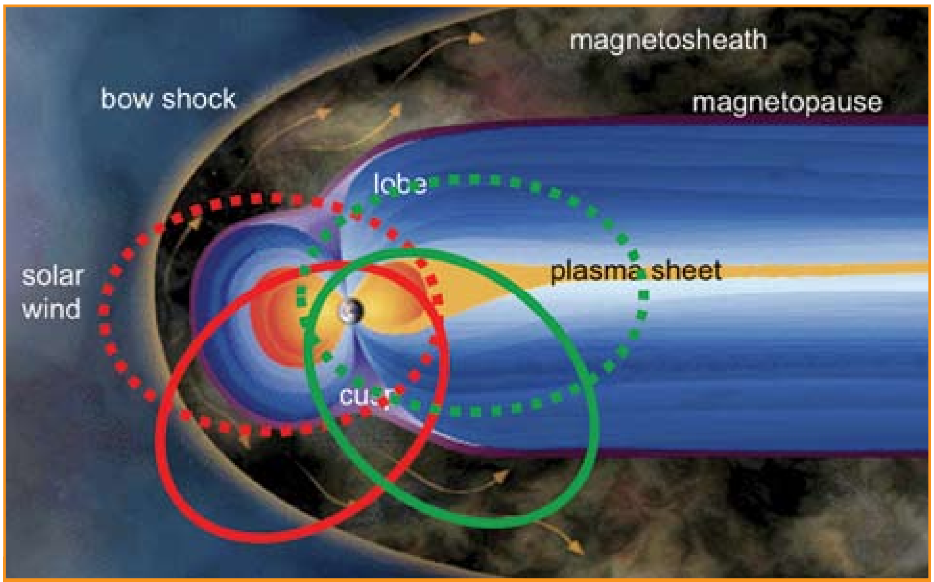


1: Cluster orbit evolution over the course of the mission. Dashed orbits represent Cluster's initial orbit while solid orbits represent the orbit in 2009–2010. Green orbits represent the magnetotail seasons and the red the dayside seasons. (Magnetosphere image courtesy ESA)

10 years of the Cluster mission

Andrew Walsh and UK Cluster specialists mark 10 years of innovation and discovery by ESA's multi-spacecraft magnetosphere mission.

The Earth's magnetosphere is the region of space close to our planet that is dominated by the terrestrial magnetic field. It is filled with plasma of ionospheric and solar wind origin and interacts with the solar wind and interplanetary magnetic field such that the dayside (Sunward side) magnetosphere is compressed from an undisturbed dipole configuration and the nightside (anti-Sunward) is stretched into a long magnetotail that reaches beyond the orbit of the Moon.

The magnetosphere is by no means static. The terrestrial magnetic field couples to the interplanetary magnetic field (carried by the solar wind) through magnetic reconnection at the dayside magnetopause, opening the Earth's magnetic field to the solar wind. These newly opened magnetic field lines are dragged away frm the Sun by the solar wind flow, stretching and forming the geomagnetic tail, where they eventually reconnect and convect back to the dayside (a process known as the Dungey Cycle, after British physicist Jim Dungey). When field lines are opened on the dayside at a greater rate than they can be closed in the tail, open magnetic flux and energy builds up in the magnetotail until it reaches a critical point; the flux is then explosively closed in what is known as a substorm, which is a process that leads to some of the brightest and most dynamic aurora.

In order to study the magnetosphere, and indeed the majority of solar system space plasmas, one must sample the plasma and electromagnetic fields directly, using spacecraft which make *in situ* measurements of their local environment. *In situ* measurements can be tremendously detailed – allowing the direct measurement of particle distribution functions, for example. However, an *in situ* measurement can only describe the conditions around the measuring spacecraft at the time the measurement was taken. The magnetosphere is a complex time-varying system, so one cannot tell whether any changes in an *in situ* data time series from a single spacecraft are a result of motion of the spacecraft or plasma, or a result of large scale, temporal changes in the magnetosphere.

Cluster, along with SOHO, made up the first cornerstone of ESA's Horizon 2000 programme and was a multi-spacecraft mission designed to investigate how the solar wind interacts with the Earth's magnetosphere. On 4 June 1996, an Ariane 501 rocket carrying the four Cluster spacecraft exploded soon after lift off from Kourou, French Guyana. ESA decided to rebuild the spacecraft and, just four years later on 16 July 2000, the first pair of Cluster II (now usually referred to simply as Cluster) spacecraft were launched on a Soyuz-Fregat launcher from Baikonur, Kazakhstan, followed on 9 August 2000 by the second pair of spacecraft. By 1 September 2000, the two pairs of Cluster spacecraft had been brought together into their characteristic tetrahedron formation approximately 1000 km apart, and placed into their operational orbits. The 10th anniversary of this challenging manoeuvre was commemorated by ESA with a special event at the European Spacecraft Operations Centre (ESOC), Darmstadt, Germany on 1 September this year. A period of commissioning followed, during which the 44 separate instruments (11 on each spacecraft) were readied for scientific operations, which officially commenced on 1 February 2001.

The great strength of Cluster is its multi-spacecraft nature. The four identical spacecraft allow us to distinguish between spatial and temporal changes in the magnetosphere: if all four spacecraft register the same change in conditions at the same time, then a temporal change that is uniform on at least the scale of the spacecraft separation has been observed, whereas if the different spacecraft observe a change at different times it is more likely that a more localized structure has propagated across the spacecraft. The tetrahedron formation of the four Cluster spacecraft allows the velocity vector of these propagating features to be determined in three dimensions. Another unique capability of Cluster is its ability to measure the spatial gradients of quantities by comparing measurements made by the four spacecraft. These measurements allow us to calculate electric current density from Ampère's law by measuring the curl of the magnetic field – the so-called "curlometer" technique (Dunlop *et al.* 1988). The same technique can be applied to any other vector quantity that is well-measured by each of the four Cluster spacecraft.

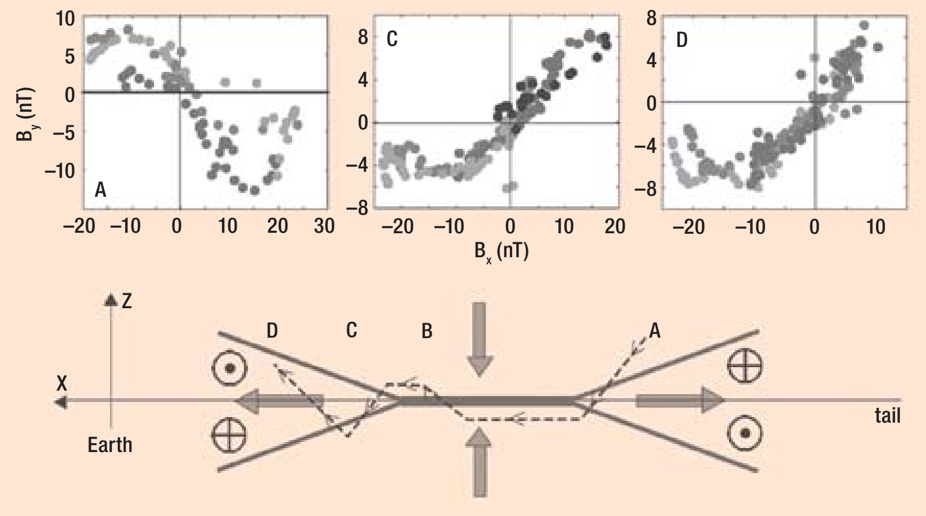
UK involvement

The UK community has been heavily involved with the Cluster mission from the outset. Three of each spacecraft's instruments are UK-built and have UK Principal Investigator institutions. The fluxgate magnetometer (FGM, Imperial College), electron spectrometer (PEACE, Mullard Space Science Laboratory, UCL) and the Digital Wave Processor (DWP, University of Sheffield) are UK-built and the UK has additional hardware involvement in the energetic particle instrument (RAPID), parts of which were built at the Rutherford Appleton Laboratory, which also contributed to PEACE. The Joint Spacecraft Operations Centre, also at RAL, is central to Cluster's payload operations and the UK has also led work on coordinating

Cluster observations of the magnetosphere with ground-based observations of the ionosphere. More than 10 UK research institutes have been actively involved with the Cluster mission.

Orbits and science goals

The Cluster spacecraft were inserted into an elliptical polar orbit with a perigee of 4 R_E (Earth radii) and apogee of 19 R_E. The plane of the orbit is fixed in inertial space so it rotates with respect to the magnetosphere over the course of a year, allowing the spacecraft to pass through and measure different regions of the magnetosphere. The dashed orbits on figure 1 show the location of apogee and perigee in green in the early part of the mission during the "tail season" (northern hemisphere summer) when apogee is on the nightside and in red for the "dayside season" when the apogee is in the solar wind. Over the course of the mission the orbit has evolved, bringing exciting new science opportunities.



2: The quadrupolar Hall magnetic field observed during a Cluster encounter with a reconnection region in the magnetotail, and a schematic of Cluster's trajectory through the reconnection region (dashed lines – Cluster trajectory, solid grey lines – current sheet structure, grey arrows – inflow/outflow, black symbols– Hall magnetic field). (Adapted from Runov *et al.* 2003)

During the dayside season Cluster flies through the magnetospheric cusps – funnel shaped openings that provide an important point of entry for solar wind plasma into the magnetosphere – as well as crossing the high-latitude magnetopause, the current layer that separates the magnetosphere from the solar wind. With a 19 R_E apogee, Cluster also crossed the bow shock upstream of the magnetopause, where the supersonic solar wind is slowed down and diverted around the magnetosphere (which acts as an obstacle to the solar wind's flow).

In flying through these regions, which reveal interesting magnetospheric physics, Cluster has also been able to shed new light on plasma physical processes that occur throughout Nature. The solar wind is increasingly recognized as a turbulent medium (e.g. Chen *et al.* 2010), and only with multi-point measurements can turbulence in space plasmas be fully investigated. Collisionless shocks are abundant in astrophysical plasmas, but the Earth's bow shock is by far the easiest to measure *in situ* and gain detailed observations of upstream and downstream conditions simultaneously, data that again require multi-point measurements.

During the tail season, Cluster's orbit was such that the spacecraft cut through the magnetotail current sheet close to apogee at 19 R_E and as such was ideally placed to measure the products of magnetotail reconnection and, indeed, make the first multi-point measurements of reconnection sites themselves (e.g. Alexeev *et al.* 2005, Eastwood *et al.* 2010). Reconnection plays an integral part in the substorm process, and is responsible for much of the energy transfer from the solar wind to the magnetosphere.

As Cluster's orbit has evolved over time, its unique ability to measure plasmas in three dimensions has been brought to bear on new regions of the magnetosphere. Spacecraft perigees have dropped to only a few thousand kilometres and the orbit has precessed away from the Sun–Earth plane. The spacecraft now pass through the auroral acceleration region (AAR), that region which accelerates electrons up to energies necessary to generate aurorae, and the near-Earth magnetotail, a key region in the substorm cycle in which magnetospheric currents are disrupted and directed into the ionosphere. Cluster now also visits the subsolar magnetopause, where terrestrial and interplanetary magnetic field lines reconnect. Although other spacecraft have studied these regions, Cluster is the first mission to provide the necessary four point measurements to understand them in 3D.

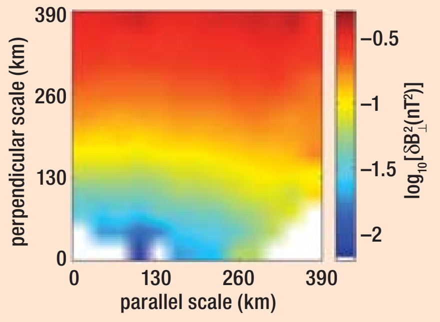
Underpinning all of Cluster's high quality science is a remarkable feat of spacecraft operations and manoeuvring accomplished by the operations team at ESOC. Maintaining Cluster's characteristic tetrahedron formation is itself challenging, but the team has also responded to every request by the Cluster science team to change the spacecraft separation so that phenomena on different scale sizes can be studied. The spacecraft have been placed as far apart as 10 000 km and as close together as 25 km – no mean feat when they have no inter-spacecraft ranging or communication capability, are spinning at 15 rpm and come equipped with 100 m long antennas! This flexibility in the tetrahedron scale size has meant that in the magnetotail, for example, the electron-scale physics of reconnection (Henderson *et al.* 2006) has been studied, as have features on the magnetohydrodynamic (MHD) scale, where the plasma can be treated as a conducting fluid (e.g. Walsh *et al.* 2009).

Below, we discuss some specific scientific highlights based on the past 10 years of Cluster observations.

Magnetic reconnection in the magnetotail

Despite being a well-studied phenomenon, magnetic reconnection is still not properly understood. Multi-point measurements can provide a unique insight into the reconnection process by measuring both the inflow and outflow regions of a reconnection site simultaneously, for example. Electric currents play a key role in reconnection, so Cluster is in a unique position to contribute to our knowledge of this universal physical process. In an early paper, Runov *et al.* (2003) used Cluster to investigate the current sheet and magnetic structure at a reconnection site in the Earth's magnetotail.

Of many different potential reconnection geometries, Runov *et al.* (2003) identified this particular reconnection site as consistent with a Hall reconnection geometry (figure 2, bottom). Hall reconnection geometries are formed because ions and electrons demagnetize (become decoupled from the magnetic field) at different spatial scales. The ions demagnetize at the ion inertial scale (a few hundred km on the magnetotail) while the electrons demagnetize at the electron inertial scale (a few km in the magnetotail). This leads to a structure in which the electron diffusion region, where reconnection itself is thought to occur, is surrounded by the ion diffusion region. The difference in behaviour of ions and electrons in the ion diffusion region sets up a Hall electric field and Hall currents, which have a distinctive quadrupolar magnetic field signature that changes depending on the location of the observation point (Earthward, tailward, north or south of the reconnection site). Runov *et al.* (2003) identified this signature (figure 2, top) in the Cluster data, taking advantage of the multi-point measurements to measure different sectors of the quadrupolar magnetic field simultaneously.



3: Variation of turbulent energy with scale parallel and perpendicular to the local magnetic field in the solar wind between the ion and electron gyroscales (590 km and 10 km respectively). The contours are anisotropic, indicating that the eddies are elongated in the field parallel direction. (Adapted from Chen *et al.* 2010)

Furthermore, Runov *et al.* used the unique capabilities of Cluster to observe the predicted bifurcated current sheets at the edges of the reconnection outflow regions, further confirming the Hall reconnection geometry. Subsequent work (Eastwood *et al.* 2010) has shown that Hall reconnection was observed in more than half of the reconnection site encounters made by Cluster in the magnetotail.

Reconnection is driven by the reconnection electric field, which, in the magnetotail, points across the tail in an east–west direction. Electric fields in space plasmas are governed by the generalized Ohm's law:

$$E = -v_i \times B + \frac{j \times B}{en_e} - \frac{\nabla.P_e}{en_e} - \frac{m_e}{e}\frac{dv_e}{dt} + \eta j \qquad (1)$$

Successive terms in this equation are important at increasingly small scale sizes. The first term on the right-hand side of the equation is the ideal MHD term, which describes "convection" electric fields supported by plasma frozen onto magnetic field lines moving the magnetic field around. This term operates on the largest scales and can be well measured by a single spacecraft. The second term is the Hall term, responsible for the Hall magnetic fields described above. This term operates when the ions have been decoupled from the magnetic field while the electrons are still magnetized at the ion inertial scale; at smaller scales still it is only the electrons that can support the electric field. The first electron term describes electric fields supported by the divergence of the electron pressure tensor. This quantity was measured for the first time with Cluster and PEACE by Henderson *et al.* (2006) using the same "curlometer" technique that is used in calculating electric current density. Henderson *et al.* found that the electric field supported by the divergence of the electron pressure is indeed significant in reconnection and points in the opposite direction to the Hall electric field, consistent with the predictions of simulations.

Anisotropic plasma turbulence in the solar wind

For a few months each year, the orbit of the Cluster spacecraft reaches past the Earth's bow shock, allowing multi-spacecraft investigations of the free solar wind and its turbulent properties. Understanding plasma turbulence is important, not only as a fundamental physics question in itself, but also in its application to other areas of physics, such as cosmic-ray propagation, magnetic reconnection and fusion power.

Turbulence can be thought of as the process by which energy that is injected into a fluid at large scales cascades to smaller scales where it can be dissipated. One of the key differences between turbulence in plasmas and turbulence in neutral fluids is the influence of the magnetic field, which introduces a special direction, allowing the turbulence to be anisotropic.

There are competing theories of what happens to the solar wind cascade when it reaches the ion gyroscale (the scale at which ions gyrate around the magnetic field lines). Popular suggestions include damping of the fluctuations or a further cascade of energy, for example as whistler or kinetic Alfvén waves.

In 2002, for the solar wind section of the orbit, the average separation of the Cluster spacecraft was about 100 km. This, combined with the high-resolution multi-point measurements, enabled Chen *et al.* (2010) to measure the anisotropy of solar wind turbulence between the ion and electron gyroscales. They did this by combining data from the two magnetic field instruments (FGM and STAFF) on each spacecraft. They could then measure how the fluctuations between spacecraft varied with scale in a variety of directions relative to the local magnetic field. The use of the multi-point Cluster measurements enabled many directions to be probed simultaneously.

Figure 3 shows the energy in the magnetic fluctuations as a function of scale, parallel and perpendicular to the magnetic field. It can be seen that the energy contours are elongated in the direction of the magnetic field, rather than being circular. Because the contours correspond to the shapes of the turbulent eddies, this tells us that between the ion and electron gyroscales, the eddies are anisotropic: elongated in the field parallel direction. This is an important prerequisite for some of the theories that attempt to explain the behaviour in this range.

To make detailed comparisons to the theoretical predictions, Chen *et al.* (2010) also measured the energy scaling in different directions to the magnetic field. The scaling of the field perpendicular component was found to be anisotropic and close to the predictions of a whistler or kinetic Alfvén wave cascade in critical balance (i.e. the wave timescale balancing the nonlinear eddy timescale). There has been previous evidence for critical balance at large scales so this new result below the ion gyroscale suggests that it may be a universal property of turbulent systems. The scaling of the parallel component, however, did not agree with the theoretical expectations. Cluster will continue to challenge theories and make new discoveries in this area in the years to come.

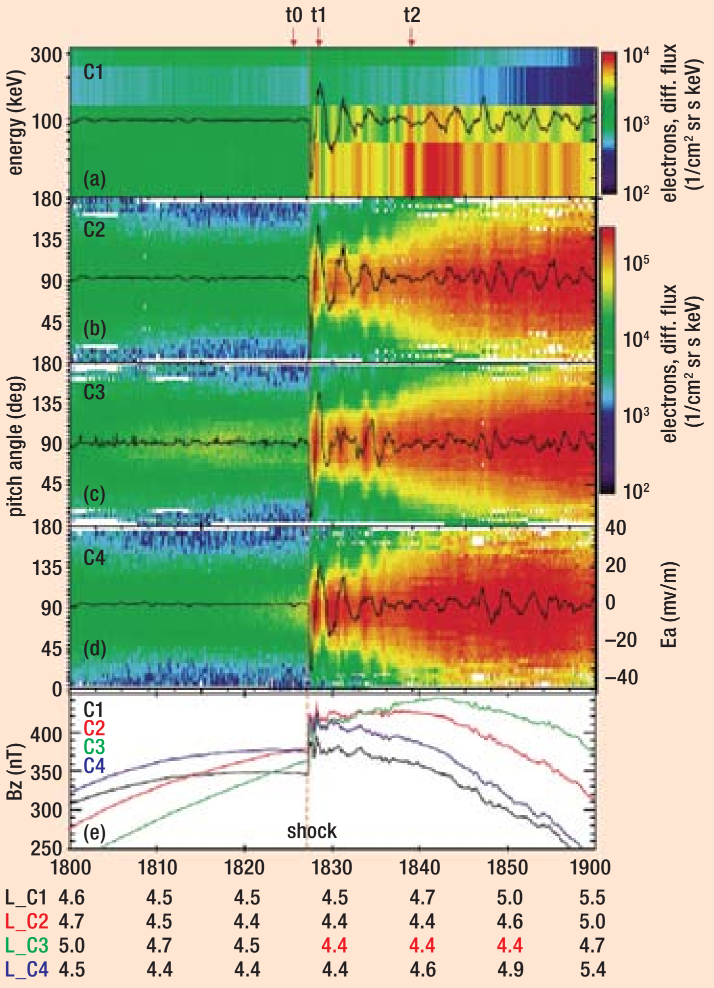
Multi-scale shock observations

When an obstacle is immersed in a supersonic flow a shock wave is formed upstream of the obstacle, for example the shock formed by a supersonic aircraft. In ordinary gases or liquids shocks are formed due to collisions between particles. However, the rarefied nature of space plasma implies that the mean free path of the particles is extremely large and the plasma is essentially collisionless. In collisionless plasmas the spatial scales associated with shocks are much shorter than the mean free path length so electromagnetic fields and waves play the role of collisions in the formation of a collisionless shock. Collisionless shocks are ubiquitous in the universe. They can be found mediating the interaction between planets and ordinary stars' stellar winds, in supernova remnants, space jets and gamma-ray bursts. These shocks are efficient accelerators of particles, capable of accelerating cosmic-ray particles to energies beyond 10^{20} eV.

In situ, multi-spacecraft observations provide the best way to examine collisionless shocks in detail and are only available for the terrestrial bow shock. Observations made by Cluster have underpinned major breakthroughs in the understanding of the physical processes responsible for the formation of the main shock transition for high Mach number quasiperpendicular shocks, and led to the clarification of some important questions regarding the physics of such strong, collisionless shocks. The multi-point measurements at the shock front enable the separation between temporal and spatial changes and study of the spatial scales of the shock front. The spatial scales are closely related to the type of physical process that is responsible for shock formation.

A Cluster-based statistical study of shock scales (Lobzin *et al.* 2007) has unambiguously shown that as the magnetic field and electrostatic potential increase, the characteristic scales of the shock transition are smaller than the ion inertial length and correspond to several electron skin depths. The precursor wave train, observed upstream of the shock, was shown to be generated by the shock front itself and is not the result of any instability due to particle motion. This leads to the conclusion that the major transition, so called ramp region, is determined even for supercritical shocks by the

4: The energetic electron response to ULF wave activity is revealed by the upper four panels. (a): The energetic electron spectrum from the RAPID-IES instrument on Cluster 1. (b)–(d): The electron pitch angle distribution at energies around 80 keV from Cluster 2, 3 and 4, with the azimuthal electric field overlaid as a black line. (e): The southward component of the magnetic field from the FGM instrument on all four Cluster spacecraft. Shock impact is marked by a red dashed line. (Adapted from Zong *et al.* 2009)



interaction of nonlinear and dispersive effects.

Theoretical analysis shows that when the velocity of a shocked supersonic flow becomes larger than maximum velocity for a whistler precursor to be established, the shock becomes unstable, collapses and a new shock is formed, a process known as reformation. Cluster was able to observe several characteristic features of this process: the presence of two comparable maxima of the magnetic field corresponding to "old" and "new" overshoot regions, typical rotational features of the magnetic field around these maxima that indicate their similarity to nonlinear whistler waves, and, most importantly, oscillations of the number of reflected ions with the characteristic period comparable to the typical ion gyro-period. These observations and statistical determination of characteristic scales of the shock transition are the keys to understanding of the major physical processes determining shock front structure and the transition from stationary to nonstationary shock dynamics.

Interplanetary shocks and killer electrons

The interaction of interplanetary shocks with the Earth's magnetic field can result in the production of so-called "killer electrons" – highly energetic electrons trapped in the Earth's outer radiation belt. Their name derives from the fact that, due to their energy, they penetrate the shielding of satellites and can cause irreparable damage to vital onboard electronic components. The mechanism by which these killer electrons achieve energies of the order of hundreds of keV has been a topic of significant debate for many years; among the candidates, energization by very-low frequency (VLF) waves has been widely considered as the principal process that spawns these potentially damaging particles.

Recent work by Zong *et al.* (2009) using data from the quartet of Cluster spacecraft has revealed that an alternative two-stage mechanism involving ultra-low frequency (ULF) waves appears a much more likely candidate for the generation of these shock-related killer electrons. This new insight was gleaned from observations of an Earth-impacting interplanetary shock, generated by a coronal mass ejection (CME), which took place on 7 November 2004. At shock passage, the Cluster constellation was located in the inner magnetosphere, near the plasmasphere boundary, and was able to make detailed *in situ* observations of the particles and fields of the shock-associated phenomena. Figure 4, taken from Zong *et al.* (2009), presents Cluster/RAPID observations showing an enhancement of energetic electron fluxes in the radiation belt that was initiated almost immediately after the shock arrival; the close correlation between the wave-like oscillations in the shock-induced azimuthal electric field and the electron fluxes suggests that the shock-induced ULF waves had a strong effect on the electrons. When viewed in conjunction with measurements from a widely distributed flotilla of international spacecraft, it has been possible to gain a global perspective of the processes giving rise to the generation of killer electrons. The postulated mechanism comprises two contributing parts: an initial acceleration due to the strong shock-related magnetic field compression, followed by a drift resonant acceleration by poloidal and toroidal ULF waves excited at different L-shells by the passage of the interplanetary shock.

The current rising phase of solar activity will no doubt result in many more interplanetary shocks, meaning that such insights into the physical processes that give rise to these hazardous killer electrons may prove crucial to our increasing reliance on space-based communications.

Summary and outlook

Over the past 10 years, Cluster has provided a unique insight into the complex interaction between the solar wind and the magnetosphere. It has greatly advanced our understanding of the fundamental plasma physics that governs that interaction and is important throughout the universe. The mission has been approved to continue until December 2012 exploring the auroral acceleration region, the magnetopause and near-Earth magnetotail. Even after a highly successful operational phase ends (to date there have been more than 1200 Cluster-related publications in refereed journals), the Cluster Active Archive, a public repository of high-quality data which already has more than 1000 registered users, means that Cluster will continue to be a fantastic resource for physicists in the years to come. ●

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References

Alexeev I V *et al.* 2005 *Geophys. Res. Lett.* **32** L03101.
Chen C H K *et al.* 2010 *Phys. Rev. Lett.* **104** 255002.
Dunlop M W *et al.* 1988 *Adv. Space Res.* **8** 273–277.
Eastwood J P *et al.* 2010 *J. Geophys. Res.* **115** A08215.
Henderson P D *et al.* 2006 *Geophys. Res. Lett.* **33** L22106.
Lobzin V V *et al.* 2007 *Geophys. Res. Lett.* **34** L05107.
Runov A *et al.* 2003 *Geophys. Res. Lett.* **30** 11, 1579.
Walsh A P *et al.* 2009 *Ann. Geophys* **27** 2, 725–743.
Zong Q-G *et al.* 2009 *J. Geophys. Res.* **114** A10204.