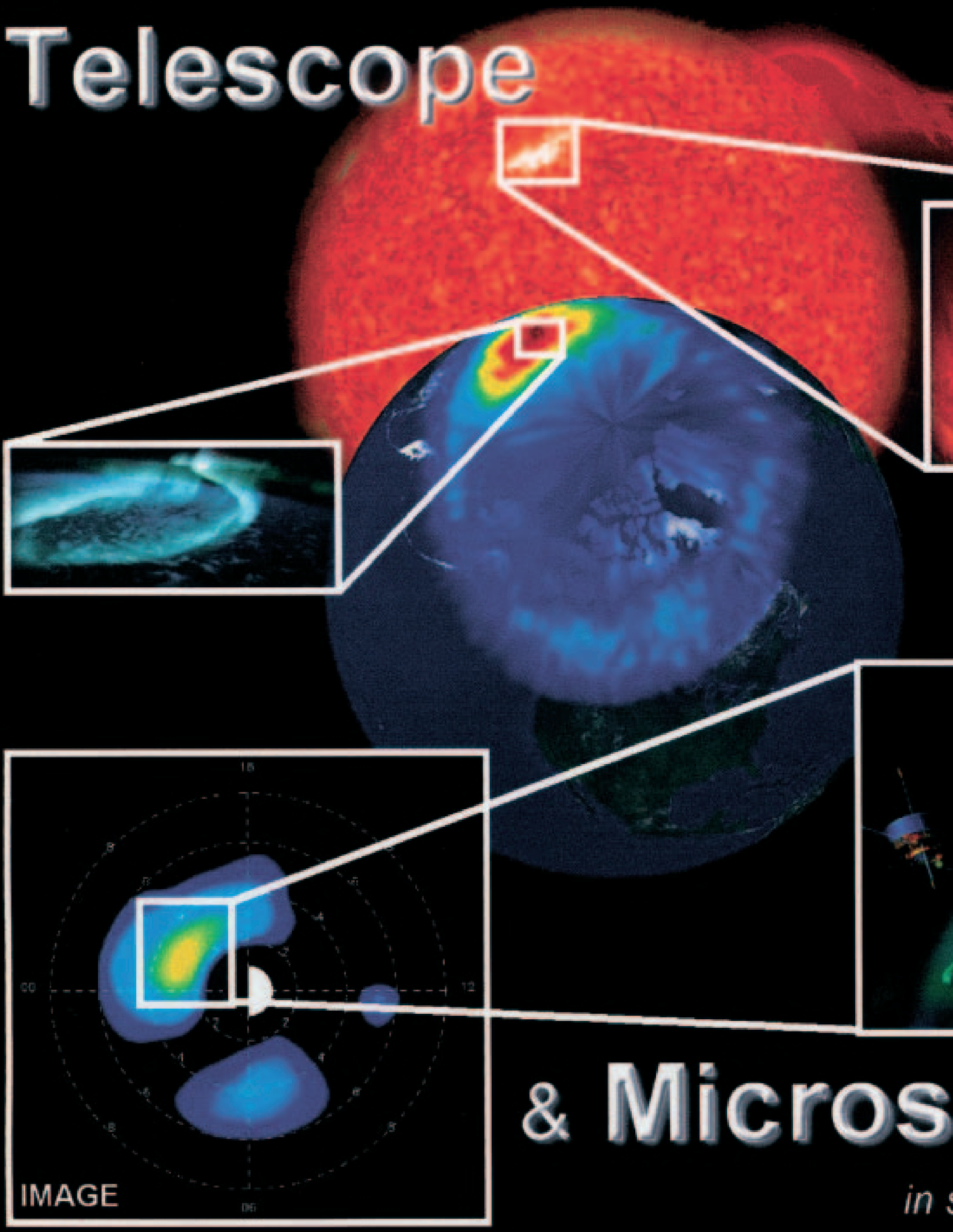
Telescope



& Micros

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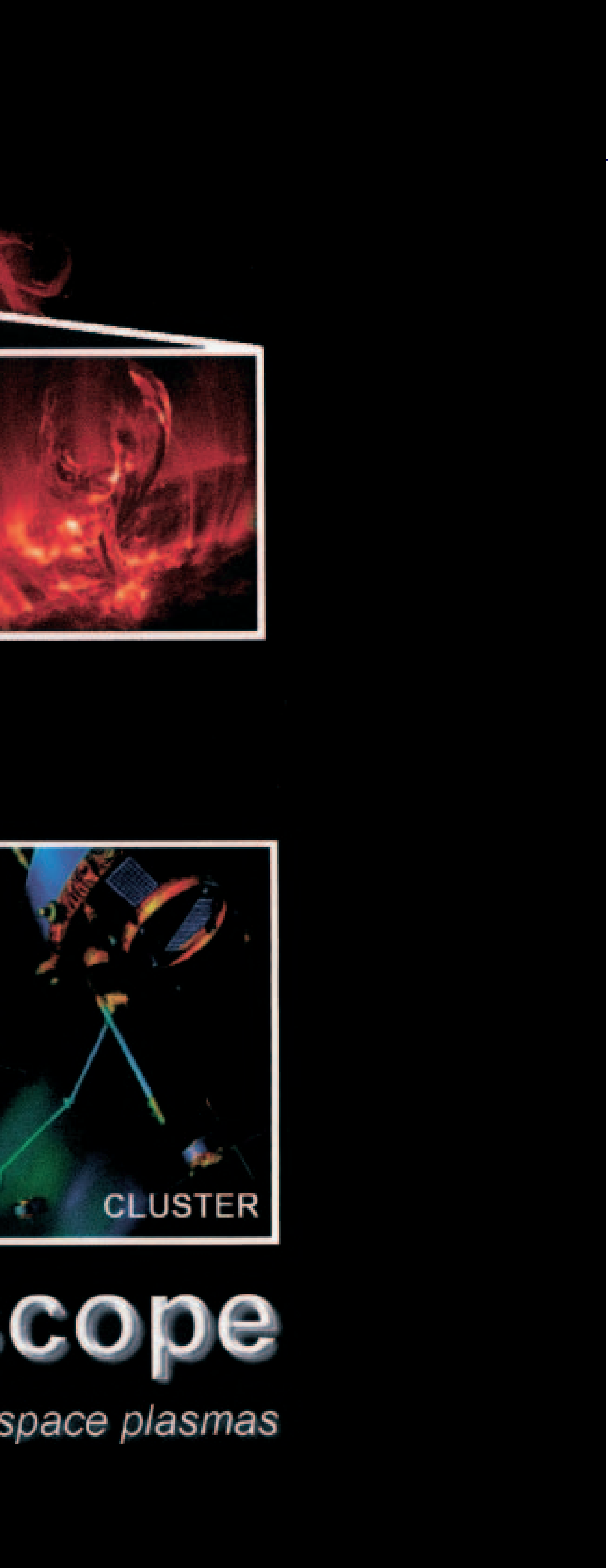
Courtesy of AGU/D.N. Baker, Univ. of Colorado



Cluster

– A microscope and a telescope for studying space plasmas

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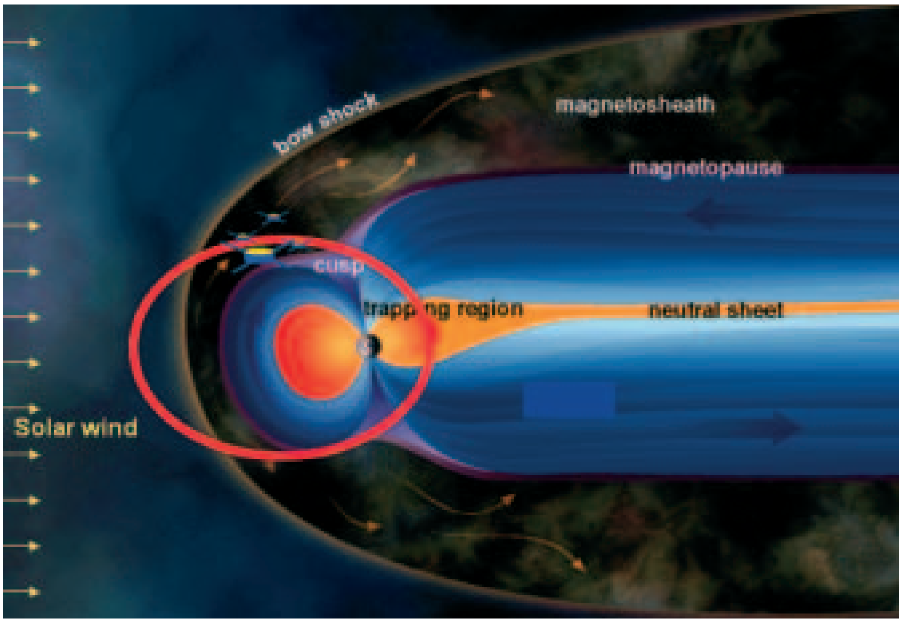
The four-satellite Cluster mission serves as both a 'microscope' and a 'telescope' for magnetospheric scientists. Using its suite of state-of-the-art instruments, it is providing a close-up view of complex small-scale physical processes occurring around the Earth. These processes are often reflections of other, sometimes violent processes that are taking place much further away from our spacecraft, which means that Cluster also serves as a 'telescope' for observing those more distant processes.

Introduction

We have been investigating the Earth's magnetosphere with space probes for nearly 50 years, allowing us to draw a general picture of the space environment that surrounds our planet. The origin of the magnetosphere lies in the Earth's internal magnetic dynamo, and without the solar wind the picture would be quite simple. However, with the solar wind – a magnetised supersonic stream of electrons and ions continuously escaping from the Sun, which interacts with the Earth's magnetic field – the picture becomes highly complex. Under the solar wind's influence, the shape of the Earth's natural magnetic field lines is transformed from a dipolar form into a large tail-like structure which is called 'the magnetosphere' (see adjacent sketch).

At the same time as the solar wind is distorting the magnetosphere's outer boundaries, the ultraviolet and X-rays emanating from the Sun are ionising the Earth's upper atmosphere, making it highly electrically conductive. This region, known as 'the ionosphere', is coupled to the magnetosphere via the Earth's magnetic field lines. Above 1000 km altitude from the ground, the neutral and plasma particle densities are sufficiently low for the medium to be fully conductive. At higher altitudes in the magnetosphere, the resistance in the plasma can suddenly increase in certain localised regions, giving rise to some of the most fascinating processes that occur in space.



A sketch of the Earth's magnetosphere; the Sun is to the left. The distance of the magnetopause on the dayside is approximately 10 R_e (where R_e is the Earth's radius, equal to 6370 km), while the bow shock is at 14 R_e. The long tail of the magnetosphere in the nightside can continue for more than 100 R_e. Cluster orbits the Earth at between 4 and 20 R_e distance, during which the four satellites encounter most of the key magnetospheric regions. The orbit shown in red is for February-March, and half a year later the apogee is in the magnetotail

The Sun-Earth Connection

Many details of how our terrestrial environment responds to variations in solar radiation and solar wind, and their implications for humans and man-made technologies in space and on the ground, remain unresolved. Understanding and predicting such conditions in space requires multi-point measurements at critical locations in the magnetosphere and solar wind.

Basically all of the unresolved Sun-Earth connection issues can be grouped under three fundamental questions:

(i) How and why does the Sun vary?
(ii) How does the Earth's environment respond to such variations?
(iii) What are the consequences for humanity?

The Cluster mission objectives belong primarily to the second category.

The four Cluster satellites have been orbiting the Earth since August 2000, and their observations have improved and often even fundamentally changed our previous understanding of near-Earth space. The primary aim of the mission is to characterise and model the near-Earth plasma regions and boundaries, as well as to understand the physical processes taking place there. Cluster cannot solve all of the mysteries of the Sun-Earth connection, but it is providing us with the first real 3-D measurements in space that allow us to separate the temporal and spatial features. Some of the key issues are related to the existence and characteristics of magnetic reconnection, plasma turbulence, and charged-particle acceleration. These are the main processes that control the transfer of energy, momentum and particles from one region of space to another – for instance, between the solar wind and the magnetosphere, or between the magnetosphere and the Earth's atmosphere.

Electric Currents

One of the most difficult measurements in space is the determination of the electric currents that extend over vast distances in three dimensions. The magnitudes of the currents are very large, typically in the range of 1-10 million Amperes, but as the cross-sections of the current systems are also large, Cluster needs to be able to detect very weak current densities, typically not more than a few 100 nano Amperes per square metre.

In principle, the currents can be estimated by calculating the fluxes of electrons and ions, but in fact the only reliable method in space is to use Ampere's Law. This technique is based on accurate magnetic-field measurements at four points, from which one can calculate the electric current crossing the Cluster constellation. The Cluster spacecraft carry very stable and sensitive magnetometers that can provide the required measurements. Unfortunately, this does not always work in practice, either because the physics turns out to be more complex than described by Ampere's Law, or because the separations between the four spacecraft are not optimal with respect to the size of the current region being studied. By varying the spacecraft separations during the mission, we have been able to determine the strengths and directions of the electric currents in many regions, and these data are of fundamental importance for magnetospheric modelling.

Electric Fields

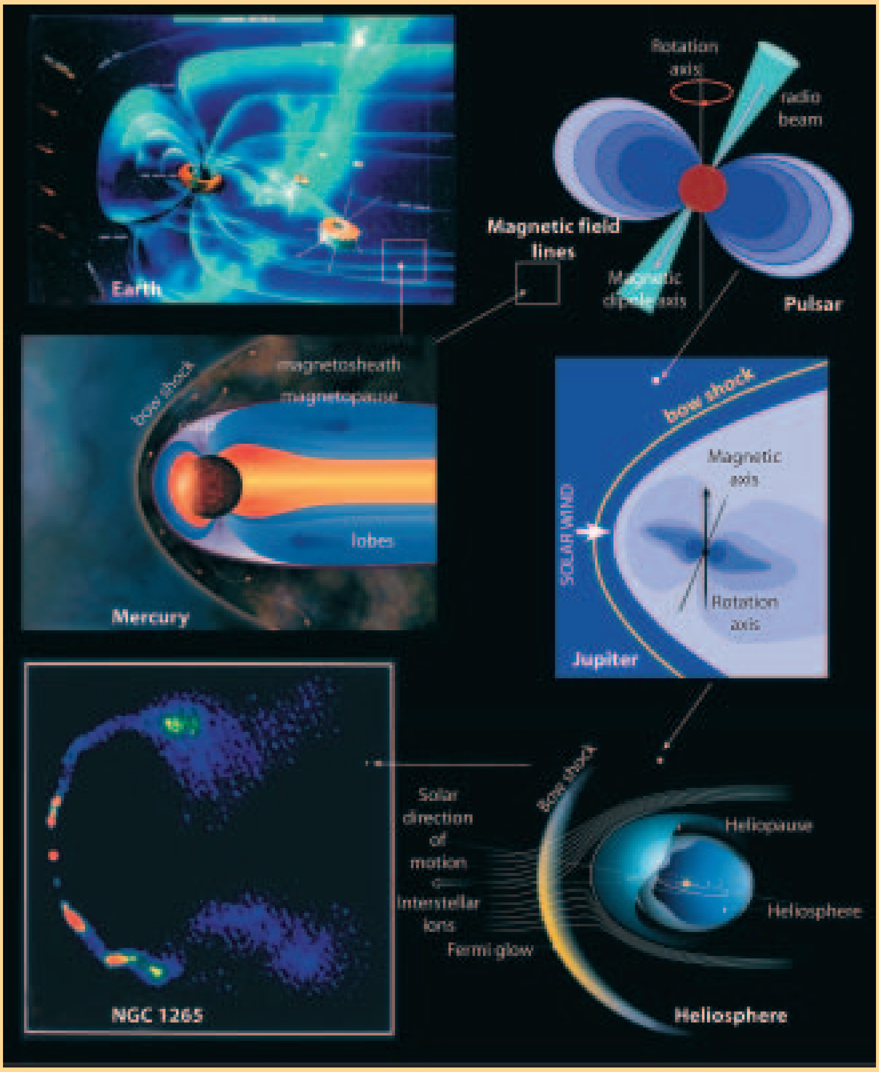
Another difficult task is the measurement of electric fields, which are needed to understand how the charged particles flow

Comparative Magnetospheres

By understanding how the Earth's magnetosphere functions and how it is driven by the energy from the solar wind, we can also better model other magnetosphere-like systems that are common not only in our own Solar System but throughout the Universe in stars, galaxies, etc. More than 99% of material in space appears as plasma, or an electrically charged gaseous medium. There are a multitude of complex physical processes occurring in such a medium, and our geospace is the only place where we can monitor and investigate them in-situ. The observational problem, however, is that the processes occur in spatially limited regions, their locations are constantly moving, and they occur for only short periods. One therefore has to be in the right place at the right time, which is very difficult, and so one needs to collect large data sets over various time and spatial scales in many locations in order to fully understand, model and predict the occurrence of the processes.

Having some knowledge of how the Earth's magnetosphere behaves, it is fascinating to visit other magnetospheres to observe similarities or dissimilarities between them and the Earth. Venus and Mars (and perhaps Pluto) are the only planets in the Solar System that have no magnetosphere due to the lack of an internal magnetic dipole. In such cases, the solar wind interacts directly with the atmosphere. Single space probes have been used to get a view of the magnetospheres of the other planets, and the interpretation of such data is made much easier by observing the processes in detail first at the Earth, especially using multiple satellites like Cluster.

The Sun also has its own magnetosphere, called the 'heliosphere'. The solar wind expands to very large distances of the order of 100–1000 AU in the Solar System (1 AU is the distance between the Sun and the Earth), and this expansion is eventually stopped by the pressure of the interstellar plasma. Currently a few satellites launched in the early 1970's are approaching the edge of the heliosphere and will soon be able to study the coupling between it and the interstellar wind, which is somewhat similar to the interaction between the Earth's magnetosphere and the solar wind.

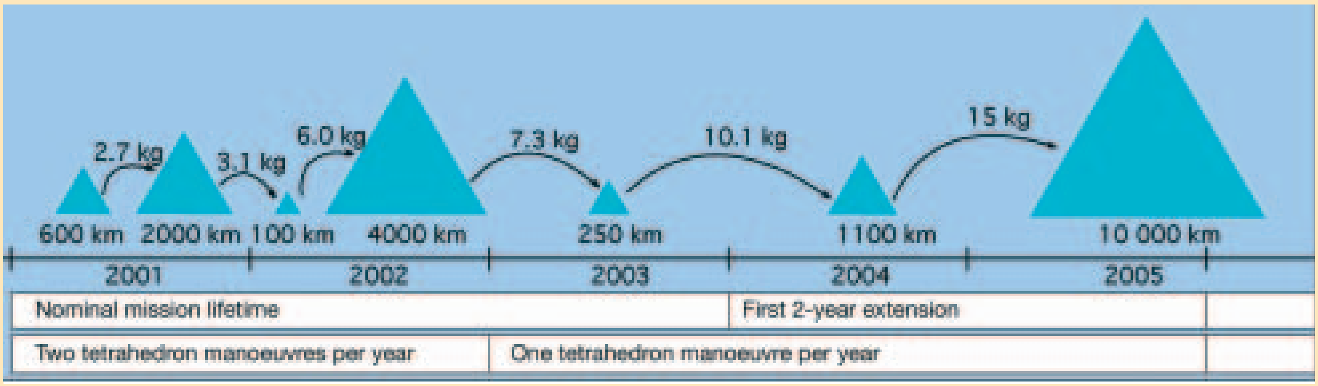


Magnetospheres, or magnetized plasma regions, are common in our Universe. These examples show simple models for Mercury, Earth, pulsar, and Jupiter, whose sizes are within a few orders of magnitude. However, similar systems also occur on larger scales, such as the heliosphere formed by the solar magnetic field as well as the galaxy NGC 1265 (courtesy of C. O'Dea & F. Owen, NRAO/AUI).

The Cluster Mission and Its Instruments

Cluster is the first space physics mission to be made up of several identical spacecraft. Each of them carries a complete suite of instruments to measure particles, magnetic fields, electric fields, and electromagnetic waves. In addition a unique spacecraft potential-control instrument (which keeps the electrical potential of the spacecraft themselves at typically 5-7 Volts) allows the scientists to monitor low-energy electrons and ions in the plasma, which would otherwise not be possible.

In any region of the magnetosphere the spatial scales (i.e. the distances over which the plasma characteristics change) appear to be highly variable. This complexity is increased by varying time scales, which makes sound interpretations highly challenging. Having Cluster measurements at four different points is fundamentally important here, although ideally many more than four satellites are needed to measure different scales simultaneously. So, having only four satellites, it is essential to change their separations regularly, because the most important scale length for one region can be completely wrong for another. For changing the side lengths of the tetrahedron-shaped formation in which the Cluster satellites fly, each satellite originally had 63 kg of fuel onboard to perform the necessary manoeuvres; at the moment, approximately half of that fuel is left. A change of constellation from one tetrahedron to another requires a complicated set of over 40 individual manoeuvres that last approximately 6 weeks. During the first two years of the mission, two constellation changes were performed annually. Since 2003, only one constellation change per year has been made.

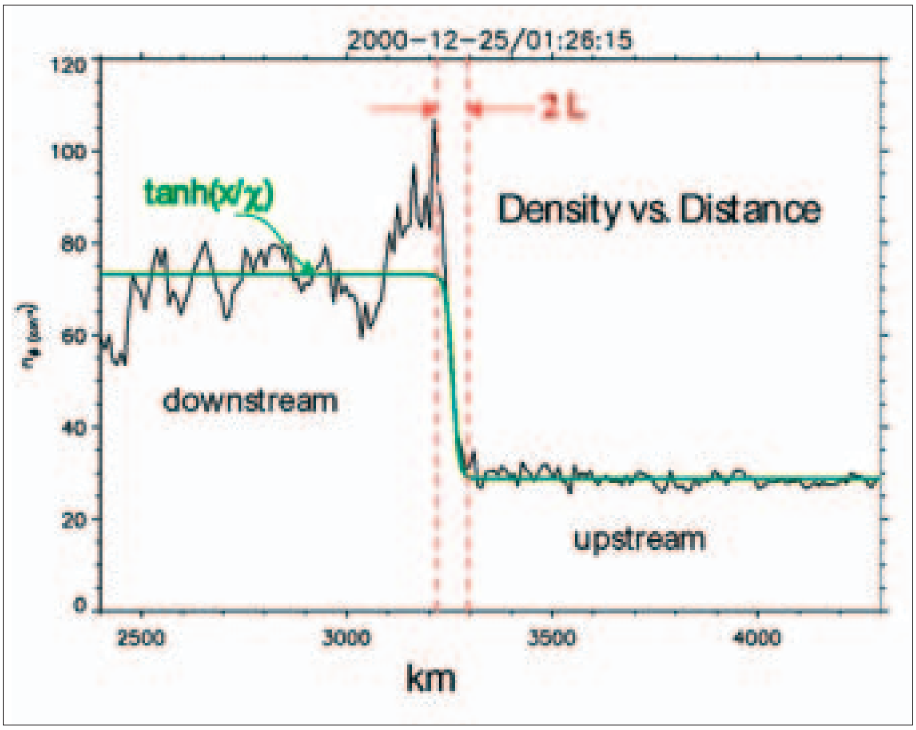


The triangles show schematically the size of separation distances of the four Cluster satellites, with the actual separation distances in kilometres given below the triangles. The masses show how much fuel was consumed during the manoeuvres conducted for each new tetrahedron constellation (Courtesy of D. Sieg, ESOC)

The Eleven Instruments on Each of the Four Cluster Spacecraft

Instrument		**Principal Investigator**
ASPOC	Spacecraft potential control	K. Torkar (IWF, A)
CIS	Ion composition, $0<E<40$ keV	H. Rème (CESR, F)
DWP	Wave processor and particle correlator	H. Alleyne (Univ. Sheffield, UK)
EDI	Plasma drift velocity	G. Paschmann (MPE, D)
EFW	Electric field and waves	M. André (IRFU, S)
FGM	Magnetometer	A. Balogh (IC, UK)
PEACE	Electrons, $0<E<30$ keV	A. Fazakerley (MSSL, UK)
RAPID	High-energy electrons and ions, $20<E_e<400$ keV, $10<E_i<1500$ keV	P. Daly (MPAe, D)
STAFF	Magnetic and electric fluctuations	N. Cornilleau (CETP, F)
WBD	Wideband detector	D. Gurnett (Iowa, USA)
WHISPER	Electron density and waves	P. Décréau (LPCE, F)

within the magnetosphere and how they are accelerated. Although electric potential differences across many regions can be of the order of 10 - 100 kilovolts, the actual electric fields appear to be small – just 0.1-10 millivolts – as the regions are very wide. Their detection therefore requires highly sophisticated instruments. Each of the Cluster satellites carry two state-of-art instruments that can monitor such weak fields. One measures potential differences between electric sensors located at the tips of 44 metre-long booms, and each satellite carries four such booms. The other instrument measures the drift of a weak beam of 1 keV electrons emitted by the instrument, from which the electric fields can be determined.



Density transition from downstream to upstream across the Earth's bow shock in the solar wind. The green line is a theoretical fit; the red vertical lines show the thickness of the shock (Courtesy of S. Bale, University of California at Berkeley)

Scientific Highlights

Bow shock

Shocks are a common and important phenomenon in the Universe as they accelerate particles to very high speeds. Close to the Earth, shocks appear, for instance, at the fronts of massive coronal mass ejections released by the Sun. These events cause magnetic storms at the Earth and produce plenty of high-energy particles, which are eventually trapped in the radiation belts that surround it. At a distance of approximately 14 Earth radii from our planet towards the Sun, there is a permanent shock region, known as the 'bow shock'. It is formed by the interaction of the Earth's magnetosphere with the streaming supersonic solar wind. At the bow shock, the solar wind is rapidly decelerated and the interplanetary magnetic field is compressed.

For a detailed understanding of the physics of shocks, one must have measurements on both sides of the shock as well as in the shock itself. The Cluster mission is therefore helping us to model shocks not only in front of the Earth's magnetosphere, but also elsewhere in the Universe. The position of the bow shock is subject to a continuous back-and-forth motion due to pressure variations in the solar wind, which helps Cluster in its task because it means that the spacecraft usually make several crossings once they approach the shock. As the four satellites are far apart, one gets simultaneous observations from all sides of the shock.

Cluster has been able to measure the speed and thickness of the Earth's bow shock for the first time. Based on about 100 bow-shock crossings, it has been possible to show that the shock front's thickness is proportional to the gyro-radius of solar wind ions*. At the shock, the electrons and ions get separated, setting up strong electric currents. Again for the first time, Cluster has observed such currents, which are typically of the order of one million Amperes.

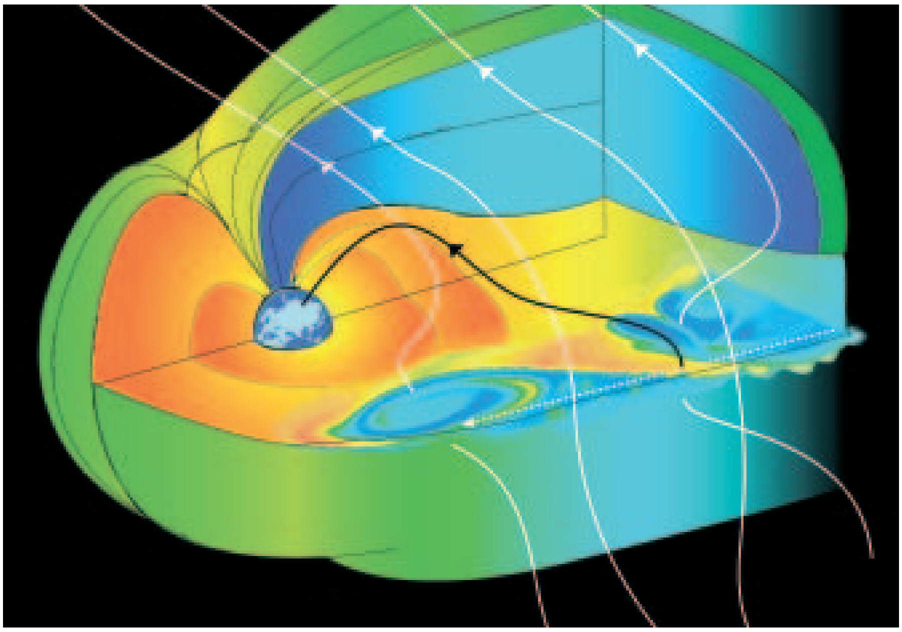
Cusps

The polar cusps are the two magnetic 'funnels' over the Earth's north and south magnetic poles, where particles from the solar wind actually penetrate the magnetosphere and reach the Earth's atmosphere. Cluster has observed so-called 'magnetic reconnection' in the neighbourhood of a polar cusp.

Magnetic reconnection occurs when two regions of oppositely directed magnetic fields interact and eventually become interconnected. It is a fundamental process in space and astrophysical plasmas through which plasmas of different origins are able to mix and become accelerated into energetic jets. It allows the transfer of charged particles between two different magnetised regions of space, for instance the solar wind and the Earth's magnetosphere. This process accelerates ions in both directions, so that the precipitating population in the cusp produces a 'bright spot' near noon, which can be observed on Earth at high latitudes (66 - 70 deg) in the form of the spectacular 'northern lights'.

On 18 March 2002, NASA's IMAGE spacecraft detected such a 'bright spot' in the northern polar cusp at the same time as Cluster detected the typical characteristics of polar-cusp reconnection. This was the first time that the reconnection process had been observed in-situ together with its effect on the Earth's ionosphere and atmosphere.

** Charged particles gyrate about magnetic field lines with a period that depends on the size of the magnetic field and the mass of the particle. The radius of the gyro motion depends on the gyro period and velocity of the gyrating particle.*



In this three-dimensional view of the Earth's magnetosphere, the curly features sketched on the boundary layer are the Kelvin-Helmholtz vortices discovered by Cluster. They originate where two adjacent flows travel with different speeds. The arrows show the direction of the magnetic field (Courtesy of H. Hasegawa, Dartmouth College)

Kelvin-Helmholtz waves

When two adjacent media flow at different speeds, waves build up at their interface and a phenomenon known as a 'Kelvin-Helmholtz instability' occurs. The wind blowing across the surface of the ocean causes waves due to this instability. Similarly in space, waves appear at the interface between two plasma media when the difference in velocity is large enough, for instance at the Earth's magnetopause.

The Cluster satellites have observed Kelvin-Helmholtz waves several times, but just recently they have discovered vortices in the Earth's magnetosphere caused by the instability. Normally, Kelvin-Helmholtz waves only distort the boundary and cannot cause particles to be transported across it. It has been suggested that the vortices let solar-wind particles enter the magnetosphere. Cluster's discovery strengthens the likelihood of this scenario, but does not yet show the precise mechanism. This is an exciting result because, with the interplanetary magnetic field and the Earth's magnetic field being aligned, the magnetopause is presently assumed to be an impenetrable barrier to the flow of solar wind, which is merely diverted around the magnetopause.

Reconnection in the magnetotail

The tail of the magnetosphere, called 'the magnetotail', appears to be an explosive region due magnetic reconnection and a source of highly energetic particles, some of which can have energies of more than 10 MeV*. There are many unsolved mysteries associated with the reconnection process in the tail, such as the actual trigger for the process and the formation of a thin current sheet that Cluster has observed to occur before the reconnection can take place.

The four Cluster spacecraft have surrounded the reconnection region in the central magnetotail several times, exploring the core region where ions and electrons get decoupled. A change of magnetic curvature across the reconnection site has also been detected. In addition, strong electric fields are observed near the site, which could explain the particle acceleration usually observed at greater distances from the site.

One of the precursor processes to reconnection is the thinning of the current sheet in the centre of the tail where the reconnection process is later going to take place. Recently, Cluster made its first measurements of such an event, showing that just before reconnection occurred the maximum current intensity was about 30 times its usual value, and that the half-thickness of the current sheet was only about 300 km, instead of the usual few 1000 km. When the current sheet becomes this thin, the motion of the ions is no longer governed by the magnetic field, and therefore they cannot be described as a fluid. The electrons, however, do still behave as a fluid and are believed to carry the main current in such a situation.

Once the reconnection process starts in the middle of the tail, a large number of charged particles are energized and sent towards the Earth. Magnetic field lines guide them to precipitate into the polar atmospheres, causing intense auroral displays. At the same time, a huge volume of tail plasma appears as an isolated 'plasmoid', which is ejected down the tail from the Earth into the solar wind. Cluster has already observed the formation of such plasmoids several times.

The consequences of reconnection are also observed in the Sun's atmosphere. Solar flares, caused by reconnection, are the most energetic explosions in the Solar System. Energetic particles accelerated in the flares escape into interplanetary space and pose a danger to astronauts, the crews of high-flying aircraft, and electronic instruments operated in space. Similar energy-release processes take place in other cosmic objects, such as stars, pulsars, black holes, quasars, and galactic accretion discs.

Remote sensing and interferometry

The magnetosphere is a strong source of a wide range of electromagnetic emissions. Some of the waves are trapped within the Earth's magnetosphere, but some, such as the non-thermal continuum radiation (NTC) and auroral kilometric radiation (AKR), can travel large distances. There are many unsolved issues concerning the generation of such waves and Cluster is also playing an important role here. The radio waves

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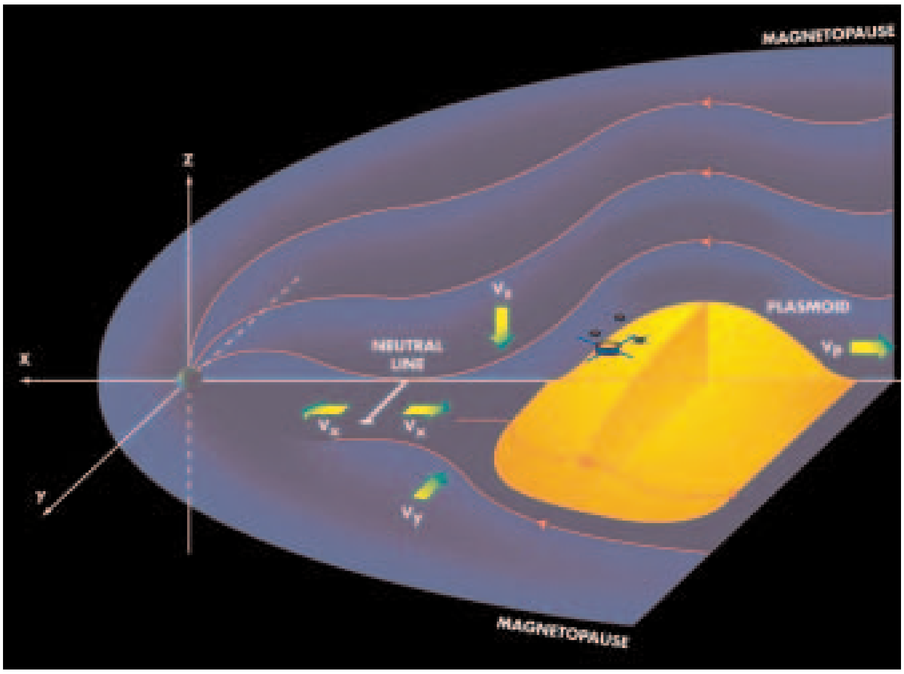
** 1 electron volt (eV) corresponds to a temperature of approximately 10 000 Kelvin. In the Sun's atmosphere, the particles have energies of 10 - 100 eV. In the Earth's upper atmosphere particle energies are of the order of 0.1 eV. In the magnetosphere, typical energies for protons and electrons are in the range 0.1 - 10 keV. In the radiation belts, some particles are relativistic, so that the electron energies are 0.1 - 1 MeV and higher and the proton energies 10 - 100 MeV and higher.*



Magnetic reconnection occurs frequently in the magnetotail, creating a magnetically neutral region called the neutral line. As a result, on over-stretched field lines earthward of the neutral line, a large amount of plasma is accelerated towards the Earth, causing fantastic auroral displays in the polar regions. Simultaneously, on the other side of the neutral line a vast plasmoid is ejected down the tail into the solar wind (Courtesy of J. Slavin, NASA Goddard Space Flight Center)

recorded by Cluster and other satellites in the Solar System have been converted into sound waves and can be played at http://www-pw.physics.uiowa.edu/space-audio/.

The AKR (20kHz – 2MHz) is the strongest signal generated around the Earth and can easily be detected from very large distances, for instance by an alien society. The Earth's magnetosphere is the only place where we can study it in detail and Cluster's orbit is ideally placed to look for its source. The wavelength of AKR is of the order of a kilometre, hence the name. The power of emission is of the order of a billion Watts, which greatly exceeds the power of any radio station. However, the waves cannot propagate through the Earth's ionosphere and are therefore not detectable on the ground, and hence cannot disturb our radio transmissions.

By using simultaneous four-point Cluster wave measurements, the exact location of AKR's source has been identified. Similar emissions are detected at all magnetised bodies in the Solar System, such as Jupiter and Saturn where they appear with different wavelengths. For instance, Jupiter's emission is called Jovian hectometric radiation. Measurements of such emissions can also be used to detect extra-solar planets.

Future Plans

Currently the Cluster mission is in a first extension phase that will end in December 2005. The spacecraft are still working perfectly and their payloads are in good health, with 41 of the total of 44 instruments still working, and expected to continue to do so until 2010. The science community is therefore looking forward to the possibility of a second extension covering the years 2005–2009, for which there is substantial scientific justification, not least to: (i) achieve full coverage of the dayside magnetosphere at large scales, (ii) start a new phase of multi-scale observations, (iii) visit new magnetospheric regions, (iv) collaborate with new missions, and (v) collect data from a large part of a solar cycle.

The first point is obviously of fundamental importance to complete the Cluster mission, because observations have not yet been collected with spacecraft separations of 10 000 km or more. The second objective is intended to collect observations on both small and large scales at the same time, by moving two spacecraft close to one another while keeping the separations between three of the satellites at 10 000 km. Such measurements are scientifically very exciting.

Due to solar perturbations, the apogee of the Cluster orbit drifts slowly towards the southern hemisphere. So far this has been corrected with special spacecraft manoeuvres, but in the future this drift will be allowed to continue, taking the satellites to encounters with new magnetospheric regions that have previously only been studied with single satellites. Plenty of exciting scientific discoveries can therefore be expected during this phase.

Collaboration with other missions is also fundamentally important to Cluster as the magnetosphere makes up a vast volume of space. In 2004, the two satellites that make up the China-ESA Double Star mission were put into favourable orbits with respect to the Cluster mission and carry similar or complementary instrumentation. In October 2006, NASA's five-satellite Themis mission will be launched to study magnetospheric substorm phenomena. The Cluster and Themis apogees will be on opposite sides of the Earth, so that when Cluster is monitoring the solar wind or the dayside magnetosphere, Themis will in the magnetotail, and vice versa.

To celebrate the 40th anniversary of the International Geophysical Year, the International Polar Year will be organized in 2007–2008 and the International Heliospheric Year in 2007. During these years, spacecraft, ground-based observatories and theoretical modelling will be brought together in a determined attempt to fully understand the Sun's effects on the Earth's environment. Cluster can make significant contributions to that effort!