We live inside an invisible magnetosphere that protects life from dangerous solar particle radiation

UK experiments on the 4 spacecraft Cluster mission investigate the magnetosphere

We are using Cluster to explore what makes the aurora borealis (the northern lights)

The Earth’s magnetic field extends into space and forms a protective bubble called the magnetosphere. Acting like a shield, it deflects the solar wind - a constant flow of material from the Sun - around the Earth. The magnetosphere is largely invisible, and so it must be measured locally by satellites that ‘touch’, ‘taste’ and ‘hear’ the magnetosphere.

The magnetosphere does a good job of protecting us from dangerous solar particle radiation most of the time, but violent events on the Sun can break down the magnetosphere’s protection. Coronal mass ejections, solar flares and solar energetic particles can cause severe space weather in the Earth’s magnetosphere. Space weather can affect satellites, electricity grids and ‘sat-nav’ devices. As our use of space technology increases, we become more exposed to the risks of space weather. It is becoming more and more important to be able to predict when space weather may get worse, and in what way.

The Sun’s activity follows an 11 year cycle. In the last few years, the Sun has been very quiet. However, the Sun’s activity is increasing, with the next maximum due in 2013. We can expect more severe space weather as the Sun becomes more active. Over the next few years, as the Sun reaches its maximum levels of activity, data from Cluster will be very important.
Cluster is a European Space Agency mission that investigates the magnetosphere and its interaction with the solar wind. Cluster was launched in 2000, and has revolutionised our understanding of the magnetosphere. This is because it studies the three-dimensional structure of the magnetosphere.

We cannot see the magnetosphere so we use satellites to ‘touch’ ‘taste’ and ‘hear’ the magnetosphere. One satellite tells you about a point in space. To answer important questions like ‘how are the particles that create the aurora accelerated?’ several points in space must be measured simultaneously.

The simplest 3D object is a tetrahedron (a pyramid with a triangular base). A tetrahedron has four corners. Cluster is made up of four satellites, flying in formation so that they make a tetrahedron. Together, the four spacecraft explore the 3D structure of the magnetosphere.

The UK plays a leading role in Cluster. Parts of the satellites were built in the UK. Scientists and engineers in the UK built several of the instruments that are now flying in space. UK scientists and engineers are also responsible for helping to operate the satellites, and for ensuring that the data they collect is returned safely to Earth and properly stored. UK scientists have led many of Cluster’s scientific discoveries.

Cluster has operated successfully for more than 10 years, and is still exploring as we approach the next solar maximum.

(Above) Launch of the first two Cluster satellites ‘Salsa’ and ‘Samba’ onboard a Soyuz-Fregat rocket on 16 July 2000. The second pair were launched on 9 August 2000. (Image credit: ESA)

(Is left) The four Cluster satellites being prepared for launch. The UK plays a major role in Cluster. (Image credit: Astrium)

UK experiments on the 4 spacecraft Cluster mission investigate the magnetosphere

The aurora is one of the most beautiful natural phenomena on planet Earth. Through the centuries, many cultures and civilisations have observed and recorded the aurora.

Seen from space, the aurora is an oval of glowing light, centred on the Earth’s magnetic poles.

The most common colour is green. However, the aurora can appear as a variety of colours. For example red and pink auroras are also observed and measurements from space show that the aurora emits X-rays and ultraviolet light too.

Although we know that the aurora is created by electrons accelerating down magnetic field lines into the atmosphere and interacting with atoms of gas in the atmosphere, there are several big questions that scientists haven’t yet been able to answer. In particular we do not understand how the electrons are accelerated.

There are lots of theories that need to be tested! The best way to do this is to fly satellites above the aurora where they can measure the properties of the electrons that end up creating the aurora.

To do this, in 2006 the shape of Cluster’s orbit was allowed to slowly change, so that the lowest point of the orbit moved closer and closer to Earth. The four Cluster spacecraft are now able to measure electrons just above the aurora, in exactly the right place. Cluster scientists are using this new data to explore the aurora, and learn how electrons are accelerated into the atmosphere.

If a coronal mass ejection strikes the Earth’s magnetosphere, this may result in a geomagnetic storm. The auroral oval increases in size, and the band of auroral light moves towards the equator. During a large geomagnetic storm, it is sometimes possible to see the aurora in the United Kingdom. This will be more likely in the next few years as the Sun’s activity increases.

Is there going to be an aurora near you? To find out, visit:
http://aurorawatch.lancs.ac.uk
Did you know that an invisible magnetic shield surrounds the Earth? It is called the magnetosphere.

The Earth’s magnetic field

The Earth has a magnetic field. This magnetic field makes compasses point north and helps birds navigate. Although the Earth’s magnetic field looks like there is a giant bar magnet inside the Earth, the reality is that the magnetic field is generated by the motion of liquid iron in the Earth's outer core. The Earth’s magnetic field extends out into space, becoming weaker further from the Earth. In space, it meets the solar wind.

What is the solar wind?

The Sun’s atmosphere - the corona - is so hot that its constituent particles ‘boil off’ into space, in a continuous stream known as the solar wind.

The existence of the solar wind was hotly debated until the beginning of the space age. The first spacecraft to leave the Earth’s magnetic field used particle detectors to measure this flow of material from the Sun that never goes away. The solar wind is invisible to the naked eye.

The solar wind is a plasma, a gas of electrically charged particles. The solar wind mainly consists of protons and electrons.

The solar wind is very fast! In fact, it flows away from the Sun faster than the speed of sound. The solar wind speed at Earth is quite variable. On average it is approximately 450 km/s, or about 1,000,000 mph, but it can reach speeds of more than 1,000 km/s! Under normal circumstances, it takes 3 - 4 days for the solar wind to travel from the Sun to the Earth.

The interaction of the solar wind and the Earth’s magnetic field creates the magnetosphere.

What is the magnetosphere?

Most of the time, the solar wind cannot penetrate the Earth’s magnetic field. It is as if the Earth’s magnetic field carves a bubble in the solar wind flow. We call this bubble the magnetosphere. The solar wind pushes against the Earth’s magnetosphere, squashing it on the side that faces the Sun. On the ‘nightside’, the magnetosphere extends far away from Earth, in a region called the magnetotail. If the solar wind pressure increases (for example, if the solar wind speed increases), this compresses the magnetosphere and makes it smaller. The edge of the magnetosphere is called the magnetopause. Visit the interactive exhibits to learn more!

How big is the magnetosphere?

At its closest point, on the side that faces the Sun, the magnetopause is approximately 70,000 km, or 43,000 miles away from you. Facing away from the Sun, the magnetopause has been measured at least 25 times further away. In fact, no-one really knows how long the magnetopause is! The Moon’s orbit passes through the magnetotail (see picture).

Whenever you look up into the sky on a clear day, or a clear night, you are looking through the magnetosphere to the magnetopause.

Magnetospheric protection

The magnetosphere does a good job of protecting us from the Sun and solar wind, most of the time. However, as well as producing the continuous flow of solar wind, from time to time the Sun also generates violent outbursts of material and energy. These events can break down the magnetosphere’s protection, leading to what is called space weather.

Understanding and predicting space weather, i.e. the response of the magnetosphere to changes in the Sun and solar wind, is a major scientific challenge, with an important impact on everyday life. Turn over to learn more.

Space isn’t empty...

When we think about space, we immediately think of emptiness; the so-called vacuum of space. But reality is a lot more complicated! In fact, space is not quite empty. It is filled with electric and magnetic fields, and particles - both electrically charged, such as protons, ions, and electrons, and neutral, such as dust grains. About 50,000 tons of solar wind flows past the Earth every day, carrying as much energy as humans use worldwide on Earth. The flow rate of the solar wind past the Earth is one hundred million billion times greater than the Amazon river.

The Earth’s magnetosphere. The magnetopause is the edge of the magnetosphere. In front of the magnetosphere is a bow shock, where the supersonic solar wind is deflected around the sides. The magnetotail forms on the side facing away from the Sun. The cusps are regions near the magnetic poles where the magnetosphere is particularly ‘leaky’. The Moon is also shown for context, at a time when it is in the magnetotail. The magnetosphere contains a variety of different plasmas such as the plasmasphere (blue, low energy), plasma sheet (green), the ring current (yellow) and the radiation belts (orange and red, high energy).
To protect ourselves from space weather, we must understand the science behind it

**Space weather (n)**: the conditions on the Sun, in the solar wind and in the Earth’s magnetosphere that can influence the performance of technological systems (in space and on the ground) and endanger human life or health.

As well as the ever-present solar wind, the Sun periodically releases violent outbursts of material and energy. The most important are:

**Solar Flares and Energetic Particles**: A flare is when energy, stored in magnetic fields in the solar atmosphere, is rapidly released in the form of X-rays and ‘Solar Energetic Particles’ (SEPs). It takes X-rays 8 minutes to travel from the Sun to the Earth at the speed of light, whereas SEPs can reach the Earth less than an hour after the flare occurs. The magnetosphere deflects some SEPs, but some can get through our shield and damage spacecraft.

**Coronal Mass Ejections (CMEs)**: huge eruptions of material ejected from the solar atmosphere into space. CMEs travel through space, taking two or three days to travel out as far as Earth’s orbit. If they hit the Earth’s magnetosphere, they can cause a geomagnetic storm. Coronal Mass Ejections can also produce SEPs.

**The Solar Cycle**: The Sun’s activity follows a cycle of increasing and decreasing activity, with ‘solar maximum’ occurring approximately every 11 years. Space weather events are more common during solar maximum. Solar activity is increasing, and the next solar maximum is predicted to occur in 2013.

This sequence of pictures shows how the Sun’s activity follows an 11 year cycle. Each image shows the structure of the solar atmosphere in the different years of the most recent cycle. In 2001 the Sun was very active, whereas by 2006 its activity had reduced. The Sun’s activity is now increasing again. (Image credit: SoHO/EIT consortium/ESA/NASA)

**Examples of space weather**:

**What would happen if there was no electricity?** Geomagnetic storms can cause ‘Geomagnetically Induced Currents’ in power lines and transformers. These naturally occurring currents have caused power grids to fail. A really big space weather storm could cause severe damage to the electricity grid which could not be quickly repaired.

**How much is your gas bill?** Oil and gas pipelines use electrical systems to prevent corrosion. Geomagnetically induced currents interfere with these systems, enhancing corrosion and preventing the correct operation of corrosion protection systems. This must be monitored to ensure there are no problems.

**Do you have a ‘sat-nav’?** Satellite navigation ‘sat-nav’ receivers use signals from satellites to determine their position. Geomagnetic storms can make it difficult for receivers to lock onto satellites, and also reduce the accuracy of their position measurements.

**Do you like waiting at the airport?** Flights over the poles must use HF (High Frequency) radio to communicate, and this can be disrupted during periods of solar activity. If HF radio is disrupted, the flight must be rerouted so that more reliable communication systems can be used. This is expensive and means delays at the airport. Polar flights could also be more exposed to SEPs, since these particles can more easily enter polar regions via the magnetospheric cusps.

**Do you have a satellite dish?** Space weather can damage satellites. It can cause internal electrical discharges (interfering with normal operations), create noise in sensors and degrade solar panels. What if you couldn’t watch satellite TV?

**Did you know...** in 1859, one of the biggest ever space weather storms occurred. It could happen again, and scientists are using Cluster data to work out how to improve our protection and mitigate the risk of damage.

**Do you want to be a space tourist?** During the solar activity and geomagnetic storms that occurred in 2003, solar flare activity caused flight controllers to ask astronauts to remain in the most shielded part of the International Space Station.
Cluster is a European Space Agency mission that investigates the Earth’s magnetic environment and its interaction with the solar wind. Cluster consists of four satellites flying in formation through the Earth’s magnetosphere and into the solar wind. The Cluster satellites were launched in the year 2000. More than 10 years after launch they are still making new and exciting scientific discoveries, travelling to different parts of the magnetosphere (for example the auroral regions). In the next few years Cluster will complete a full set of observations over a whole cycle of solar activity (see figure below).

What does Cluster measure? We cannot see the magnetosphere, so Cluster uses 11 scientific instruments to ‘touch’, ‘taste’ and ‘hear’. Cluster measures magnetic and electric fields, the solar wind and magnetospheric plasma (made of ions and electrons), and plasma waves Cluster (visit the interactive exhibits to listen to plasma waves).

Why are there four satellites? One satellite can tell you about the magnetosphere at a single point. However, we need a three dimensional view to answer the big questions, like how the particles that create the aurora are accelerated. To get a 3D view, you need more satellites. The simplest 3D object is a tetrahedron (a pyramid with a triangular base). A tetrahedron has four corners, and so the Cluster mission has four satellites to make a three dimensional observatory. Visit the interactive exhibits to learn why Cluster has four satellites!

How big is the Cluster tetrahedron? The size and shape of the Cluster tetrahedron has been changed many times, as shown in the graph below. For some investigations, a large tetrahedron the size of the Earth itself is needed, whereas for others, a much smaller tetrahedron is needed. Sometimes (e.g. 2007-08) an investigation requires the tetrahedron to be squashed, so that two of the satellites are much closer together.

Did you know? The four Cluster satellites have different names!

Cluster 1: Rumba
Cluster 2: Salsa
Cluster 3: Samba
Cluster 4: Tango

Mission control has changed the size of the Cluster satellite tetrahedron many times throughout the last 10 years. The Earth could fit inside the largest tetrahedron.

The top graph shows how the size of the Cluster satellite tetrahedron has changed with time. The coloured dots show when different regions of the magnetosphere were targeted. The bottom graph shows the number of sunspots on the Sun. This indicates the level of solar activity and space weather. Solar activity was high at the beginning of the mission, and is starting to increase again. Space weather events will be more frequent over the next few years. Cluster will be used to study these events.

Launch of the first two Cluster satellites ‘Salsa’ and ‘Samba’ onboard the Soyuz-Fregat rocket on 16 July 2000. The four satellites were launched in pairs on two rockets. (Image credit: ESA)

Photograph of the Cluster satellite ‘Tango’ separating from satellite ‘Rumba’ in orbit. ‘Rumba’ and ‘Tango were launched together on 9 August 2000. (Image credit: ESA)

Imagery credit: ESA
Scientific instruments:

PEACE:
The Plasma Electron And Current Experiment (led by University College London/ Mullard Space Science Laboratory) measures the properties of electrons in the solar wind and magnetosphere. Electrons are used to determine where in the magnetosphere the spacecraft are located, and to calculate the density, velocity and temperature of the solar wind and magnetospheric plasmas.

FGM:
The Fluxgate Magnetometer (led by Imperial College London) measures the magnetic field (strength and direction) at the location of the spacecraft. Measurements from the four spacecraft are combined together to determine the existence of boundaries, waves, and electric currents.

DWP:
The Digital Wave Processor (led by Sheffield University) controls five other instruments on Cluster that each measure different specific properties of plasma waves in the solar wind and magnetospheric plasmas. DWP ensures that these five instruments work together in concert, and pieces together the information so that scientists on the ground have a complete picture of the plasma wave activity. Sussex University provided the ‘DWP-correlator’ to measure wave-particle interactions.

RAPID:
The Research with Adaptive Particle Imaging Detectors (contributed to by the Rutherford Appleton Laboratory (RAL/STFC)) detects the most energetic particles in the magnetosphere, which are important for understanding how geomagnetic activity is related to space weather. In fact RAPID consists of two detectors – one for ions and one for electrons. The team at RAL are responsible for the electron instrument.

The satellites:
The UK space industry designed and implemented the attitude and orbit control system for each spacecraft. The propulsion system, made in Bristol by Astrium was the first bi-propellant type ever used on a science mission and was also the first use of a bi-propellant system on a spinning spacecraft.

Spacecraft operations:

JSOC:
JSOC is the Joint Science Operations Centre, located at the Rutherford Appleton Laboratory. JSOC determines how the Cluster spacecraft will be operated, based on the requests from all the instrument teams. JSOC also monitors the instruments, and the quality of the science data that the Cluster spacecraft produce.

CSDS:
CSDS is the Cluster Science Data System, where you can look at Cluster data (http://www.cluster.rl.ac.uk/csdsweb-cgi/csdsweb_pick). The Rutherford Appleton Laboratory, in conjunction with Imperial College London (and previously Queen Mary, University of London), operates the UK Cluster Data Handling Facility, one of nine data centres. Each facility holds a complete copy of Cluster summary data.

CAA:
The Cluster Active Archive is the comprehensive final repository for the complete Cluster dataset. UK scientists have played a key role in developing the CAA.

Scientific collaboration:

Cluster - ground based working group:
Scientists at the University of Leicester and Lancaster University are heavily involved in coordinating Cluster’s observations with measurements taken by ground based instruments all over the world. Comparing measurements taken in space with those made on the ground increases our understanding of the link between the magnetosphere and the aurora.

Cluster Satellite Facts

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Did you know? The first attempt to launch Cluster was actually in 1996. However, this launch of Cluster failed because the rocket on which it was being carried (the maiden flight of Ariane V) blew up! Fortunately, Cluster was rebuilt and launched successfully in 2000.
What is the aurora?
The aurora is one of the most beautiful natural phenomena on planet Earth. Appearing as ghostly lights dancing in the sky; it is no surprise that the aurora have been attributed to the supernatural by many cultures through the ages.

Where can I see the aurora?
Seen from space, the aurora is an oval of glowing light, centred on the Earth’s magnetic poles. The aurora borealis, or northern lights, are observed around the northern magnetic pole, and the aurora australis, or southern lights, are observed around the southern magnetic pole.

If there are low levels of solar activity, then the size of the auroral oval is fairly constant, and it is usually visible from the ground in Canada, Scandinavia and northern Russia for example.

During a geomagnetic storm, created for example when a coronal mass ejection strikes the Earth’s magnetosphere, the auroral oval increases in size. This means that the band of auroral light moves towards the equator. The aurora then becomes visible in places where it is normally never seen. For example, during a large geomagnetic storm, it may be possible to see the aurora in the United Kingdom.

What colour is the aurora?
The most common colour is green. However, the aurora can appear as a variety of colours. For example red and pink auroras are also observed and measurements from space show that the aurora emits X-rays and ultraviolet light too.

How are the aurora made?
The green aurora are brightest, and are formed by electrons from the magnetosphere colliding with oxygen atoms in the atmosphere. Red aurora are also caused by electrons colliding with oxygen atoms, though the collisions are higher up and have less energy so the colour of the light is different. The aurora occur about 100 km - 200 km above the ground.

How do scientists study the aurora?
Scientists use cameras on the ground to study the detailed structure of the aurora. Cameras carried by satellites orbiting the Earth are used to study the global structure of the aurora. Finally, sub-orbital rockets and single satellites in low Earth orbit fly through the aurora to measure its constituent particles and the magnetic field.

Top 5 mysteries of the aurora
• What accelerates electrons into the atmosphere to make the aurora?
• Why do auroral arcs move and curl up?
• Why are auroral arcs so thin?
• How does the aurora produce radio waves?
• How much of the atmosphere is pulled through the aurora into the magnetosphere?

The aurora in ancient Greece
In 350 BC, the Greek philosopher Aristotle wrote “Sometimes, on a fine night we see a variety of appearances that form in the sky: ‘chasms’ for instance, and ‘trenches’ and ‘blood red’ colours… For we have seen that the upper air condenses into an inflammable condition… the combustion sometimes takes on the appearance of a burning flame”
Aristotle was describing an unusual occurrence of the aurora in Greece, probably during a geomagnetic storm.

Did you know...
The name ‘Aurora Borealis’ was first used by the French scientist Pierre Gassendi in 1621. Aurora is the Roman goddess of dawn, and Boreas is the Greek word for the north wind.

Visit the interactive exhibits to learn more!
Cluster's new observations of the aurora

In the latest phase of its continuing mission to explore and understand the magnetosphere, Cluster is being used to study how the aurora work.

The problem...

Although we know that the aurora is created by electrons accelerating from the magnetosphere, along the Earth’s magnetic field and into the atmosphere where they interact with oxygen atoms, there are several big questions that scientists haven’t yet been able to answer.

• No-one knows exactly where above the aurora the electrons are accelerated.
• No-one knows exactly how the electrons are accelerated.
• And sometimes the acceleration is very strong whereas at other times it is barely present. Why is that?

Why is this important?

The aurora are a visible manifestation of electrical current systems that connects the magnetosphere and upper atmosphere.

The auroral region typically dissipates energy (like a resistor).

The magnetosphere, particularly the regions where charged particles are energised by the solar wind usually drive the electric currents (like a dynamo).

To understand space weather better we need to be able to predict how and where these current systems will appear, and how the auroral region controls their development.

A scientific investigation

There are lots of theories, but theories need to be tested! The best way to do this is to fly satellites above the aurora. There they can measure the properties of the electrons before, during and after they accelerate down the magnetic field lines to the region where they create the aurora.

But ideally, several spacecraft are needed.

The simplest situation is with two spacecraft, as shown in the picture. They fly in formation at different heights above the aurora. By comparing the measurements, you can tell if the acceleration region is above both of the satellites, between the two satellites, or below the satellites.

If you have more than one satellite, then you can measure how much the electrons have accelerated as they move between the satellites. This means you can work out exactly how the electrons are accelerated, and where they are accelerated. This allows the different theories to be tested.

Visit the interactive exhibits to learn more!

Cluster: Aurora Explorer!

When Cluster was originally launched, the four spacecraft orbited the Earth over its poles. Initially, the lowest point of the Cluster orbit was approximately 19 000 km, much too high to study how the electrons that create the aurora are accelerated.

In 2006, the shape of Cluster’s orbit was allowed to slowly change, so that the lowest point of the orbit moved closer and closer to Earth. The four Cluster spacecraft are now able to measure electrons just above the aurora, in exactly the right place.

Cluster scientists are using this new data to explore the aurora, and learn how electrons are accelerated into the atmosphere.

(Above) This picture shows how two of the Cluster satellites flew above the aurora at different heights. By looking at the differences between the two spacecraft, Cluster scientists are able to work out exactly how the electrons create the aurora.

(Image credit: ESA)

The aurora as viewed by astronauts on the International Space Station. (Image credit: NASA)

A brilliant auroral display over the city of Tromsø in arctic Norway. (Image credit: P. Lawrence)