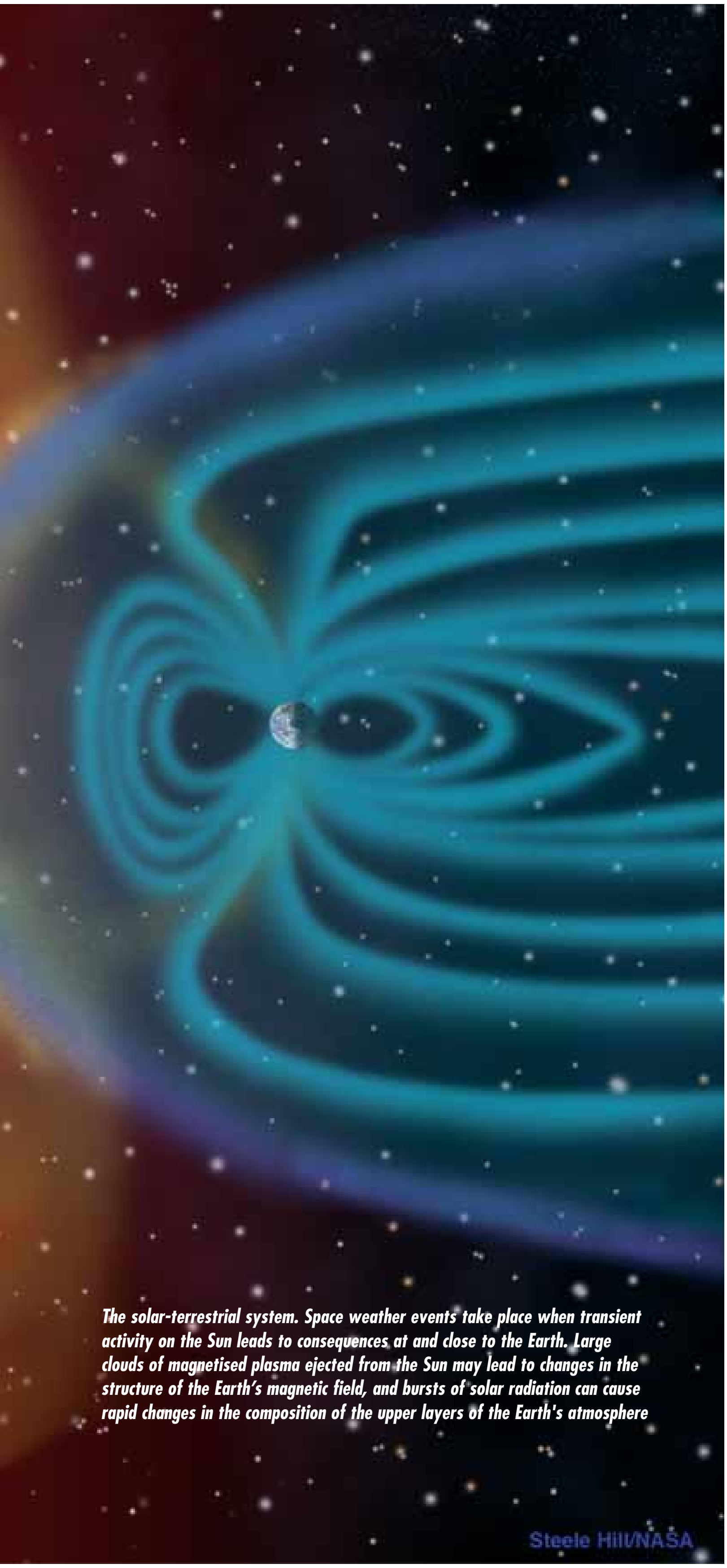
Tomorrow's Space Weather Forecast ?



The solar-terrestrial system. Space weather events take place when transient activity on the Sun leads to consequences at and close to the Earth. Large clouds of magnetised plasma ejected from the Sun may lead to changes in the structure of the Earth's magnetic field, and bursts of solar radiation can cause rapid changes in the composition of the upper layers of the Earth's atmosphere

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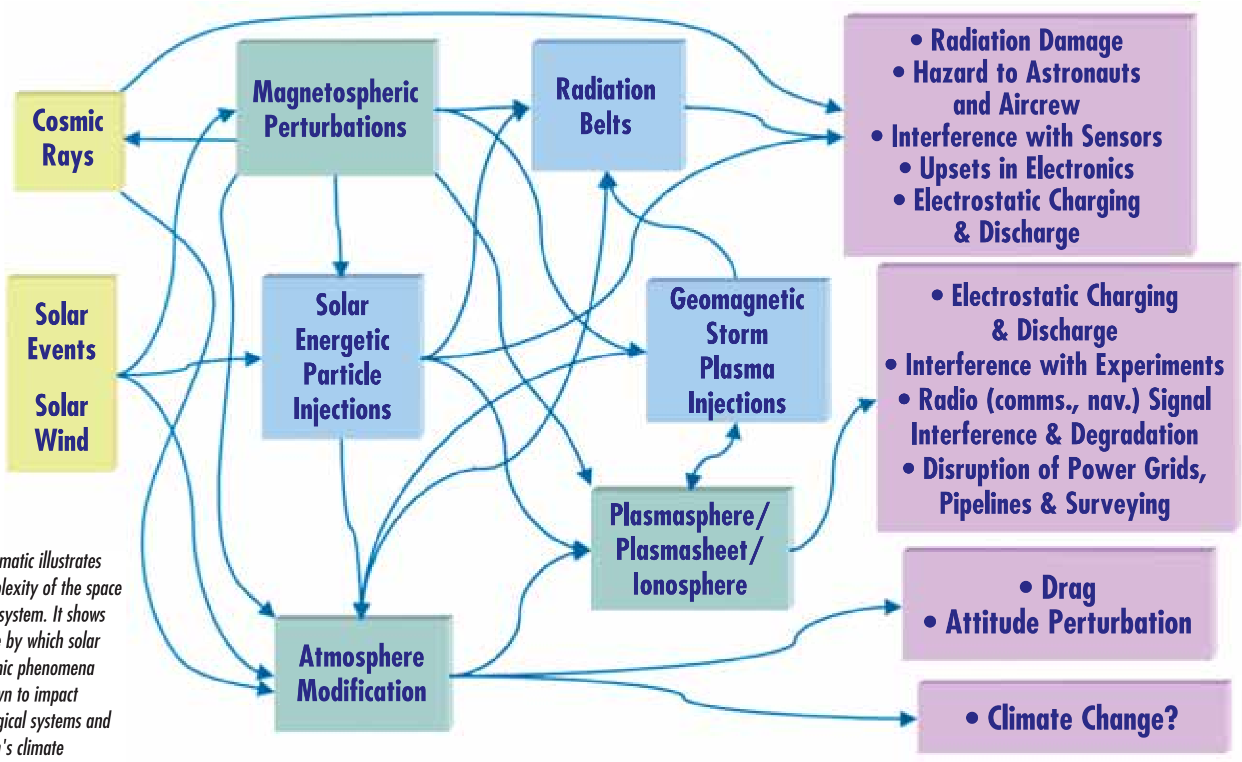
What is Space Weather? The definition most frequently quoted is that of the US National Space Weather Programme:

"conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health".

This definition demonstrates that space weather encompasses a collection of physical phenomena having their origin at the Sun and which give rise to effects that are of concern to society. The two accompanying figures illustrate the solar-terrestrial system and the complexity of the phenomena that lead to space weather effects. Much of the science that underpins space weather is part of the larger field of solar-terrestrial physics. Here we focus on some of the main aspects of the system - the Sun, heliosphere, magnetosphere and ionosphere - and the key space weather phenomena that can affect us here on Earth.



This schematic illustrates the complexity of the space weather system. It shows the route by which solar and cosmic phenomena filter down to impact technological systems and the Earth's climate

The Sun and Its Surroundings

The Sun is the primary driver of space weather phenomena. Most space weather events have their origin in the solar corona: the Sun's 'atmosphere'. The corona, which is normally visible only during a solar eclipse, is a hot (>10^6 degrees Kelvin) tenuous plasma extending away from the solar surface and out into the heliosphere. The dominant feature controlling the corona is the Sun's magnetic field. To the naked eye, the Sun appears as a constant bright yellow disk. However, in reality, the Sun is far from unchanging. This is dramatically shown by the images and movies produced by the joint ESA-NASA SOHO science mission. Viewed in these other wavelengths, the Sun is seen as a boiling cauldron of magnetic fields and plasma. Sudden changes in these coronal magnetic fields can result in explosive solar 'flares' and 'Coronal Mass Ejections' (CMEs).

Solar activity is usually classified in terms of the number of sunspots seen on the solar disk, and the frequency of occurrence of flares and CMEs. This activity shows cyclical behaviour, with a typical period of 11 years. This results in a similar variation in the number of large sporadic space weather events. These events are most frequently observed around the time of solar maximum. The most popular and visible consequences of these large events here on Earth are the spectacular aurorae or 'northern/southern lights', which may be observed at lower latitudes than normal during very disturbed space weather conditions.

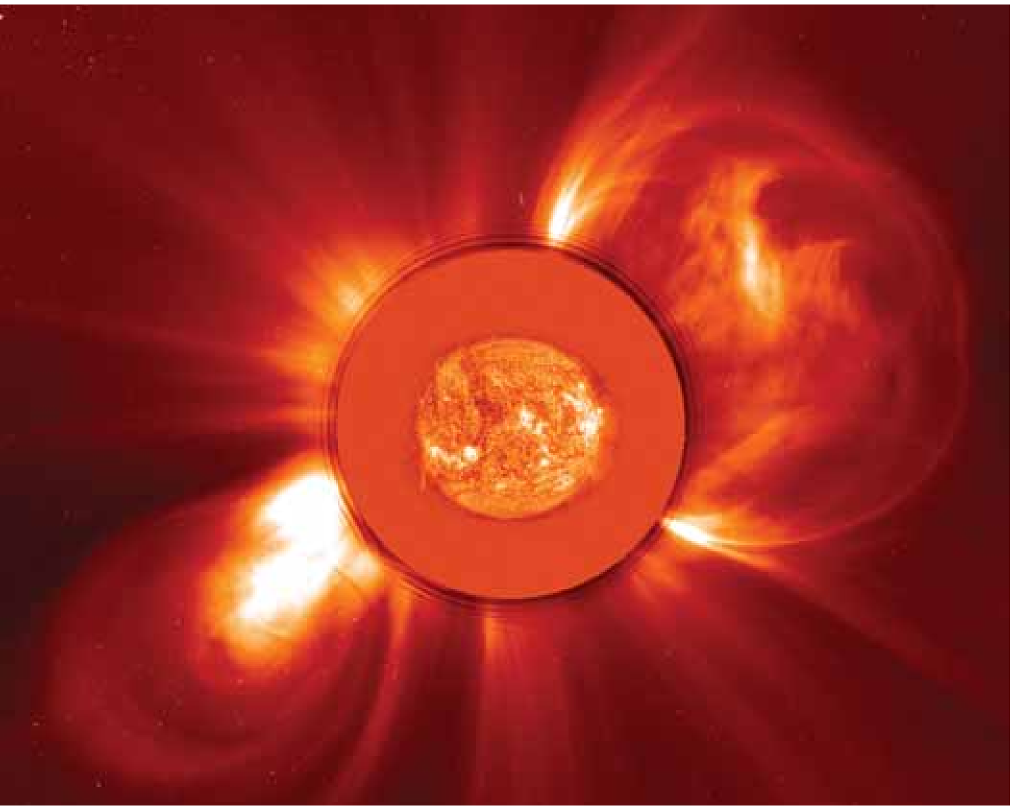
The solar wind

In addition to these transient phenomena, charged particles are constantly streaming away from the Sun in the form of the magnetised solar wind. The magnetic field lines that are carried into space by the solar wind remain tied to the Sun at one end and stretch into space at the other. Solar rotation pulls these field lines into the shape of an Archimedean spiral. During solar minimum, when the level of solar

Aurorae are caused when electrons precipitate from the magnetosphere into the atmosphere by spiralling around magnetic field lines. At altitudes of 90 to 5000 km, electrons will hit atmospheric atoms and molecules. These atoms and molecules will be given energy in the collision and will emit light. The colour of this light depends on the atom or molecule and the energy of the electron involved in the collision. Oxygen atoms will emit green and red light, whereas nitrogen atoms will emit violet and blue (Image courtesy of J. Manninen)

activity is low, the Sun's magnetic field resembles that of a bar magnet, and field lines open out into space at the northern and southern polar regions. Coronal material escapes in high-speed streams from these regions, which are known as ‘polar coronal holes’. The boundaries of these polar coronal holes can extend to quite low latitudes in places, even crossing the solar equator on occasion.

Compression regions form at the boundaries between these high-speed streams and the slower solar wind ahead. Here charged particles can be accelerated to higher energies. The interaction between these compression regions and the Earth’s magnetic field can lead to space weather effects occurring on an almost regular time scale. Coronal holes are long-lasting features and may endure for many weeks, rotating with the Sun every 27 days. This leads to recurrent space weather activity on a similar time scale. This pattern can be seen most clearly during solar minimum. During solar-active years, the changing magnetic field at the Sun disrupts this pattern, and the coronal holes become smaller and move to lower latitudes rather than remaining close to the poles.



CMEs as seen by SOHO/LASCO. CMEs are huge clouds of magnetised plasma that erupt from the solar corona with speeds of up to 2000 km/s. This figure shows two CMEs expanding simultaneously in the coronagraph image. One expands to the northwest and the other to the southeast. Note how the size of these clouds appears to dwarf the solar disk. This image of the solar disk was taken by the SOHO EIT telescope and shows solar features at temperatures of about 80 000 K

Coronal Mass Ejections (CMEs)

CMEs are huge clouds of magnetised plasma that erupt from the solar corona at speeds of up to 2000 km/s. These clouds carry a mass of the order of a billion tonnes – more than the mass of Mount Everest! – and are superimposed onto the expanding background solar wind.

The Large Angle Spectroscopic Coronagraph (LASCO) onboard the SOHO spacecraft allows us to see CMEs more often and in far greater detail than ever before. Like the Moon during a solar eclipse, a so-called ‘occulting disk’ is used to block out light from the bright solar disk (indicated by the central circle in the accompanying images). These particular CMEs were not directed towards the Earth, but illustrate the spectacular nature of such eruptions in the corona.

Most CMEs that lead to Space Weather effects at the Earth are called ‘halo’ CMEs. The Earth-directed plasma is observed as a bright halo completely surrounding the occulting disk and expanding radially outward in all directions from the Sun.

In order to be able to predict space weather effects, we need to be able to predict not only *what* will happen, but also *when*. CMEs can take several days to reach the Earth after we see them leave the Sun. Predicting whether a halo CME will lead to strong effects at the Earth, and when these effects will begin, remains a major challenge in space weather research.

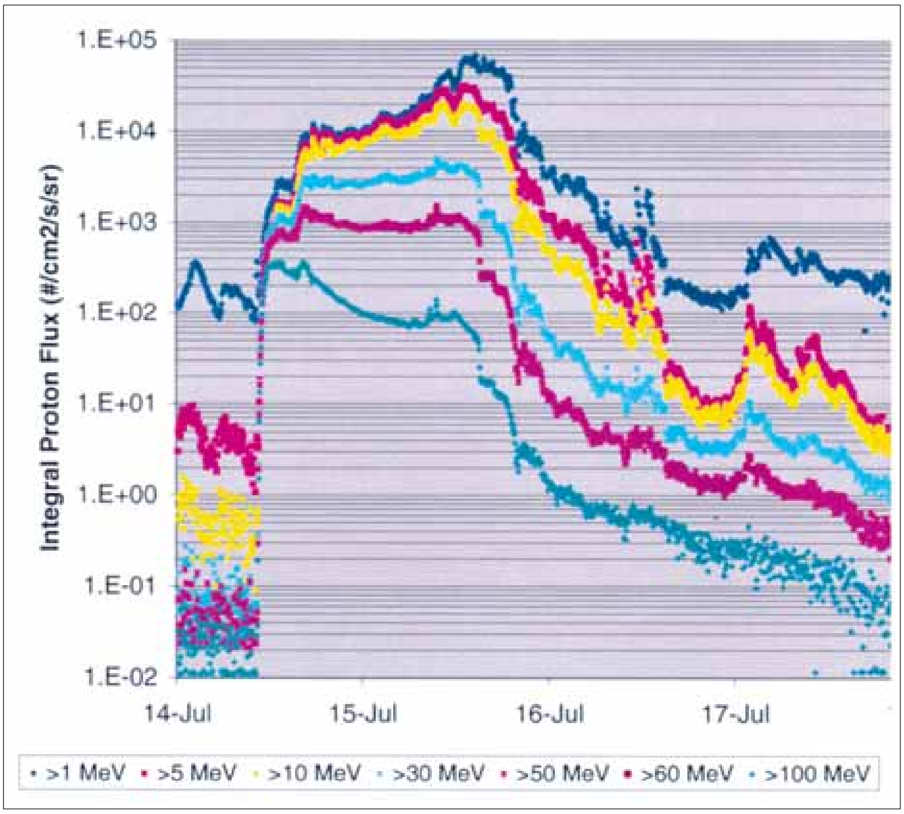
Solar flares

Solar flares are sudden and rapid releases of magnetic energy in the solar atmosphere. They are most commonly observed from sunspot regions where magnetic loops interact, with explosive consequences. Flares can last for a few minutes to several hours, releasing energies of the order of 10^{25} joules – fifty billion times the energy released by a 50-megaton H-bomb! The radiation from these events covers a wide range of wavelengths, from radio waves to gamma rays. This radiation reaches the Earth in a matter of minutes, making advance warning extremely difficult.

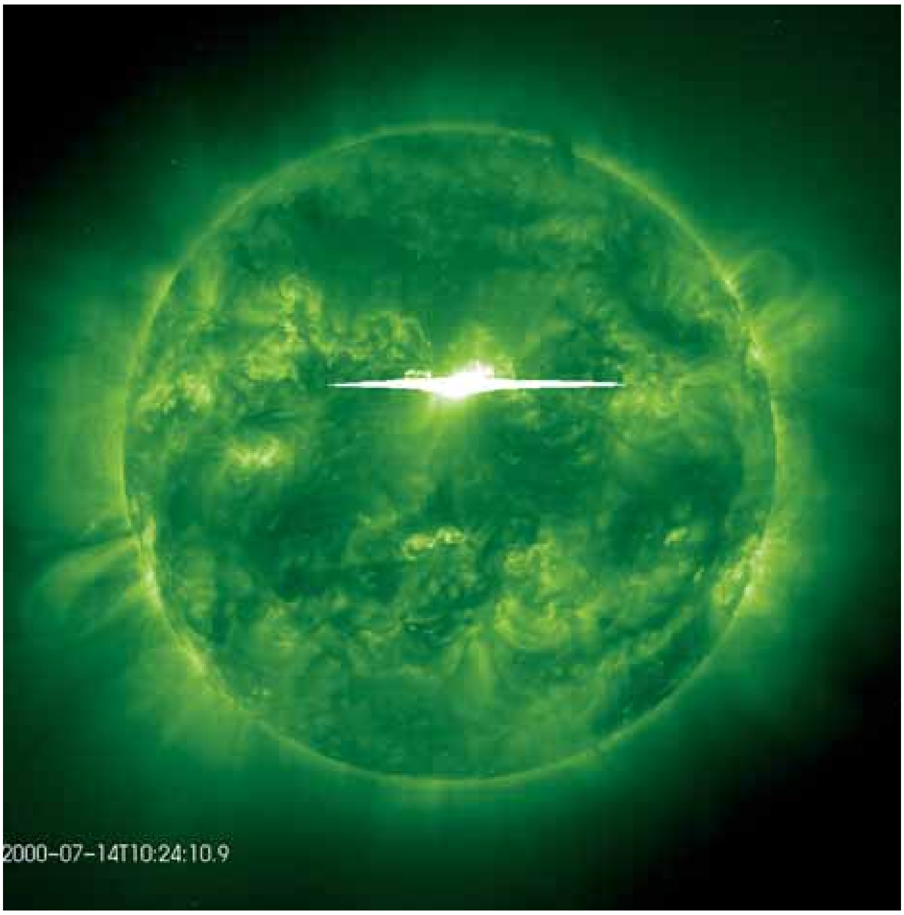
Solar Energetic Particles (SEPs)

Another key aspect of space weather is the arrival at Earth of sudden bursts of highly energetic particles originating from the Sun. The largest such events can enhance the radiation intensity in near-Earth space by several orders of magnitude.

Solar energetic particles can either originate from a solar flare or from acceleration at interplanetary shocks driven by fast CMEs. High-energy SEPs can arrive at the Earth within tens of minutes of the flare onset, and SEP events can last for several days.



A solar-particle event seen by the NOAA GOES spacecraft on 14 July 2000. This particle event followed the solar flare shown below by about 30 minutes. Note the speed with which the particles arrive and the steep increase in particle flux.



A solar flare, as seen by the Extreme Ultraviolet Imaging Telescope (EIT) onboard SOHO. This image shows solar emission in the extreme-ultraviolet (EUV) wavelength range. Features in the solar atmosphere seen here are heated to a temperature of approximately 1.5 x 10^6 K. Note the bright magnetic loops punctuating the solar disk

Because they carry an electric charge, SEPs can only propagate along magnetic field lines. Therefore, the importance of these particles at the Earth depends not only on the characteristics of the flare or shock from which they originate, but also on the structure and behaviour of the interplanetary magnetic field. Particles most readily reach us if the Earth and the source region are magnetically connected.

The Magnetosphere and Near-Earth Environment

The region surrounding the Earth that is dominated by its magnetic field is called its ‘magnetosphere’. The interaction of the solar wind with the Earth's magnetic field leads to a complicated system of plasma convection and electrical currents which form within the Earth's magnetosphere and determine its entire geometry. The energy loaded into the magnetosphere is related to the local solar wind density, speed and magnetic field. This energy is stored in the geomagnetic tail in plasma and magnetic flux and is released intermittently in events known as ‘substorms’. During such substorms, most energy is released in a direction pointing away from the Earth, but a significant part is accelerated towards us, leading to particle precipitation at high latitudes and hence to aurorae.

Substorm development involves dramatic magnetospheric changes, which have clear electromagnetic signatures in terms of waves or magnetic oscillations that are even detectable on the ground. Geomagnetic perturbations have been recorded by a worldwide network of magnetometers on a continuous basis for many decades in the form of so-called 'geomagnetic indices'. These observations provide an invaluable means of assessing the short- and long-term effects of space weather.

Earthward-directed CMEs, or solar wind stream boundaries, often interact with the magnetosphere, leading to the onset of space weather effects such as magnetic storms and enhanced aurorae. CMEs that interact with the magnetosphere are termed 'geo-effective'. It is not yet possible to predict which CMEs will be the most geo-effective before they reach the magnetosphere. However, we do know that if a CME is fast and has a strong southward magnetic field component in its magnetic structure, there is a strong probability that it will lead to geomagnetic activity. In this orientation, the magnetic field of the CME is able to connect with the Earth's magnetic field and solar wind energy can easily be transferred to the magnetosphere. The geomagnetic storm that may result from this is, however, a result of the explosive release of energy from the magnetotail: the extended, anti-sunward-pointing part of the magnetosphere. This follows some time after the CME impact.

Radiation belts

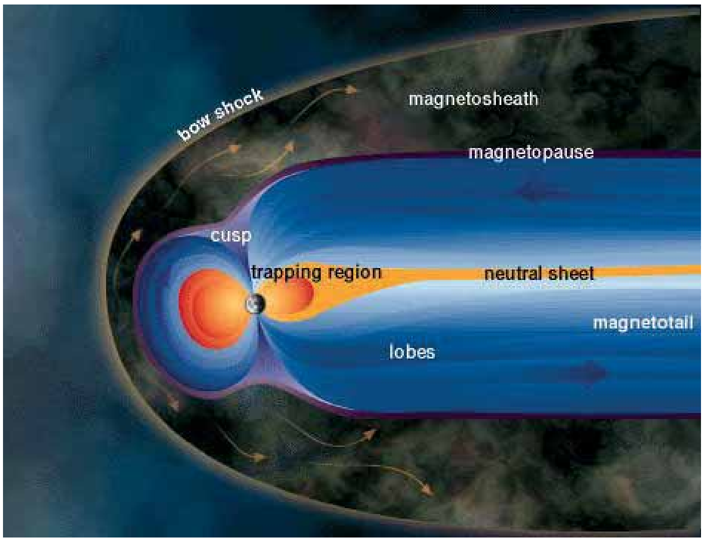
Some of the solar wind material may eventually become trapped and accelerated in the Earth's magnetic field, contributing to the filling of the radiation belts. These radiation belts are layers of intense particle fluxes in the magnetosphere. Within these belts, particles can be accelerated to high energies. High concentrations of energetic (MeV) electrons often appear in these belts after storms. These particles are often referred to as 'killer electrons', because of the effects they are known to have on spacecraft electronics. The highest concentrations of these killer electrons occur at altitudes of between 10 000 and 30 000 km. At the geostationary orbit of 36 000 km frequently used by communication and navigation satellites, the flux levels are still hazardous.

At low altitude, the major source of radiation hazards is the inner radiation belt consisting of energetic protons. This is a relatively stable population due to the decay of atmospheric neutrons created by cosmic rays.

Atmosphere and aurorae

The ionosphere is the ionised part of the Earth's atmosphere. It is composed mainly of atmospheric molecules that have been ionised by solar ultraviolet (UV) radiation. However, it also contains some particles originating from the solar wind.

Direct electrodynamic coupling between space and the upper atmosphere exists due to the magnetosphere-ionosphere coupling through precipitation of magnetospheric particles, field-aligned currents and the electric coupling along the magnetic field lines connecting the magnetosphere to the ionosphere.



Artist's impression of the Earth's magnetosphere. Close to the Earth, the field lines resemble those of a large bar magnet. However, at large distances, the influence of the solar wind results in the sunward side of the field being compressed. In contrast, on the anti-sunward side, field lines are extended to form the magnetotail, which can stretch to several hundred Earth radii

Increased numbers of charged particles can penetrate to atmospheric heights of about 90 – 130 km at high latitudes during disturbed space weather conditions. In addition to causing spectacular visible aurorae, these particles lead to an increase in heating and, therefore, ionisation at these heights.

The increased density of electrons produced by ionisation is known as an auroral E-layer. The high conductivity of this layer means that currents can flow. These are known as the 'auroral electrojet' and can reach as much as 1 million amperes, with dramatic effects on our electrical systems on the ground below.

In addition, these sudden changes in the electron content of the ionosphere may cause sudden and unpredicted changes in signal propagation paths through the ionosphere. This effect is important for both our navigation and communication systems that make use of the ionosphere for signal propagation.

Shielding the Earth from harmful cosmic rays

Geomagnetic shielding is the term given to the diverting effects of the Earth's magnetic field on cosmic-ray particles and solar energetic particles. These particles are prevented from penetrating to low altitudes above equatorial regions of the Earth's surface by the Earth's magnetic field. During disturbed space weather conditions, however, this geomagnetic shielding is weakened, leading to larger fluxes of these particles than would otherwise be the case. This may lead to an increased radiation dose being received by the passengers and aircrew onboard aircraft flying at high altitudes. While the increase is usually negligible for passengers making a single journey, it may accumulate towards the maximum permissible dose for regularly flying aircrew.

An Applications Perspective

Space weather affects a broad range of our technologies and activities, through radiation, plasmas, ionospheric currents, particulates, etc. The resulting economic

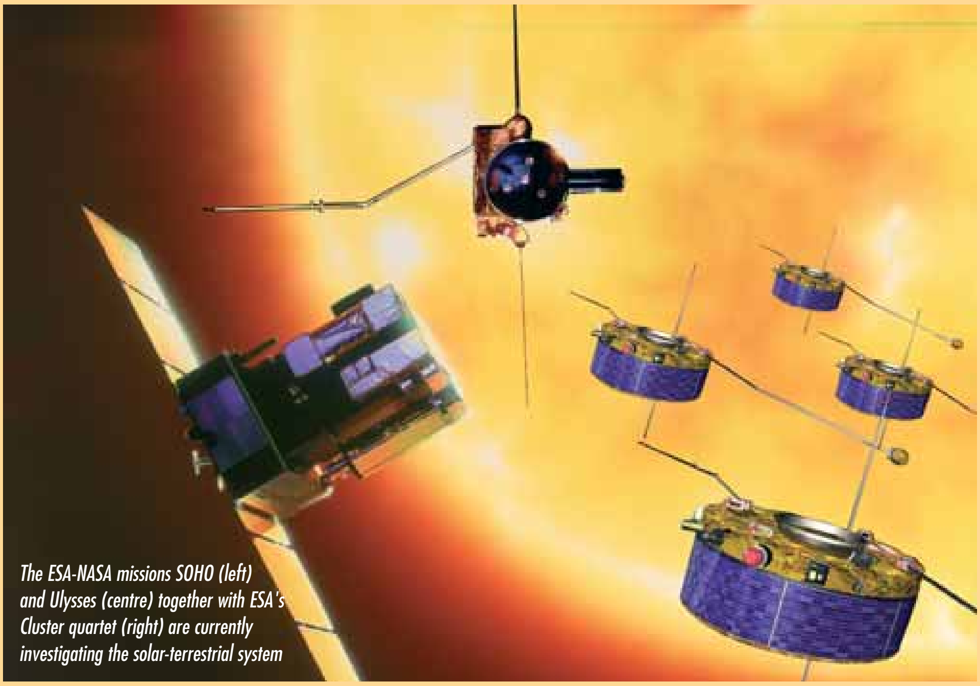
Interactions with Other Entities

The science underpinning ESA's space weather activities will remain a priority of the Agency's Science Programme, as highlighted by its future missions such as the Solar Orbiter and BepiColombo. In addition, ESA has recently announced its participation in the new International Living with a Star programme. ILWS is a new initiative in which space agencies worldwide are coordinating their activities to investigate how the Sun's variations affect the environments of Earth and other planets in the short and long term. In particular, ILWS will concentrate on those aspects of the Sun-Earth system that lead to space weather effects. The programme is a major collaborative initiative benefiting from the involvement of Europe, the United States, Russia, Japan, Canada and possibly other nations.

ESA's missions form a vital part of ILWS. SOHO, Ulysses and Cluster are already providing unprecedented data, helping us to understand the Sun, heliosphere and magnetosphere. In 2003, in collaboration with China, the Double Star mission will be launched to complement ESA's Cluster mission. In a decade's time, ESA's Solar Orbiter will follow. This spacecraft will travel closer to the Sun than any solar mission ever before. ESA will provide ground stations for Japan's Solar-B mission (launch 2005), and there is considerable European participation in NASA's STEREO (launch 2005) and Solar Dynamics Observatory (launch 2007) missions.

In addition, ESA's missions to the other terrestrial planets – Mars Express (launch 2003), Venus Express (launch 2005), and the BepiColombo mission to Mercury (launch 2011/2012), will carry experiments that look at solar-wind interactions with their respective planets.

ILWS builds upon a previous international framework between Europe, Japan, Russia (formerly the Soviet Union), and the United States established to study the Sun and its effects on the Earth. That framework was the International Solar Terrestrial Physics (ISTP) programme, in which the SOHO and Cluster missions were part of ESA's contribution. The Canadian Space Agency has joined this collaboration with the start of ILWS.



The ESA-NASA missions SOHO (left) and Ulysses (centre) together with ESA's Cluster quartet (right) are currently investigating the solar-terrestrial system

In terms of space weather applications within Europe, ESA is not alone in recognising the need for further research into the applications of space weather. Two European Commission funded COST (Coordination in Science and Technology) Actions have been initiated, focusing on increased understanding of the science behind space weather through international collaboration. Both aim to create a network of scientists and engineers with the common goal of understanding the impacts of space weather on the environment.

Monitoring of the space environment currently takes place within the framework of the International Space Environment Service (ISES), which encourages near-real-time monitoring and prediction of space weather and the space environment. Data are exchanged between several regional warning centres (RWC) distributed around the globe. The NOAA Space Environment Center plays a key role as the 'world warning centre', acting as a hub for data exchange and forecasts. ESA has recently become a member of ISES and will be responsible for creating a working group on the effects of the space environment on spacecraft.

Space weather as an application area has also recently been recognised in the European Union's Framework-6 Programme. The term 'space weather' is included under the heading of GMES (Global Monitoring for Environment and Security) 'risk management', within the thematic priority of aeronautics and space. While 'risk management' encompasses only a small subset of space weather issues, it is hoped that future EU collaborative projects will raise awareness of space weather and its impact on society.

Clearly, the scientific aspects of space weather are already well coordinated. It is hoped that through coordination of European initiatives and collaboration with the US and other national programmes such as those of Japan, Russia and China, a similar level of coordination in space weather applications can be achieved.

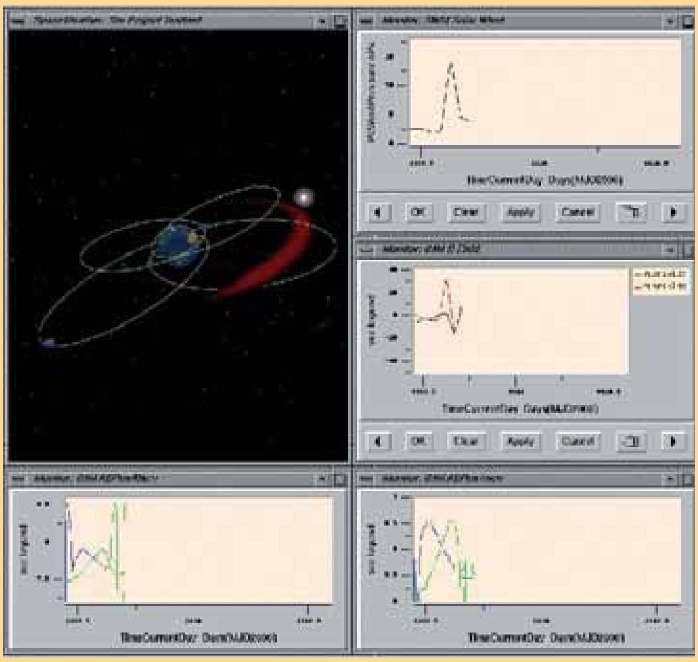
The Space Weather CDF Study

Following on from the two parallel ESA Space Weather Programme Feasibility Studies, ESA carried out an additional study to consider possible elements of a future space segment for an operational, service-oriented, European space weather system. The study was carried out using the Concurrent Design Facility (CDF) at ESTEC. Its main starting points were the space- and ground-segment recommendations proposed by the two consortia taking part in the feasibility studies.

Both the RAL and Alcatel consortia proposed several interesting options for a space weather system. As a result, it was decided that some of the proposed options should be analysed and further developed by ESA through the CDF, to establish their feasibility and cost. While a comprehensive space weather system should include elements beyond those studied by the CDF, following consultation with the consortia, it was decided to study the following demonstrator elements:
– an element for continuous monitoring of solar features that are important in ultimately causing space weather hazards near and on the Earth
– an element for continuously monitoring the solar wind upstream of the Earth, and
– a fleet of inner magnetospheric monitoring spacecraft which would observe changes taking place within the terrestrial radiation belts, the magnetosphere and partly the ionosphere.

The study was conducted between October and December 2001. The accompanying figures illustrate the space segment studied and the type of data that would be retrieved.

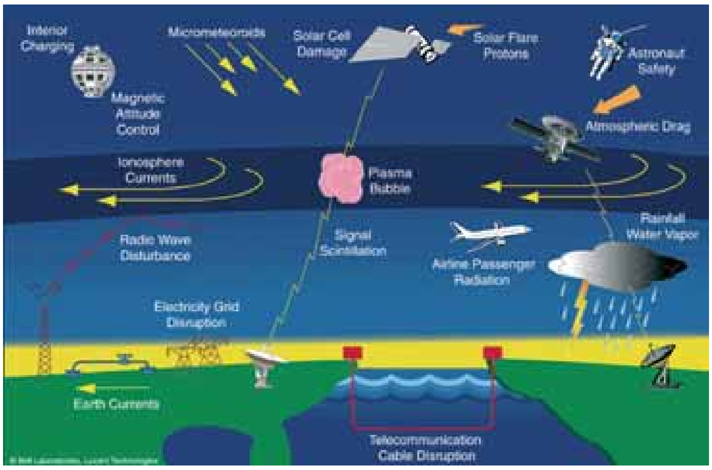
Elements of the space weather system studied within the Concurrent Design Facility (CDF) at ESTEC. This proposed space segment consisted of a solar monitor, a solar wind monitor and a fleet of four inner magnetospheric monitoring spacecraft. Both the solar and solar wind monitors would be permanently situated in the solar wind, in a halo orbit around the L1 Lagrangian point between the Sun and the Earth. The magnetospheric monitors would be located in a series of elliptical orbits within the magnetosphere, taking them though the Earth's radiation belts



A simulated space weather event in the Earth's magnetosphere. This screen shows the type of data that would be retrieved from the magnetospheric monitors examined as part of the space weather CDF study. The red arc in the top-left panel indicates the injection of energetic particles into the radiation belts. This is confirmed by the sharp deviations in the measured quantities indicated in the other four panels impact is estimated to be some tens of millions of Euros per year for those sectors that are traditionally influenced by space weather. Since society's dependence on spaceborne technology such as communication and navigation systems is continually increasing, the economic impact of space weather may grow considerably in the future.

The known 'victims' of space-weather effects already include:

- *Terrestrial power distribution grids:* These are affected by additional current flows in cables induced by currents in the Earth's ionosphere. The resulting current surges can destroy equipment, necessitate operational system reconfiguration or special designs.
- *Terrestrial communications:* Some systems that make use of transmission via the ionosphere are seriously affected. Many of these systems are military.
- *Users of space-based trans-ionospheric services:* Radio propagation through the ionosphere can be perturbed by changes in the electron content. Ground-space communications and navigation services such as GPS and the future Galileo can be disrupted, as well as radar-based remote sensing.
- *Oil and mineral prospecting and operations:* Geomagnetic field variations can perturb magnetic readings routinely used in these fields.
- *Defence:* The defence sector makes increasing use of communications and navigation services which are affected. Space systems are important to this sector. Over-the-horizon radars are also adversely affected.
- *Airlines and aircraft developers:* Advanced avionics systems are becoming susceptible to cosmic radiation effects. Aircrew are exposed to doses of cosmic radiation, for which European legislation now requires monitoring.
- *Space agencies and commercial space system operators:* Space systems are subject to numerous types of serious radiation damage and interference. Radiation hazards to astronauts are significant. Spacecraft can discharge following plasma-induced charging, causing anomalies. Rapid atmospheric variations can affect spacecraft orbits and stabilisation.
- *Climate:* Recent research has indicated that space weather may have important effects on climate. Global surface temperature is thought to vary with the solar cycle and the level of cloud cover is also thought to vary in accordance with cosmic ray flux. Clearly, these effects need to be accounted for in global change programmes.



An overview of space weather effects, showing the wide range of domains that it influences. Not only space-borne systems are affected: terrestrial systems such as electrical power distribution grids and telecommunication cables also feel the effects of space weather (Image courtesy of Bell Laboratories, Lucent Technologies)

Service requirements

Regarding space weather as a hazard and developing strategies and systems to circumvent the problems that it can cause gives a very different perspective from the scientific investigation of the solar-terrestrial system. These different perspectives frequently mean that the requirements of scientific and service-oriented missions are not the same. For example, any monitoring service will require real-time or near-real-time data downlinking, together with a negligible delay in data processing and supply of data to the relevant users. In contrast, scientific measurement of the same system may require observations made at unprecedented resolution for a short period of time with no real-time constraint on data acquisition.

Availability of data may also prove a problem when instrument teams with scientific goals wish to restrict data access prior to publication of scientific results. In the context of space weather monitoring and prediction, the availability of real-time data is of paramount importance to allow users to take appropriate action if a space weather event is predicted/detected.

Continuity of observations and longevity of the mission might also be considered less important in terms of scientific mission objectives, whereas these would be of key importance in terms of a monitoring mission. Indeed, science missions are normally unique and have a finite expected lifetime. In contrast, a space weather monitoring system should have a replacement procedure built in such that, as one element begins to fail, a replacement can be called into operation at short notice to maintain an operational service.

ESA Initiatives for Space Weather Applications

A European Space Weather Programme?

In 1999, ESA embarked on an investigation into the feasibility of a coordinated space weather programme. Contracts were placed with two consortia consisting of experts in the fields of engineering, solar-terrestrial science and space weather effects. These consortia were led by Alcatel Space (F) and the Rutherford Appleton Laboratory (UK).

The consortia performed wide-ranging analyses of the need for a European space weather programme and the possible content of such a programme, including:

- analysis of space weather effects
- analysis of the requirements of a space weather system

– definition of a service including prototyping aspects of this service
– definition of the space segment
– analysis of programmatic and organisational issues.

These studies were supported by a Space Weather Working Team consisting of external experts who provided input to the studies, analysed the work of the consortia, and advised ESA on its future strategy.

Together, the studies identified a wealth of expertise in space weather already existing within Europe. Key strengths were identified in the areas of scientific research, modelling and observatory infrastructure. It was stressed that federation of these activities, which are currently spread throughout Europe, would strongly benefit the space weather community, both in terms of the development of an applied service and in terms of coordinated research into the solar-terrestrial system as a whole.

It was noted that, at the present time, many European space weather applications are based on a US service. It is frequently the case that tools developed in Europe to mitigate space weather effects rely heavily on a US service provision infrastructure based at the NOAA Space Environment Centre in Boulder, Colorado. Consequently, they receive data via an Internet link, which may be subject to disruption. Security of this data may also become an issue in the future due to military involvement in US space weather data measurements and the increasing dependency of society on systems affected by space weather.

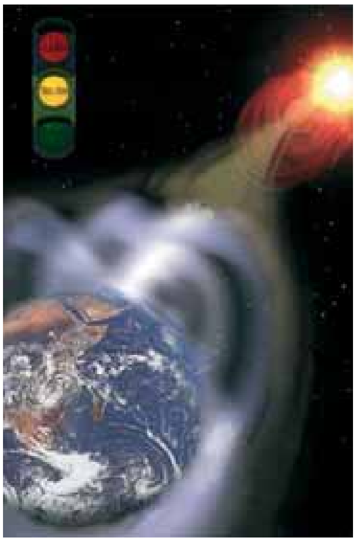
The results of these studies are accessible via ESA's Space Weather Applications website at:
www.estec.esa.nl/wmwww/wma/spweather/esa_initiatives/index.html.

At present, most space weather data is provided by scientific missions and the US NOAA meteorological spacecraft. However, useful space weather information is also provided by small, low cost 'hitchhiker' instruments, of which the Standard Radiation Environment Monitor (SREM) is an example. This instrument, which provides data on the space weather conditions in the vicinity of the spacecraft, has been flown on several ESA missions including Integral (shown here in the ESTEC Test Centre prior to launch) and Proba. Future missions that will carry SREM monitors include Rosetta, Herschel and Planck. The SREM was developed under the ESA Technology Research Programme (TRP)

The Space Weather Applications Pilot Project

This two-year Pilot Project follows on from the two parallel space weather studies described above. It seeks to expand the results of these studies and further develop the community of space weather service users and developers in Europe. It will focus on the development of targeted space weather services based on existing or easily adaptable sources of data, but there will also be a strong emphasis on outreach activities, collaboration, and the coordination of existing activities. A quantitative evaluation of the benefits that a future coordinated space weather service would bring to European industry and society will be carried out in parallel. This evaluation will independently assess the benefits of a service devoted to space weather across the wide range of domains that it affects.

The Pilot Project will focus on the development of a number of space weather applications projects in key areas. These will be integrated into a common network, which will be developed in parallel. This network, in turn, will provide support to the individual service development activities and will create a space weather application service provision infrastructure.



Space weather services are often targeted at users who are not specialists in space weather effects. These users require that the complex space weather system and how it affects their interests be interpreted by the service provider and converted into a format that is easily understandable. This might take the form of a 'traffic light' system

Areas in which service activities will be developed include (but are not limited to):
– Ground-based power distribution systems
– Space-based communication services
– Space-based navigation services and users
– Spacecraft development and operations (including drag effects)
– Scientific spacecraft users (instrument interference and campaign planning)
– Aircrew radiation-exposure monitoring
– Public outreach and tourism.

It is anticipated that this network of pilot services will pave the way for a future coordinated European Space Weather Applications Service.

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