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Space weather

ALEXI GLOVER*, EAMONN DALY*, ALAIN HILGERS* and DAVID BERGHMANS**

*Space Systems Environment Analysis Section, ESA/ESTEC, Keplerlaan 1, Postbus 299, 2200 AG Noordwijk, The Netherlands. **Research and Scientific Support Department, ESA/ESTEC, Keplerlaan 1, Postbus 299, 2200 AG Noordwijk, The Netherlands and SIDC, Royal Observatory of Belgium, Ringlaan 3, B-1180, Brussels, Belgium. E-mail: Alexi.Glover@esa.int

Space weather is caused by conditions on the Sun and in the solar wind, the magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can affect human life or health. It affects man-made systems such as satellite electronics, terrestrial power grids and radio communications. This paper provides an overview of how space weather arises in the solar–terrestrial system and how physical processes are able to cause space weather effects. We also discuss European perspectives and activities geared towards the possible initiation of a European Space Weather programme.

What is Space Weather?

The Earth orbits the Sun at a distance of 150 million km. The sun's light and heat shine on to the Earth, warming the surface of the continents, the upper metres of the seas and the atmosphere. This radiant energy is what primarily drives meteorological weather. Convection of air up from the surface of the Earth draws in the wind, and raises humid air up into the colder upper atmosphere. These physical effects of damp air in motion cause the weather to be warmer or colder, cloudy or clear, rainy or dry, windy or calm. These meteorological conditions alter our behaviour. Based on the weather, we make decisions as to whether to go out for a picnic, how much fuel to put on a plane, what agricultural activity to plan for the week, which route for a ship to take. These practicalities are all dependent both on the weather itself and on the predictions that can be made about what the weather will be in the immediate future.

The Sun has an atmosphere which, together with embedded magnetic fields, extends outwards from its surface past the Earth and beyond, towards the edge of the solar system and interstellar space. The entire sphere of influence of the sun is the heliosphere. The Earth orbits within the sun's atmosphere. The sun's atmospheric material bathes the Earth and its immediate space environment.

The sun itself is not a solid body, but comprises a hot ionized gas called a plasma. At the surface of the sun, the photosphere, the magnetic field that breaks through the surface is tied to the dense plasma and, as the sun rotates and the gas moves, the magnetic fields are deformed into a spiral pattern. These fields envelop the magnetic field of the Earth and deform it from a pattern similar to that of a large bar magnet into a teardrop shape, compressing the field on the sunward side and extending it on the opposite side. In addition, a persistent outflow of material from the sun is also detected at Earth: combined with the magnetic fields, this outflow is termed the 'solar wind'. Under certain conditions, particles from the solar wind are caught in the Earth's magnetosphere and are able to flow along magnetic field lines attached to the Earth. This may lead to the formation of electric currents at the Earth's surface. In addition, these particles may impact on the atmosphere (causing the aurora) or irradiate equipment above the atmosphere (such as artificial satellites). High energy solar radiation may also affect the Earth's ionosphere – the layers of charged particles that surrounds the Earth at heights of about 60–400 km – and the thermosphere – the boundary between space and the Earth's atmosphere – leading to radio communication difficulties when the level of radiation changes over very short time scales.

The effects of space weather are varied, but are not as pronounced on everyday life as meteorological weather. A broad range of technologies may be affected by space weather, the consequences of which have become more pronounced as the technology has advanced.

Equipment that nearly continuously observes the Sun in the range covering ultraviolet to X-ray wavelengths is now in place and other space missions have been launched to measure the Sun–Earth connection. It has thus been possible to establish close correlation between space weather in the near-Earth environment and the events on the Sun from which this weather has its origin. Predicting space weather has become a possibility, although many questions remain to be answered before accurate predictions of space weather events will be complete.

The Sun and the Earth

Most space weather effects have their origins in the solar corona, the lower part of the Sun's atmosphere. The brighter, inner parts of the corona are visible in a total solar eclipse. The corona is a hot ($> 10^6$ K) tenuous plasma extending away from the solar surface and out into the heliosphere. The dominant feature controlling the corona is the solar magnetic field. Solar activity varies with an 11 year cycle, with sunspots numerous and frequent during the period of solar maximum.

The structure of the corona also changes during the solar cycle. At solar minimum, when the Sun is least active, the magnetic field of the Sun is oriented in a simple dipole configuration, in a similar manner to that of the Earth. Near the solar equator, field lines originate from opposite hemispheres of the Sun and have opposite polarities. The magnetic field lines meet in a narrow layer in which the interplanetary magnetic field changes polarity abruptly, this implies that there is, at this layer, a thin sheet of electric current of very high density called the heliospheric current sheet.[2]

Near the Sun, the heliospheric current sheet appears during total solar eclipses as streamers extending outwards from the Sun's equator and is especially noticeable near the minimum of solar activity. Rotation of the Sun twists the interplanetary magnetic field lines into the shape of an Archimedian spiral.[3] As the solar cycle progresses towards higher activity levels, the magnetic field of the Sun deviates more and more from the original dipole. The current sheet near the Sun's equator becomes warped into a structure that resembles a ballerina's twirling skirt. Because the Sun's equator is nearly aligned with the ecliptic (the plane of the Earth's orbit), the Earth crosses the current sheet at least twice during each solar rotation of 27 days. At the north and south polar regions of the Sun, the magnetic field of the Sun extends into space. This allows the solar wind to escape in streams, referred to as holes in the corona. The boundaries of distinct high-speed streams are shock fronts where charged particles (ions and electrons) are accelerated. In addition, the interaction between this shock front and the Earth's magnetosphere triggers geomagnetic storms, during which the magnetic field of the Earth fluctuates. Coronal holes are long-lasting features, which survive for many weeks and are seen to rotate with the Sun as it rotates every 27 days, leading to recurrent geomagnetic storms observed approximately every 27 days.

Coronal mass ejections

The properties of the heliosphere are changed dramatically by the irregular occurrence on the Sun of Coronal Mass Ejections (CMEs). These CMEs are huge plasma clouds erupting from the solar corona and are now routinely observed with the Large Angle Spectroscopic Coronagraph (LASCO) on board the ESA-NASA SOHO space-borne solar observatory.[1] SOHO lies about 1.5 million km from Earth in the sunward direction, looking constantly at the Sun. Figure 1 illustrates a CME observed by SOHO.

Figure 1 provides multiple evidence of a space weather incident. The CME, observed here as a white cloud expanding to the right-hand side of the image, was ejected from the sun and travelled through interplanetary space at a speed of several hundreds of kilometres a second in the direction of the Earth. On reaching SOHO, the cloud enveloped the spacecraft. The white flecks in the final image are the effects on the camera of energetic particles in the cloud. The effects propagated the further 1.5 million km to the Earth and affected our immediate terrestrial environment.

There are more frequent CMEs at the maximum of the solar cycle, where there might be several CMEs per day, while during solar minimum conditions there will be only about 1 CME every two days. The expelled mass is of the order of 10^{12} kg (1000 million tonnes).[4]

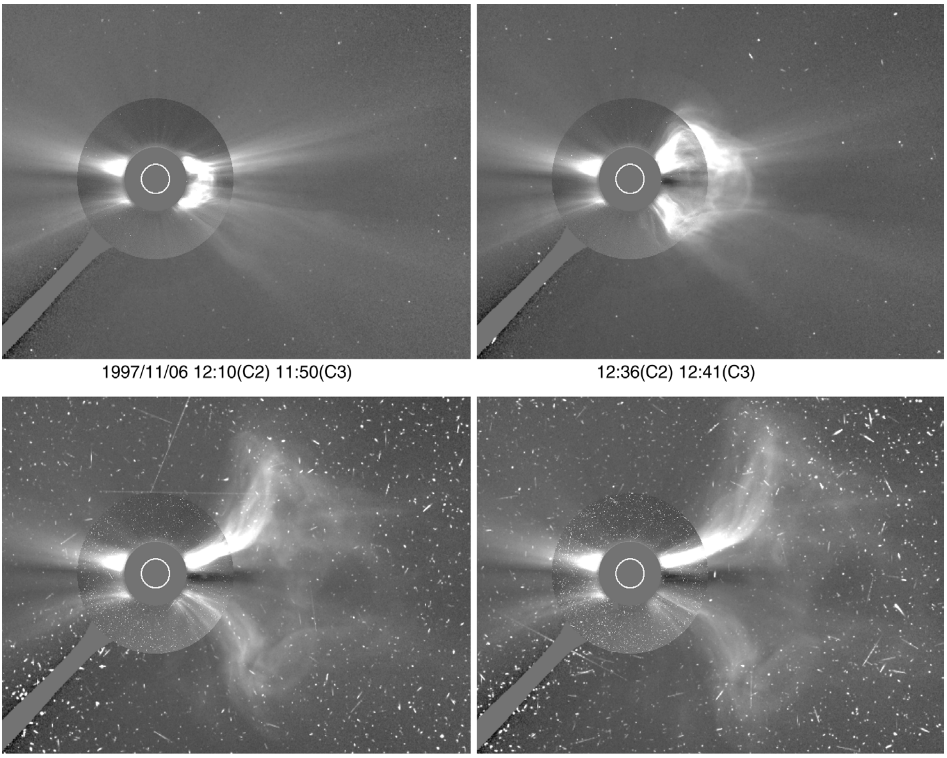
The CMEs that affect the Earth with space weather are among the so-called 'halo' CMEs and are observed as a halo of excess brightness completely surrounding the occulting disk and propagating radially outward in all directions from the Sun.[5] These characteristics are interpreted as CMEs travelling along the Sun–Earth line, either towards or away from Earth.

Identifying the eruption of a front-side halo CME in coronagraph images is the most practical way of getting advance warning of solar disturbances heading towards Earth. CMEs tend to arrive at the Earth at between 2 and 5 days, with an average travel time of approximately 80 hours. It is not easy to predict whether a front-side halo CME will lead to strong geomagnetic effects, nor when these might begin.

Prediction of CME onset

Two day's notice of a space weather event might not be sufficient in some cases. Long-range space weather forecasting might be possible if one could predict the onset of a CME itself by identifying its precursors on the Sun. CMEs erupt from active regions on the Sun, which are observed in X-ray or extreme-ultraviolet images as collections of bright loops extending out from the photosphere. Understanding the structure, evolution and stability of active regions and seeing what happens in the time before CMEs start is therefore an essential part of CME research.

With the advent of SOHO's Extreme Ultraviolet Imaging telescope (EIT),[6] a closer link between CMEs and early, related activity has been established. CMEs have frequently been associated with a dimming of extreme-UV emission in the corona caused as a wave transient crosses the disk.[7] Figure 2 is a sequence of SOHO/EIT images, showing one of these waves. Other possible precursors of CMEs currently being studied are so-called sigmoidal (S-shaped) features.[8] These features, when observed prior to CME onset, are thought to indicate those parts



1997/11/06 12:10(C2) 11:50(C3)

12:36(C2) 12:41(C3)

13:30(C2) 13:46(C3)

14:26(C2) 14:12(C3)

SOHO/LASCO

Figure 1. Development of a large coronal mass ejection (CME) as seen by the LASCO coronagraphs. The CME originated approximately 30 degrees off the west limb of the Sun on 6 November 1997. The four photographs are composite images as seen from the C2 and the C3 coronagraph of the LASCO experiment onboard SOHO. (Field of view, C2: 6 solar radii; C3: 32 solar radii.) At 12:10 UT the magnetic flux rope CME emerges from behind the C2 occulter with a velocity of 1500 km s^{-1}. At 12:41 UT the CME has expanded into the C3 field of view. At 13:46 UT the middle part of the CME has become a large, diffuse cloud with a dark hole in the centre. The two legs, which are still connected to the solar surface have been deflected away to the north and south. At the west limb the dark structure in the equatorial plane is caused by the blow-out of material from an equatorial streamer. Highly energetic ($E > 100$ MeV) protons accelerated at the site of the flare arrive at 13:46 UT at the location of SOHO and cause numerous bright points and streaks in the images. (Courtesy of the SOHO/LASCO and SOHO/EIT consortia.)

of the sun's magnetic field where a large amount of energy is stored. This energy is then released with CME onset and the S-shaped feature is no longer observed. These features were initially identified with data from the Japanese Yohkoh

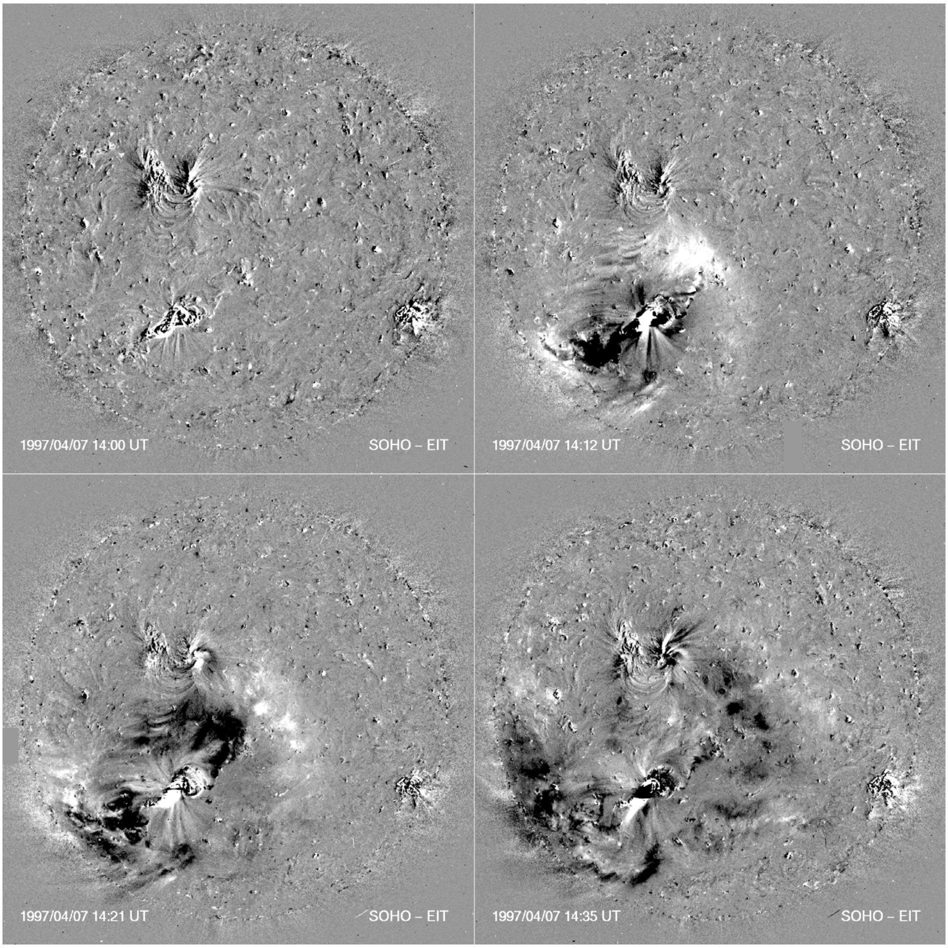


Figure 2. Sequence of SOHO/EIT images showing a shock wave running across the solar disc. The shock wave originated in the vicinity of a flaring solar active region; the flare began on 7 April 1997 at 13:59 UT, in conjunction with the flare was a large 'halo' coronal mass ejection (CME). EIT recorded these images in emission lines of Fe XII at 195Å; this ion is formed at a temperature of about 1.5 million degrees. Since the shock is relatively difficult to see in the original images, displayed here are running difference images, i.e. each image shows the difference from the previous image. The speed at which the shock wave runs across the solar disc was estimated at 1.5 million km h^{-1}. (Courtesy of the SOHO/LASCO and SOHO/EIT consortia.)

satellite.[9] Further research into sigmoidal features might lead to a more robust method to predict the onset of CMEs, even if the mechanism by which the eruption takes place is not yet fully understood.

Solar flares

Solar flares are sudden and rapid releases of magnetic energy in the solar atmosphere and are most commonly observed from active regions when magnetic loops interact, with explosive consequences. Flares can last for a few minutes to several hours, releasing power of order of 10^{25} W. Reaching Earth in a matter of minutes, these bursts of radiation have an ionizing effect on the upper atmosphere. In some extreme cases it may also lead to a slight increase in the radiation dose experienced at high aircraft altitudes. As a result, cosmic radiation monitoring onboard planes at these altitudes has been introduced in order to monitor any long-term effects this may have on aircrew who fly these routes regularly. The increased dose of X-ray and ultraviolet radiation is potentially harmful to the health of astronauts. By the time you are aware that a solar flare has taken place, you are being bathed in X-ray and ultraviolet radiation, and it may be too late to take many precautions. It may, however, be possible to predict when flares are likely to occur. Predictions rely on images of the solar disk, observing sunspots.

Solar energetic particle events

Another key aspect of space weather is the arrival at the Earth environment of solar energetic particles, consisting of ions and energetic electrons. The largest such events can enhance the radiation intensity in near-Earth space by several orders of magnitude. The particles travel at speeds approaching the speed of light. They arrive within tens of minutes after an eruptive event and can last for several days. Solar energetic particles can either originate from a solar flare or from interplanetary shocks. Owing to their charged nature, they can only propagate along magnetic field lines and, therefore, the importance of such an event at Earth depends not only on the characteristics of the source region but also on the structure of the interplanetary magnetic field. The particles can only reach us if the Earth and the solar source region are magnetically connected.

Space weather and the near-Earth environment

Earthward-directed CMEs are often observed to interact with the magnetosphere, leading to the onset of geomagnetic activity (magnetic storms). Figure 3 (not to scale) provides a simplified illustration of a CME crossing the interplanetary medium in the direction of the Earth, where it may interact with the Earth's magnetosphere.

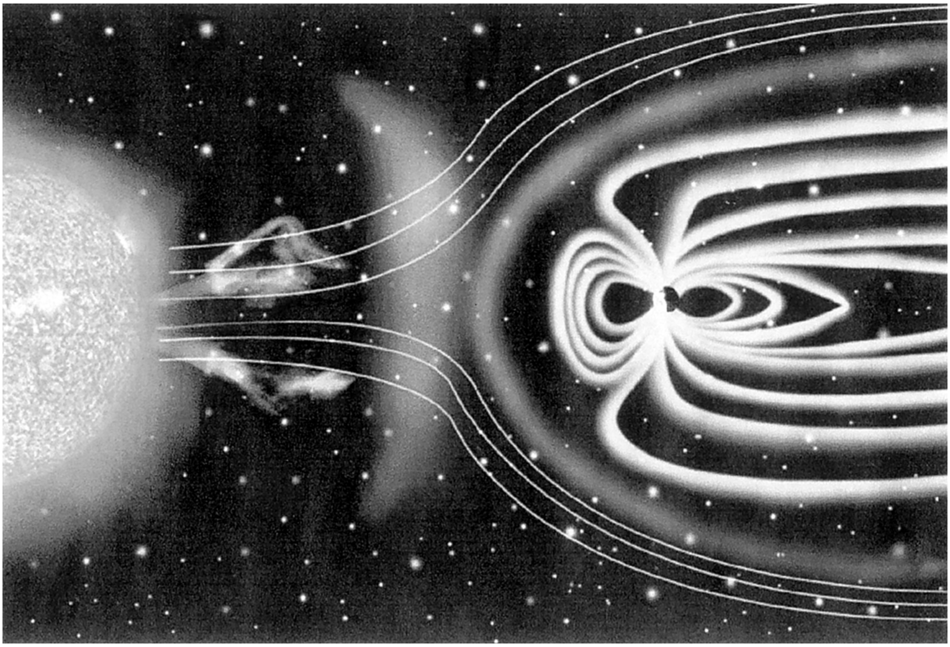


Figure 3. A schematic illustration of the solar terrestrial system. A continuous outflow of plasma and magnetic field from the sun causes the Earth's magnetic field to be distorted into a tear drop shape: being compressed on the sunward side and extended over a distance of several hundred Earth radii on the opposite side. An increase in solar wind speed and density often observed when a coronal mass ejection reaches the magnetosphere leads to increased compression on the sunward side and, under some circumstances, field lines from the CME are able to connect to Magnetospheric field lines, allowing material of solar origin to enter the magnetosphere, leading to strong geomagnetic effects such as the aurora borealis.

These interacting CMEs are geoeffective if they have a strong southward magnetic field component. In this orientation, the CME connects readily on to the Earth's magnetic field and allows material of solar origin to stream into the Earth's magnetosphere. Within the Earth's magnetosphere, particles are transported and accelerated to high energies. Remarkably, more than 30 years after the discovery of the Earth's radiation environment (the van Allen belts), the way in which this happens is still not clear. One of the issues most relevant to space weather is how energetic electrons appear after storms. These particles (the so-called 'killer electrons') are particularly responsible for important space weather hazards, including radiation hazards and electrostatic charging effects, which build up to a high electric potential on satellite structures and then spark as there it discharges. This can destroy sensitive microelectronics.

Hot plasmas are also responsible for space weather effects. They generate aurorae when the particles scatter down the Earth's magnetic field lines and impinge on the upper atmosphere.

At low altitude, the major source of radiation hazard is the inner radiation belt consisting of energetic protons. This is a relatively stable population due to the decay of cosmic rays but is subject to space weather variations in the form of changes in the atmosphere and thus has its lowest fluxes during solar maximum periods.

A further important space weather effect is on geomagnetic shielding. Geomagnetic shielding is the term given to the diverting effects of the Earth's magnetic field. Cosmic rays or solar energetic particles are prevented from penetrating into low altitudes above the equatorial regions of the Earth's surface. During space weather events this geomagnetic shielding is weakened, leading to larger fluxes than would otherwise be the case.

The effect of all these ionizing radiations may be to produce radiation hazards for aircraft flying at high altitude. While the hazard is usually negligible for passengers on a single journey, it may accumulate towards the maximum permissible dose for regularly flying aircrew. The amount of radiation received is usually lower for a given altitude when the aircraft are flying over the equator than over the poles, but changes in geomagnetic shielding may alter the safety factor.

Practical space weather effects

Electricity grids are affected by very rapid large current-flows in cables induced by currents in the ionosphere. The resulting current surges can destroy equipment hooked on to the grid, necessitate operational system reconfiguration or require special designs. Such an event produced a blackout of the Quebec electricity system in 1989 and its effects propagated across the United States, with tripped and burnt out equipment.

Some terrestrial communication systems are seriously affected by changes in the structure of the ionosphere induced by space weather, affecting the clarity of signal transmission or information for navigational position. As airspace becomes more crowded and planes more reliant on automatic navigation this issue becomes even more critical. Satellites communicate with the ground by exchange of radio signals. Radio propagation through the ionosphere can be perturbed by the influence of space weather. Ground-based communications and navigation services can be disrupted as well as radar-based remote sensing.

Geomagnetic field variations caused by space weather effects can perturb magnetic readings routinely used in oil prospecting. For example, oil drill heads are navigated at the end of long, flexible pipes with respect to the Earth's magnetic field.

Advanced avionics systems are becoming susceptible to cosmic radiation hazards. Space systems are subject to numerous types of serious radiation damage and interference. The solar panels of spacecraft are degraded by space weather radiation. Spacecraft can also suffer electric discharge following plasma-induced charging. Rapid atmospheric variations can affect spacecraft orbits and stabilization. The Hubble Space Telescope and the International Space Station both suffer from drag in the Earth's atmosphere, which is intensified during space weather events.

Reacting to space weather predictions

The strategies for dealing with space weather effects have different forms. In some cases this requires better equipment design, with increased reliability and/or economy. Appropriate electrical connection of electricity distribution subsystems, shielding of vulnerable satellite components against electrical discharge or radiation, and control of the electric potential of pipelines to avoid corrosion are some examples. In other cases, day-to-day or hour-to-hour prediction and monitoring of space weather can be used to alter operational behaviour. Astronauts on space walks can be brought inside their spacecraft if there is a potential hazard from a solar energetic particle (SEP) event. The spacecraft can be oriented with the largest mass (storage tanks, metal walls) towards the expected direction from which the radiation will come, to shield the astronaut inside. Aircrew are also at risk and vulnerable aircrew can be scheduled on flights at low altitude or in non-hazardous areas if there is a radiation health risk at high altitudes over the north or south poles. In the electricity industry, additional generators can be loaded on to power distribution networks to absorb power surges if there is increased probability that they will occur. The UK National Grid purchases tailored space weather predictions in order to identify such times.

European space weather activities

The joint ESA-NASA SOHO mission, situated upstream of the Earth towards the

Sun, continuously provides data about the Sun, and solar activity and its effects on the interplanetary environment. In this way it is able to provide space weather warnings as solar events occur. In addition, ESA's Cluster II fleet of four spacecraft flying in formation through the magnetosphere is able to observe changes resulting from the arrival of a CME. This has led to an increased understanding of what happens during active periods and further enhances our ability to predict space weather effects, such as those described in the previous section. The future ESA Solar Orbiter mission, whilst primarily a science mission, will further enhance space weather prediction capability. Solar Orbiter is part of the NASA initiated International Living with a Star Project (http://lws.gsfc.nasa.gov). It will orbit the Sun at a close distance, down to a fifth the Earth–Sun distance (45 solar radii), in an orbit that will, for the first time, provide images of the far side of the Sun. This gives information regarding the build up of activity and active centres on the far side of the Sun, before solar rotation brings them into view around the disk. It is hoped this will help to provide an earlier warning for space weather effects.

In addition to scientific research to predict space weather, engineers use computer-based models in order to estimate the level and type of radiation that will be experienced by a spacecraft throughout its lifetime. This aids in the design of spacecraft able to operate correctly without being subject to radiation damage. As spacecraft and their payloads have become more sophisticated, they have become more susceptible to the effects of the space weather environment. Miniaturization is itself a space weather hazard as it increases the vulnerability of satellite equipment. However, many models of the effects of space weather on satellites address the empirical needs of the space system developer and often oversimplify the physics of the phenomena. It is often the case now that spacecraft are considerably over-engineered to survive extreme worst-cases. Better data would lead to more rational risk analysis and lower-cost designs. A long-term goal of space satellite manufacturers is to produce models that are both physically accurate and responsive to user needs. ESA's Space Environments and Effects Analysis Section has responsibility for supporting the development of ESA missions.

The essential goal of a space weather service is to provide to affected sectors (spacecraft engineering, power networks, communications, etc) the data and services they need to be able to design and operate their systems in the presence of space weather hazards. ESA maintains a space weather web server through which the ESA initiatives and those of the European member states are accessible (http://www.estec.esa.nl/wmwww/spweather).

References

1. G. E. Brueckner, R. A. Howard, M. J. Koomen, C. M. Korendyke,

D. J. Michels, J. D. Moses, D. G. Socker, K. P. Dere, P. L. Lamy, A. Llebaria, M. V. Bout, R. Schwenn, G. M. Simnett, D. K. Bedford and C. J. Eyles (1995) The Large Angle Spectroscopic Coronagraph (LASCO). *Solar Phys*, **162**, 357–402.

2. B. J. Thompson, S. P. Plunkett, J. B. Gurman, J. S. Newmark, O. C. St. Cyr and D. J. Michels (1998) SOHO/EIT observations of an Earth-directed coronal mass ejection on May 12, 1997. *Geophysical Research Letters*, **25**(14), 2465.
3. E. Parker (1958) Dynamics of the interplanetary gas and magnetic fields. *Astrophysical J.*, **128**, 664.
4. R. A. Howard (1985) Coronal mass ejections 1979–1981. *J. Geophysical Research*, **90**, 8173.
5. R. A. Howard, D. J. Michels, N. R. Sheeley Jr. and M. J. Koomen (1982) The observation of a coronal transient directed at Earth. *Astrophysical J.*, **263**, L101–L104.
6. J.-P. Delaboudiniere, G. E. Artzner, J. Brunaud, A. H. Gabriel, J. F. Hochedez, F. Millier, X. Y. Song, B. Au, K. P. Dere, R. A. Howard, R. Kreplin, D. J. Michels, J. D. Moses, J. M. Defise, C. Jamar, P. Rochus, J. P. Chauvineau, J. P. Marioge, R. C. Catura, J. R. Lemen, L. Shing, R. A. Stern, J. B. Gurman, W. M. Neupert, A. Maucherat, F. Clette, P. Cugnon, and E. L. van Dessel (1995) The extreme-ultraviolet imaging telescope for the SOHO mission. *Solar Phys*, **162**, 291–312.
7. C. W. Smith, W. H. Matthaeus, G. P. Zank, N. F. Ness, S. Oughton, and J. D. Richardson (2001) Heating of the low latitude solar wind by dissipation of turbulent magnetic fluctuations. *Journal of Geophysical Research*, **106**(A5), 8253–8272.
8. R. C. Canfield, H. S. Hudson and D. E. McKenzie (1999) Sigmoidal morphology and eruptive solar activity. *Geophysical Research Letters*, **26**(6), 627.
9. S. Tsuneta, L. Acton, M. Bruner, J. Lemen, W. Brown, R. Caravalho, R. Catura, S. Freeland, B. Jurcevich and J. Owens (1991) The soft X-ray telescope for the Solar-A Mission. *Solar Physics*, **136**, 37–67.

About the Authors

David Berghmans is interested in the solar corona and is involved in the development of the Solar Influences Data analysis Center as a forecast centre for space weather effects. He is currently on leave at the Research and Scientific Support Department (RSSD) of ESTEC/ESA, Noordwijk.

Eamonn Daly is Head of the Space environments and Effects analysis section of ESA. He has been concerned with the development of ESA projects on radiation and plasma environments including potential hazards to spacecraft.

Alain Hilgers is currently the ESA technical officer of the ESA feasibility study of a space weather programme (Mar 2000–Nov 2001). He is an expert on body–plasma interactions.

Alexi Glover has worked in Solar Physics at University College London's Mullard Space Science Laboratory. She is currently based at ESA/ESTEC within the Space Environments and Effects Analysis Section.