THE SUN AND SPACE WEATHER

POST 130

Post Note November 1999

In much the same way as the weather on Earth can change rapidly, conditions in space are also very variable. One of the main factors affecting this so-called 'space weather' is the level of solar activity. Although this is constantly changing, one feature is a cyclical variation, with solar activity peaking every 11 years or so. The next such peak is due in 2000; there are concerns over its disruptive potential due to our increasing reliance on satellite-based services.

This POST Note describes the factors influencing space weather, examines its potential disruptive effects and discusses the issues that arise.

SPACE WEATHER

Space weather depends on complex interactions between the Sun and the Earth (**Box 1**). The outer part of the Sun's atmosphere envelopes the Earth and the other planets, so that its radiation (light, heat, x-rays, etc.), magnetic field and atmospheric structure all influence conditions in near-Earth space. Earth's own magnetic field and atmosphere also interact with the Sun's various outputs (Box 1), creating a highly variable system of magnetic fields, electric currents and charged particles.

THE SOLAR CYCLE

Measurements of the fluctuations in the various solar phenomena outlined in Box 1 are a recent development. However, other measurements of solar activity date back for many centuries. These include:

- Reports of sunspots (dark regions on the disc of the Sun). European records since 1610 include details of the area and number of groups of sunspots.
- Records of geomagnetic storms on Earth. These are caused by disruption of the Earth's magnetic field (especially at higher latitudes) and are characterised by auroral displays.

Such records reveal the cyclical nature in the intensity of solar activity. A striking feature is a repeated fluctuation in sunspot numbers over approximately 11 years (**Figure 1**). The next sunspot peak should be in 2000 but the prediction shown is subject to uncertainty in both the timing and height of the next peak. It was produced to help NASA and other space agencies plan the building of the International Space Station[1], because some changes in solar activity could be hazardous for humans in space (see below). Also shown in Figure 1 is the variation in the number of geomagnetic storms; the relationship between the two is by no means straightforward.

BOX 1 FACTORS INFLUENCING SPACE WEATHER

THE SUN

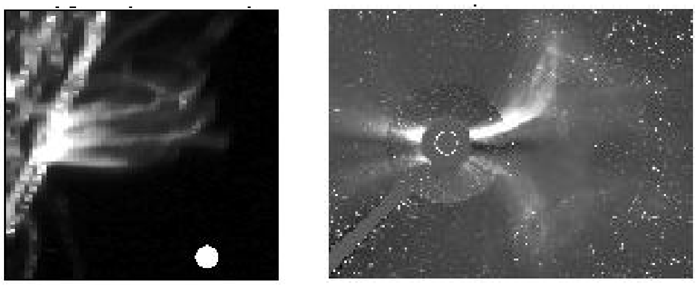
Radiation – the Sun emits radiation across the entire electromagnetic spectrum including x-rays, UV and visible light, heat, and radio waves.

Particles – the visible surface of the Sun is a **plasma**, a constantly moving flow of charged particles. This plasma extends to the Sun's outer atmosphere - the **corona**, which is normally only visible during a total solar eclipse. An image of loops of plasma outlining the local magnetic field at the Sun's edge is shown in the **Figure** below (left). The white filled circle shows the size of the Earth to the same scale. The hot plasma in the corona flows out continuously into interplanetary space as the **solar wind**.

Solar Eruptions - as well as the gradual trends above, abrupt changes in the corona can also occur. **Coronal mass ejections** (CMEs) and **prominence eruptions** hurl material into inter-planetary space. An image of a CME is shown in the **Figure** below (right). Localised flare events also occur, often in association with a CME or a prominence eruption. Flares produce a short-lived enhancement in the Sun's output across the electromagnetic spectrum and can also produce large fluxes of highly accelerated charged particles. All of these changes in the corona affect the solar wind.

Magnetic fluctuations - because plasma is composed of charged particles, its movement causes complex and changing magnetic fields. These are associated not only with the Sun's surface (strong polar magnetic fields grow and decay over the course of the solar cycle) and corona, but also with the solar wind.

FIGURE LOOPS IN THE SOLAR ATMOSPHERE (LEFT) AND A CORONAL MASS EJECTION (RIGHT)



Courtesy Rutherford Appleton Laboratory (left) and the Space Sciences Department, University of Birmingham (right).

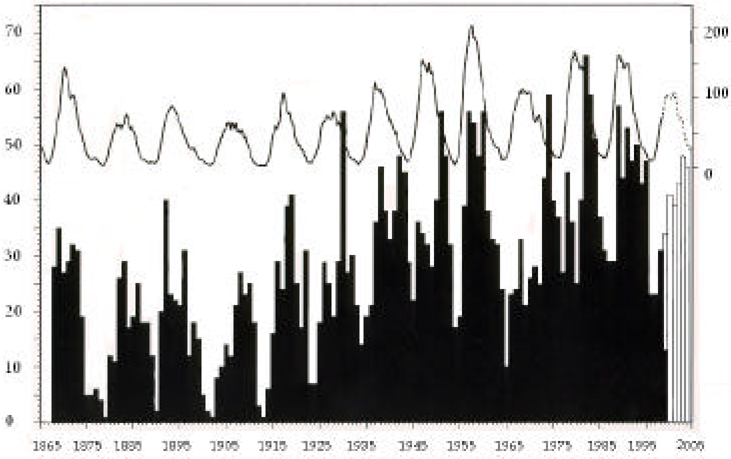
THE EARTH

Earth's magnetic field - is generated by fluid motions in the planet's core. On the Earth's surface, the field's strength and direction and the location of the magnetic poles change with time. This field is detectable in space at distances several times more than the Earth's diameter. It acts as a barrier to the solar wind, diverting it around the Earth. This causes a shock wave within which the solar wind becomes turbulent, interacting with the Earth's magnetic field to create the **magnetosphere**, bounded by the **magnetopause** (usually about 60,000km from the Earth). The locations of these depend on the speed and density of the solar wind. Charged particles from the Earth's own atmosphere also form part of the magnetosphere. These give rise to features such as the **ring current** and **radiation belts** (which contain more energetic particles). The location of these features also depends on levels of solar activity.

The Ionosphere – solar UV radiation has sufficient energy to break-up gases in the upper atmosphere. The resulting charged particles form the ionosphere, which is structured into layers and extends from ~80km to 1000km. Lower parts of the atmosphere are shielded from UV radiation by the ozone layer. Ionospheric particles move along magnetic field lines, especially at higher altitudes, and travel from one hemisphere to another.

1 See POSTNote 7, International Space Station, January 1990

FIGURE 2 SUNSPOT CYCLE AND GEOMAGNETIC ACTIVITY



The historical sunspot pattern is shown in the upper part of the Figure by the solid line (dotted for a prediction of the near future maximum), with the scale on the right hand side. The solid bars below give the number of geomagnetic storms per year (left hand scale), with the white bars showing a prediction for the next maximum. Figure and geomagnetic storm prediction supplied by the British Geological Survey (BGS).

SPACE WEATHER EFFECTS

It has been known for many years that changes in solar activity can have adverse effects. Some recent examples are given in **Box 2**.

Radio Communications

By the end of the 19th century it was clear that variations in the reception of radio signals was affected by solar activity. Short, medium and long wave radio communications are all affected by changes in space weather because such transmissions reflect radio waves off the ionosphere. TV and VHF radio communications are less prone to fluctuations in solar activity because they are not 'bounced' off the ionosphere. However, such services may be disrupted if they rely on satellites (see later).

As noted in Box 1, the Sun is itself a major radio source. Levels of solar radio emissions vary considerably and enhanced outputs may be detectable as 'noise' in terrestrial radio signals (usually in VHF transmissions). Major solar eruptions (see Box 1) can affect the ionosphere and cause local interference from distant stations not usually in range. Such events may also cause longer term disruption of radio communications lasting from days to weeks.

Spacecraft

Spacecraft may contain a wide range of commercial, military or scientific instruments, as well as those needed for their own control. These may be damaged by space weather in two main ways:

- Through exposure to a permanent level of highly energetic particles, UV/X-rays, etc. This can lead to a gradual and cumulative degradation over time, especially in a spacecraft's materials.
- More dramatic damage can also occur during extreme solar events such as eruptions (Box 1). Such events may expose spacecraft to highly energetic particles that can damage the sensitive electronic components in space instruments. In some cases the logic-state of a semiconductor device may be permanently changed, with unpredictable consequences for its operation.

BOX 2 EXAMPLES OF THE EFFECTS OF SOLAR EVENTS

March 1989 - An electrical blackout in Quebec, Canada, affected several million people. VHF signals travelled unusually long distances and caused interference problems. Many satellites were affected, and over a thousand objects (both spacecraft and debris) were "lost" in that they were no longer in their pre-storm orbits. The 'Northern Lights' were seen much further south than usual.

May 1998 – Communication with the Galaxy 4 satellite (in geostationary orbit) was lost, affecting 90% of the pager and cell phone networks in the USA. Recovery of the service involved moving other spacecraft from around the geostationary orbital ring and using spare capacity on other providers' spacecraft. In addition, all contact was lost with the Equator S spacecraft, which had recently been launched for the scientific study of just such events!

The extent to which satellites and other spacecraft are vulnerable to such effects depends on their orbit. Among the most vulnerable are satellites whose orbits overlap the Earth's radiation belts and/or ring current since solar disturbances increase the number and energy of particles in these features. Satellites in geostationary (GEO) orbits - i.e. equatorial orbits ~42,000km high - are generally outside such features but may still be adversely affected by the solar wind during extreme solar events. Another hazard for satellites in lower orbits (a few hundred kilometres high) is that they are still within the Earth's residual atmosphere; this causes drag on the satellite. This drag varies with the solar cycle, as the atmosphere expands (at increased solar activity) and contracts. Abrupt drops in altitude can occur after individual solar events; in extreme events hundreds of satellites and pieces of space debris lose altitude, disrupting service provision.

Navigation

Some modern applications rely on accurate maps of variations in the Earth's magnetic field. These chart variations in both time (from long-term changes in the global field) and place (depending on the local geology). One such example is the oil industry, which relies on geomagnetic maps to guide the drill and monitor the well direction. Accurate and safe drilling is usually achieved using data from the UK magnetic observatories provided by the British

Geological Survey (BGS). But such operations may be affected by solar events that cause magnetic storms, since these can cause large magnetic field fluctuations lasting from minutes to hours.

Recent years have also seen increasing reliance on satellite-based navigation systems; these too are vulnerable to solar events. They rely on the transmission and reception of gigaHertz (GHz) radio signals for determining a precise location. The best known example is the US military GPS (Global Positioning Satellite) system. Space weather conditions that affect the ionosphere can distort the satellite signal, causing an error in the location derived. Major solar events have also occasionally affected the satellites themselves (in a mid-altitude orbit), causing them to change orbit unpredictably.

Terrestrial Installations

Changes in space weather that lead to magnetic storms cause large fluctuations in the Earth's magnetic field. These in turn can induce electric currents in the ground, in pipelines, electrical transmission systems, etc. This can lead to pipeline corrosion and damage to transformers in electricity distribution systems, with power failures in extreme cases (see Box 2).

Effects on Humans

Exposure to ionising radiation and energetic particles also damages human cells, especially those that divide rapidly. This was mainly considered a risk to astronauts. But there is now a growing concern over the safety of aircrews, especially on trans-polar flights, since these routes involve maximum exposure to energetic particles. Moreover, as the altitude of air flights increases, so does the risk of exposure.

ISSUES

Changing Use of Satellites

Recent years have seen significant changes in satellites and the way they are used. These include:

- Increased reliance on satellites for providing an ever wider range of services.
- Changes in the types of orbits in which satellites operate.
- Changes in the design of the satellites themselves.

Our increasing reliance on satellites is not always obvious to the purchaser of the services they provide, especially in the communications area. It is expected that more Internet, e-mail, pagers and tracker services will use space-based links, with increases in both the total traffic and in the proportion carried by satellites. Such services will thus be vulnerable to the effects of space weather[2], and users may find that they have lost, or have a reduced quality of, service.

As far as the types of orbit are concerned, GEO orbits have been a popular choice in the past for telecommunication or weather satellites since they provide maximum coverage of the Earth's surface. Because of the popularity of this orbit, it has become very crowded, and other approaches are now being considered and adopted. One such new concept is satellite 'constellations', where tens to hundreds of small satellites are placed in a specified configuration in low or medium height orbits. Each satellite gives only a small surface coverage, but the constellation as a whole can service a very large area. Launches planned for the next few years will see a significant increase in satellites at these lower altitudes (the number of active GEO satellites will remain about the same). As noted previously, such orbits are more vulnerable to the effects of space weather. This has led to concerns over the possible disruption of services during extreme solar events as well as during the forthcoming peak in the solar cycle. One contingency being adopted in the constellation approach is to place spare satellites in orbit to provide extra capacity if problems do occur.

The design of space-borne devices is improving all the time – they are becoming smaller and using less power than before. But such a trend also makes them more vulnerable to changes in space weather, especially to damage from energetic particles. When a spacecraft does not behave in the way expected it is not always easy to diagnose the source of the problem, as information about disruptions and failures of service is regarded as commercially sensitive. The space industry has developed insurance packages to protect against losses arising from events such as launch failure and extreme space weather.

Solar Effects on Terrestrial Climate

Space weather does not only affect satellite-based services – there is also an emerging interest in its long-term effects on the Earth's climate. There are well known periods in the historic sunspot record when there has been lower sunspot activity than at present, and these are associated (at least in western Europe) with colder climatic conditions. As noted previously, sunspots are only one indicator of solar activity. Many in the climate science community see an urgent need for more detailed studies of possible

2 As well as direct effects on the operational spacecraft there is also the possibility of impact by space debris, the orbits of which are also affected by space weather events (see POST Note 80).

links between the Earth's climate and the various other measures of the Sun's activity.

Geomagnetic field variations have been measured for many years. The resulting picture shows changes in the levels of geomagnetic activity over each succeeding solar cycle, suggesting that longer-term solar trends may be present. It is also now possible to assemble a record of measurements of the solar wind stretching back long enough to suggest that the solar magnetic field may also be changing over recent solar cycles. There is also increasing evidence for long-term changes in the Sun's output. This applies to total radiation, magnetic field and solar particles (especially the latter two). However, the relationship between these long-term changes and measurements such as sunspot numbers is not straightforward (see Figure 2).

Monitoring, Prediction and Forecasts

Space weather has become an issue of rising concern, largely because of the increasing reliance of modern commerce and society on advanced technology. While it may be inconvenient to lose a satellite TV broadcast, the loss of a satellite-based communications service can have major economic impact or even result in loss of life.

Major initiatives in Europe and the US aim to develop improved understanding of space weather. This includes the continued scientific observation of the Sun and all parts of the interplanetary environment and support for increased work on prediction and forecasting. The aim is to enhance the provision and rapid dissemination of such forecasts. This may enable operators of vulnerable technologies to make informed commercial decisions about their response, such as to shut down, have staff on standby, or risk the consequences of a major event.

Long-term monitoring activities are also important. There is a need to monitor trends in solar activity and space weather, as well as to provide details of immediate conditions. However, the continuation of such apparently routine activity is often under pressure, as it costs time and money to maintain a consistent and accessible archive. UK research establishments active in this area include:

- British Antarctic Survey, with its ionospheric monitoring in the Antarctic.
- Rutherford Appleton Laboratory (RAL)
- British Geological Survey

Such organisations have developed products for commercial exploitation. However, in most cases they also contribute data to international databases, (and in return gain access to data from other countries). This raises a potential conflict between commercial exploitation of such information and international obligations relating to data exchange.

These long-term records and detailed space-based measurements (which are only intermittent) provide the basis for developing a predictive capability for space weather. However, deriving accurate forecasts is an extremely complex process. Users of space weather forecasts currently have one major supplier (a US government supported service). The European Space Agency (ESA) of which the UK is a member, is planning to establish its own forecasting service. It is hoped that this will improve the reliability and response through testing and development of independent systems.

Although space-based measurements have a key role in space weather predictions, the space record started only in 1957 so lacks the long time base of some of the ground based systems. Also, there are often gaps, especially in the direct measurement of solar wind conditions.

The Role of the UK

The UK space industry (excluding insurance services) encompasses a wide range of companies from large generalists to providers of highly specialist services including the development and marketing of data products. These companies have a turnover approaching £1 billion. Tele-communications and Earth observation dominate the UK industry and UK companies supply space users throughout the world. In both the commercial and scientific arenas the UK's success is built on a good long-term track record. In such a business, with high costs for failure (such as an instrument failing to operate after launch), those with a proven track record are at an advantage. However, there is also a need for continuous innovation.

Further Information

http://www-istp.gsfc.nasa.gov/Education/gloss.html

http://sohowww.nascom.nasa.gov

http://www.solar.isas.ac.jp/english/index.html

http://www.esa.int

http://www.bnsc.gov.uk

Parliamentary Copyright 1999
The Parliamentary Office of Science and Technology, 7 Millbank, London SW1P 3JA, tel: [0171] 219 2840.
See also www.parliament.uk/post/home.htm